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Taylor-Type Rules and Permanent Shifts in Productivity Growth

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ABSTRACT:

This paper examines the impact of a permanent shock to the productivity growth rate in a New Keynesian model when the central bank does not immediately adjust its policy rule to that shock. Our results show that inflation and productivity growth are negatively correlated at business cycle frequencies when the central bank follows a Taylor-type policy rule that targets the output gap. We then demonstrate that inflation is more stable after a permanent productivity shock when monetary policy targets the output growth rate (not the output gap) or the price-level path (not the inflation rate). As for the welfare implications, both the output growth and price-level path rules generate much less volatility in output and inflation after a productivity shock than occurs with the Taylor rule.

JEL Codes: E30, E42, E58

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1. Introduction

During the 1990s, inflation rate averaged 3 percent per year in the United States, well below the 5- to 10-year-ahead forecasts of 5 percent made in 1989. In retrospect, the surprisingly low inflation of the 1990s is attributable to a permanent rise in productivity growth. Orphanides et al. (2000) likewise argue that rising U.S. inflation from 1965 to 1980 was the result of real-time errors in the measurement of potential output.[1] They contend that a productivity slowdown reduced the actual growth rate of potential output below its perceived growth rate, which led policymakers inadvertently to follow an inflationary policy. This paper investigates one source of the negative correlation between inflation and productivity growth to determine whether policymakers can prevent an unintentional change in monetary policy after a productivity growth shock.

Taylor (1993) outlines a simple monetary policy rule in an attempt to describe how the Federal Reserve has conducted monetary policy in recent years. The Taylor rule says that the nominal interest rate target adjusts according to deviations of output from its potential and the inflation rate from its target rate. Recently, researchers also have examined how well the Taylor rule achieves the objectives of the monetary authority. Although it is not usually the optimal monetary policy rule, researchers find that the Taylor rule performs relatively well in a variety of macroeconomic models under alternative assumptions about potential output and real interest rates.[2] We, however, find that the Taylor rule does not work well when there is a permanent shift in the productivity growth rate that is not immediately observed by policymakers.

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[1] See also Orphanides (2003a, 2003b). Edge, Laubach, and Williams (2007) investigate a model in which agents learn about shifts in long-run productivity growth.

[2] See, for example, the papers collected in Taylor (1999b) and on the "Monetary Policy Rule Home Page" website: http://www.stanford.edu/~johntayl/PolRulLink.htm.

This paper examines the impact of a permanent shock to the productivity growth rate in a standard New Keynesian model under alternative monetary policy rules. Our results indicate that a permanent rise in productivity growth causes an unstable decline in inflation when the central bank follows the standard Taylor rule and does not immediately observe the shock. The negative correlation between productivity growth and inflation, however, is specific to the Taylor rule. When the central bank targets the output growth rate or the price-level path instead of the level of output, we show that inflation initially rises and eventually returns to its target without any intervention by the central bank. Furthermore, inflation and the output gap vary much less when the output growth rate or the price-level path is the target of monetary policy as opposed to the level of output, which is used in the Taylor rule. Those results suggest that the Taylor rule has it backwards. That is, we find that the monetary authority should target the output growth rate and the price-level path instead of the level of output and the inflation rate as suggested by Taylor (1993).

The paper proceeds in the following manner. Section 2 outlines a conventional New Keynesian model with a permanent productivity growth shock. Section 3 examines how the economy responds to a permanent productivity growth shock under various monetary policy rules. To assess the welfare implications of the alternative policy rules, Section 4 examines the volatility of inflation and output over horizons ranging from 1 quarter to 5 years after a permanent productivity shock. Section 5 concludes.

2. The Model

We use a standard New Keynesian model with infinitely lived households who maximize utility over consumption and leisure. Our model features include Calvo-style price setting, capital adjustment costs, monopolistically competitive firms, a role for money via a “shopping-time” constraint, and alternative nominal interest rate rules for implementing monetary policy. In our model, the central bank’s optimal policy is to stabilize the inflation rate at its steady state to eliminate the sticky price distortion.

Our analysis evaluates the effects of a permanent shift in the productivity growth rate on the economy under alternative monetary policy rules.[3] An abbreviated version of our model is presented below, whereas the entire model is outlined in the appendix.[4]

2.1 Households

Households are infinitely lived agents who seek to maximize their expected utility from consumption, c_t, and leisure, l_t,

$$E_0\left[\sum_{t=0}^{\infty}\beta^t\left(\ln(c_t)+\chi\frac{l_t^{1-\omega}}{1-\omega}\right)\right] \tag{1}$$

subject to the following budget constraint, time constraint, and capital accumulation equation:

$$c_t+i_t+M_t/P_t+B_t/P_t=w_tn_t+q_tk_t+d_t+M_{t-1}/P_t+R_{t-1}B_{t-1}/P_t+T_t/P_t, \tag{2}$$

$$l_t+n_t+s_t=1, \text{ and} \tag{3}$$

$$k_{t+1}-k_t=\varphi(i_t/k_t)k_t-\delta k_t, \tag{4}$$

where P_t is the price level, i_t is investment, M_t is the nominal money stock, B_t is government bonds, w_t is the real wage, n_t is labor, q_t is the capital rental rate, k_t is the capital stock, d_t is the firms’ real profits remitted to the households, R_t is the gross nominal interest rate from period t to $t+1$, T_t is a transfer from the monetary authority, E_0 is the expectational operator at time 0, β is the discount factor, δ is the depreciation rate, χ and ω are preference parameters, and s_t represents

[3] See Pakko (2002) for a richer discussion of the transitional effects associated with a permanent change in the growth rate of technological progress.
[4] Our model is a modified version of the model in Gavin, Keen, and Pakko (2005).

the shopping-time costs of holding money balances: $s_t = \zeta(P_t c_t/M_t)^{\gamma}$. The parameter $\varphi(\cdot)$ represents capital adjustment costs that are given by $i_t - \varphi(i_t/k_t)k_t$. We assume that the average and marginal capital adjustment costs are zero around the steady state (i.e., $\varphi(i_t/k_t) = i/k$ and $\varphi'(i_t/k_t) = 1$).

2.2 Firms

Each firm produces a heterogeneous good in a monopolistically competitive market. Specifically, firm f produces its output, $y_{f,t}$, according to the following production function:

$$y_{f,t} = k_{f,t}^{\alpha}(Z_t n_{f,t})^{(1-\alpha)}, \tag{5}$$

where $n_{f,t}$ is firm f's labor demand, $k_{j,t}$ is firm f's capital demand, Z_t is an economy-wide productivity factor, and $0 < \alpha < 1$. The differentiated output of all the firms is then combined to generate aggregate output:

$$y_t = \left[\int_0^1 y_{f,t}^{(\epsilon-1)/\epsilon} df\right]^{\epsilon/(\epsilon-1)}, \tag{6}$$

where $-\varepsilon$ is the price elasticity of demand for $y_{f,t}$ and $y_t = c_t + i_t$. The productivity factor, Z_t, evolves such that its growth rate follows a random walk:

$$\ln(Z_t/Z_{t-1}) = \ln(Z_{t-1}/Z_{t-2}) + v_t, \tag{7}$$

where $v_t \sim N(0,\sigma^2)$. Initially, productivity grows at a deterministic rate of $\bar{g}$. Following Calvo (1983), the probability that a firm can set a new price is η, and the probability that a firm cannot change the price that it charged last period is $(1 - \eta)$.[5]

2.3 Calibrating the Model

Our calibration of the parameters is consistent with that of the literature. The household discount

[5] Since the steady-state inflation rate is zero in our model, indexation is not included in the price-setting rule.

factor, β, is set to 0.99 and the preference parameter, χ, is set so that the steady-state labor supply, $\overline{n}$, equals 0.3. In the steady state, shopping time, $\bar{s}$, equals 1 percent of the time spent working. The other preference parameter, ω, is calibrated to 7/9, which implies that the elasticity of labor supply with respect to the real wage is approximately equal to 3.[6] The shopping-time parameter, γ, is set to unity, so that the interest rate elasticity of money demand equals –0.5.[7] The capital share of output, α, is set to 0.33 and the capital stock is assumed to depreciate at 2 percent per quarter. The price elasticity of demand, ϵ, is set equal to 6, which is consistent with a steady-state markup of 20 percent. We calibrate the probability of price adjustment, η, equal to 0.25. That parameterization implies that firms change prices on average once a year. Capital adjustment costs are calibrated so that the elasticity of the investment-to-capital ratio with respect to Tobin's q, $[(i/k)\varphi''(\cdot)/\varphi'(\cdot)]^{-1}$, is equal to 5. The steady-state gross inflation rate, $\bar{\pi}$, is 1. Finally, we consider the specification and calibration of various monetary policy rules.

2.4 The Monetary Authority

The monetary authority targets the nominal interest rate, R, as follows:

$$\hat{R}_t = (1+\theta_\pi)\,\hat{\pi}_t + \theta_y\ \hat{y}_t + \theta_g\,\hat{g}_t + \theta_p\ \hat{p}_t, \tag{8}$$

where $\theta_\pi \geq 0$, $\theta_y \geq 0$, $\theta_g \geq 0$, $\theta_P \geq 0$, p_t is the log of the price level, and g_t is the growth rate of output. The symbol '^' indicates the variable's percentage deviation from its steady state observed before the permanent shift in productivity growth. Equation (8) then resembles a Taylor (1993) rule in which θ_g and θ_P are set = 0. In our sticky price model, the optimal monetary policy rule, if it were implementable, prevents the inflation rate from deviating from its target by setting $\theta_\pi = \infty$. We initially analyze the effects of a permanent productivity growth shock on key

[6] The elasticity of labor supply with respect to the real wage equals $(1-\bar{n}-\bar{s})/(\bar{n}\omega)$.
[7] The interest rate elasticity of money demand is approximately equal to $-1/(1+\gamma)$.

economic variables under the optimal policy rule and then use those results to evaluate alternative and more politically feasible monetary policies.

3. Monetary Policy's Response to a Productivity Growth Shock

This section examines the impact of a permanent shock to the productivity growth rate for various parameterizations of the monetary policy rule given in Equation (8). We assume that productivity increases at 0.4 percent per period (or quarter) and then a productivity shock (v_1 = 0.1) permanently raises the productivity growth rate to 0.5 percent per period. Impulse response functions for capital stock growth, the inflation rate, real and nominal interest rates, real wage growth, real marginal cost, hours worked, and output growth to that productivity growth shock are shown for each monetary policy rule considered.

3.1 The Optimal Policy

Our initial objective is to establish the optimal monetary policy for comparison with alternative monetary policy rules. King and Wolman (1999), Woodford (2003), and Canzoneri, Cumby, and Diba (2004) find that a monetary policy rule that eliminates the distortions caused by nominal frictions, such as sticky prices, is approximately optimal. That rule is approximately optimal because distortions due resulting from real features, such as monopolistic competition and the shopping-time costs, are small relative to distortions associated with nominal rigidities. In our model, price stickiness is the only nominal friction and the distortions caused by it can be eliminated by perfectly stabilizing inflation.

The solid line in Figure 1 shows the impulse responses of key economic variables to a permanent productivity growth shock in which the monetary authority follows the optimal policy rule ($\theta_\pi = \infty$, and all the other θ_is equal zero). That shock immediately causes households' permanent income to rise, which in turn leads to an upward spike in consumption and a decline in hours worked as households increase their leisure time. Furthermore, firms raise their demand for labor which, when combined with the decline in labor supply, causes hours worked to fall and the real wage to spike upward.[8] That instantaneous decline in labor dominates the rise in productivity, so that output initially falls. The decrease in output and the rise in consumption require that investment sharply declines and the growth rate of capital stock slows. The capital stock response, however, is not unexpected. According to the Solow model, a rise in technology growth causes capital per effective unit of labor to decline as the economy transitions to its new balanced growth path. The increase in productivity raises future capital rental rates, so that the real interest rate jumps on impact. Under the optimal policy rule, the nominal interest rate response mimics the real interest rate because inflation remains unchanged. Finally, the central bank's policy of keeping inflation constant guarantees that firms' price markup and real marginal cost remain unchanged.

In subsequent periods, the economy begins to transition to its new steady state. Consumption growth moderates to a degree consistent with the real interest rate. Faster productivity growth raises the growth rate of the real wage, which encourages households to substitute away from leisure and toward more work. The increase in hours worked and the growth rate of productivity raises the growth rates of output and investment. Both real and nominal interest rates continue to rise as the returns to capital increase.

Although placing an extreme weight on inflation (i.e., $\theta_\pi = \infty$) is theoretically the optimal monetary policy, most central banks are unable politically to implement such a policy. Therefore,

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[8] Basu, Fernald, and Kimball (2006) and Francis and Ramey (2005) provide empirical evidence that hours worked declines after a positive technology shock.

we will measure how close alternative monetary policy rules, which are more politically feasible, come to the optimal policy.

3.2 The Weak Inflation Rule

We begin by considering a policy in which the central bank weakly targets the deviation of inflation from its target. Specifically, the monetary authority sets its nominal interest rate target in response to changes in the inflation rate:

$$\hat{R}_t = (1 + \theta_\pi)\,\hat{\pi}_t, \tag{9}$$

where $\theta_\pi > 0$ is a necessary condition for the model to have a stable and unique solution.[9] The longer dashed lines in Figure 1 depict the impulse responses to a 0.1 percent permanent increase in the productivity growth rate when the monetary authority follows the weak inflation rule (θ_π = 0.5). The key difference between the weak inflation rule and the optimal rule ($\theta_\pi = \infty$) is that a permanent productivity growth shock causes inflation to increase and the rise in the nominal interest rate to be greater with the weak inflation rule. To understand that result, substitute the long-run Fischer equation, $\bar{R}_t = \bar{r}_t + \bar{\pi}_t$, into a long-run version of Equation (9), so that inflation can be solved as a function of the long-run real interest rate:

$$\bar{\pi}_t = \bar{r}_t/\theta_\pi. \tag{10}$$

Since the 0.1 percent increase in productivity growth boosts the long-run real interest rate by approximately the same amount, long-run inflation rises by 0.2 percent with the weak inflation rule, whereas it remains unchanged under the optimal policy rule.[10] The long-run nominal interest rate then increases by 0.3 percent with the weak inflation rule according to the Fischer

[9] This condition, sometimes referred to as the "Taylor principle" [Taylor (1999a)], states that a percentage point change in the nominal interest rate target must exceed the corresponding change in the inflation rate.
[10] The one-for-one relationship between productivity growth and the real interest rate is due to our assumption that utility is a function of the logarithm of consumption.

equation but by only 0.1 percent with the optimal policy.

The inflation caused by the permanent productivity growth shock with the weak inflation rule also affects real variables, albeit only slightly. Firms, which can adjust their prices only infrequently, raise their prices aggressively whenever given the opportunity because they expect long-run inflation to increase. Those higher prices further dampen output growth, which then causes the real marginal cost to fall modestly and capital stock growth and hours worked to decline even more.

The results for Equation (10) also illustrate the effect of θ_π on both the inflation rate and the nominal interest rate. Specifically, a lower value for θ_π implies that the endogenous response of the inflation rate and the nominal interest rate to an exogenous shock will be higher and those variables will fluctuate more. An economy with a central bank that aggressively responds to inflation (i.e., θ_π is large) will not observe large nominal interest rate fluctuations unless there are similarly large movements in the real interest rate.

3.3 The Taylor Rule

The shorter dashed lines in Figure 1 show the impulse responses for the Taylor (1993) rule in which the nominal interest rate target responds to both the inflation rate and the level of output:

$$\hat{R}_t = (1 + \theta_\pi)\,\hat{\pi}_t + \theta_y\ \hat{y}_t, \tag{11}$$

where $\theta_\pi = 0.5$ and $\theta_y = 0.5$. The impulse responses in Figure 1 demonstrate that setting $\theta_y > 0$ in the Taylor (1993) rule has a dramatic effect on both nominal and real variables. To understand the impact of θ_y, Equation (11) is solved for the long-run inflation rate using the same procedure as for Equation (10):

$$\bar{\pi}_t = \frac{1}{\theta_\pi}\bar{r}_t - \frac{\theta_y}{\theta_\pi}\bar{y}_t. \tag{12}$$

The 0.1 percent increase in the productivity growth rate affects inflation by boosting both the long-run real interest rate and the output growth rate by 0.1 percent each. The inflation rate in Equation (12), however, responds to the deviation of output from its potential, which is now growing faster. If the policymaker's response to the change in the underlying productivity growth rate is slow, then the Taylor rule generates a negative correlation between inflation and productivity growth at business cycle frequencies.[11] Specifically, the long-run output gap in Equation (12) will get progressively larger each period, which corresponds to a continually falling inflation rate. The persistent decline in inflation highlights a critical problem with the Taylor rule. That is, a permanent productivity growth shock causes an unstable response when the monetary authority follows the Taylor rule but fails to adjust that rule to the productivity shock's effect on potential output.

Firms' pricing decisions are affected by the original Taylor rule's endogenous response to a permanent productivity shock. The prospect of a declining inflation rate forces firms, which can infrequently adjust their prices, to select a lower price than they otherwise would if they could adjust their prices every period. Those lower prices lead to higher output demand, a smaller price markup, and a rise in the real marginal cost compared with the weak inflation rule and the optimal policy rule. To raise production, firms increase their demand for inputs, which raises the real wage and the rental rate of capital and dampens the decline in hours worked and the capital stock growth rate. The higher capital rental rate then boosts the real interest rate. The nominal interest rate initially rises with the real interest rate, but then declines in subsequent periods as expected inflation falls. Therefore, our results indicate that the Taylor rule generates a negative correlation between inflation and real output growth after a permanent productivity

[11] Kiley (2003) provides detailed evidence about this negative correlation. He uses an elementary aggregate demand/aggregate supply model in which the Federal Reserve targets constant money growth to explain this empirical regularity.

growth shock.

3.4 An Output Growth Rule

Figure 2 displays the impulse responses to the optimal policy and two proposed policy rules that improve on Taylor's rule. The output growth rule ($\theta_\pi = 0.5$ and $\theta_g > 0$) replaces the output gap in the Taylor rule with the change in the output gap.[12] This specification is appealing because output growth converges to a constant growth rate after a permanent productivity shock, whereas the output gap grows into perpetuity if the monetary authority does not recognize the shock. To understand why the monetary authority should target the output growth rate, consider the intertemporal Euler equation from the households' problem. For simplicity, we abstract from the complications introduced by the shopping-time specification and assume that consumption enters the utility function in logged form. The resulting intertemporal Euler equation relates the growth rate of consumption to the real interest rate:

$$c_{t+1}/\beta c_t = 1 + r_t. \tag{13}$$

Since long-run consumption grows at the steady-state productivity growth rate, $\bar{g}$, Equation (13) shows that the real interest rate is positively related to $\bar{g}$:

$$(1 + \bar{g})/\beta = 1 + \bar{r}.$$

That is, a long-run increase in the productivity growth rate of 0.1 percent will permanently raise the real interest rate by 0.1 percent. As a result, we set $\theta_g = 1$.

The output growth rule assumes that the monetary authority's nominal interest rate target responds to both the inflation rate and to the output growth rate:

$$\hat{R}_t = (1 + \theta_\pi)\,\hat{\pi}_t + \theta_g\,\hat{g}_t. \tag{14}$$

[12] Several authors, including Orphanides and Williams (2002) and Walsh (2003), have recommended replacing the output gap with the growth rate of the output gap.

Using the long-run Fischer equation, we can show that the inflation rate is related to the real interest rate and the growth rate of output:

$$\bar{\pi}_t = \frac{1}{\theta_\pi}\bar{r}_t - \frac{\theta_g}{\theta_\pi}\bar{g}_t.$$

Since both the real interest rate and output grow at the same long-run rate and $\theta_g = 1$, the inflation rate will equal zero.

The longer dashed lines in Figure 2 illustrate the impulse responses of key economic variables to a permanent productivity growth shock when the monetary authority follows our output growth rule. Initially, the increase in the real interest rate dominates the small rise in output growth, so inflation rises. Over the next several periods, the inflation rate falls as output grows faster than the real interest rate. Falling inflation expectations induce price-adjusting firms in our sticky price model to set their prices lower than they would in the absence of price rigidities. The lower prices stimulate output demand, dampen the decline in capital stock growth, and raise the real marginal cost relative to their responses with the optimal policy. The higher demand for output raises firms' labor demand, relative to the optimal policy, which increases real wage growth and dampens the fall in hours worked. Furthermore, the reduced decline in the capital stock limits the increase in future capital rental rates, which leads to a smaller rise in the real and nominal interest rates when compared with the optimal policy.

Within two years, the impulse responses for the real variables under the output growth rule converge to the responses with the optimal policy: The output growth target in the policy rule indirectly captures the changes in the long-run real interest rate. Therefore, a permanent shock to productivity growth does not have any long-run effects on inflation.

A comparison of Figures 1 and 2 reveals that inflation is more than 5 times more variable with either the weak inflation rule or the Taylor rule than it is with the output growth rule.

Specifically, inflation under the output growth rule rises by slightly less than 0.02 percent and falls by less than 0.03 percent. That small variation compares favorably with the optimal monetary policy in which inflation remains constant.

3.5 A Price-Level Path Rule

Another monetary policy rule that improves on the Taylor rule is one that responds to deviations of the deterministic price level from its target path. [13] Svensson (1999) shows that the discretion solution to a model with a price-level path target is equivalent to the commitment solution to that same model with an inflation target.[14] The key difference between a price-level path target and an inflation target is the policy response when inflation rises above its target. A price-level path target automatically forces inflation to fall below its target to "undo" the previous inflation, whereas an inflation target ignores previous deviations and simply seeks to return the inflation rate to its target. Our price-level path rule assumes that the nominal interest rate target moves one-to-one with the inflation rate and also responds to deviations of the price level from its long-run price path:

$$\hat{R}_t = \hat{\pi}_t + \theta_p \ \hat{p}_t. \tag{15}$$

By substituting $\hat{p}_t = \hat{\pi}_t - \hat{p}_{t-1}$ into Equation (15), the long-run link between inflation and the real interest rate under a price-level path rule can be expressed as follows:

$$\bar{\pi}_t = \frac{\bar{r}_t}{\theta_p} - \bar{p}_{t-1}. \tag{16}$$

The shorter dashed lines in Figure 2 show the impulse responses of key variables to a

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[13] The target price-level path grows at the target inflation rate. A price-level path target is essentially a long-run inflation target.

[14] Gaspar, Smets, and Vestin (2007) survey the literature on price-level path rules, and Gorodnichenko and Shapiro (2007) show that including a price-level path target in the policy rule generally improves the performance of the economy in the presence of temporary shifts in productivity growth.

permanent productivity growth shock when policymakers implement a price-level path rule (θ_p = 1).[15] The productivity shock initially raises the real interest rate faster than the lagged price level, so the inflation rate rises. In subsequent periods, the increase in the lagged price level catches up with the higher real interest rate. Therefore, inflation gradually returns to its steady state. Price stickiness prevents some firms from raising their prices, so those firms must accommodate the higher demand for their goods by raising their output. The higher output increases firms' demand for factor inputs, which raises hours worked, capital stock growth, and real wage growth above their respective levels with the optimal policy. The higher capital stock growth then dampens the rise in the capital rental rate, which leads to a more modest rise in the real interest rate. The impulse responses of those real variables with the price-level path rule, however, are closer to their respective responses with the optimal policy than with either the output growth rule or the Taylor rule. The nominal interest rate mimics the optimal policy almost perfectly because the smaller short-run rise in the real interest rate is offset by the higher inflation rate.

4. Inflation and Output Volatility: A Measure of Welfare

Researchers have shown that monetary policy minimizes welfare losses when it eliminates the output fluctuations caused by nominal frictions. That result indicates that the welfare loss in our model is proportional to the variance of the output gap (the deviation of output from its path in the absence of nominal rigidities).[16] Although welfare loss is properly measured using current-quarter output volatility, our New Keynesian model, like most other models, does not incorporate

[15] Our calibration of θ_p is based roughly on the relationship between Hodrick-Prescott-filtered data on the price level and the nominal interest rate. Specifically, volatility of the percent deviation of the Consumer Price Index from its long-run trend is similar to that of the federal funds rate over the past two decades.
[16] This definition of the output gap is suggested by Neiss and Nelson (2003).

characteristics of the real economy that make the long-term horizon relevant. For example, our model does not include long-term loans or long-term planning problems which, although difficult to model, are essential to the real economy. Since central banks are concerned about the long-run consequences of their policy decisions, we examine the impact of permanent productivity growth shocks on the long-term volatility of the output gap and inflation under the Taylor rule, the output growth rule, and the price-level path rule.[17]

Our analysis focuses on the output and inflation fluctuations over forecast horizons as long as 5 years because we believe that interval is a reasonable time for policymakers to recognize changes in the balanced growth trend. We assume that the economy begins at its steady state and then simulate 5 years of permanent productivity growth shocks over 1,000 times in which the standard deviation of the productivity shock is 0.1 percent per quarter. At each forecast horizon, we calculate the average deviation of the annual inflation rate and the output gap from their respective values under the optimal policy.

Figure 3 shows the impact of permanent productivity growth shocks on the standard deviations of inflation and output growth from the optimal policy over forecast horizons of 1 quarter, 1 year, 2 years, 3 years, 4 years, and 5 years ahead. The upper panel displays the results for the inflation rate. When comparing the three rules, inflation varies the most at all forecast horizons with the Taylor rule. Inflation volatility in that model is modestly high in the short-run forecast horizons, declines over the 2- and 3-year horizons, and then skyrockets in later years. As for the other two monetary policy rules, inflation variability is modestly lower with the output growth rule for the 1-quarter- and 1-year-ahead forecast, whereas inflation fluctuates the least with the price-level path rule at forecast horizons of 2 years and beyond. In fact, inflation

[17] The long-term volatility of the output gap and inflation is considered because many papers measure welfare loss as a weighted average of the fluctuations in the output gap and inflation.

volatility continues to fall with the price-level path rule after 2 years, while it keeps rising with the output growth rule. Our results suggest that, on average, a price-level path rule minimizes inflation fluctuations after a permanent productivity growth shock.

The bottom panel of Figure 3 depicts the impact of permanent productivity growth shocks on output growth over a forecast horizon ranging from 1 quarter to 5 years. Our findings reveal that the relative ranking of the alternative policies remains the same over the full horizon. Specifically, the growth rate of the output gap fluctuates the most under the Taylor rule and the least under the price-level path rule. The distinction among the three policy rules in Figure 3 is due mostly to the differences in the impulse responses of output growth in the first two years after a productivity growth shock. During that time, output growth under the price-level path rule is closest to the optimal policy, whereas it is farthest under the Taylor rule. The longer-run differences among the policy rules in Figure 3 persist because they are averages that include the short-run effects.

5. Conclusion

Empirical evidence suggests that the inflation rate rises when the productivity growth rate permanently decreases and vice versa. Orphanides (2003a) argues that the central bank does not immediately observe a decline in productivity growth, so it does not correspondingly lower the money growth rate, which results in higher inflation. Our paper analyzes the impact of a permanent productivity growth shock when the central bank fails to immediately adjust its policy rule to that shock. We find that the negative correlation between inflation and productivity growth occurs because the central bank follows a Taylor-type rule, which responds to the level of the output gap.

Our paper shows that a permanent increase in productivity growth affects inflation differently with either the output growth rule or the price-level path rule than with the Taylor rule. Specifically, the Taylor rule causes inflation to continually decline after a permanent rise in productivity, whereas inflation initially rises and eventually returns to its target under both the output growth rule and the price-level path rule. The output growth rule and the price-level path rule also generate less variation in inflation and the output gap than the Taylor rule after a permanent shift in productivity growth. Those findings indicate that the central bank should target the price-level path and the output growth rate, which is the direct opposite of that advocated by Taylor (1993). In particular, the Taylor rule targets the growth rate of the price level and the level of output, whereas we find that the central bank should target the price level and the growth rate of output. Our result is practical because policymakers can easily observe and target a price-level path in real time but must estimate the output gap, which can result in large errors that persist for many years.

Our finding that a price-level path target reduces the volatility of inflation and the output gap due to uncertainty about the growth rate of potential output further complements a growing literature on targeting the price-level path. Svensson (1999), Roisland (2006), and Vestin (2006), among others, argue that price-level path targeting is preferable to inflation targeting. On the other side, Lebow, Roberts, and Stockton (1992), Haldane and Salmon (1995), and Black, Macklem, and Rose (1997) contend that the transition costs to a price-level path target and backward-looking expectations greatly reduce the benefits from price-level path targeting. One drawback to all such models is that they fail to incorporate realistic features such as risk and the interaction between risk-taking and the monetary policy rule. Building dynamic stochastic general equilibrium models with those characteristics will enable researchers to better address a wider set of problems confronting policymakers.

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Appendix

A.1 Nonlinear Equations

$$\frac{\lambda_t}{P_t} = \beta R_t E_t\left[\frac{\lambda_{t+1}}{P_{t+1}}\right] \qquad \text{A.1.1}$$

$$\text{a}w_t\lambda_t = \chi(l_t)^{-\omega} \qquad \text{A.1.2}$$

$$\text{a}\frac{1}{c_t} = \lambda_t + \gamma\frac{s_t}{c_t}\chi(l_t)^{-\omega} \qquad \text{A.1.3}$$

$$\text{a}\gamma w_t s_t = (1-\frac{1}{R_t})m_t \qquad \text{A.1.4}$$

$$\text{a}\lambda_t = \tau_t\varphi'\left(\frac{i_t}{k_t}\right) \qquad \text{A.1.5}$$

$$\tau_t = \beta \mathrm{E_t}\left[\tau_{t+1}\left((1-\delta)+\varphi\left(\frac{i_{t+1}}{k_{t+1}}\right)-\varphi'\left(\frac{i_{t+1}}{k_{t+1}}\right)\left(\frac{i_{t+1}}{k_{t+1}}\right)+\varphi'\left(\frac{i_{t+1}}{k_{t+1}}\right)q_{t+1}\right)\right] \qquad \text{A.1.6}$$

$$l_t + n_t + s_t = 1 \qquad \text{A.1.7}$$

$$k_{t+1} - k_t = \varphi\left(\frac{i_t}{k_t}\right)k_t - \delta k_t \qquad \text{A.1.8}$$

$$s_t = \zeta\left(\frac{c_t}{m_t}\right)^{\gamma} \qquad \text{A.1.9}$$

$$c_t + i_t = y_t \qquad \text{A.1.10}$$

$$y_t = (k_t)^{\alpha}(Z_t n_t)^{(1-\alpha)} \qquad \text{A.1.11}$$

$$q_t = \alpha\psi_t(Z_t)^{(1-\alpha)}(k_t)^{(\alpha-1)}(n_t)^{(1-\alpha)} \qquad \text{A.1.12}$$

$$w_t = (1-\alpha)\psi_t(Z_t)^{(1-\alpha)}(k_t)^{\alpha}(n_t)^{-\alpha} \qquad \text{A.1.13}$$

$$P_t = \left[\eta(P_t^*)^{(1-\varepsilon)} + (1-\eta)(P_{t-1})^{(1-\varepsilon)}\right]^{1/(1-\varepsilon)} \qquad \text{A.1.14}$$

$$P_t^* = \left(\frac{\varepsilon}{\varepsilon-1}\right)E_t\left[\frac{\sum_{i=0}^{\infty}\beta^i(1-\eta)^i\lambda_{t+i}P_{t+i}^{\varepsilon}\psi_{t+i}y_{t+i}}{\sum_{i=0}^{\infty}\beta^i(1-\eta)^i\lambda_{t+i}P_{t+i}^{\varepsilon-1}y_{t+i}}\right] \qquad \text{A.1.15}$$

$$R_t = \pi_t^{(1+\theta_\pi)}y_t^{\theta_y}g_t^{\theta_g}P_t^{\theta_p} \qquad \text{A.1.16}$$

$$g_t = \frac{y_t}{y_{t-1}} \qquad \text{A.1.17}$$

$$\pi_t = \frac{P_t}{P_{t-1}} \qquad \text{A.1.18}$$

$$\frac{Z_t}{Z_{t-1}} = \left(\frac{Z_{t-1}}{Z_{t-2}}\right)^{\rho}(\bar{g})^{1-\rho}e^{\nu_t} \qquad \text{A.1.19}$$

A.2 Steady-State Equations

$$\beta\overline{R} = \overline{g}\,\overline{\pi} \tag{A.2.1}$$

$$\overline{w}\,\bar{\lambda} = \chi(\bar{l})^{-\omega} \tag{A.2.2}$$

$$\frac{1}{\bar{c}} = \bar{\lambda} + \gamma\frac{\bar{s}}{\bar{c}}\chi(\bar{l})^{-\omega} \tag{A.2.3}$$

$$\bar{\lambda} = \bar{\tau}\varphi'(\cdot) \tag{A.2.4}$$

$$\overline{q} = \frac{\overline{g}}{\beta} - 1 + \delta \tag{A.2.5}$$

$$\overline{w}\,\bar{s}\,\gamma = \left(1 - \frac{1}{\overline{R}}\right)\overline{m} \tag{A.2.6}$$

$$\bar{l} + \overline{n} + \bar{s} = 1 \tag{A.2.7}$$

$$\bar{i} = (\overline{g} - 1 + \delta)\overline{k} \tag{A.2.8}$$

$$\bar{s} = \zeta\left(\frac{\bar{c}}{\overline{m}}\right)^{\gamma} \tag{A.2.9}$$

$$\bar{c} + \bar{i} = \overline{y} \tag{A.2.10}$$

$$\overline{y} = (\overline{Z})^{(1-\alpha)}\left(\overline{k}\right)^{\alpha}(\overline{n})^{(1-\alpha)} \tag{A.2.11}$$

$$\overline{q} = \alpha\overline{\psi}(\overline{Z})^{(1-\alpha)}\left(\overline{k}\right)^{(\alpha-1)}(\overline{n})^{(1-\alpha)} \tag{A.2.12}$$

$$\overline{w} = (1-\alpha)\overline{\psi}\left(\overline{Z}\right)^{(1-\alpha)}\left(\overline{k}\right)^{\alpha}(\overline{n})^{-\alpha} \tag{A.2.13}$$

$$\overline{\psi} = \frac{(\varepsilon-1)}{\varepsilon} \tag{A.2.14}$$

$$\bar{P} = \bar{P}^{*} = 1 \tag{A.2.15}$$

A.3 Linearized Equations

$$\hat{\lambda}_t - \hat{R}_t = E_t\left[\hat{\lambda}_{t+1} - \hat{\pi}_{t+1}\right] \quad \text{A.3.1}$$

$$\widehat{w}_t + \hat{\lambda}_t = -\omega \hat{l}_t \quad \text{A.3.2}$$

$$\left[\left(\frac{1}{\bar{c}}\right) - \gamma\left(\frac{\bar{s}}{\bar{c}}\right)\chi(\bar{l})^{-\omega}\right]\hat{c}_t + \bar{\lambda}\hat{\lambda}_t + \left[\gamma\left(\frac{\bar{s}}{\bar{c}}\right)\chi(\bar{l})^{-\omega}\right]\left(\hat{s}_t - \omega\hat{l}_t\right) = 0 \quad \text{A.3.3}$$

$$\widehat{w}_t + \hat{s}_t - \left(\frac{1}{\bar{R}-1}\right)\hat{R}_t = \widehat{m}_t \quad \text{A.3.4}$$

$$\left(\frac{\left(\frac{\bar{i}}{\bar{k}}\right)\varphi''(\cdot)}{\varphi'(\cdot)}\right)\left(\hat{\mathrm{i}}_t - \hat{\mathrm{k}}_t\right) + \hat{\tau}_t = \hat{\lambda}_t \quad \text{A.3.5}$$

$$\hat{\tau}_t = \mathrm{E}_t\left[\left[\left(\frac{\beta}{\bar{\mathrm{g}}}\right)\left(\frac{\bar{i}}{\bar{k}}\right)\varphi''(\cdot)\left(\bar{\mathrm{q}} - \left(\frac{\bar{i}}{\bar{k}}\right)\right)\right]\left(\hat{\mathrm{i}}_{t+1} - \hat{\mathrm{k}}_{t+1}\right) + \left(\frac{\beta\varphi'(\cdot)\bar{\mathrm{q}}}{\bar{\mathrm{g}}}\right)\hat{\mathrm{q}}_{t+1} + \hat{\tau}_{t+1}\right] \quad \text{A.3.6}$$

$$\bar{l}\hat{l}_t + \bar{n}\hat{n}_t + \bar{s}\hat{s}_t = 0 \quad \text{A.3.7}$$

$$\left(\frac{\bar{i}}{\bar{k}}\right)\varphi'(\cdot)\hat{\mathrm{i}}_t + [1 - \delta + \varphi(\cdot) - \left(\frac{\bar{i}}{\bar{k}}\right)\varphi'(\cdot)]\hat{\mathrm{k}}_t = \bar{\mathrm{g}}\hat{\mathrm{k}}_{t+1} \quad \text{A.3.8}$$

$$\hat{c}_t - \widehat{m}_t = \left(\frac{1}{\gamma}\right)\hat{s}_t \quad \text{A.3.9}$$

$$\bar{c}\hat{c}_t + \bar{i}\hat{i}_t = \bar{y}\hat{y}_t \quad \text{A.3.10}$$

$$\alpha\hat{k}_t + (1-\alpha)(\hat{Z}_t + \hat{n}_t) = \hat{y}_t \quad \text{A.3.11}$$

$$\hat{\psi}_t + (1-\alpha)(\hat{Z}_t + \hat{n}_t - \hat{k}_t) = \hat{q}_t \quad \text{A.3.12}$$

$$\hat{\psi}_t + (1-\alpha)\hat{Z}_t + \alpha(\hat{k}_t - \hat{n}_t) = \widehat{w}_t \quad \text{A.3.13}$$

$$\hat{\pi}_t = \left(\frac{\eta(1-\beta(1-\eta))}{(1-\eta)}\right)\hat{\psi}_t + \beta E_t[\hat{\pi}_{t+1}] \quad \text{A.3.14}$$

$$\hat{R}_t = (1+\theta_\pi)\,\hat{\pi}_t + \theta_y\,\hat{y}_t + \theta_g\,\hat{g}_t + \theta_p\,\hat{p}_t \quad \text{A.3.15}$$

$$\hat{\pi}_t = \hat{p}_t - \hat{p}_{t-1} \quad \text{A.3.16}$$

$$\hat{g}_t = \hat{y}_t - \hat{y}_{t-1} \quad \text{A.3.17}$$

$$\hat{Z}_t = (1+\rho)\hat{Z}_{t-1} - \rho\hat{Z}_{t-2} + \nu_t \quad \text{A.3.18}$$

Figure 1. Responses to a Permanent 0.1% Increase in Productivity Growth Under Optimal Policy, Weak Inflation Rule, and a Taylor Rule

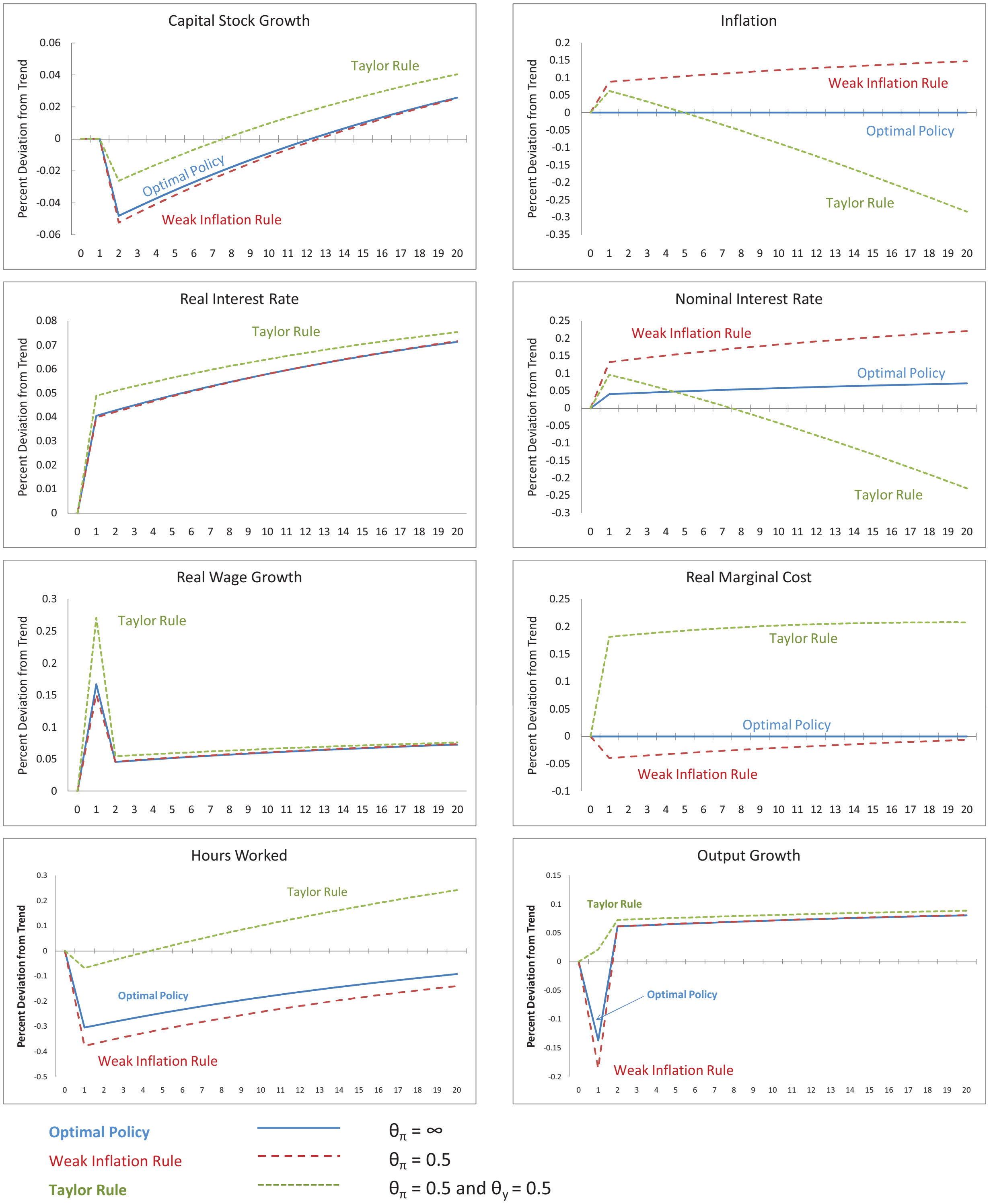

Figure 2. Responses to a Permanent 0.1% Increase in Productivity Growth Under Optimal Policy, Output Growth Rule, and a Price-Level Path Rule

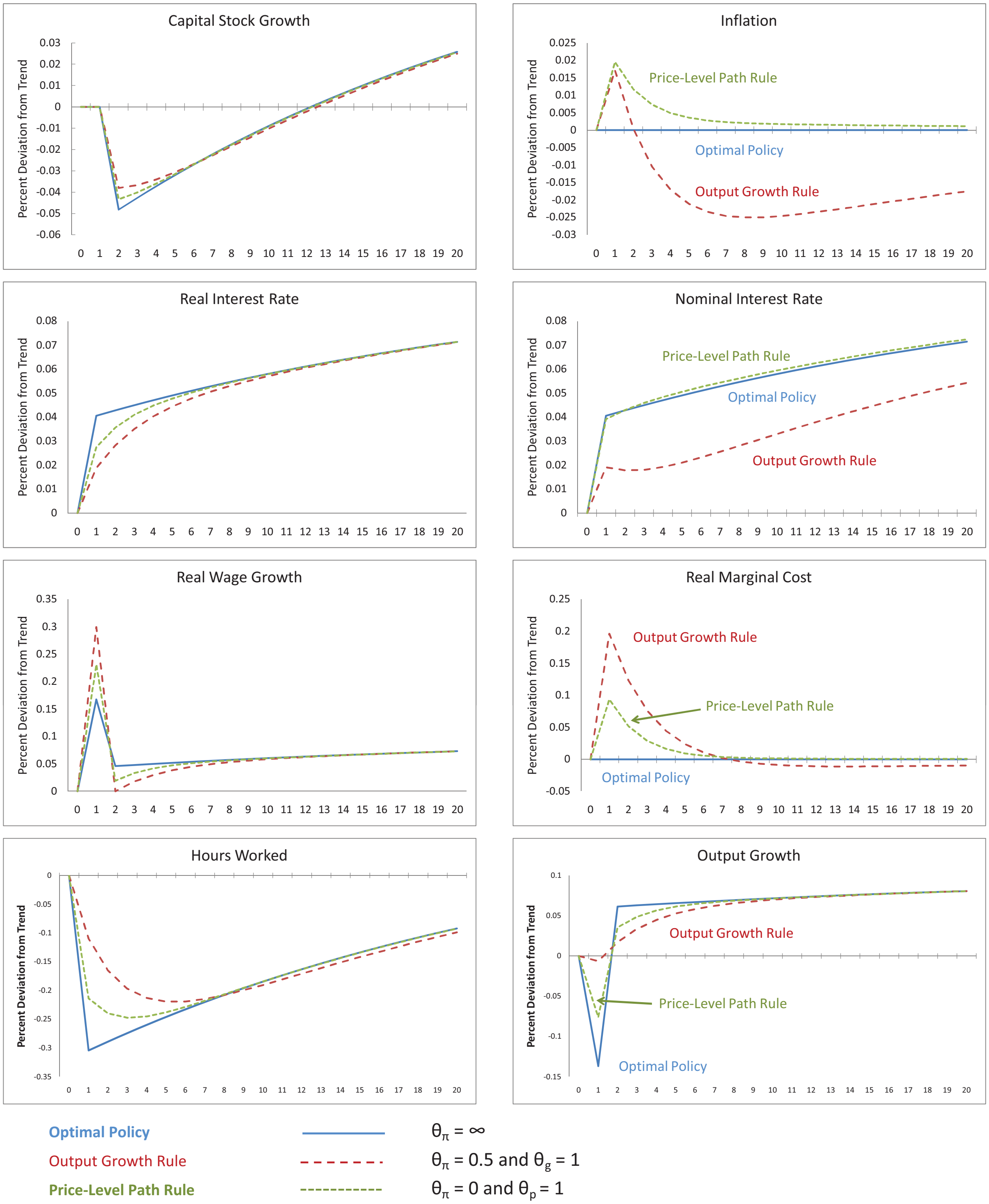

Figure 3. Root Mean Square Deviations (from the Optimal Path)