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Productivity Shocks, Investment, and the Real Interest Rate*

Abstract

I analyze the effects of a favorable shift in expected future productivity on the current level of investment and the real interest rate. In a standard RBC model, an increase in expected future productivity raises the real rate, but decreases the current level of investment for plausible parameter values of the intertemporal elasticity of substitution in consumption. However, it is shown that such a conclusion is unwarranted when nominal rigidities are introduced into the analysis. In contrast with the flexible-price case, the favorable shift in future productivity can lead to an increase in current investment, while at the same time driving up significantly the real rate of interest. The model with nominal rigidities lends theoretical support to the view expressed by some authors (e.g., Blanchard and Summers (1984), and Barro and Sala-i-Martin (1990)), that the surge in investment and the real rate across industrialized countries in 1983-84 was caused by a favorable shift in expected future profitability.

JEL classification: E32; E22; E43

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1 Introduction

The reasons for the historically high world real interest rates of the early 1980s have been widely debated among macroeconomists, and several explanations have been put forward to account for this episode. A standard explanation is that real rates were high because of unrelentingly tight money in the United States since 1979, which, among other things, eventually forced many European countries into tight money in order to defend their currency values. Moreover, from 1982 to 1986, tight money was coupled with a large fiscal stimulus from President's Reagan program. The result of high real rates is exactly what one would expect from such a policy mix of temporarily loose fiscal policy and contractionary monetary policy (cfr. Blinder, 1984).

In a thought-provoking paper, Blanchard and Summers (1984) first challenged this standard explanation, noting that, during the early 1980s, the real yield curve was not downward sloping, as tight money would suggest, and that the fiscal expansion in the United States was largely offset by fiscal contractions in other OECD countries, leaving little, if any, net world fiscal stimulus. Blanchard and Summers proposed another explanation, which focussed on favorable shifts in expected future investment profitability as the primary reason for high world real interest rates. In particular, they showed that for the six most industrialized countries, the high level of investment during 1983 and early 1984 could not be accounted for entirely by unexpected strength in output, and argued that a favorable shift in future investment profitability would instead explain the increase in investment and the real rate, together with the stock market boom of 1982-83. In subsequent empirical work, Barro and Sala-i-Martin (1990) have shown that a proxy for future expected profitability, i.e., the change in the price of industrial shares, had a positive effect on world investment and the real interest rate over the period 1959-1988, lending support to Blanchard and Summers' contention that the primary cause for the surge in investment and the real rate during the early 1980s was traceable to a favorable shift in expected future profitability.

While the empirical evidence reported in Barro and Sala-i-Martin has been largely unchallenged thus far, it has been noted that the argument that an increase in expected future profitability can explain a simultaneous rise in current investment and the real rate of interest is not well grounded from a theoretical standpoint (see Obstfeld and Rogoff (1996, ch.1)). This can be easily shown with the help of a standard general equilibrium dynamic real model, interpreting a favorable shift in future profitability as an increase in expected future productivity. In this context, consumers will try to spread the increase in income expected to take place in the future to the current period by decreasing current savings, thus driving up the real interest rate. At standard values for the intertemporal elasticity of substitution in consumption, the decrease in current savings pushes the real rate so high that current investment declines. With an elastic labor supply, the increase in current consumption decreases the amount of labor supplied by the representative household, so that not only investment but also the current level of economic activity declines. In order to obtain the result that a future productivity shock increases current investment, it is necessary to impose an implausibly large value for the intertemporal elasticity of substitution in consumption, a value that finds scant support in extant empirical evidence. Therefore, the result that a future increase in expected productivity *decreases* the current level of investment appears inescapable from the perspective of a standard general equilibrium real model.

In this paper, I show that such a conclusion is unwarranted when nominal rigidities are introduced into the analysis. In particular, in a model with predetermined wages which shares many features of the so-called "new neoclassical synthesis", it is shown that, for plausible parameter values, a future expected increase in productivity raises both current output and investment, while driving up significantly the real rate of interest. The increase in expected future disposable income raises the current price level and, for a predetermined nominal wage, decreases the real wage, thus promoting the increase in current output. This result allows for the possibility for current investment to increase when adjustment costs to the capital stock are present, and for the real interest rate to rise markedly, since the expected future increase in productivity implies that the dollar value of installed capital will rise in the future. While providing a theoretical support for the Blanchard and Summers and Barro and Sala-i-Martin explanation for the high real rates of the early 1980s, this paper gives another example of how the economy's response to shocks differs from the baseline flexible-price case, when nominal rigidities are introduced into an otherwise standard general equilibrium dynamic macro model.[1]

The rest of the paper is structured as follows. Section 2 reviews the effects of future productivity shocks on current real variables using the standard real business cycle model. Section 3 shows how the results change when one allows for the presence of nominal rigidities, while the last section provides some concluding remarks.

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[1] Basu, Fernald, and Kimball (1997) also consider the effects of productivity shocks on output and input utilization in a sticky price model that draws on Kimball (1995). However, their emphasis is not on expected future shocks, but on current productivity shocks.

2 A Real Model with Variable Labor Supply

In this section I start by reviewing the effects of productivity disturbances in the context of a standard real model with a (possibly) elastic labor supply. The model has been studied extensively in the literature (see, e.g., King, Plosser, and Rebelo (1988), and Campbell (1994)), and it provides a useful benchmark for evaluating how the introduction of nominal rigidities affects the economy's response to productivity shocks.

Using the notation of Y_t for output, A_t for technology, K_t for capital, and L_t for labor, the production function with labor augmenting technological progress can be written as follows:

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

The capital accumulation equation is the one of a closed economy,

$$K_{t+1} = (1-\delta) K_t + Y_t - C_t, \tag{2}$$

where δ is the depreciation rate of capital, and C_t is private consumption. Investment at time t becomes productive in the next period, so that capital at time t is a predetermined quantity. The representative agent has separable preferences over consumption and leisure, and its objective function is

$$U_t = \mathrm{E}_t \sum_{s=t}^{\infty} \left[\frac{C_s^{1-\rho}}{1-\rho} + \phi \frac{(1-L_s)^{1-\gamma_L}}{1-\gamma_L} \right], \tag{3}$$

where $1/\rho$ is the intertemporal elasticity of substitution in consumption, and $1/\gamma_L$ is the intertemporal elasticity of substitution in leisure. As is well known, the case

$$u(C, L) = \ln(C) + \phi \frac{(1-L)^{1-\gamma_L}}{1-\gamma_L}, \tag{4}$$

which obtains when $\rho \to 1$, is the only type of additively time-separable utility function that allows income and substitution effects on labor supply to cancel out in the long run, so that the presence of a trend in the real wage does not induce a trend in the representative household's supply of labor (see, e.g., King, Plosser, and Rebelo (1988)). The form of the utility function for leisure is not restricted by the balanced growth requirement. The power utility specification is used here for convenience, and because it nests two popular cases often analyzed in the real business cycle literature: the divisible labor model of log utility ($\gamma_L = 1$) and the invisible labor model of Hansen (1985) and Rogerson (1988), ($\gamma_L = 0$), where workers choose lotteries over hours worked rather than choosing hours worked directly.

The representative household maximizes eq.(3) at each date over consumption, C_t, labor, L_t, and capital K_{t+1}, subject to the constraints (1) and (2). Defining the variable R_{t+1} as being equal to the gross marginal product of capital:

$$R_{t+1} \equiv (1-\alpha)\left(\frac{A_{t+1}L_{t+1}}{K_{t+1}}\right)^{\alpha} + (1-\delta)\,, \tag{5}$$

the first-order conditions from the maximization problem are given by an intertemporal Euler equation for consumption:

$$C_t^{-\rho} = \beta \mathrm{E}_t \left\{ C_{t+1}^{-\rho} R_{t+1} \right\}, \tag{6}$$

and by a static first-order condition for labor supply:

$$C_t^{-\rho} \alpha A_t^{\alpha} \left(\frac{K_t}{L_t}\right)^{1-\alpha} = \phi\,(1-L_t)^{-\gamma_L}\,. \tag{7}$$

The marginal utility of leisure is set equal to the marginal utility of consumption times the marginal product of labor. For simplicity, in what follows productivity growth is assumed to be zero, but this assumption could be readily relaxed without affecting this section's qualitative results.

Characterization of the nonstochastic steady-state is straightforward. The Euler equation for consumption implies that in the steady-state $1 = \beta\overline{R}$, and therefore, as one can see from eq.(5), that the steady-state technology to capital ratio is $(\overline{AL}/\overline{K})^{\alpha} = (\beta^{-1} - (1-\delta))/(1-\alpha)$. This last expression can be substituted in the production function, eq.(1), to obtain the steady-state output to capital ratio $\overline{Y}/\overline{K} = (\beta^{-1} - (1-\delta))/(1-\alpha)$. Moreover, from the capital accumulation equation, it is possible to derive the steady-state consumption to capital ratio, $\overline{C}/\overline{K} = \overline{Y}/\overline{K} - \delta$. Finally, note that $\overline{Y} = \left(\overline{Y}/\overline{K}\right)^{-\frac{1-\alpha}{\alpha}} \overline{AL}$, which implies that imposing a specific steady-state for $\overline{A}$ and $\overline{L}$ is equivalent to calibrating the utility function parameter ϕ in eq.(7).

Outside the steady-state, the model is a system of nonlinear equations in the logs of technology, capital, labor, output, and consumption, where the nonlinearities are caused by incomplete capital depreciation in eqs.(2) and (5), by the marginal disutility from labor in eq.(7), and by the time variation in the consumption to output ratio when $\rho \neq 1$. An exact analytical solution to the model is possible only in the special case where capital depreciates fully in one period, and agents have a log utility in consumption and leisure.[2] Absent such conditions, it is necessary to rely on an approximate solution. A standard procedure is to log-linearize the model around the nonstochastic steady-state just described, to obtain a linear difference equation system in the logs of capital, labor, consumption, and technology. Derivation of the log-linear approximations to eqs.(1)-(2) and (5)-(7), is left to the appendix.

[2] See Long and Plosser (1983), and McCallum (1989).

Here, it is important to note that in the derivation of the log-linear relationships, the random variable $C^{-\rho}R$ on the right-hand side of the Euler equation (6) is assumed to be lognormally distributed, with a conditional variance that is constant over time. The assumption of joint lognormality is consistent with a lognormal homoskedastic productivity shock, and with the approximations used here to solve the model.

The system can be reduced to a pair of log-linear expectational difference equations in technology, capital, and consumption, written in vector form as follows:

$$\mathrm{E}_t\Theta_{t+1} = B\Theta_t + C\left(\mathbf{F}\right)\mathrm{E}_t a_t, \tag{8}$$

where Θ_t is a column vector that contains the variables c_t and k_t (with lower case variables denoting the natural logarithm of the corresponding upper case variables), B is a conformable matrix of constants, and $C\left(\mathbf{F}\right)a_t$ is a distributed lead effect of the exogenous variable, with $\mathbf{F}$ denoting the lead operator which shifts the dating of the variable but not the information set, and C_i's are vectors of constants. This system can be solved following Blanchard and Kahn (1980) canonical variables method, and the solution is given by the following set of equations:

$$k_{t+1} = Mk_t + \Psi_c\left(\mathbf{F}\right)\mathrm{E}_t a_t, \tag{9.1}$$

$$c_t = -Nk_t - \Psi_k\left(\mathbf{F}\right)\mathrm{E}_t a_t, \tag{9.2}$$

where rank and order conditions on the transformation between original and canonical variables have to be satisfied for a stable and unique solution to exist, and the coefficients M, N, and the polynomials $\Psi_c\left(\mathbf{F}\right)$ and $\Psi_k\left(\mathbf{F}\right)$ are computed from the system matrices B and $C\left(\mathbf{F}\right)$. Eqs.(9.1) and (9.2) allow to perform simulations and compute impulse-response functions.[3]

[3] King and Watson (1995) describe a general approach to solve a broader class of models. The King and

Given the model's solution, I now proceed to consider how future innovations in technology affect the current level of investment, consumption, output, and the real interest rate. Calibration of the model's parameters follows standard values found in the literature (see, e.g., Campbell (1994)). In particular, β is set equal to 0.957, implying an annual net real return on capital of approximately 0.045, while the depreciation rate δ is an annual 0.075. α is equal to 0.667, while the steady-state allocation of hours to market activities, $\overline{L}$, is set equal to 1/3, the value advocated by Prescott (1986). Calibrated values for the elasticities of substitution in consumption and leisure are reported in what follows, along with the simulations. The exercise I conduct throughout is to assess the response of real variables at time 0 and in subsequent periods following an unanticipated permanent increase in expected productivity, to occur from time 1 on. Since I have assumed that the variance-covariance structure of the model is constant over time, I am also implicitly assuming that the regime shift that takes place from time 1 on changes the expected value of productivity, but otherwise leaves second moments unaltered.

In order to evaluate how different values for the intertemporal elasticities of substitution in consumption and leisure affect the results, I first consider the special case where labor supply is fixed ($\gamma_L \to \infty$). Although in this case there is no labor-leisure substitution, the representative household still has incentives to substitute consumption intertemporally. Figure 1 reports impulse-response functions for investment and the real interest rate when the intertemporal elasticity of substitution in consumption is unity. The figure shows that at time 0, for an unchanged level of total output, investment declines while consumption

Watson's MATLAB codes `reds.m` and `solds.m` are used here to perform all the simulations. The simulations reported in this paper are available upon request.

increases. The reason for this result is that the representative household wants to spread the increase in income, which takes place starting from period 1 on, over period 0. In order to do so, the household will reduce period 1 savings, thus pushing the real interest rate so high that investment actually falls. With a lower elasticity of substitution, the desire for smoothing consumption is even stronger than in the log case, and therefore the real interest rate rises and investment falls even more sharply. To obtain the result that a future productivity shock increases the current level of investment, it is necessary to impose an implausibly large value for the elasticity of substitution. Specifically, in this simple case with completely inelastic labor supply, the intertemporal elasticity of substitution in consumption has to be above 2.5 for the calibrated parameters. As is well known, while many estimates of the intertemporal elasticity of substitution are below 0.5, few are significantly higher than unity.

Figure 2 reports impulse-response functions for investment and the real rate when the household supply of labor is elastic, so that eq.(7) binds. In particular, impulse-responses are drawn for a value of unity for both the intertemporal elasticity of substitution in consumption and the intertemporal elasticity in leisure, implying a period utility function of the form $u(C, L) = \ln C + \phi \ln (1 - L)$.[4] Therefore, figure 2 can be easily compared with the preceding figure, since the only parameter change is in γ_L. As can be readily seen, the introduction of an elastic labor supply increases the initial drop in investment, while the effect on the path for consumption is approximately the same. Whereas total output at time 0 does not change when labor supply is inelastic, in the present case output decreases. The reason is

[4] Note that the intertemporal elasticity of labor supply is $\frac{1-\overline{L}}{\overline{L}}\gamma_L^{-1}$. Therefore, with a value of unity for γ_L, and a steady-state share of household's time devoted to market activities equal to 1/3, the implied calibrated value for the intertemporal elasticity of labor supply is 2.

that the number of hours that the household devotes to work also depends on the marginal utility of consumption, as the static labor-leisure trade-off condition, eq.(7), shows. The increase in current consumption brought by the household's desire to smooth consumption intertemporally lowers the marginal utility of income and tends to reduce work effort. As a result, current output decreases, and investment must decline even more than in the inelastic labor supply case in order to finance the increase in consumption. It is then clear that the larger the intertemporal elasticity of substitution in leisure ($\gamma_L \to 0$), the larger the decline in current output and investment.

It is also possible to consider alternative specifications for the utility function consistent with a balanced growth path. As an example, the non-additively separable Cobb-Douglas utility function,

$$u(C, L) = \frac{\left[C^{\gamma}\left(1-L\right)^{1-\gamma}\right]^{1-\zeta}}{1-\zeta}, \tag{4'}$$

has been used by several authors (see, e.g., Prescott (1986) and Eichenbaum, Hansen, and Singleton (1988)). $1/\zeta$ now denotes the elasticity of substituting between different dates the composite commodity $C^{\gamma}\left(1-L\right)^{1-\gamma}$. When the intertemporal elasticity of substitution in the composite commodity is unity, this function becomes the same as the additively separable log utility function, eq.(4), with a unitary elasticity of substitution in leisure. The parameter γ determines the steady-state fraction of time devoted to market activities, $\overline{L}$. Given $\overline{L}$, the implied γ can be computed as $\gamma = 1/(1 + [(1-\overline{L})\alpha(\overline{Y}/\overline{C})/\overline{L}]$, which is equal to 0.37 at benchmark parameter values. Because the nonseparable model does not fix the curvature of the utility function, it allows a much wider range of responses for private consumption as ζ varies, compared with the case in which utility is separable. However, one can show that the response for investment does not differ sensibly from the previous case reported in figure 2 with separable log utility in consumption.[5] This is not very surprising, since the labor-constant intertemporal elasticity of substitution in consumption, equal to $(1-\gamma(1-\zeta))^{-1}$, is too small at actual estimates of the curvature parameter of the utility function, ζ, which usually range in the interval $[1,2]$. In the class of non-additive separable utility functions considered by King, Plosser, and Rebelo (1988),

$$u(C,L)=\frac{C^{1-\rho}}{1-\rho}\nu(1-L), \tag{4''}$$

where $\rho<1$ and $\nu(1-L)$ is an increasing and convex function of $1-L$, in order for investment not to decline at time 0 the labor-constant intertemporal elasticity of substitution in consumption, ρ^{-1}, must be approximately equal to 2 at the benchmark calibrated parameters, with a consumption-constant intertemporal elasticity of labor supply of 3.[6]

While the issue of how the introduction of adjustment costs to the capital stock affects the results is taken up in more detail in the next section, I here note that adjustment costs dampen the decline in investment at time 0, because the expected permanent increase in productivity calls for a higher stock of capital at the new steady-state, with the dollar value of installed capital expected to increase in the future. However, it turns out that the presence of adjustment costs is not sufficient *per se* to generate an increase in time 0 investment for a value of unity of the intertemporal elasticity of substitution in consumption, even when one imposes a completely inelastic labor supply and large adjustment costs.

In summary, in a standard frictionless real model, an unanticipated increase in future

[5] On the response of investment to productivity shocks when the utility function is given by eq.(4'), see also Campbell (1994).

[6] The calibrated parameter values for ρ and the consumption-constant intertemporal elasticity of substitution in labor ensure the overall concavity of $u(C,L)$ (see King, Plosser, and Rebelo (1988)).

productivity is unlikely to generate a surge in current investment for plausible parameter values of the intertemporal elasticity of substitution in consumption. This outcome is robust to changes in the calibrated value for the elasticity of labor supply, and to changes in the specification of the representative household's preferences over consumption and labor, for example via the introduction of a non-additive separable utility function. In the following section, I examine whether and how the results change with the introduction of nominal rigidities into the model.

3 A Model with Nominal Rigidities

I now describe an extension of the model outlined in the previous section which encompasses nominal rigidities, introduced in the form of predetermined wages. Since the dynamics of capital accumulation are generally believed to be slow, the time interval considered in this setup is one year. Because most wages appear to be set for a year, the simplification of having wages predetermined should not be a bad approximation as a basis for heuristic analysis. Moreover, positing the nominal rigidity in the labor market instead of in the final goods market has the advantage of allowing for an upward-sloping, short-run aggregate supply curve, in accordance with the general belief that while wages are set for a year, very few prices are. Monopolistic competition is introduced in the labor market, in order to rationalize the willingness of workers to increase *ex post* their work effort in response to a shock to the economy. This way of modelling the nominal rigidity in the labor market has been illustrated, among others, by Blanchard and Kiyotaki (1987), Obstfeld and Rogoff (1996, ch. 10), Corsetti and Pesenti (1998), and Rankin (1998), and it gives micro-foundations to the previous *ad hoc* models of Gray (1976) and Fischer (1977), in which equilibrium in the labor market, rather than being the outcome of an explicit optimization process, results from the assumption that the market clears in expectations.

The economy consists of a continuum of infinitely lived households that supply labor monopolistically to a representative competitive firm, which produces an intermediate good from the different types of labor. Since each household is a monopolistic supplier of labor, it will have the power to set its wage, and I assume that the wage for period t must be set at the end of period $t-1$, before the shocks to the economy in period t are observed. The intermediate good is used as an input in the production of a final good by another competitive firm, which sells its output to the households.[7] Denoting by λ the constant elasticity of substitution among different labor inputs, the linear homogeneous CES production function for the intermediate good is given by the following expression:

$$L = \left[\int_0^1 L(i)^{\frac{\lambda-1}{\lambda}} di \right]^{\frac{\lambda}{\lambda-1}}, \tag{10}$$

where $L(i)$ denotes the quantity of labor monopolistically supplied by household $i \in [0,1]$, and $\lambda > 1$. The firm producing the intermediate good maximizes profits in a competitive market

$$WL - \int_0^1 W(i)L(i)di,$$

subject to the production function in eq.(10), where $W(i)$ is the nominal wage for differentiated labor of type i, while W denotes the price index of the intermediate good.[8] The

[7] The presence of the intermediate good, a device introduced to simplify notation, can obviously be avoided. If this is the case, the firm producing the final good would choose the different types of labor optimally, as in Blanchard and Kiyotaki (1987). All the results derived in this section continue to hold when one dispenses with the assumption of an intermediate good.

[8] At the zero profit symmetric equilibrium, the price index for the intermediate good is going to be defined

maximization problem yields the labor demands

$$L(i) = \left[\frac{W(i)}{W}\right]^{-\lambda} L, \qquad i \in [0,1]. \tag{11}$$

Representative household i will take this demand function into account when maximizing utility.

In each period, the household decides how much to consume of the final good, and sets its optimal level of nominal wage for the next period. Specifically, household i chooses the optimal sequence $\{C_t(i), W_{t+1}(i)\}_{t=0}^{\infty}$ resulting from the maximization of the utility function

$$U_t = \mathrm{E}_t \sum_{s=t}^{\infty} \beta^{s-t} \left[\frac{C_s(i)^{1-\rho}}{1-\rho} + \phi \frac{(1-L_s(i))^{1-\gamma_L}}{1-\gamma_L}\right],$$

subject to the constraints

(a) $Q_s B_{s+1}(i) = B_s(i) + P_t D_t + W_s(i) L_s(i) - P_s C_s(i)$,

(b) $L_s(i) = \left[\frac{W_s(i)}{W_s}\right]^{-\lambda} L_s$,

(c) $W_{s+1}(i)$ is chosen conditional on period s information set.

$B_t(i)$ is household i's nominal value of the bond portfolio at the beginning of period t. The only bond in the economy is a zero-coupon bond with a one-period maturity, so that Q_t is the bond's nominal price at time t for one dollar in period $t+1$, and D_t are the real profits of the firm producing the final good, while all other variables have been defined previously. The information set at time t is given by all the variables in period t and in earlier periods.

as

$$W = \left[\int_0^1 W(i)^{1-\lambda}\right]^{\frac{1}{1-\lambda}}.$$

The nominal rigidity, introduced by imposing that wages in period $t+1$ be set conditional on the information set at time t, is usually rationalized with the presence of an implicit cost in setting wages. It is assumed that the labor contract stipulates that the household will meet all demand for its labor input at its preset nominal wage. The presence of a markup of the wage over the marginal rate of substitution between leisure and consumption means that the representative household typically benefits from working additional hours. Only in the presence of shocks to the demand for its labor that are large enough to raise the marginal rate of substitution above the current real wage, is the representative household's behavior constrained by the terms of the contract.

Maximization of U_t with respect to B_{t+1} gives the familiar Euler equation for private real consumption[9]

$$Q_t = \beta \mathrm{E}_t \left\{ \frac{P_t}{P_{t+1}} \left(\frac{C_{t+1}(i)}{C_t(i)} \right)^{-\rho} \right\}. \tag{12}$$

While this condition holds irrespective of the presence of nominal rigidities, the expression for the optimal wage at time $t+1$ conditional on the information at time t, derived from maximizing U_t with respect to W_{t+1}, is given by

$$W_{t+1} = \frac{\lambda}{\lambda - 1} \frac{\mathrm{E}_t \left(\phi \Lambda_{t+1} \left(1 - L_{t+1}(i)\right)^{-\gamma_L} \right)}{\mathrm{E}_t \left(\Lambda_{t+1} \left(C_{t+1}(i)\right)^{-\rho} P_{t+1}^{-1} \right)}, \tag{13}$$

where $\Lambda = W^{\lambda} L$. The presence of the expectations operators stems from the assumption

[9] Given that the economy is closed to foreign trade and there is no government debt, in equilibrium trade in bonds is zero, because households are identical. This, however, does not preclude the possibility of pricing other assets: for example, the price of a one-period risk-free zero-coupon indexed bond, Q_t^*, is given by the consumption-based Fisher equation

$$Q_t^* = Q_t \frac{\mathrm{E}_t C_{t+1}(i)^{-\rho}}{P_t \mathrm{E}_t \left\{ \frac{C_{t+1}(i)^{-\rho}}{P_{t+1}} \right\}}.$$

that the wage is predetermined one period in advance. This equation does not bind *ex post* in period $t+1$, but does govern wage setting in period t. If nominal wages were flexible, expectations would not enter into the expression, and the equation would say that the real wage is a markup $\frac{\lambda}{\lambda-1}$ on the competitive supply wage, $-U_L/U_C$.

The final good is produced from the intermediate good L and from capital, according to the constant returns to scale Cobb-Douglas function

$$Y = (AL)^{\alpha} K^{1-\alpha}, \tag{14}$$

where, as in the previous section, A is the technology parameter, and the stock of capital K is accumulated directly by the final good competitive firm. Since households own a constant share in the firm, they are the ultimate recipients of the services provided by capital. The existing capital depreciates at a constant rate δ. Investment is productive in the next period, and therefore the stock of capital at time t is predetermined. In particular, the evolution equation for capital is given by

$$K_{t+1} - K_t = \phi\left(\frac{I_t}{K_t}\right) K_t - \delta K_t, \tag{15}$$

where I denotes investment, and $\phi(I/K)$ is a positive, increasing, and concave function that embodies costs of adjustment for the capital stock. It is assumed that there are no average or marginal adjustment costs, locally to the steady-state, so that $\phi(\delta) = \delta$, and $\phi'(\delta) = 1$.

The presence of investment and adjustment costs for capital makes the firm's problem dynamic. Specifically, the firm chooses labor and capital to maximize its total market value, equal to

$$V_t = \mathrm{E}_t \sum_{s=t}^{\infty} \beta^{s-t} C_s^{-\rho} D_s, \tag{16}$$

where $\beta^{s-t}C_s^{-\rho}$ is the marginal utility value to the representative household of an additional unit of profits during period s, and

$$D_s = Y_s - \frac{W_s}{P_s}L_s - I_s,$$

subject to the production function schedule, eq.(14), and the capital accumulation relationship, eq.(15). The first-order condition for investment is given by

$$C_t^{-\rho} = \phi'\left(\frac{I_t}{K_t}\right)\Psi_t, \tag{17}$$

where Ψ is the Lagrange multiplier for the capital accumulation equation. Ψ_t has an interpretation as the marginal utility of capital in place at the end of period t, and $\Psi_t C_t^{\rho}$ is the real value of an additional unit of installed capital (that is, the value of a small change in K_{t+1} within the constraint (15)). The condition states that the marginal value of capital equals the marginal cost of investment, or that the investment rate I_t/K_t is determined by the ratio of the shadow price of installed capital to the price of replacement capital.

The first-order condition for capital is

$$-\Psi_t+\beta \mathrm{E}_t\left\{C_{t+1}^{-\rho}(1-\alpha)\frac{Y_{t+1}}{K_{t+1}}+\Psi_{t+1}\left(1-\delta+\psi\left(\frac{I_{t+1}}{K_{t+1}}\right)-\psi'\left(\frac{I_{t+1}}{K_{t+1}}\right)\frac{I_{t+1}}{K_{t+1}}\right)\right\}=0. \tag{18}$$

This condition is an investment Euler equation, which states that the marginal utility of capital in place at the end of period t is the discounted sum of next period's marginal productivity of capital, weighted by the marginal utility of consumption, and of the marginal utility of next period's capital stock, which includes the contribution of an additional unit of K_{t+1} to lower installation costs in period $t+1$. Finally, the firm equates the marginal productivity of labor to its rental rate:

$$\alpha \frac{Y_t}{L_t} = \frac{W_t}{P_t}. \tag{19}$$

From eqs.(14) and (19) it is then possible to derive the economy's aggregate supply schedule, which is given by

$$Y_t = K_t A_t^{\frac{\alpha}{1-\alpha}} \left[\alpha^{-1} \frac{W_t}{P_t} \right]^{-\frac{\alpha}{1-\alpha}}. \tag{20}$$

The economy-wide resource constraint is the one of a closed economy, and it is described by the following equation:

$$Y = C + I, \tag{21}$$

with per capita real quantities equal to aggregate real quantities.

In order to close the model, it is necessary to specify the monetary policy regime. I assume that monetary policy is formulated in terms of a feedback rule for the price of the one-period nominal bond of the form

$$Q_t = \Upsilon \left(\frac{P_t}{P_{t-1}} \right). \tag{22}$$

The rule says that the central bank responds to changes in the rate of inflation only, and it is such that $\beta = \Upsilon(1)$ in a nonstochastic steady-state with zero inflation. Specifically, the monetary authority will raise the one-period nominal interest rate (i.e., it will decrease Q) whenever current inflation is above a target level. In this model, the absence of liquidity services provided by money is to be understood as a simplification. Introducing money services in the utility function in a separable form would imply an additional first-order condition for the household problem, besides eqs.(12)-(13). This condition relates real balances to the consumption of the final good C, and to the price of the nominal bond Q. With the interest rule, eq.(22), the first-order condition for money would just determine residually the level of nominal money balances, while playing no role in the determination of the equilibrium path of the other quantities. For this reason, it can be ignored in what follows.[10]

The economy's symmetric equilibrium is given by the first-order conditions for the representative household and for the firm producing the final good, eqs.(12)-(13) and (17)-(19) respectively, together with the aggregate production function, eq.(14), the capital accumulation equation, eq.(15), the economy-wide resource constraint, eq.(21), and the monetary reaction function, eq.(22). Under the assumption of zero growth and a zero steady-state inflation, for arbitrary $\overline{P}$ and $\overline{A}$, and a given value for $\overline{L}$, the equilibrium symmetric steady-state can be characterized in a straightforward manner.[11] In particular, given the assumptions on the shape of the function $\phi\left(I/K\right)$, it follows from eq.(17) that $\overline{I}/\overline{K} = \delta$, and from eqs.(17) and (18) that $\overline{K}/\overline{Y} = \left(1-\alpha\right)/(\beta^{-1} - (1-\delta))$. From these two values one can compute $\overline{I}/\overline{Y}$, and therefore also $\overline{C}/\overline{Y}$. The steady-state values for $\overline{W}/\overline{P}$ and $\overline{K}/\overline{L}$ then follow from eqs.(19) and (14) respectively, while $\overline{Y} = \left(\overline{Y}/\overline{K}\right)^{-\frac{1-\alpha}{\alpha}} \overline{AL}$.

Off the steady-state path, the model consists of a system of nonlinear expectational difference equations. To solve the system, the equilibrium conditions are log-linearized in the neighborhood of the steady-state just illustrated. Again, it is assumed that the technology shocks are homoskedastic, and that the variance terms that would appear in the approximations are constant. Derivation of the approximated equations is detailed in the appendix.

[10] The present setup can also be interpreted as the limit of a model where real money balances provide services but where, in the limit, these services are arbitrarily small (see Rotemberg and Woodford (1997), and Woodford (1997)).

[11] Imposing a specific steady state value for L is equivalent to calibrating the utility function parameter ϕ, as long as λ has been previously calibrated.

The log-linear system can be written in vector form as eq.(8) in the previous section, where now $\Theta_t \equiv [c_t \; k_t \; p_t \; p_{t-1} \; \psi_t \; w_t \; a_t]'$, and $\mathrm{E}_t k_{t+1} = k_{t+1}$, $\mathrm{E}_t w_{t+1} = w_{t+1}$, and lower-case variables denote the natural logarithm of the corresponding upper-case variables. The system's solution is given by the following set of equations:

$$s_{t+1} = M s_t + \Psi_s(\mathbf{F})\,\mathrm{E}_t a_t, \tag{9.1'}$$

$$d_t = -N s_t - \Psi_d(\mathbf{F})\,\mathrm{E}_t a_t, \tag{9.2'}$$

where s_t is the vector of state variables (predetermined or exogenous) and d_t is the vector of controls:

$$s_t = \begin{bmatrix} w_t \\ k_t \\ p_{t-1} \end{bmatrix}, \qquad d_t = \begin{bmatrix} c_t \\ p_t \\ \psi_t \end{bmatrix},$$

and the matrices M, N, and the polynomials $\Psi_s(\mathbf{F})$ and $\Psi_d(\mathbf{F})$ are computed from the system matrices B and $C(\mathbf{F})$ in eq.(8). From the solution, it is obviously also possible to compute the dynamics of investment $[i_t = \delta^{-1}(k_{t+1} - (1-\delta)k_t)]$, labor $[l_t = k_t + \frac{1}{1-\alpha}(\alpha a_t - w_t + p_t)]$, output $[y_t = \alpha(a_t + l_t) + (1-\alpha)k_t]$, and the real interest rate $[r_{t+1} = \rho(\mathrm{E}_t c_{t+1} - c_t)]$.

To gain some intuition for how the model works, it is useful to consider the log-linear version of the consumption Euler relationship, eq.(12),

$$q_t = p_t - \mathrm{E}_t p_{t+1} + \rho c_t - \rho \mathrm{E}_t c_{t+1}, \tag{23}$$

and the log-linear reaction function for the monetary authority, eq.(22),

$$q_t = -\eta(p_t - p_{t-1}), \tag{24}$$

where constants have been omitted. When $\eta > 1$, a necessary condition for determinacy of the model's equilibrium, it is possible to combine the two previous equations and solve forward, thus obtaining the following expression relating current inflation to current and future consumption:

$$p_t - p_{t-1} = -\frac{\rho}{\eta} c_t + \frac{\rho}{\eta} (\eta - 1) \sum_{s=t+1}^{\infty} \left(\frac{1}{\eta} \right)^{s-t} \mathrm{E}_t c_s. \tag{25}$$

The expression shows that higher expected future consumption raises the current price level, while it lowers future expected inflation. Higher expected future consumption also raises the real interest rate, with the increase in the real rate being greater than the decline in future expected inflation, as the monetary reaction function, eq.(22), shows.

The aggregate supply schedule for the economy, eq.(20), can be written in logarithms as follows:

$$y_t = k_t + \frac{\alpha}{1-\alpha} a_t - \frac{\alpha}{1-\alpha} \left(w_t - p_t \right), \tag{26}$$

where k_t and w_t are predetermined quantities at time t. Consider now the effects of an unanticipated permanent increase in expected future productivity, to occur at time $t+1$. The new steady-state will be characterized by higher private consumption, and, for the usual intertemporal smoothing reasons, households will want to spread the increase in income over period t by consuming more. However, eq.(25) implies the price level p_t will go up, since the increase in consumption at time t is lower than during subsequent periods. But given that k_t and w_t are predetermined, for an unchanged a_t the increase in price will translate into an increase in output, y_t, as eq.(26) shows, because the real wage declines and the labor-leisure trade-off condition, eq.(13), does not bind ex post.

This result stands in sharp contrast with the analysis of the previous section, which showed that for a plausible parametrization of the intertemporal elasticity of substitution in consumption, current output y_t decreases. The reason is that, in the absence of nominal rigidities, households are always on their labor supply curve: therefore, the increase in current consumption is accompanied by a decline in the quantity of labor supplied, and by an increase in the real wage $w_t - p_t$. The behavior of the monetary authority is central for the determination of the investment's equilibrium path. A high value for η implies that the monetary authority reacts strongly to changes in current inflation, raising the real rate of interest significantly for a given change in prices. In the absence of adjustment costs to the capital stock, the net marginal product of capital, $(1-\alpha)\,\mathrm{E}_t\left(A_{t+1}L_{t+1}/K_{t+1}\right)^{\alpha} + (1-\delta)$, must equal the real interest rate. If the monetary authority drives the real rate high following an increase in current inflation, it is possible for K_{t+1} to decrease, despite the expected increase in $A_{t+1}L_{t+1}$. When adjustment costs to the capital stock are present, the expected future increase in productivity implies that the dollar value of installed capital will rise in the future, so that, for a given η, an increase in current investment, I_t, becomes more likely than in the case without adjustment costs.

Eqs.(9.1') -(9.2') allow us to simulate the model and compute impulse-response functions. In addition to the parameters already calibrated in section 2, it is necessary to calibrate the coefficient η of the monetary authority's reaction function, and the elasticity of I/K with respect to the ratio of the shadow price of installed capital to the price of replacement capital, ς.[12] Note that without nominal rigidities and adjustment costs to capital, the response functions for investment and the real rate would be identical to those reported in figure 2,

[12] The near-steady-state analysis does not require the specification of a functional form for the adjustment cost function, $\phi\left(I/K\right)$. As already noted, the function is such that the model has the same steady-state as a model with no adjustment costs to capital. A parameter which must be specified is the elasticity of the marginal adjustment cost function, $\varsigma \equiv \left(\overline{I}/\overline{K}\phi''\left(\overline{I}/\overline{K}\right)/\phi'\left(\overline{I}/\overline{K}\right)\right)$, which governs the response of I/K to movements in the ratio of the shadow price of installed capital to the price of replacement capital.

irrespective of the value of η. Figure 3 reports impulse-responses for investment and the real rate at time 0 and in subsequent periods, following an unanticipated permanent increase in expected productivity, to occur from time 1 on, when $\eta = 1.5$, $\varsigma = 0$, $\rho = \gamma_L = 1$, and with all the other parameters calibrated as in the previous section. For the calibrated parameter η, the stock of capital stays unchanged from period 0 to period 1. For values of $\eta < 1.5$, the capital stock will increase at time 1, while it will decrease for values of $\eta > 1.5$. As already noted, the monetary policy's reaction function is crucial in determining the response of current investment to future changes in productivity. Rotemberg and Woodford (1997) estimate the inflation coefficient in a monetary reaction function for the United States during the period 1980-95 to be equal to 2.13,[13] a value that would imply a decline in the capital stock at time 1 in the present simulations. However, the introduction of adjustment costs to capital allows for the possibility that time 0 investment increases, even when the coefficient η of the monetary reaction function is above 2.

Figure 4 reports impulse-responses for investment and the real interest rate when $\eta = 2.5$, $\varsigma = 0.5$, with all the other parameters calibrated as in the simulations reported in figure 3. A value of 0.5 for ς is in line with Chirinko's (1993) overview of empirical investment functions. Investment at time 0 now increases, and, other things equal, the real interest rate increase is much more pronounced than in the case in which $\varsigma = 0$. The reason is that while the response of consumption at time 0 is approximately the same with or without adjustment

[13] The estimate is derived from a monetary policy reaction function of the following form

$$r - r^* = \eta\,(\pi_t - \pi^*) + \nu y_t,$$

where r is the nominal interest rate, r^* the central bank's target value for the nominal interest rate, $\pi_t - \pi^*$ is the deviation of current inflation from its target value, and y_t is the deviation of output from trend. Because of the presence of the output term, this reaction function is clearly more general than the one considered in the present setup.

costs, the increase in time 0 total output and the price level is much more sizeable in the presence of adjustment costs to capital. As a result, the monetary authority drives the real rate of interest up by a much larger amount, and the difference between the real rate and period 1 marginal product of capital is covered by an increase in the dollar value of installed capital.

Given that adjustment costs appear to be an important component in explaining a contemporaneous increase at time 0 of investment and the real rate in response to a favorable shift in future productivity, the question naturally arises of whether the introduction of adjustment costs in the real model of the previous section would be sufficient to generate a positive comovement in investment and the real rate. Figure 5 plots impulse-response functions for investment and the real rate in the absence of nominal rigidities, when $\varsigma = 0.5$, and $\rho = \gamma_L = 1$. Time 0 investment still declines, although it is evident that, compared with the impulse-response reported in figure 2, the decrease is now less pronounced. This result continues to hold even when labor supply is completely inelastic ($\gamma_L \to \infty$). While there is no firm consensus in the literature about the value that ς should take, it has been claimed that $\varsigma = 0.5$ already gives a very slow partial equilibrium adjustment rate for capital, and that larger values for ς are thus to be considered unlikely (see, e.g., Kimball (1995), who advocates a value for ς close to 0.2). It then appears that adjustment costs to capital are not sufficient *per se* to reverse the result of a decline in time 0 investment following a favorable shift in expected future profitability.

In summary, the presence of nominal rigidities combined with adjustment costs to capital drastically changes the results of the previous section, according to which a future expected increase in productivity decreases current investment and output for a unitary elasticity of substitution in consumption. With nominal rigidities, not only current output but also current investment increases, provided that adjustment costs to capital are present. Moreover, these costs drive a wedge between the real rate and the marginal productivity of capital, and since a future increase in productivity implies that the value of installed capital will rise in the future, they allow for a significant increase in the real rate of interest.

4 Final Comments

This paper has offered another example of how the economy's response to shocks differs from the baseline flexible price case when nominal rigidities are introduced into a general-equilibrium macro model. In particular, I have considered the effects on current investment and the real rate of interest of a permanent increase in future expected productivity. The motivation for this exercise stems from work by Blanchard and Summers (1984) and Barro and Sala-i-Martin (1990), who have identified anticipated future investment profitability as a primary cause for the high world real interest rates in the early 1980s. Specifically, Barro and Sala-i-Martin have provided econometric evidence that future expected investment profitability had a positive effect on world investment and the world real interest rate over the period 1959-1988. However, thus far the possibility that an increase in expected future investment profitability could explain a simultaneous rise in current investment and the real rate of interest was considered remote from a theoretical standpoint. The reason is that in a standard general equilibrium model with perfectly flexible prices, it is necessary to posit an implausibly large value for the intertemporal elasticity of substitution in consumption in order to obtain a positive comovement of current investment and the real rate in response to an anticipated increase in future productivity.

In this paper, I have shown that this conclusion is unwarranted when one introduces nominal rigidities in the analysis. In particular, the presence of predetermined wages in a model with adjustment costs to capital allows for current output, investment, and the real rate to rise in response to a future increase in productivity for a plausible parametrization of the model. While this result has been derived in the context of a very stylized framework, it generalizes to virtually any dynamic general-equilibrium model with sticky prices. Also, the model has posited a very simple monetary reaction function, according to which the monetary authority reacts to changes in current inflation only. As is well known, it is generally believed that central banks respond not only to deviation of current inflation from target, but also to deviations of current output from trend (see, e.g., Taylor (1993)). While the introduction of a more general reaction function complicates the analysis somewhat, it leaves all the main results in the previous section unchanged. Moreover, it is also possible to show that the results carry over to a money-in-the-utility-function setup with an exogenous money supply, provided the interest semi-elasticity of money demand is sufficiently small, as it appears to be the case in actual economies.[14] The reason is that a low interest semi-elasticity ensures that future increases in private consumption raise the nominal interest rate and the current price level, thus inducing an expansion in current output when the nominal wage is predetermined, and triggering the same kind of responses for investment and the real interest rate as those analyzed in the previous section.

[14] See, e.g., Stock and Watson (1993), who estimate a value of -0.10 for the interest semi-elasticity of money demand in the United States over the period 1959-1988.

A Appendix

This appendix briefly describes the log-linear relationships that make up the systems in sections 2 and 3. In the following, constants have been omitted and lower-case variables denote the natural logarithm of the corresponding upper-case variables. The system in section 2 for a utility function additively separable in consumption and leisure is

$$
\begin{aligned}
\rho\left(\mathrm{E}_t c_{t+1} - c_t\right) &= \frac{\beta^{-1} - (1-\delta)}{\beta^{-1}} \alpha \mathrm{E}_t \left(a_{t+1} + l_{t+1} + k_{t+1}\right), \\
\alpha a_t + (1-\alpha) k_t - \rho c_t &= \left(1 - \alpha + \frac{\overline{L}}{1-\overline{L}} \gamma_L\right) l_t, \\
k_{t+1} - \beta^{-1} k_t &= \frac{\beta^{-1} - (1-\delta)}{1-\alpha} \alpha \left(l_t + a_t\right) \\
&\quad + \delta \left(1 - \frac{\beta^{-1} - (1-\delta)}{\delta (1-\alpha)}\right) c_t .
\end{aligned}
$$

The first relationship is the log-linear version of eqs.(5) and (6), the second is the log-linear version of the static first-order condition for labor supply, eq.(7), while the third equation is the log-linear economy-wide resource constraint, derived from eqs.(1) and (2). It is evident that the system can be further reduced by substituting labor from the log-linear labor-leisure trade-off condition in the other two expressions, to obtain a system of log-linear expectational difference equations in technology, capital, and consumption. With consumption and leisure non-additively separable, as in the utility function of eq.(4'), the capital accumulation equation does not change, but the intertemporal Euler equation for consumption is modified as follows

$$
\begin{aligned}
&\left[1 - \gamma (1-\zeta)\right] \left(\mathrm{E}_t c_{t+1} - c_t\right) + (1-\zeta)(1-\gamma) \frac{\overline{L}}{1-\overline{L}} \left(\mathrm{E}_t l_{t+1} - l_t\right) \\
= \; &\frac{\beta^{-1} - (1-\delta)}{\beta^{-1}} \alpha \mathrm{E}_t \left(a_{t+1} + l_{t+1} - k_{t+1}\right),
\end{aligned}
$$

while the static log-linear first-order condition for labor supply becomes

$$\alpha a_t + (1-\alpha)\, k_t - c_t = \left(1 - \alpha + \frac{\overline{L}}{1-\overline{L}}\right) l_t.$$

The log-linear relationships that comprise the system in section 3 are

$$\begin{aligned}
p_t - p_{t-1} - \frac{1}{\eta}\left(\mathrm{E}_t p_{t+1} - p_t\right) &= -\frac{\rho}{\eta}\left(\mathrm{E}_t c_{t+1} - c_t\right), \\
w_{t+1} - \frac{\overline{L}}{1-\overline{L}}\gamma_L \mathrm{E}_t l_{t+1} &= \rho \mathrm{E}_t c_{t+1} + \mathrm{E}_t p_{t+1}, \\
-\rho c_t - \psi_t &= \frac{\varsigma}{\delta}\left(k_{t+1} - k_t\right), \\
\psi_t - \mathrm{E}_t\left(\beta\psi_{t+1} - (1-\beta)\rho c_{t+1}\right) &= \alpha\left(1 - \beta\left(1-\delta\right)\right) \mathrm{E}_t\left(a_{t+1} + l_{t+1} - k_{t+1}\right), \\
l_t &= k_t + \frac{1}{1-\alpha}\left(\alpha a_t - w_t + p_t\right), \\
\alpha\left(a_t + l_t\right) + (1-\alpha)k_t - \frac{\overline{C}}{\overline{Y}} c_t &= \frac{\overline{I}}{\overline{Y}}\left(\frac{1}{\delta}k_{t+1} - \frac{1-\delta}{\delta}k_t\right).
\end{aligned}$$

The first relationship is derived from the Euler consumption eq.(12), and from the monetary reaction function, eq.(22), with η denoting the elasticity of Υ with respect to changes in inflation. The second relationship is the log-linear version of eq.(13). The next two equations are obtained from the first-order conditions for capital and investment, eqs.(17) and (18), together with the accumulation equation for capital, eq.(15), where the parameter $\varsigma \equiv \left(\overline{I}/\overline{K}\phi''\left(\overline{I}/\overline{K}\right)/\phi'\left(\overline{I}/\overline{K}\right)\right)$ is (minus) the elasticity of I/K with respect to the ratio of the shadow price of installed capital to the price of replacement capital. The last two equations are the log-linear versions of the aggregate supply schedule, eq.(20), and of the economy-wide resource constraint, eq.(21), respectively, where use has been made of eqs.(14)-(15), and (19).

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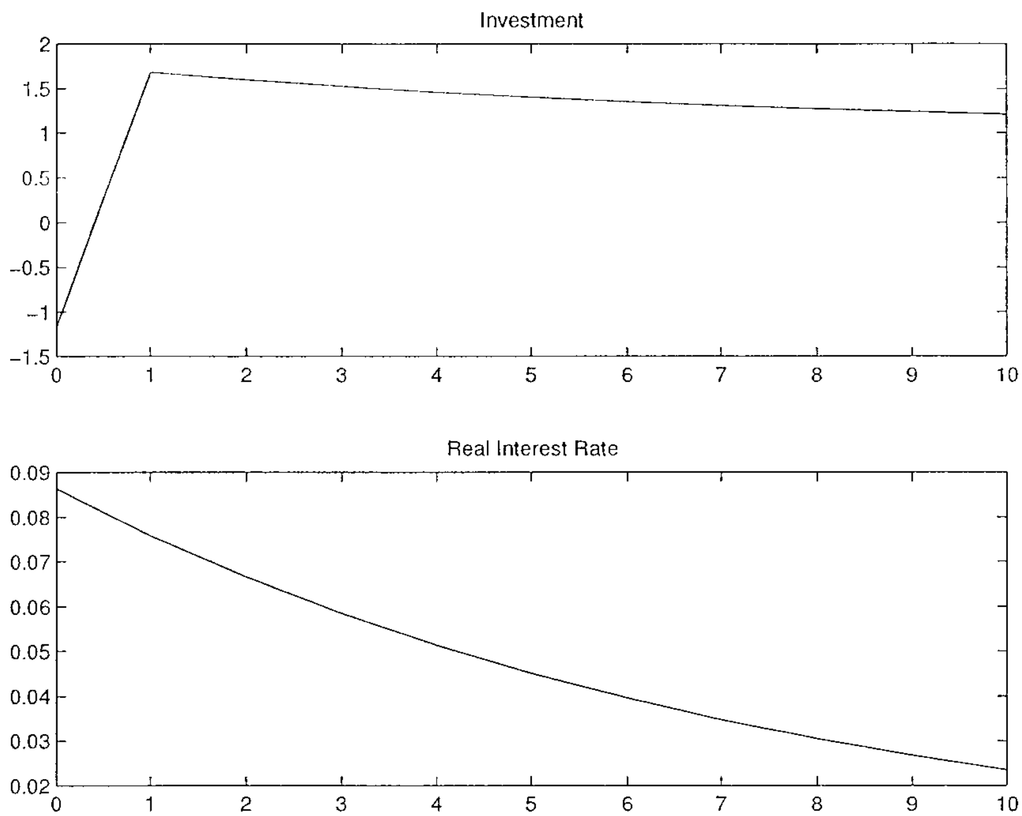
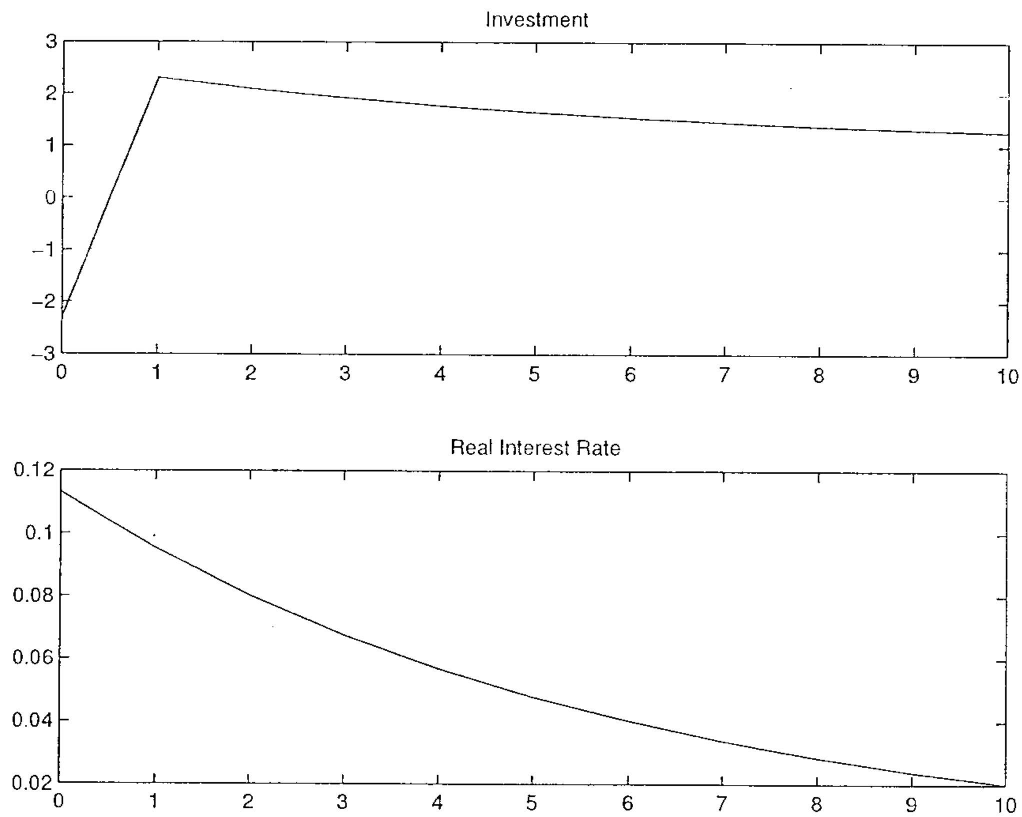
FIGURE 1
real model with fixed labor supply



Note: The figure depicts impulse-response functions for investment and the real interest rate following a permanent 1 percentage point increase in expected productivity, to occur from period 1 on. The case depicted is the one with a perfectly inelastic labor supply. Calibrated parameter values are given in section 2 in the text.

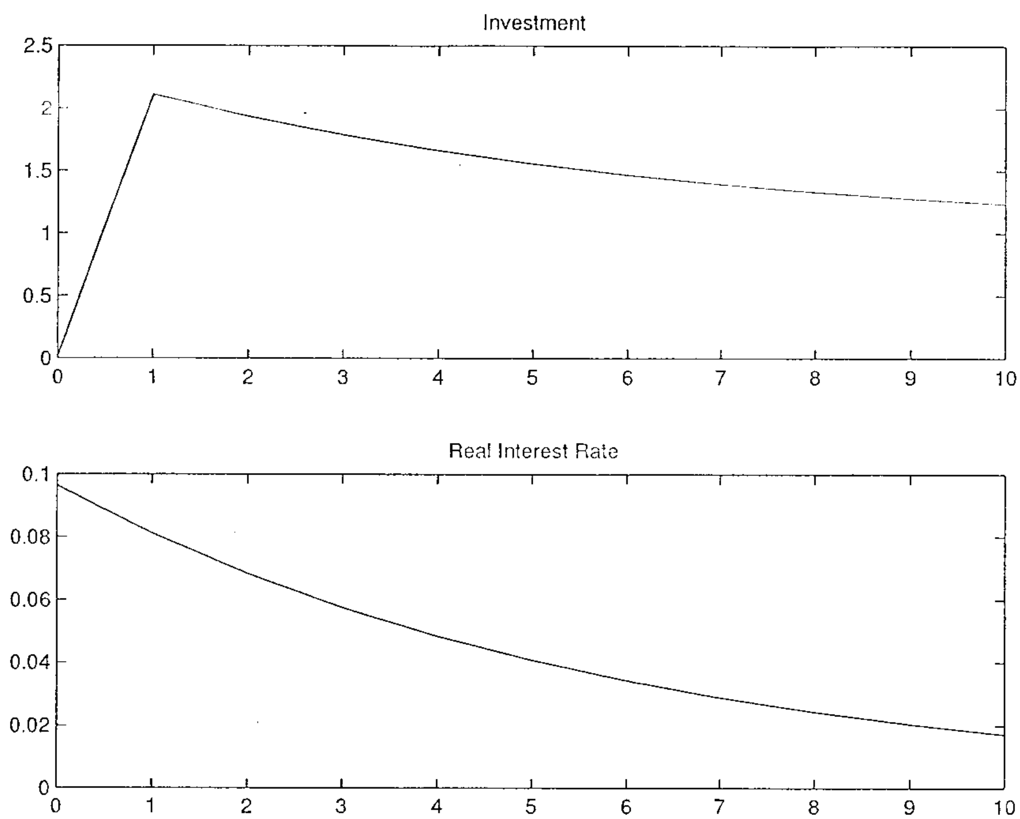
FIGURE 2
real model with variable labor supply



Note: The figure depicts impulse-response functions for investment and the real interest rate following a permanent 1 percentage point increase in expected productivity, to occur from period 1 on. The case depicted is the one with an elastic labor supply. Calibrated parameter values are given in section 2 in the text.

FIGURE 3

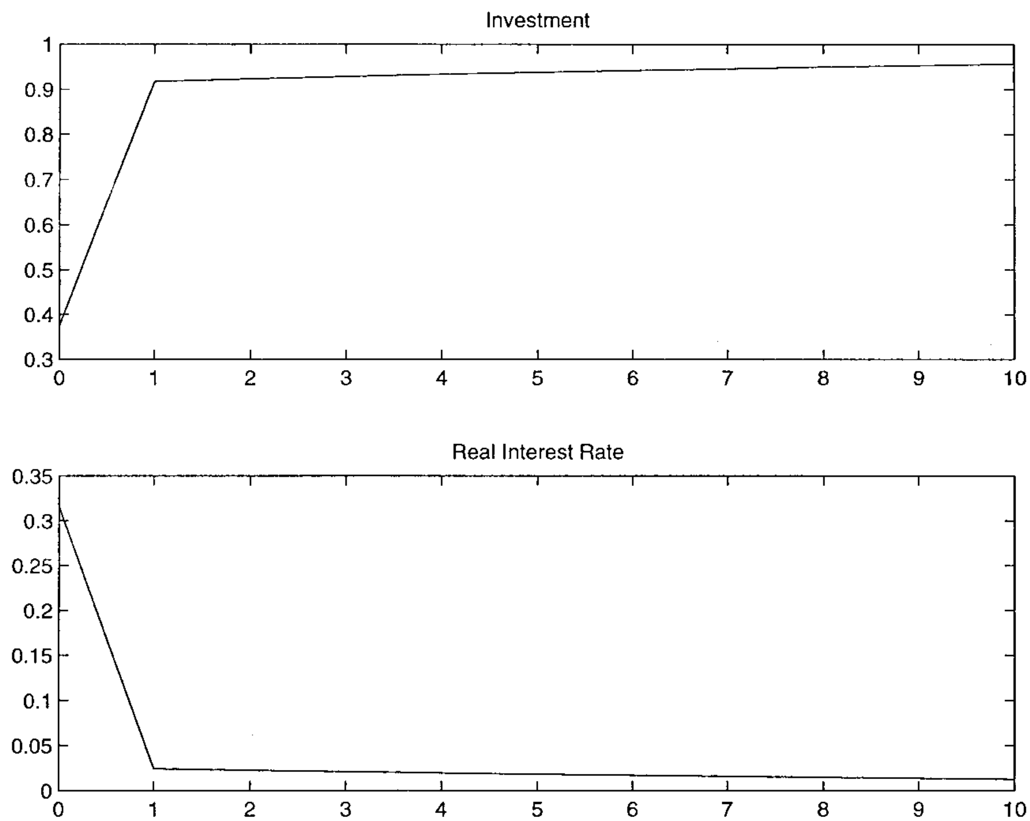
model with predetermined wages and no adjustment costs to capital



Note: The figure depicts impulse-response functions for investment and the real interest rate following a permanent 1 percent point increase in expected productivity, to occur from period 1 on. The case depicted is the one with nominal rigidities and no adjustment costs to capital. Calibrated parameter values are given in section 3 in the text.

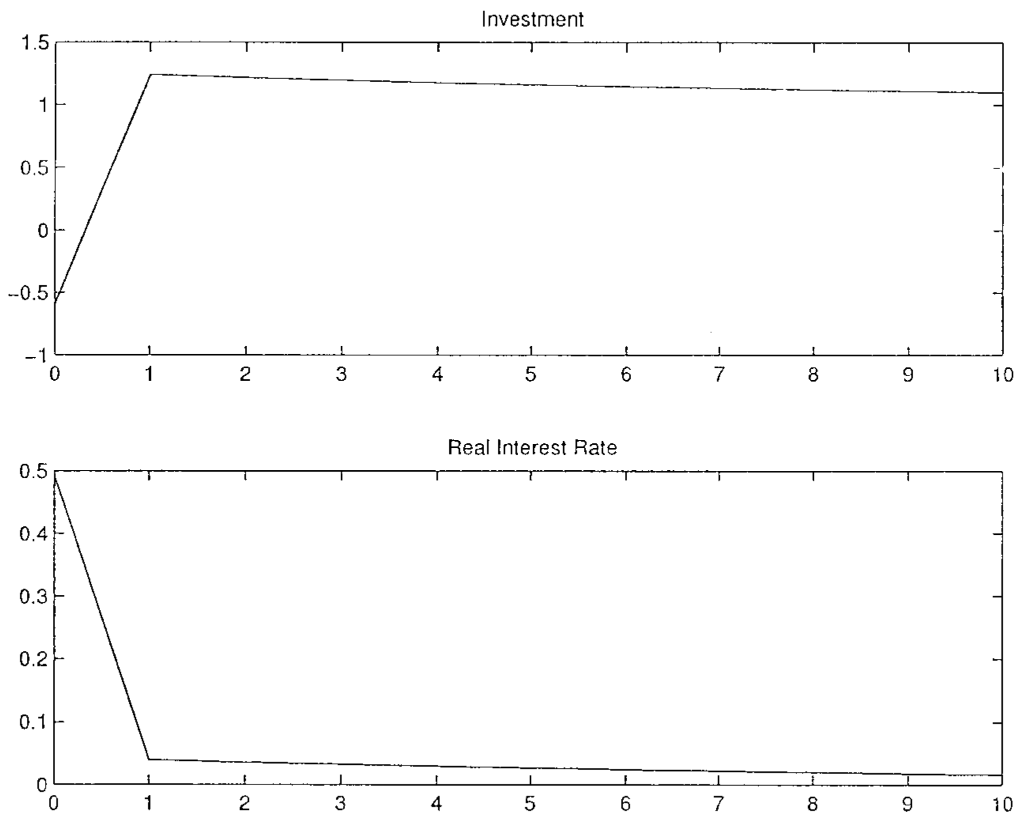
FIGURE 4

model with predetermined wages and adjustment costs to capital



Note: The figure depicts impulse-response functions for investment and the real interest rate following a permanent 1 percent point increase in expected productivity, to occur from period 1 on. The case depicted is the one with nominal rigidities and adjustment costs to capital. Calibrated parameter values are given in section 3 in the text.

FIGURE 5
model with flexible wages and adjustment costs to capital



Note: The figure depicts impulse-response functions for investment and the real interest rate following a permanent 1 percent point increase in expected productivity, to occur from period 1 on. The case depicted is the one with no nominal rigidities and adjustment costs to capital. Calibrated parameter values are given in section 3 in the text.