Is the technology-driven real business cycle hypothesis dead?

Shocks and aggregate fluctuations revisited

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**Abstract**

This paper re-examines recent empirical evidence that positive technology shocks lead to short-run declines in hours. Building on Galí's (1999) work, which uses long-run restrictions to identify technology shocks, we analyze whether the identified shocks can be plausibly interpreted as technology shocks. We first examine the validity of the identification assumption in a DGE model with several possible sources of permanent shocks. We then empirically assess the plausibility of the shocks using a variety of tests. After finding that the shocks pass all of the tests, we present two examples of modified DGE models that match the facts.

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## 1. Introduction

Real business cycle theory assigns a central role to technology shocks as the source of aggregate fluctuations. As King and Rebelo (1999) discuss in "Resuscitating Real Business Cycles," when persistent technology shocks are fed through a standard real business cycle model, the simulated economy displays patterns similar to those exhibited by actual business cycles. While the last decade has seen the addition of other types of shocks in these models, such as monetary policy and government spending, none has been shown to be a central impulse to business cycles.

A trio of recent papers has called into question the notion that technology shocks have anything to do with business cycles. Although they use very different methods, Galí (1999), Shea (1998) and Basu, Fernald, and Kimball (1999) all present the same result: *positive technology shocks appear to lead to declines in labor input*.[1] Galí identifies technology shocks using long-run restrictions in a structural VAR; Shea uses data on patents and R&D; and Basu, Fernald, and Kimball identify technology shocks by estimating Hall-style regressions with proxies for utilization. In all cases, they find significant negative correlations of hours with the technology shock.[2]

Galí's paper also studies the effects of the non-technology shocks, which he suggests might be interpreted as demand shocks. These shocks produce the typical business cycle

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[1] The fall in labor input is a long run response in Shea. Labor rises in the short run and then eventually falls.

[2] Blanchard and Quah (1989) and Shapiro and Watson (1988) uncovered this result years ago, but it apparently went unnoticed.

comovement between output and hours. In response to a positive shock, both output and hours show a rise in the typical hump-shaped pattern. Productivity also rises, but only temporarily.

We view the empirical results of these papers to be potential paradigm shifters. If these results prove to be robust, the idea of technology-driven business cycles loses all of its appeal. If it is “demand” shocks that are producing the classic business cycle patterns, then renewed emphasis should be devoted to understanding the imperfections in the economy that allow these shocks to have these types of effects.

In this paper, we re-examine the effects of technology shocks on the economy. First, we assess the validity of the technology shocks identified using long-run restrictions by subjecting the model to a host of tests. These tests include: (i) controlling for the effects of changes in capital income tax rates, (ii) over-identifying restrictions derived from a DGE model with various types of permanent shocks, (iii) Evans and Hall exogeneity tests, and (iv) sensitivity tests to different assumptions about the hours process. Second, we study whether suitably altered dynamic general equilibrium models can explain the facts. We present examples of two models that can explain these effects of technology shocks, without resorting to assumptions about sticky prices. One model assumes Leontief technology with variable utilization and the other model includes habit formation in consumption and adjustment costs in investment. Despite their ability to explain these effects, the modified models do not resuscitate technology shocks as the driving force of business cycles. In that sense, the original technology-driven real business cycle hypothesis does appear to be dead.

## 2. Long-Run Effects of Shocks

To assess the plausibility of the identified shocks as technology shocks, we reexamine the identification assumption in a DGE (dynamic general equilibrium) model with several possible sources of permanent shocks. This theoretical analysis not only allows us to assess Galí's identifying assumption, but also provides additional long-run restrictions that can be used in tests of over-identifying restrictions. We begin by specifying a nonstochastic model and then discuss how the results extend to the case of stochastic trends. Consider the following model:

| | | |
|---|---|---|
| $Y_t = (A_t N_t)^{\alpha} K_t^{1-\alpha}$ | Production Function | |
| $A_t = \mu^t A_0, \quad \mu > 1$ | Technology Growth | |
| $K_{t+1} = (1-\delta)K_t + I_t$ | Capital Accumulation | (1) |
| $C_t + I_t + G_t \leq Y_t$ | Resource Constraint | |
| $U(C_t, N_t) = \ln(C_t) + \phi_t \ln(1-N_t)$ | Utility | |
| $C_t + I_t = (1-\tau_{nt})W_t N_t + (1-\tau_{kt})r_t K_t + \delta\tau_{kt} K_t - \psi_t$ | Household Budget Constraint | |
| $G_t = \tau_{nt} W_t N_t + \tau_{kt}(r_t - \delta)K_t + \psi_t$ | Government Budget Constraint | |

*Y* is output, *A* is an exogenous process for labor augmenting technical change, *K* is capital, *N* is labor input, δ is the depreciation rate, *I* is investment, *C* is consumption, *G* is government purchases, $\phi_t$ is a preference shifter, *W* is the real wage, $r_t$ is the pre-tax return on capital, $\tau_n$ is the tax on labor income, $\tau_k$ is the tax on capital income, and ψ is a lump-sum tax. The representative consumer chooses capital, consumption and labor to maximize the expected present discounted value of utility, with discount factor $\beta$. Consumers own the capital and rent it to firms. The government finances its spending through a combination of lump-sum taxes and distortionary labor and capital income taxes.

Following standard practice, we transform the economy to eliminate the nonstationarity arising from technology by dividing $Y_t$, $K_t$, $I_t$, $C_t$, $G_t$, $W_t$ and $\psi_t$ by $A_t$. Since the first-order conditions to this problem appear in many parts of the literature, we move directly to the key equations of the steady-state balanced growth path.[3] Let lower case letters denote variables divided by $A_t$, and lower case letters with tildes denote variables divided by output $Y$, i.e., $k_t = K_t/A_t$ and $\tilde{k}_t = K_t/Y_t$. The following set of equations represents the key equations characterizing the balanced growth path of the economy:

| | | |
|---|---|---|
| $1+(1-\tau_k)[(1-\alpha)\left(\frac{k}{N}\right)^{-\alpha}-\delta]=\frac{\mu}{\beta}$ | MP of Capital-Time Preference Link | (2) |
| $\tilde{c}+\tilde{g}+\tilde{i}=1$ | Resource Constraint | (3) |
| $\frac{1-N}{N}=\frac{\phi}{\alpha(1-\tau_n)}[1-\tilde{i}-\tilde{g}]$ | Marginal Rate of Substitution | (4) |
| $\tilde{i}=(\mu+\delta-1)\left(\frac{k}{N}\right)^{\alpha}$ | Investment Rate | (5) |
| $Y=AN\left(\frac{k}{N}\right)^{1-\alpha}$ | Production Function | (6) |
| $\alpha\frac{Y}{N}=W=\alpha A\left(\frac{k}{N}\right)^{1-\alpha}$ | Labor Productivity | (7) |

[3] See King and Rebelo (1999) for the nondistortionary tax case and Atkeson, Chari, and Kehoe (1999) for the distortionary tax case.

Suppose first that technology is the only source of permanent shifts. It is well-established that while output, consumption, investment, the capital stock, real wages and labor productivity will grow at the same rate as *A*, the great ratios *C/Y* and *I/Y* will be constant along the nonstochastic steady-state growth path, as will the transformed capital-labor ratio, *k/N*. Furthermore, with the type of utility function given above, hours will also be constant on the steady-state growth path since the income and substitution effects exactly cancel. Standard DGE models use utility functions with this feature in order to match the growth facts. Thus, the technology shock has permanent effects on labor productivity and real wages, but not on hours.

Do any other variables have permanent effects on labor productivity, wages, or hours? Consider permanent shifts in the share of government spending $\tilde{g}_t$, labor income tax rates $\tau_{nt}$ (both financed by changes in the nondistortionary lump-sum tax) or the preference parameter $\phi_t$. Since none of these variables enters the equation linking the marginal product of capital to the consumer's discount rate (equation (2)), it is clear that the transformed capital-labor ratio *k/N* must be invariant to shifts in $\tilde{g}_t$, $\tau_{nt}$, and $\phi_t$. Labor productivity and the wage depend only on *A* and *k/N* (equation (7)), so they are also invariant to changes in $\tilde{g}_t$, $\tau_{nt}$, and $\phi_t$.

On the other hand, equation (4) implies that shifts in $\tilde{g}_t$, $\tau_{nt}$, or $\phi_t$ will affect $(1-N_t)/N_t$. A permanent rise in $\tilde{g}_t$ leads to a permanent decline in the ratio of leisure to labor because of the negative wealth effect (Baxter and King (1993)). A permanent rise in $\phi$, which indicates more weight on leisure in the utility function, leads to a permanent decline in hours. A permanent rise in $\tau_n$ has the same effect.

Now consider changes in the capital income tax rate, $\tau_k$, offset by a change in lump-sum taxes. From equation (2), a rise in $\tau_k$ lowers the steady-state transformed capital-labor ratio, *k/N*.

Tracing the impact of the lower capital-labor ratio through the other equations, it is clear that a higher capital income tax rate lowers the investment-output ratio, labor productivity, real wages, and hours.

Let us summarize the key results of this analysis. First, both technology shocks and permanent shifts in capital income tax rates can affect labor productivity in the long-run. Thus, the shocks identified using Galí's assumption could include capital income tax rate shocks. Second, technology shocks and capital tax shocks are also distinguished from the other shocks in their long-run effect on the real wage. Third, while permanent shifts in technology should not affect long-run labor supply, shifts in the share in government spending, preference shocks, labor income tax rates and capital income tax rates can all have permanent effects on labor.

So far we have only discussed the effects of permanent shifts in the non-technology variables in the nonstochastic steady-state. King, Plosser, Stock and Watson (1991) show that when technology has a stochastic trend, the same variables that are *constant* on the nonstochastic balanced growth path will be *stationary* along the stochastic balanced growth path. When technology has a stochastic trend, output, consumption, investment, capital, labor productivity, and real wages will all share the common stochastic trend, and the great ratios and hours will be stationary. Ahmed and Yoo (1995) extend the model to include an additional stochastic trend in the share of government spending (financed by lump-sum taxes) and analyze the effects on the cointegrating relationships. Similarly, in our model variables or ratios that are predicted to be constant in the non-stochastic steady-state should be stationary in the stochastic model. Variables that are affected by permanent shifts in taxes, spending or preference parameters in the nonstochastic model will be nonstationary in the stochastic model.

In the empirical section, we will perform unit root tests on the key variables. Of course, bounded variables such as the government share of output, hours per capita, and tax rates cannot literally have unit roots. It is reasonable, however, to consider their behavior as governed by a unit root data generating process within a certain range, with trigger points at the limits of the range. As long as the variances of the innovations are small, then the unit root specification may be a good approximation in many samples where the trigger points are not reached.

## 3. Empirical Framework

### *3.1 Identification*

Consider the following bivariate model of labor productivity and hours:

$$\begin{bmatrix} \Delta x_t \\ \Delta n_t \end{bmatrix} = \begin{bmatrix} C^{11}(L) & C^{12}(L) \\ C^{21}(L) & C^{22}(L) \end{bmatrix} \begin{bmatrix} \varepsilon_t^z \\ \varepsilon_t^m \end{bmatrix} \tag{8}$$

$x_t$ denotes the log of labor productivity, $n_t$ denotes the log of labor input, $\varepsilon^z$ denotes the technology shock, and $\varepsilon^m$ denotes the non-technology shock. C(L) is a polynomial in the lag operator. We invoke the usual assumption that $\varepsilon^z$ and $\varepsilon^m$ are orthogonal. The assumption identifying the technology shock implies that $C^{12}(1) = 0$, which restricts the unit root in productivity to originate solely in the technology shock. Implicit in this specification, but not necessary for identification, is the assumption that the log of labor input has a unit root. Permanent shifts in labor input are completely consistent with the model presented in the last section. We will discuss the empirical validity of this assumption in detail in a later section.

Consider now the alternative long-run restriction involving real wages. Analogous to the case of labor productivity, only a technology shock should have a permanent effect on real wages. Thus, an alternative way to identify the technology shock is to substitute real wages for productivity and impose the same restriction in (8) that $C^{12}(1) = 0$.

But we can go even farther by considering the third long-run restriction that technology shocks have no long-run effect on hours. We can thus create a shock that excludes permanent technology shocks. We impose this restriction by constraining $C^{21}(1) = 0$ in equation (8) above. Note, though, that in contrast to the previous systems, the residual in the productivity equation may include other shocks in addition to the technology shock. For example, a monetary shock that has no long-run effect on hours would be included with the technology shock. There is not a perfect correspondence between the shocks in this third system and those from the previous systems.

As the theoretical model made clear, though, the first two identification methods are not full-proof because permanent changes in capital income taxation can also have permanent effects on productivity and wages. While one could attempt to untangle technology shocks and capital tax shocks using combinations of long-run restrictions implied by the model, the most direct way to deal with the issue is to use more data. In particular, since capital taxes are observable, we control for them in the estimation.

### *3.2 Data*

We use quarterly data from 1947:1 to 2003:1 to estimate the model. For the series on labor productivity and labor input, we use the BLS series "Index of output per hour, business" and "Index of hours in business," respectively. This productivity measure has the advantage that the output series covers the same sector as the hours series so that productivity is more accurately measured. The real wage measure is the BLS measure of nominal hourly compensation in private business divided by the BLS deflator for private business. The capital tax series, kindly provided by Craig Burnside, was constructed by Jones (2002) and updated by Burnside, Eichenbaum and Fisher (2003). The other series are chain-weighted 1996 dollar NIPA series from the BEA Web site. All relevant variables are put on a per capita basis by dividing by the population age 16 and above. All variables except the tax rate are entered in logarithms.

Standard ADF tests of a unit root against the alternative of a linear trend suggest that one cannot reject a unit root.[4] The p-values are above 0.3 for productivity and hours and above 0.6 for real wages. Thus, in the baseline specification of the model, we assume that all variables have unit roots. We will discuss in detail below the results using alternative assumptions for hours. We include four quarterly lags of each variable in the estimation; the results are similar if we use eight lags instead.

Before turning to the estimation of the models, it is useful to review the unconditional correlations displayed by the post-WWII data. These correlations constitute some of the key stylized facts of business cycle analysis. Considering all variables in growth rates, the unconditional correlation between output and hours is 0.68; between output and productivity, 0.69; and between productivity and hours, –0.059. The correlation is 0.48 between real wages and productivity, and –0.22 between real wages and hours.

## 4. Empirical Results

### *4.1 Comparison of Different Identification Schemes*

We begin by analyzing whether Galí's results are due to the confounding of technology shocks and capital tax rates, both of which can have permanent effects on labor productivity. We

[4] Subject to the caveat discussed in the last section.

estimate two versions of the baseline equation (8), one that does not control for capital tax rates and one that does. The latter includes current and four lags of the level of capital tax rates as exogenous variables in the VAR.

Figure 1A shows the results. [5] The solid line shows the results with no controls for tax rates and the line with circles shows the results with controls for capital tax rates.[6] The graph makes it very clear that controlling for tax rates has no effect on the results: both models reproduce Galí's results. An identified technology shock leads to an immediate and permanent rise in productivity. In response to the same shock, hours worked decline and do not return to near normal for a year and a half. Thus, we conclude that changes in the capital income tax rate are not a significant part of the identified technology shocks, and omit them from the rest of the analysis in order to be able to use the full sample.

We next determine how the effects of a technology shock differ across the three long-run identification schemes. Figure 1B shows the effect of a technology shock identified as the only shock that permanently affects real wages. The results are the same: a technology shock leads to an immediate and permanent rise in real wages and a decline in hours. Figure 1C shows the effect of a shock that does not have a permanent effect on hours. The results are surprisingly similar to the previous ones: productivity jumps immediately and permanently and hours fall in the short-run. Hours do show a quicker tendency to return to normal, taking about a year.

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[5] The standard error bands were computed using a bootstrap Monte Carlo procedure with 1000 replications.

[6] The model with tax rates is estimated only up through 1997:4 because the tax rate data do not extend beyond this point.

The next step is to specify a unified model in which the additional restrictions can be used as overidentification tests. The two additional restrictions are incorporated in different ways. The first restriction on wages, in conjunction with Galí's restriction on labor productivity, implies labor productivity and real wages should be cointegrated. Thus, the test of the joint restriction that technology shocks are the only shocks that have permanent effects on both productivity and real wages is a test of cointegration between the two variables.

The theoretical model implies that the (log) ratio of productivity to wages should be stationary. An ADF test with four lags rejects the null hypothesis of a unit root in the ratio with a p-value of 0.015, supporting the theory. However, the estimate of the cointegrating coefficient of productivity on wages is 1.04112, with a standard error of 0.0068.[7] Since the coefficient is significantly different from –1, we use the estimated cointegrating vector rather than the theoretical one.

To test the third restriction concerning hours, we specify a trivariate vector error-correction model (VECM) which incorporates the other two restrictions. This model takes the form $y_t = C(L)u_t$, where $y_t$ is a 3 x 1 vector consisting of labor productivity growth ($\Delta x_t$), hours growth ($\Delta n_t$), and the error correction term between productivity and wages ($xw_t$). $u_t$ consists of the shocks $\varepsilon_t^z, \varepsilon_t^m, \varepsilon_t^w$, in that order. To estimate the system properly, we should include $p$ lags of labor productivity growth and hours growth and $p+1$ lags of the error correction term between productivity and wages.

[7] The coefficient was estimated using Dynamic OLS with optimal lead and lag selection. The standard error is heteroscedastic and autocorrelation consistent based on a Barlett kernel with 8 lags.

The long-run restrictions are imposed by constraining the matrix of long-run multipliers, C(1), as follows:

$$C(1) = \begin{bmatrix} c_{11} & 0 & 0 \\ 0 & c_{22} & 0 \\ c_{31} & c_{32} & c_{33} \end{bmatrix} \tag{9}$$

The combination of setting the $c_{1j} = 0$ for j = 2, 3 and estimating the system in error correction form has the effect of imposing the two long-run constraints with respect to productivity and wages. Conditional on the assumption of cointegration, the overidentifying test for the third restriction is the test that the shock with a long-run effect on hours is uncorrelated with the technology shock.

In practice, the test must be performed in two steps. The first step estimates the permanent hours shock directly from the bivariate model. The second step uses Generalized Method of Moments (GMM) to estimate the trivariate system. The separately estimated nontechnology shock is used as an additional instrument in the productivity equation, since it should be uncorrelated with the technology shock.

The test of overidentifying restrictions is based on Hansen's J-statistic with one degree of freedom. Hansen's J-statistic is 0.005, with a p-value of 0.945. Hence, there is no evidence against the overidentifying restriction with respect to hours. The formal test supports the results given in the impulse response functions from the bivariate model: all three identification schemes are mutually consistent.

### *4.2 Exogeneity of Identified Technology Shocks*

As argued by Hall (1988) and Evans (1992), the technology shock should not in principle be correlated with other exogenous shocks that are not related to technology, nor with lagged endogenous variables. Evans cast doubt on the use of the Solow residual as a measure of technology shocks by showing that money, interest rates and government spending Granger-cause the Solow residual. Thus, an additional means to test whether the identified shocks are really technology shocks is to test whether other exogenous variables (which should not be related to technology) are correlated with the shocks.

We consider four types of shocks that have been used in the literature: Romer and Romer's (1989) monetary indicators, Hoover and Perez's (1994) oil shock dummies, Ramey and Shapiro's (1998) war dates, and the federal funds rate (Bernanke and Blinder (1992). All of these variables have been shown to have significant effects on GDP. We test whether current and four lagged values of the three sets of dummy variables have significant predictive power for the shock derived from the baseline bivariate model. Since the federal funds rate may respond to the contemporaneous shock, we include only the four lagged values of the funds rate in the test. [8] We do not include lags of the technology shock in the regression since it is by construction not serially correlated.

Consider the first row of Table 1. The p-values for the F-tests show that none of the variables is significant in explaining the technology shock. The lowest p-value is for Ramey-Shapiro war dates, but even then the p-value is 0.12. Hence, there is no evidence that the technology shock identified using long-run restrictions is correlated with any of the exogenous shocks or that the funds rate Granger-causes the shock. In contrast, the second row shows that all but the Romer dates have significant predictive power for the nontechnology shock. Thus, the Evans-Hall type tests support our interpretation of the shocks.

[8] The federal funds rate is only available starting in 1954.

*4.3 Unit Root versus Stationary Hours*

Galí (1999), using total hours rather than per capita, showed that his results did not hinge on the assumption of a unit root versus trend-stationary hours. Recently, Christiano, Eichenbaum and Vigfusson (2003) (CEV) have argued that technology shocks lead to a positive hours response when identified in a model in which hours *per capita* are assumed to be stationary. CEV counter the evidence provided by classical statistical tests of a unit root in hours per capita by declaring conventional classical methods to be useless in this case and making "encompassing" arguments in favor of their specification. In this section, we discuss the impact of making alternative assumptions on the hours process and then present evidence and arguments against the stationary hours specification.

A look at the data is always a best first step. Figure 2 shows the behavior of hours per capita during our sample. The movements are obviously very persistent. CEV argue that hours are stationary, but as discussed in a previous section, one fails to reject a unit root in hours against the linear trend stationary alternative. Figure 2 suggests that perhaps a better alternative to the unit root specification is a quadratic trend. Indeed, one can reject a unit root in hours in favor of a quadratic trend (the p-value is 0.034). Furthermore, the quadratic trend term has a very high t-statistic (above 8 using autocorrelation consistent standard errors).

Figure 3 shows the impulse response functions from these two alternatives. The top panel shows the effect of a technology shock in the specification that assumes a unit root in labor productivity but stationary hours. This specification produces very different results from the others. A positive technology shock leads both productivity and hours to increase. Labor productivity has a reverse hump-shape, while hours have a standard hump-shape. The bottom panel shows the effects of a technology shock from the quadratic trend model. The results are qualitatively similar to the unit root model: in response to a positive technology shock, productivity increases but hours fall. Hours return to normal in a year and a half.

Thus, the unit root and quadratic trend models of hours produce declines in hours in the short-run in response to a positive technology shock, whereas the stationary hours model produces the opposite result. The results from the unit root and quadratic trend models are consistent with those of Basu, Fernald and Kimball, who use completely different techniques, whereas the stationary hours model is consistent with the predictions of the standard RBC model. The question, then, is which specification is correct? We now present arguments for why the unit root specification should be favored over the stationary hours specification.

First, the technology shock identified under the assumption of stationary hours does not pass the Evans and Hall tests. Table 2 shows the results of exogeneity tests applied to shocks from the stationary hours model. The first row shows that the technology shock from this model is predicted by the military variables, oil variables and federal funds rate. For example, the p-value for whether the lagged federal funds rate Granger-causes their technology shock is 0.000. In contrast, the "nontechnology" shock is not correlated with any of those variables! It appears that the stationary hours model inadvertently puts nontechnology shocks in the technology shock and vice versa.

Second, the estimated response of productivity to a nontechnology shock suggests that the stationary hours model does not adequately impose the identifying restriction. The top panel of Figure 4 shows the response of productivity and hours to a nontechnology shock using the unit root model. The bottom panel shows the same responses using the stationary hours model. Note that the impact of the nontechnology shock on labor productivity is short-lived in the unit root model, consistent with the basic identifying assumption that it cannot have a permanent effect on productivity. In contrast, the impulse response functions from the stationary hours model in the lower panel indicate that nontechnology shocks have long-lived significant effects on labor productivity. *This response is inconsistent with the fundamental identifying assumption.*

Thus, the only model that produces a positive hours response is one in which both the shocks and their responses are fundamentally at odds with the notion of a technology shock.[9]

*4.4 Evidence from a 5 –Variable Model*

Our final empirical investigation studies the effects of a technology shock on a broader set of variables. We wish to determine whether the responses of any of the other variables are anomalous. We study a model with productivity, hours, wages, consumption, and investment.[10] Because productivity is defined as private output divided by private hours, output is implicitly included in the system

We specify the five-variable model as follows:

$$y_t = C(L)u_t \tag{10}$$

[9] Francis and Ramey (2003) offer further critiques of the stationary hours model in their study of technology shocks using historical US and UK data. They also discuss the issue of the instruments used.

[10] Consumption is defined as the sum of nominal nondurable and services consumption expenditures, deflated by the price deflator for all consumption. Investment is defined as the sum of nominal total private investment and consumer expenditures on durable goods, deflated by the price deflator for investment. Both variables are in logarithms.

$$C(1)=\begin{bmatrix} c_{11} & 0 & 0 & 0 & 0 \\ c_{12} & c_{22} & c_{23} & c_{24} & c_{25} \\ c_{31} & c_{32} & c_{33} & c_{34} & c_{35} \\ c_{41} & c_{42} & c_{43} & c_{44} & c_{45} \\ c_{51} & c_{52} & c_{53} & c_{54} & c_{55} \end{bmatrix}$$

$y_t$ is now a 5 x 1 vector consisting of the labor productivity growth ($\Delta x_t$), hours growth ($\Delta n_t$), the error correction term between productivity and wages ($xw_t$), an error correction term between investment and output ($iy_t$), and an error correction term between consumption and output ($cy_t$).[11] $u_t$ consists of the shocks $\varepsilon_t^z, \varepsilon_t^m, \varepsilon_t^w, \varepsilon_t^i, \varepsilon_t^c$, in that order.

The zero restrictions in the first row of the matrix of long-run multipliers are the natural extension of Galí's restrictions to the larger model. We do not impose the additional restriction with respect to the long-run effect of productivity on hours; the results are similar in either case.

Figure 5 shows the effect of the identified technology shock on the logs of productivity, labor input, private output, real product wage, investment, and consumption. Consistent with the bivariate results, the shock raises productivity and real wages permanently, and lowers hours. Output dips initially, then rises. Investment rises after the first two quarters, displaying a hump-shape. Consumption slowly rises. The increase in both investment and consumption are qualitatively consistent with the standard model. The sluggishness of the short-run responses, however, seems to suggest some type of adjustment cost.

[11] Standard cointegration tests reject noncointegration, with p-values of 0.018 or below. The investment error correction term is based on DOLS estimates of the coefficient on output of 1.2319 with a standard error of 0.0360, and the consumption error term is based on DOLS estimates of the coefficient on output of 1.01954 with a standard error of 0.0095.

To summarize, all of the results shown in this section support the plausibility of interpreting the shock as a technology shock. Capital tax rates play no role. The use of alternative long-run restrictions for identifying the technology shock leads to similar results. The shocks appear to be uncorrelated with other key exogenous variables. Furthermore, the effect of the technology shock on key variables such as wages, consumption and investment is in line with those that we would expect. The only result at odds with the standard RBC model is the negative effect of the shock on labor input. The next section will examine whether the standard model can be modified to produce these results.

## 5. Two DGE Models with Negative Technology-Hours Correlations

Galí (1999) and Basu, Fernald, and Kimball (1999) suggest that the negative correlation between the technology shock and labor input is evidence in favor of a sticky-price model.[12] In a sticky-price model, a positive technology shock can lead to a decline in labor input if the monetary authority is not too accomodative. King and Wolman (1996) and Dotsey (1999) present dynamic models with sticky prices in which technology shocks have negative effects on labor in the short-run. King and Wolman use Calvo-type random price adjustment, whereas Dotsey uses staggered price contracts. Both papers show that if the monetary authority targets the money supply, a positive technology shock causes labor input to drop. After a positive productivity shock, firms' markups rise, so there is a greater wedge between the marginal productivity of labor and the real wage. Because the wedge is expected to decrease over time,

[12] Galí, López-Salido and Vallés (2003) present further evidence based on the changing response of monetary policy.

real wages are expected to rise in the future, so individuals reduce their labor supply in the short-run due to the intertemporal substitution effect.[13]

To illustrate, Figure 6 plots the dynamic responses of selected variables when hit with a one percent positive technology shock in the King and Wolman (1996) framework with money supply targeting. Notice that, along with the fall in labor, most of the other variables' responses from the model accord well with our impulse responses shown above. For example, output, consumption, and investment rise gradually in response to a positive technology shock.

But sticky-price models are not the only types of models that can produce the negative correlation. In this section, we offer two examples of DGE models with flexible prices that also imply a short-run negative correlation between technology shocks and labor input. The first model uses habit formation in consumption combined with adjustment costs in investment. The second model changes the production technology so that it is closer to Leontief in the short-run.

### *5.1 Model 1: Habit Formation in Consumption and Adjustment Costs on Investment*

Previous work by Beaudry and Guay (1996), Jermann (1998) and Boldrin, Christiano, and Fisher (2001) has used models with habit formation in consumption and adjustment costs in investment to study asset pricing in production economies. Jermann incorporates habit formation in preferences and capital adjustment costs in order to explain the equity premium and the average risk-free rate observed in the data. His model assumes no utility from leisure, so

[13] It is important to note, however, that these papers find that labor input *rises* under all other monetary policy rules investigated. For example, monetary rules based on inflation targeting, Taylor rules, and Clarida, Gali and Gertler's estimate of the Volker-Greenspan rule all imply that labor input rises in response to a positive technology shock, even in the face of sticky prices.

employment does not fluctuate. Boldrin, Christiano and Fisher and Lettau and Uhlig (2000) criticize Jerman's model because once employment is allowed to fluctuate, it produces a persistently negative response of hours worked to a positive technology shock, which they argue is counterfactual. In light of the previous empirical results, this implication is not counterfactual. We will now explore how the combination of habit persistence in consumption and adjustment costs in investment produces responses that are consistent with the empirical impulse response functions.

The model takes the following form:

$$E_0 \sum_{t=0}^{\infty} \beta^t [\log(C_t - bC_{t-1}) - N_t], \quad 0 < \beta < 1, \; b \geq 0 \qquad \text{Preferences}$$

$$Y_t = A_t N_t^{\alpha} K_t^{1-\alpha}, \quad 0 < \alpha < 1 \qquad \text{Technology}$$

$$Y_t = C_t + I_t \qquad \text{Resource constraint} \qquad (13)$$

$$K_{t+1} = (1-\delta)K_t + \phi\left(\frac{I_t}{K_t}\right)K_t \qquad \text{Capital accumulation}$$

$$\text{where} \qquad \phi\left(\frac{I_t}{K_t}\right) = \frac{a_1}{1-\theta}\left(\frac{I_t}{K_t}\right)^{1-\theta} + a_2$$

In the first equation, $C_t$ denotes consumption in period t, $N_t$ denotes hours worked, and the E denotes conditional expectations. The term $bC_t$ is the household's habit stock. Setting b = 0 recovers the standard type of preferences.

The economy's technology and resource constraints are given by the standard equations where $Y_t$ denotes output, $A_t$ denotes technology, $K_t$ is the capital at the beginning of period t, and $I_t$ is investment. In the capital accumulation equation the function $\phi$, which is positive and concave in the investment-capital ratio, captures the capital adjustment costs. If $\theta = 0$, then this part of the model collapses to the standard equation of motion for capital. If $\theta$ is positive, then there are adjustment costs to changing the capital stock too rapidly. In this case, Tobin's $q$ can deviate from unity.

We calibrate the model along the lines of Boldrin et al. (2001), who were trying to match the asset pricing facts. The standard RBC parameters are set so that $\beta = 0.99$, $\delta = 0.021$, and $\alpha = 0.64$. Following Jermann and Boldrin et al, we set the habit persistence parameter very high at 0.9 and the adjustment cost parameter very high, at over 4. We set $a_1$ and $a_2$ so that the balanced growth path is invariant to the value of $\theta$. In particular, we set $a_1 = \delta^{\theta}$ and $a_2 = -\delta \cdot \theta / (1-\theta)$.

In order to compare the predictions of the model to the results from the data, we investigate the effect of a permanent, unanticipated one percent jump in the technology variable *A*. We compare the responses of key variables to this shock in our model to those from a standard RBC model with b = 0 and θ = 0.

Figure 7 shows the paths of the technology variable, output, hours, the real wage, consumption, and investment. All variables are in percent deviations from their pre-shock levels. Consider first the responses of output, investment, and consumption. The modified model produces slower responses of these variables relative to the standard model. In the modified model, consumption does not jump up at all, but increases only gradually.

In contrast, hours and wages respond more dramatically, and in different ways, in the modified model. In the standard model, hours rise temporarily because the substitution effect due to higher wages and real interest rates outweighs the wealth effect in short-run. The opposite is true in the modified model. The level of hours falls temporarily in response to a positive technology shock. Thus, in the modified model consumption and hours move in the opposite direction. In both cases, the real wage rises, but it rises more in the short-run in the modified model.

The modified model produces responses that are broadly consistent with the empirical results shown in the last section. In particular, both show a gradual, but permanent, rise in output, investment and consumption. Both show an immediate rise in productivity and real wages. Finally, both show a drop in hours worked in response to a positive technology shock.

Why is the response of hours worked so different from the response in a standard RBC model? In the standard model, the wealth effect has an immediate impact on consumption; the only reason consumption does not immediately jump to its new steady-state level is that real interest rates are temporarily high. In the modified model, habit persistence induces a sluggishness in the response of consumption. Consumers prefer not to change their consumption by too much. The natural alternative would be to put the extra resources into investment. However, the high adjustment cost on investment makes investment a relatively expensive good in the short-run. Thus, the households "spend" the new wealth on the only remaining alternative: leisure.

### *5.2 Model 2: A Leontief Model with Labor-Saving Technology Shocks*

We now explore the effects of labor-saving technology shocks when the short-run production function features fixed proportions. Although the negative relationship between hours and technology is easily reproduced in a simple model, we explore a slightly more general version because of its improved predictions for wages. In particular, we use a one-sector version of the variable-utilization model employed by Ramey and Shapiro (1998) to study the effects of military buildups.

The model takes the following form:

$$Y_t = (1+S_t)\cdot \min\left(\frac{N_t}{\alpha_n}, \frac{K_t}{\alpha_k}\right) \qquad \text{Production Function}$$

$$K_{t+1} = (1-\delta)K_t + I_t \qquad \text{Capital Accumulation} \qquad (14)$$

$$C_t + I_t \le Y_t \qquad \text{Resource Constraint}$$

$$V = E_0 \sum_{t=0}^{\infty} (1+\rho)^{-t}\{\log(C_t) + 2\cdot\log(T - L_t) - \theta\cdot N_t S_t^2\} \qquad \text{Utility}$$

$$\text{where} \quad L_t = (1+S_t)N_t$$

The specification of technology implies that at any instant in time, workers (N) and machines (K) must be combined in fixed proportions. Thus, firms can increase output within the period only by increasing the workweek of capital. The workweek of capital is given by (1 + S), where the standard 40 hour workweek has been normalized to unity, so that S is the proportion relative to the standard week.

The preferences are standard, except for the addition of a term that involves hours beyond the standard workweek. In this specification, hours worked outside the standard daytime hours generate disutility. In addition to the standard effects of a decline in leisure, nonstandard hours generate increasing marginal disutility. Ramey and Shapiro (1998) discuss the empirical justification for these preferences.

We choose values of the parameters to match capital-output ratios and estimated overtime premia. In the production function, we set initial values so $\alpha_n = \alpha_k = 8$. In the preference specification, we set $\theta = 0.05$ and T = 50. The quarterly discount factor β is set equal to 0.99 and the depreciation rate to 0.021. These values generate an overtime premium of 33 percent and a value of $S$ equal to 0.172 in the steady-state. Using this model, we explore the effect of an unanticipated permanent one percent decline in the value of $\alpha_n$ from 8 to 7.92. The decline in $\alpha_n$ implies that fewer workers are needed to operate each machine.

Figure 8 shows the results of the simulations. Output shows a small amount of sluggishness relative to the RBC model, whereas consumption shows substantial sluggishness. In fact, consumption dips slightly on impact. The source of the slow rise of consumption is the high real interest rate. The shock to labor saving technology raises the marginal product of capital, leading to higher desired investment. The limited opportunities to extend the workweek of capital dampen the output response, so consumption must rise by less than it would in the standard model. The behavior of hours is the key result. Total hours fall in the short-run in response to the labor-saving technology shock.

To summarize, the models we have presented demonstrate that modifications to either preferences or the substitution possibilities between capital and labor can produce a negative correlation between hours and technology. None of these models requires sticky prices or wages to produce the results.

## 6. Conclusions

The purpose of this paper was twofold. The first purpose was to assess whether the shocks identified using long-run restrictions could plausibly be interpreted as technology shocks. The second purpose was to investigate whether flexible price models could produce these results.

In pursuit of the first purpose, we estimated models in which we controlled for capital income tax rates, subjected the models to various overidentifying tests and exogeneity tests, and investigated alternative identification schemes. All but one specification produced the results that a positive technology shock leads to a short-run decline in hours. The only specification that produced the opposite result failed on other specification tests.

The last part of the paper showed that while sticky price models could explain some of these findings, so too could two flexible price models. We showed that two models previously used in the literature – a model with habit formation in consumption and adjustment cost in investment and a model with Leontief production – could also qualitatively match the empirical effects of a technology shock.

These results lead us to two conclusions. First, the data are at odds with the predictions of the technology-driven real business cycle hypothesis. At the heart of this hypothesis is the idea that positive technology shocks lead to positive comovements of output, hours, and productivity. Our empirical results show the robustness of the negative impact of technology on hours in the short-run. Second, abandoning the standard technology-driven real business cycle hypothesis does not require adherence to sticky price models. We have presented two examples of models that capture these new facts, but that do so without resort to sticky price assumptions. These models do not, however, resurrect the technology-driven RBC hypothesis.

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**Table 1: P-Values for Exogeneity Tests**
**Bivariate model, Unit root in hours**

| Shock | Ramey-Shapiro War Dates | Hoover-Perez Oil Dates | Romer-Romer Monetary Dates | Federal funds rate |
|---|---|---|---|---|
| **Technology** | 0.123 | 0.922 | 0.320 | 0.149 |
| **Nontechnology** | 0.026 | 0.000 | 0.336 | 0.002 |

The F-test is based on a regression of the identified technology shock on a constant and current and four quarterly lags of the variable in question, except the federal funds rate, where no current value is included. The null hypothesis is that all of the coefficients on the variable in question are jointly equal to zero.

**Table 2: P-Values for Exogeneity Tests**
**Bivariate model, stationary hours specification**

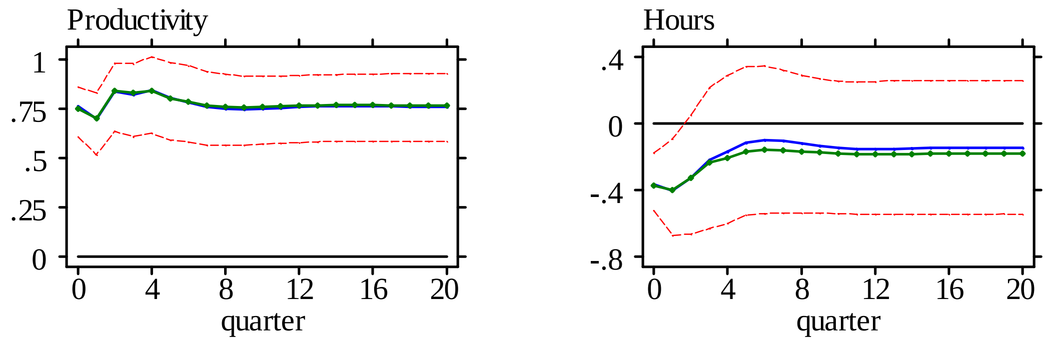
**Dependent Variable: Technology Shocks**

| **Shocks** | **Ramey-Shapiro War Dates** | **Hoover-Perez Oil Dates** | **Romer-Romer Monetary Dates** | **Federal funds rate** |
|---|---|---|---|---|
| **Technology** | 0.021 | 0.000 | 0.252 | 0.000 |
| **Nontechnology** | 0.235 | 0.546 | 0.288 | 0.736 |

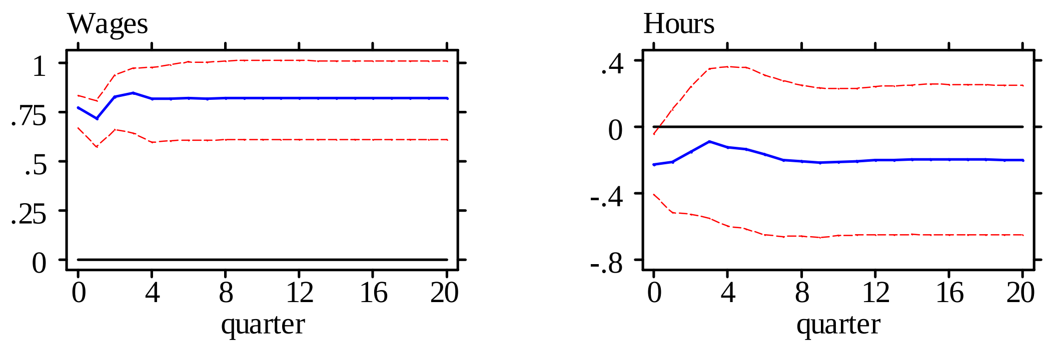
See notes to Table 1.

**Figure 1: Comparison of Technology Shock Effects Across Identification Schemes**
**(90 percent confidence bands)**

A. **Only technology shocks can have permanent effects on labor productivity**
(Hatched line controls for capital income tax rates)




B. **Only technology shocks can have permanent effects on real wages.**




C. **Technology shocks cannot have permanent effects on hours.**

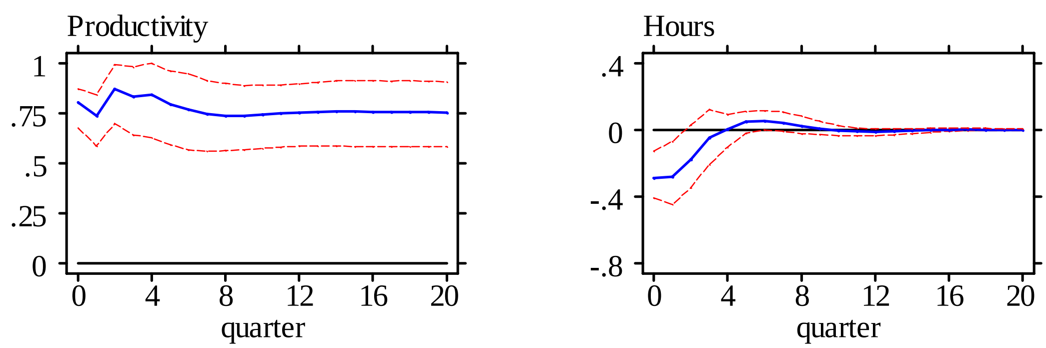


**Figure 2: Log of Hours Per Capita**

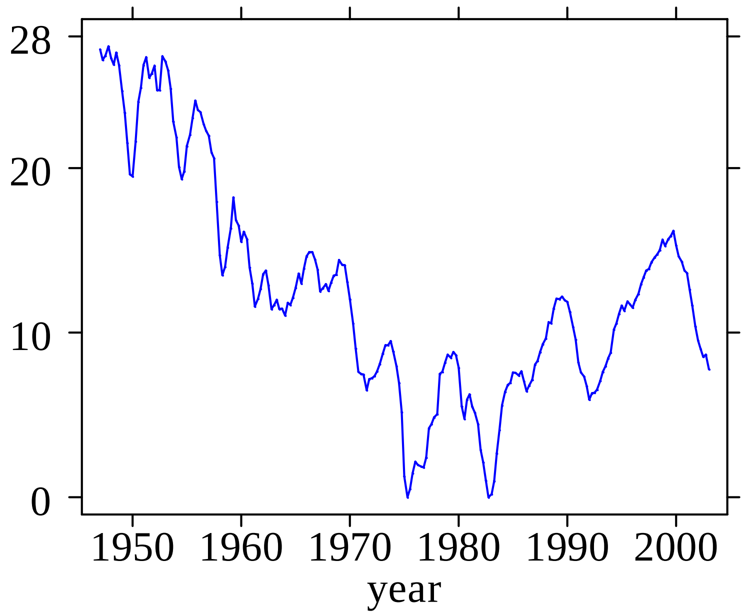
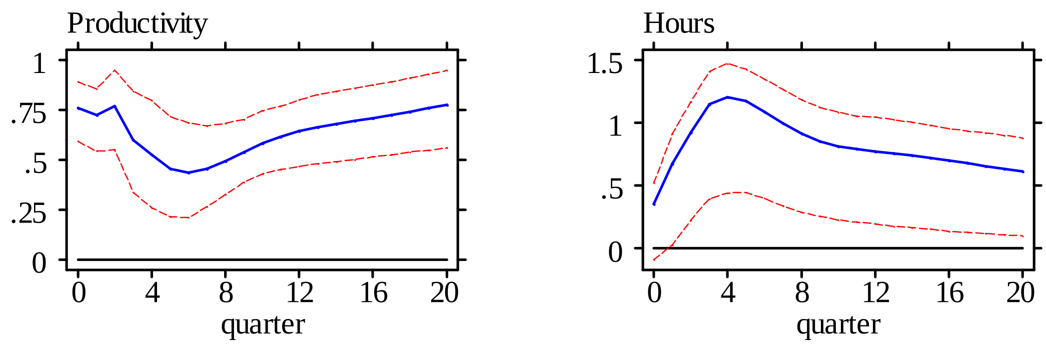


**Figure 3: Comparison of Technology Shock Effects across Models with Different Assumptions on Hours**

**A. Model with Stationary Hours**




**B. Model with Quadratic Trend in Hours**

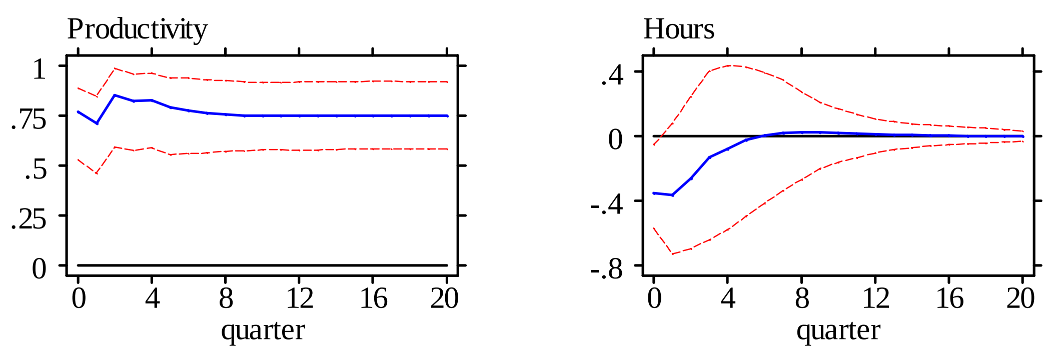
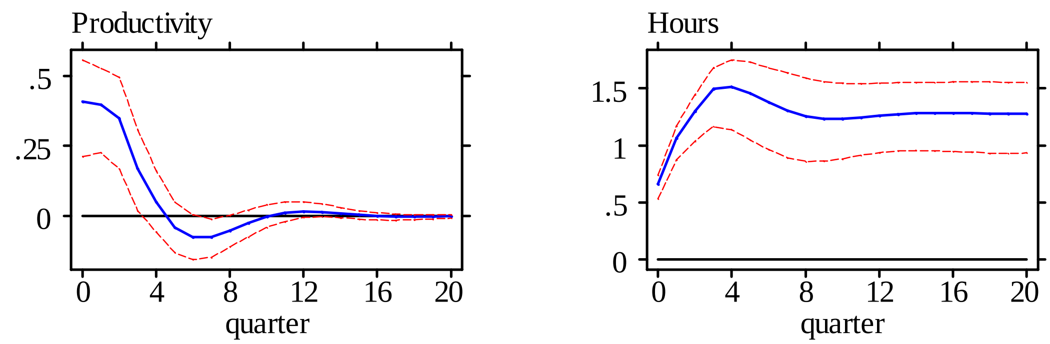


**Figure 4: Effects of Nontechnology Shocks**

**A. Model with a Unit Root in Hours**




**B. Model with Stationary Hours**

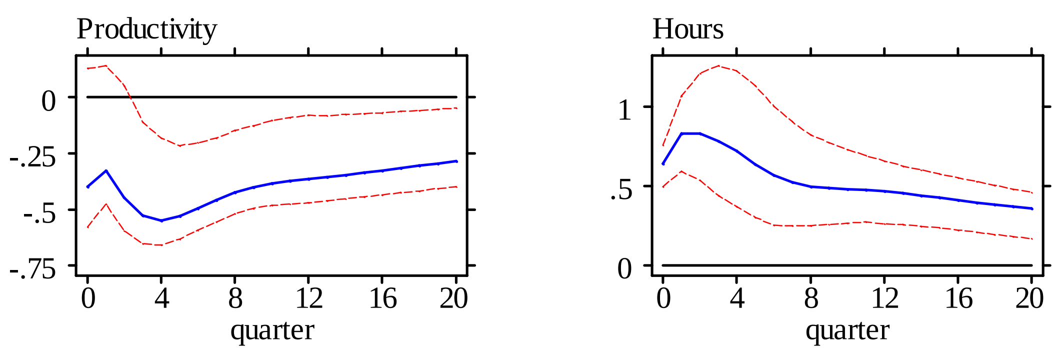


**Figure 5: Impulse Response to a Technology Shock**
**5-Variable Vector Error Correction Model**

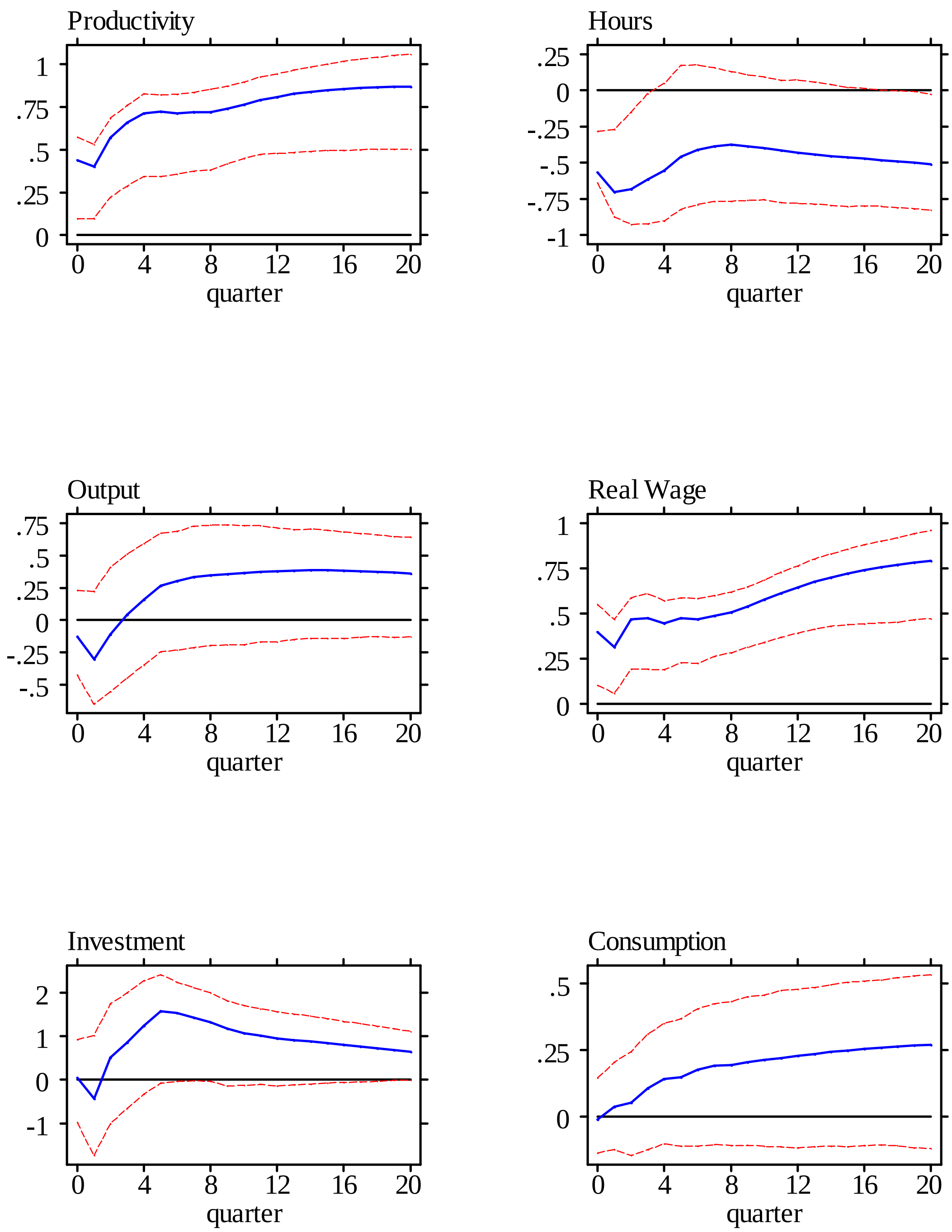


**Figure 6: Theoretical Effect of a Positive Technology Shock**
**King-Wolman (1996) Sticky Price Model**

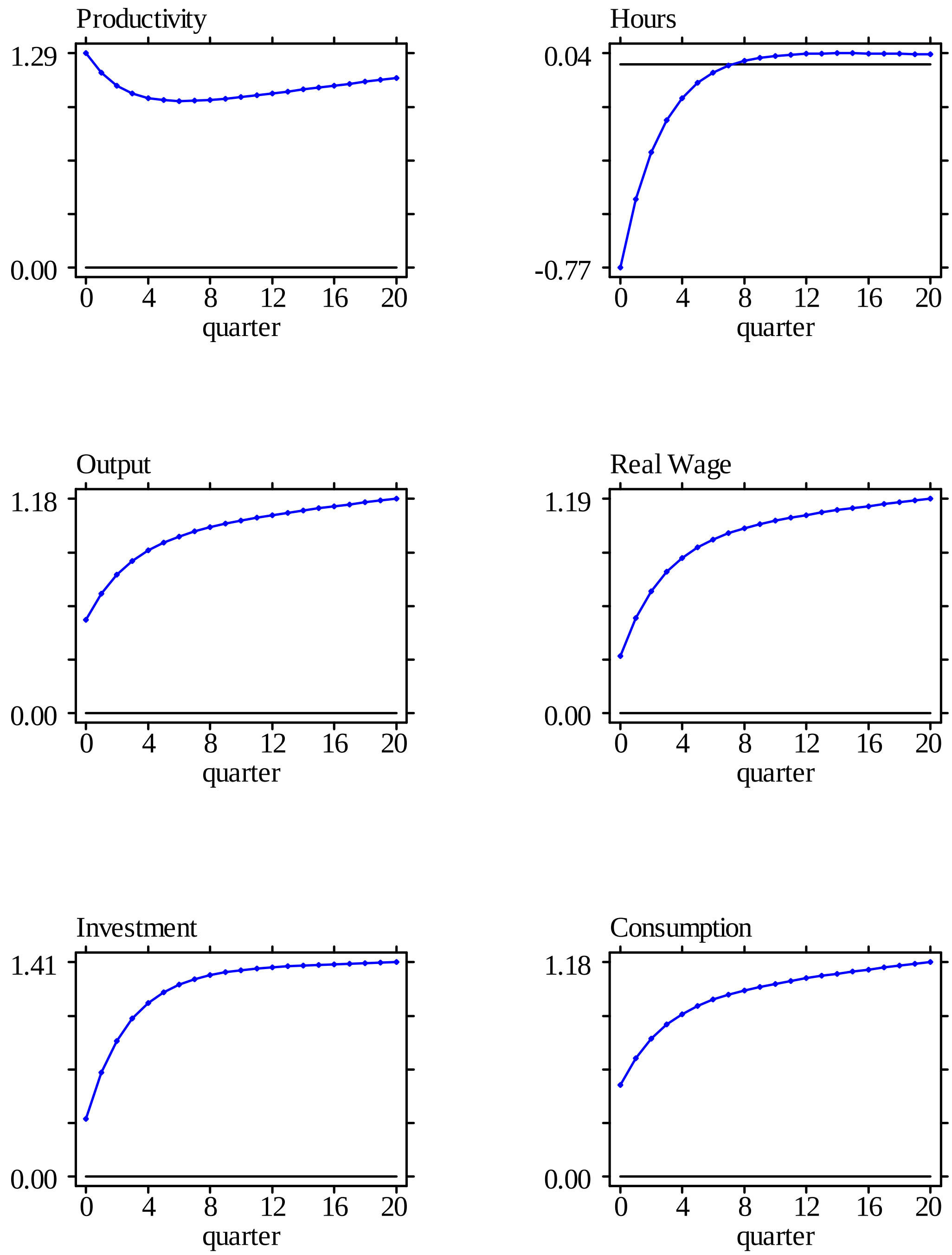


**Figure 7: Theoretical Effect of a Positive Technology Shock**
**RBC (dashed) vs. Habit Formation-Investment Adjustment Cost (solid with diamonds)**

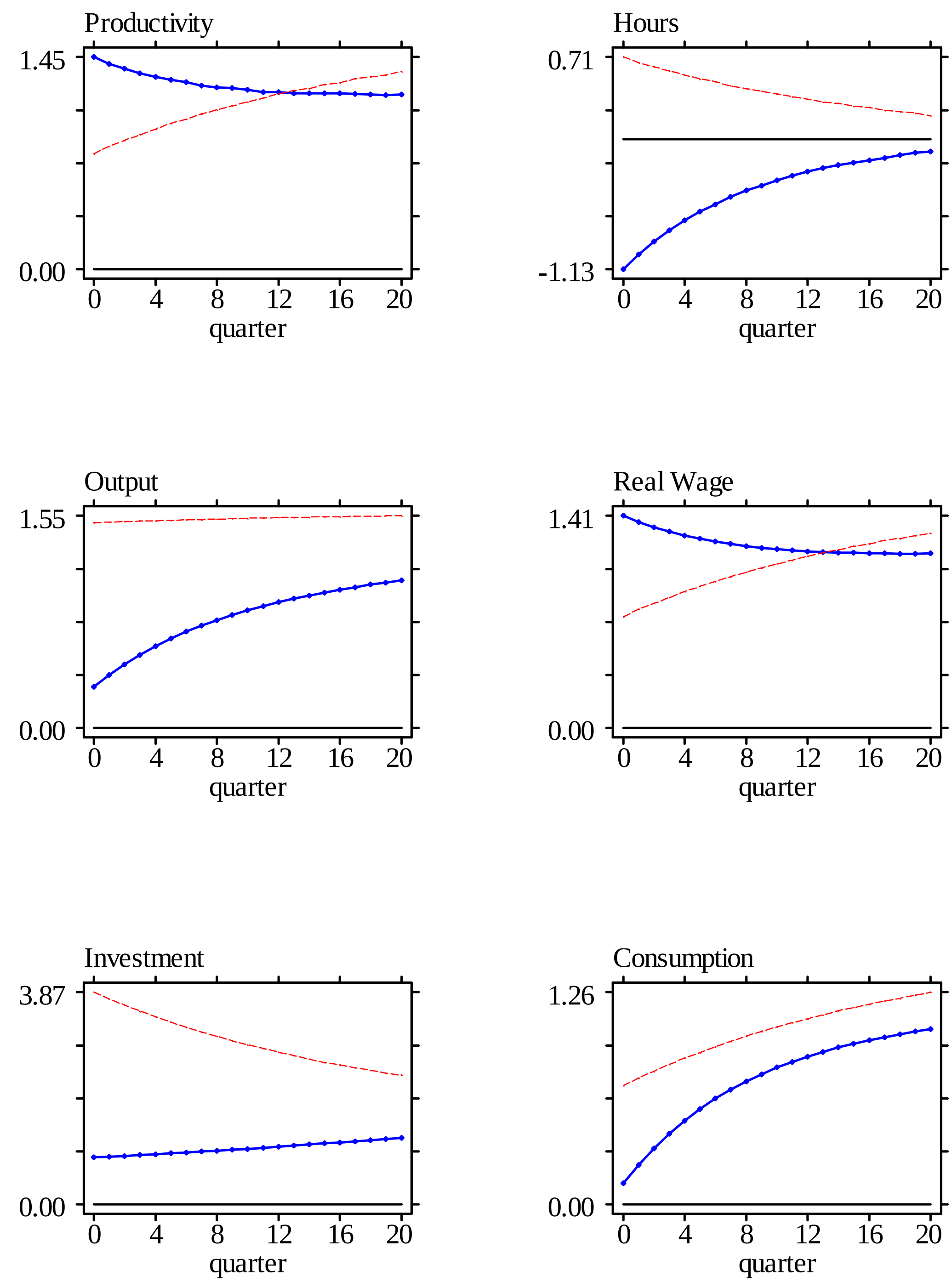


**Figure 8: Theoretical Effect of a Positive Technology Shock**
**Leontief Production with Variable Capital Utilization**