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Growth, slowdowns, and recoveries☆

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ABSTRACT

We construct and estimate an endogenous growth model with debt and equity financing frictions to understand the relation between business cycle fluctuations and long-term growth. The presence of spillover effects from R&D imply an endogenous relation between productivity growth and the state of the economy. A large contractionary shock to equity financing in the 2001 recession led to a persistent growth slowdown that was more severe than in the 2008 recession. Equity (debt) financing shocks are more important for explaining R&D (physical) investment. Therefore, these two financing shocks affect the economy over different horizons.

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1. Introduction

Macroeconomic growth rates exhibit low-frequency patterns often associated with innovation and technological change. The advent of electricity and the introduction of computers are each associated with persistent waves in the trend component of productivity.[1] Aggregate patterns in innovative activity, as measured by research and development (R&D) expenditures, are closely related to waves in external equity financing. For example, the R&D boom in the 1990s was fueled by an expansion in the supply of equity finance, while the sharp decline in R&D in the early 2000s coincided with a contraction in supply.[2] Despite the efforts in the growth literature, there is no consensus on the macroeconomic or financial origins of

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[1] See, for example, Jovanovic and Rousseau (2005) and Gordon (2010) for surveys.

[2] Brown et al. (2009) provide micro-evidence showing shifts in the supply of external equity finance can explain most of the 1990s boom in R&D.

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prolonged productivity slowdowns and the subsequent recoveries. In particular, there is substantial disagreement in projecting the long-run effects of the recent Great Recession on economic growth (e.g., Summers, 2013).[3]

In this paper we quantitatively explore the role of macroeconomic and financial shocks for understanding economic growth and business cycle fluctuations in a Dynamic Stochastic General Equilibrium (DSGE) model (e.g., Christiano et al., 2005) with two key departures. First, our model features endogenous technological progress through vertical innovations (e.g., Aghion and Howitt, 1992; Barlevy, 2004b; Grossman and Helpman, 1991; Peretto, 1999) and endogenous utilization of existing technologies. In equilibrium, total factor productivity (TFP) growth is endogenously related to knowledge accumulation through R&D and technology utilization rates. The presence of spillover effects from knowledge accumulation provides a link between business cycle fluctuations and long-term growth.

Second, the model incorporates explicit roles for firms' debt and equity financing along with frictions associated with adjusting capital structure following Jermann and Quadrini (2012). Debt is preferred over equity due to a tax advantage, however borrowing is limited by an enforcement constraint. The intangible nature of the knowledge stock implies that it provides poor collateral to creditors (e.g., Shleifer and Vishny, 1992). We capture this link between asset tangibility and liquidation values by assuming that only physical capital is pledgeable as collateral in the debt contract. We also model financial shocks that affect the ease to which firms can access external financing. The *equity financing shock* is captured by disturbances to the cost function for net equity payouts. Following Jermann and Quadrini (2012), the *debt financing shock* is modeled as disturbances to liquidation values in the enforcement constraint for the debt contract.

We conduct a structural estimation of the model using standard macroeconomic data, together with the newly-released series for R&D investment and the series for net debt issuance and net equity financing. Thus, our results are disciplined by the joint observation of macroeconomic dynamics and financing flows. Given that only physical capital (and not knowledge capital) is pledgeable as collateral, shocks to liquidation values have a stronger impact on the marginal value of physical investment relative to R&D investment. Consequently, we find that the debt financing shocks are relatively more important for explaining physical investment dynamics, while equity financing shocks are relatively more important for explaining R&D investment dynamics. Due to the presence of spillover effects from the accumulation of the knowledge stock, shocks that have a sizable effect on R&D investment also have a significant impact on growth rates in the long run. Therefore, accounting for the tangibility of assets in the enforcement constraint and the production externalities implies that debt financing shocks have immediate effects on macroeconomic variables, while the effect of equity financing shocks builds over time.

Our model-implied TFP can be decomposed into an exogenous and an endogenous component. The exogenous component is represented by a stationary TFP shock. The endogenous component can be further decomposed into knowledge accumulation and technology utilization. Both of these components provide a link between TFP and the state of the economy. We interpret technology utilization as the *absorptive capacity* of the firm with respect to the ability to adapt raw knowledge to the production process. The stock of knowledge is accumulated through R&D investment, then resources are expended for the stock of knowledge to be utilized in production. Given that it is more difficult to make large adjustments to a stock (knowledge capital) rather than a flow (technology utilization) input, we find that higher-frequency disturbances are absorbed by the technology utilization margin. In the estimated model, the endogenous component of TFP explains most of the variability in TFP growth through technology utilization. In contrast, the accumulation of knowledge is primarily related to long-run trends in TFP growth.

Accounting for these two margins of technology adjustment, R&D accumulation and technology utilization, has important implications for the consequences of a recession, especially over longer horizons. We find that the Great Recession was associated with a large drop in utilization rates, while R&D was not equally affected. In contrast, during the 2001 recession there was a significant decline in R&D investment after the bust of the information technology (IT) boom. Controlling for the size of the two recessions, the decline in R&D investment – and therefore knowledge accumulation – was substantially more pronounced in the 2001 recession than in the 2008 recession. Also, the decline in knowledge accumulation started in the 2001 recession, while the 2008 recession exacerbated the pre-existing downward trend.

Consequently, while the 2008 recession was substantially more severe in the short-term, our model suggests that trend growth was less affected during the Great Recession compared to the 2001 recession when controlling for the relative size of the two recessions. Importantly, the decline in R&D and the low frequency component of TFP growth started with the 2001 recession, which accords with the empirical evidence from Fernald (2014). The current model projections suggest that long-run growth prospects remained relatively stable during the 2008 recession, however, our results also imply that if market conditions did not improve, R&D would eventually start declining.

We then move to interpret these results in light of the different sources of financing. Specifically, we use two counterfactual simulations to account for the different behavior of the economy during the two recessions. The 2001 recession coincided with the end of the IT boom, an event that particularly affected high tech firms (i.e., high R&D intensity firms) that rely on equity issues to finance R&D investment. Our model captures this fact through the dynamics of the equity financing shock. We compare the actual data with a counterfactual simulation in which all shocks are set to zero starting from the first quarter of 2000, except for the shocks to equity financing that are instead left unchanged. This exercise shows that the bulk of the decline in knowledge growth that started with the 2001 recession can be captured by a sequence of contractionary shocks to equity financing that is consistent with microevidence (e.g., Brown et al., 2009). The large adverse

[3] Benigno and Fornaro (2015), Gordon (2014), and Fernald (2014) are examples that provide opposing views.

shocks to equity financing that coincided with the 2001 recession led to a persistent decline in R&D, which in the context of our model implies a long-lasting adverse effect on trend growth.

In contrast, the 2008 recession originated from a severe financial crisis. We then show that a counterfactual experiment in which all shocks are set to zero – except for the debt financing shock – closely tracks the large decline in real activity during the Great Recession, but that it only had a limited impact on the accumulation of knowledge. This is consistent with our impulse response analysis that shows that shocks to collateral values have an immediate impact on investment in physical capital and R&D. However, the impact on R&D, and therefore long-term growth prospects, is less pronounced than when the economic contraction originates from a shock to equity financing.

Further, counterfactual experiments suggest that during the Great Recession, accommodative monetary and fiscal policies helped to stabilize both R&D rates and the utilization of existing technology, which has important consequences on the trend component of productivity. In a model with exogenous growth, TFP and trend growth do not depend on policymakers' actions. As a result, these models generally imply a steady and relatively fast return to the trend, independent from the actions undertaken by the fiscal and monetary authorities. Instead, in the present model sustaining demand during a severe recession can deeply affect the medium- and long-term outcomes for the economy. This result has important implications for the role of policy intervention during recessions. For example, we believe that the link between policy interventions and growth is particularly salient in light of the recent debate on the consequences of performing fiscal consolidations during recessions (Alesina and Ardagna, 2010 and Guajardo et al., 2014 provide opposing views).

The endogenous growth mechanism generates positive responses in consumption and investment to debt financing shocks, which is sometimes a challenge in DSGE models (e.g., Barro and King, 1984). In standard DSGE models, positive investment shocks often lead to a decline (or an initial decline) in consumption, while investment, hours, and output increase. In our model, the investment shocks are amplified, as they affect TFP growth through the knowledge accumulation and endogenous TFP channels. Thus, a positive investment shock increases output more than in the standard models without the endogenous technology margins, which helps our model generate a positive consumption response. Finally, monetary policy shocks induce positive comovement between measured productivity and inflation, consistent with evidence from Evans and dos Santos (2002).

Our approach of estimating a structural model helps to elucidate the link between R&D, growth, and business cycle dynamics. Due to data limitations, it would be hard to learn about the impact of R&D by only looking at its effect on growth *decades* later. Instead, our endogenous growth framework imposes joint economic restrictions on the evolution of macroeconomic quantities at short- and long-horizons. Therefore, conditional on the model, the dynamics at business cycle frequencies are also informative about the low-frequency behavior of the economy. This is because, given a parametric specification, the deep parameters that govern high- and low-frequency movements are invariant and can be inferred by examining fluctuations at all frequencies.

This paper is related to the literature linking business cycles to growth. Barlevy (2004a, 2007) show that the welfare costs of business cycle fluctuations are higher in an endogenous growth framework due to the adverse effects of uncertainty on trend growth. Basu et al. (2006) explore the impact of technological change on labor and capital inputs over the business cycle. Kung and Schmid (2015) examine the asset pricing implications of a stochastic endogenous growth model and relate the R&D-driven low-frequency cycles in growth to long-run risks. Kung (2015) builds a New Keynesian model of endogenous growth and shows how the model can rationalize key term structure facts. In the context of the asset pricing literature on long-run risks based on the work by Bansal and Yaron (2004), our results imply that financing shocks, typically associated with business cycle fluctuations, are an important source of low-frequency movements in consumption growth. Guerron-Quintana and Jinnai (2013) use a stochastic endogenous growth model to analyze the effect of liquidity shocks on trend growth.

We also relate to papers examining the causes and long-term impact of the Great Recession. Benigno and Fornaro (2015) analyzes how animal spirits can generate a long-lasting liquidity trap in a New Keynesian growth model with multiple equilibria. Eggertsson and Mehrotra (2014) illustrate how a debt deleveraging shock can induce a persistent, or even permanent, economic slowdown in a New Keynesian model with overlapping generations. Christiano et al. (2014a) show how interactions of financial frictions with a zero lower bound constraint on nominal interest rates in a DSGE framework can help explain the dynamics of macroeconomic aggregates during the Great Recession. Bianchi and Melosi (2014) link the outcomes of the Great Recession to policy uncertainty. Our paper focuses on the effects of the Great Recession through the R&D and technology adoption margins, and thus, we view our contribution as complementary to the existing literature.

The financial frictions in our DSGE model relate to a vast literature (see, among many others, Bernanke et al., 1999; Christiano et al., 2014b; Kiyotaki and Moore, 1997. We closely follow Jermann and Quadrini (2012) in modeling the financial frictions and financial shocks that affect the substitution between debt and equity. Explicitly accounting for the differences in collateralizability between physical and knowledge capital relates to Garcia-Macia (2017). We differ from these papers by incorporating an endogenous growth margin, which allows us to study the impact of external financing shocks on macroeconomic variables, including TFP and R&D, at different horizons.

This paper makes two methodological contributions with respect to the existing literature. We embed an endogenous growth framework in a medium-size DSGE model with nominal rigidities. Second, we structurally estimate the model using Bayesian methods. To the best of our knowledge, this is the first paper that estimates a quantitative model of the business cycle augmented with endogenous growth and technology utilization by using data on the amount of R&D investment. In this respect, our work is related to, but differs from the seminal contribution of Comin and Gertler (2006) and the subsequent work by Anzoategui et al. (2016) across several dimensions. First, our model incorporates financial constraints and external financing shocks. These explicit financial elements allow us to have different interpretations of the 2001 and 2008 recessions, and in particular, for explaining the divergence in R&D dynamics during the two events. Our interpretation of the two recessions relate to differences in debt and equity financing conditions, while Anzoategui et al. (2016) relate to differences in R&D productivity. Second, we make use of the recently released series for quarterly R&D investment to inform us on the process of knowledge accumulation. Finally, these papers use an endogenous growth framework with horizontal innovations (i.e., expanding variety model of Romer, 1990) whereas we use a growth model with vertical innovations.

The paper is organized as follows. Section 2 illustrates the model. Section 3 presents the estimates. Section 4 studies the Great Recession and the 2001 Recession in light of our model. Section 5 present an analysis of the model across different frequency intervals. Section 6 concludes.

2. Model

The benchmark model is a medium-scale DSGE model with endogenous growth and technology utilization. The endogenous growth production setting of within-firm vertical innovations follows Kung (2015), the financial structure is modeled following Jermann and Quadrini (2012), and the additional macroeconomic frictions and shocks are standard in the literature and taken from Christiano et al. (2005).

2.1. Representative household

There are a continuum of households, each with a specialized type of labor $i \in [0, 1]$. Household i is also assumed to have external habits over consumption $C_{i,t}$.

$$E_t \sum_{s=0}^{\infty} \beta^s \zeta_{C,t+s} \left\{ \log\left(C_{i,t+s} - \Phi_c \bar{C}_{t+s-1} \right) - \chi_{t+s} L_{i,t+s}^{1+\sigma_L} / (1+\sigma_L) \right\},$$

where β is the discount rate, Φ_c is an external habit parameter, $\bar{C}_t$ is average consumption, $L_{i,t}$ denotes the labor service supplied by the household, and σ_L is the inverse of the Frisch labor supply elasticity. The variable $\zeta_{C,t}$ represents an intertemporal preference shock with mean one and the time series representation, $\log(\zeta_{C,t}) = \rho_{\zeta_C} \log(\zeta_{C,t-1}) + \sigma_{\zeta_C} \epsilon_{\zeta_C,t}$, where $\epsilon_{\zeta_C,t} \sim N(0, 1)$. The variable χ_t represents shocks to the marginal utility of leisure and has the following time series representation, $\log(\chi_t) = (1-\rho_\chi)\log(\chi) + \rho_\chi \log(\chi_{t-1}) + \epsilon_{\chi,t}$, where $\epsilon_{\chi,t} \sim N(0, 1)$.

The household budget constraint is given by:

$$P_t C_{i,t} + P_t T_t + B_{t+1}/(1+r_t) = W_{i,t} L_{i,t} + P_t D_t + B_t,$$

where P_t is the nominal price of the final goods, T_t is the amount of taxes paid by the households, $W_{i,t}$ is the wage rate paid to the supplier of $L_{i,t}$, B_t is the amount of debt issued by the firm, D_t is the net equity payout paid by the firms, and r_t is the interest rate. Households are monopolistic suppliers of labor to intermediate firms following Erceg et al. (2000). In particular, intermediate goods firms use a composite labor input:

$$L_t = \left[\int_0^1 L_{i,t}^{\frac{1}{1+\lambda_w}} di \right]^{1+\lambda_w},$$

where λ_w is the wage mark-up. Employment agencies purchase labor from the households, package the labor inputs, and sell it to the intermediate goods firms. The first-order condition from profit maximization yields the following demand schedule:

$$L_{i,t} = (W_{i,t}/W_t)^{-\frac{1+\lambda_w}{\lambda_w}} L_t.$$

The aggregate wage index paid by the intermediate firms for the packaged labor input L_t is given by the following rule:

$$W_t = \left[\int_0^1 W_{i,t}^{-\frac{1}{\lambda_w}} di \right]^{-\lambda_w}.$$

The household sets wages subject to nominal rigidities. In particular, a fraction $1-\zeta_w$ can readjust wages. The remaining households that cannot readjust wages will set them according the following indexation rule, $W_{j,t} = W_{j,t-1}\left(\Pi_{t-1} M_{n,t-1}\right)^{\iota_w} (\Pi \cdot M_n)^{1-\iota_w}$, where $M_{n,t} \equiv N_t/N_{t-1}$, M_n is the steady-state value of $M_{n,t}$, ι_w is the degree of indexation of wage, $\Pi_{t-1} = P_{t-1}/P_{t-2}$ is the gross inflation rate at $t-1$, and Π is the steady-state value of the gross inflation rate.

2.2. Firms

A representative firm produces the final consumption goods in a perfectly competitive market. The firm uses a continuum of differentiated intermediate goods, $Y_{j,t}$, as input in the CES production technology:

$$Y_t = \left(\int_0^1 Y_{j,t}^{1/\lambda_{f,t}}\, dj\right)^{\lambda_{f,t}},$$

where $\lambda_{f,t}$ is the markup over marginal cost for intermediate goods firms and evolves in logs as an AR(1) process, $\log(\lambda_{f,t}) = (1-\rho_{\lambda_f})\log(\lambda_f) + \rho_{\lambda_f}\log(\lambda_{f,t-1}) + \sigma_{\lambda_f}\epsilon_{\lambda_f,t}$, where $\epsilon_{\lambda_f,t} \sim N(0,1)$.

The profit maximization problem of the firm yields the following isoelastic demand schedule

$$Y_{j,t} = Y_t\left(P_{j,t}/P_t\right)^{-\lambda_{f,t}/(\lambda_{f,t}-1)},$$

where P_t is the price of the final goods and $P_{j,t}$ is the price of intermediate good j. The price of final goods is obtained by integrating over the intermediate goods prices.

The intermediate good j is produced by a price-setting monopolist using the following production function:

$$Y_{j,t} = \left(u^k_{j,t}K_{j,t}\right)^{\alpha}\left(Z_{j,t}L_{j,t}\right)^{1-\alpha},$$

and measured TFP at the firm level is $Z_{j,t} \equiv A_t(u^n_{j,t}N_{j,t})^{\eta}(u^n_t N_t)^{1-\eta}$, where $K_{j,t}$ is physical capital, $N_{j,t}$ is knowledge capital, $u^k_{j,t}$ is the physical capital utilization rate, $u^n_{j,t}$ is the technology utilization rate, $u^n_t \equiv \int_0^1 u^n_{j,t}dj$ is the aggregate technology utilization rate, $N_t \equiv \int_0^1 N_{j,t}dj$ is the aggregate stock of R&D capital, and $(1-\eta) \in [0,1]$ represents the degree of spillovers over the utilized stock of knowledge. This specification of technology spillovers assumes that there are positive externalities from the creation of new knowledge and the increased utilization of the knowledge stock. Increased utilization requires increased maintenance costs in terms of investment goods per unit of physical or knowledge capital measured by the function $a_i(u^i)$, for $i = k, n$ (in the steady-state $a_i(u^i) = 0$). We interpret technology utilization as the absorptive capacity of the firm with respect to the ability to adapt raw knowledge to the production process (e.g., Cohen and Levinthal, 1990).

The variable A_t represents a stationary aggregate productivity shock that is common across firms and evolves in logs as an AR(1) process, $a_t = (1-\rho_a)a^{\star} + \rho_a a_{t-1} + \sigma_a\epsilon_{a,t}$, where $a_t \equiv \log(A_t)$, $\epsilon_{a,t} \sim N(0,1)$ is an i.i.d. shock, and $a^{\star}$ is the unconditional mean of a_t.

The intermediate firm j accumulates physical capital according to the following law of motion:

$$K_{j,t+1} = (1-\delta_k)K_{j,t} + \left[1 - \Psi_k\left(I_{j,t}/I_{j,t-1}\right)\right]I_{j,t},$$

where δ_k is the depreciation rate, $I_{j,t}$ is physical investment, Ψ_k is a convex adjustment cost function (in the steady-state $\Psi_k = 0 = \Psi'_k$). Knowledge capital is accumulated by firm j according to:

$$N_{j,t+1} = (1-\delta_n)N_{j,t} + \left[1 - \Psi_n\left(S_{j,t}/S_{j,t-1}\right)\right]S_{j,t},$$

where δ_n is the depreciation rate, $S_{j,t}$ is R&D investment, and Ψ_n is a convex adjustment cost function (in the steady-state, $\Psi_n = 0 = \Psi'_n$).

Intermediate firms face nominal price adjustment costs following Rotemberg's approach:

$$\Gamma_P\left(P_{j,t}, P_{j,t-1}\right) = 0.5\phi_R\left(P_{j,t}/P_{j,t-1} - \Pi^{1-\iota_p}\Pi_{t-1}^{\iota_p}\right)^2 Y_t,$$

where ϕ_R is the magnitude of the costs, ι_p is the degree of indexation of prices, Π is steady-state inflation and Π_{t-1} is the inflation in the previous period.

The financial structure of intermediate firms is modeled following Jermann and Quadrini (2012). Firms use equity and debt to finance their operations. Debt is preferred to equity because of the tax advantage (e.g., Hennessy and Whited, 2005). The effective gross rate paid by firms is $R_t = 1 + r_t(1-\tau)$, where τ captures the tax benefits of debt.

Firms also face adjustment costs for net equity payouts that affect the substitution between debt and equity financing:

$$\Gamma_D\left(D_{j,t}, D_{j,t-1}\right) = 0.5\phi_D\left(D_{j,t}/D_{j,t-1} - \zeta_{D,t}\Delta D\right)^2 Y_t,$$

where ΔD is the steady-state growth of the net equity payout and ϕ_D is the magnitude of the costs.[4] The variable $\zeta_{D,t}$ represents a mean one shock to the target growth rate of net equity payouts and evolves as, $\log(\zeta_{D,t}) = \rho_{\zeta_D}\log(\zeta_{D,t-1}) + \sigma_{\zeta_D}\epsilon_{\zeta_D,t}$, where $\epsilon_{\zeta_D,t} \sim N(0,1)$. We refer to $\zeta_{D,t}$ as an *equity financing shock*. This shock captures unspecified changes in aggregate market conditions affecting equity payouts/financing, which is in similar spirit as Belo et al. (2016).

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[4] The growth rate specification for the equity payout adjustment costs is well-defined in our estimation as the net equity payout series is positive in our data sample.

The firms use intra- and intertemporal debt. The intraperiod debt, X_t, is used to finance payments made before the realization of revenues at the beginning of the period and is repaid at the end of the period with zero interest. The size of the intraperiod loan is equal to

$$X_{j,t} = W_t L_{j,t} + P_t I_{j,t}/\zeta_{\Upsilon,t} + P_t S_{j,t} + P_t \Gamma_P(P_{j,t}, P_{j,t-1}) + P_t D_{j,t} + P_t \Gamma_D(D_{j,t}, D_{j,t-1}) + P_t a_k(u^k_{j,t})K_t + P_t a_n(u^n_{j,t})N_t + B_{j,t+1}/R_t - B_{j,t}.$$

The budget constraint of the firm is:

$$W_t L_{j,t} + P_t I_{j,t}/\zeta_{\Upsilon,t} + P_t S_{j,t} + P_t \Gamma_P(P_{j,t}, P_{j,t-1}) + P_t D_{j,t} + P_t \Gamma_D(D_{j,t}, D_{j,t-1}) = P_{j,t} Y_{j,t} - P_t\left(a_k(u^k_{j,t})K_t + a_n(u^n_{j,t})N_t\right) + B_{j,t+1}/R_t - B_{j,t}.$$

Therefore, the size of the intraperiod loan is equal to the revenues, $X_{j,t} = P_{j,t}Y_{j,t}$. The intra- and intertemporal debt capacity of the firms is constrained by the limited enforceability of debt contracts. In particular, firms can default on their debt obligations after the realization of revenues but before repaying the intraperiod loan. It assumed that the lender will not be able to recover the funds raised by the intraperiod loan in the event of default.

We allow for changes in the relative price of physical investment to capture technological progress that affects the rate of transformation between consumption and investment, but that is not directly linked to the accumulation of knowledge through R&D investment. The currency price of the consumption good is P_t, the currency price of a unit of investment good is $P_t\zeta^{-1}_{\Upsilon,t}$. The law of motion for $\zeta^{-1}_{\Upsilon,t}$ is given by, $\log(\zeta_{\Upsilon,t}) = \rho_{\zeta_\Upsilon}\log(\zeta_{\Upsilon,t-1}) + \sigma_{\zeta_\Upsilon}\epsilon_{\zeta_\Upsilon,t}$, where $\epsilon_{\Upsilon,t} \sim N(0, 1)$. Variation in the relative price of investment is needed mostly to correctly measure the process of physical capital accumulation that occurred in the US starting from World War II.

The intangible nature of knowledge capital implies that it provides poor collateral to creditors. We capture this notion, in reduced-form, by assuming that knowledge capital, $N_{j,t}$, has a zero liquidation value in the event of default while the liquidation value of physical capital, $K_{j,t}$, is positive, but uncertain, at the time of contracting. Uncertainty in the liquidation value of physical capital is modeled as follows. With probability $\zeta_{B,t}$ the lender can recover the full value of physical capital, but with probability $1-\zeta_{B,t}$ the recovery rate is zero. As shown in Jermann and Quadrini (2012), the renegotiation process between the firm and lender implies the following enforcement constraint:

$$X_{j,t} \le \zeta_{B,t}\left[K_{j,t+1} - B_{j,t+1}/(P_t(1+r_t))\right].$$

We label $\zeta_{B,t}$ as a *debt financing shock*. This shock is interpreted as unspecified disturbances in aggregate market conditions affecting liquidation values for physical capital, and therefore debt capacity. The law of motion for $\zeta_{B,t}$ is given by, $\log(\zeta_{B,t}) = (1-\rho_{\zeta_B})\zeta_B + \rho_{\zeta_B}\log(\zeta_{B,t-1}) + \sigma_{\zeta_B}\epsilon_{\zeta_B,t}$, where $\epsilon_{\zeta_B,t} \sim N(0,1)$.

The intermediate firms maximize shareholder value subject to the real and financial constraints outlined above. A detailed characterization of the intermediate firm's program is outlined in Section 1 of the Online Appendix.

2.3. Market clearing and fiscal authority

The market clearing condition for this economy is $C_t + \zeta^{-1}_{\Upsilon,t}I_t + S_t + G_t = Y^G_t$, where G_t denotes government expenditures and Y^G_t is measured GDP (i.e., $Y^G_t = Y_t - a_k(u^k_t)K_t - a_n(u^n_t)N_t - \Gamma_{P,t} - \Gamma_{D,t}$). The government raises lump-sum taxes to finance government expenditures and the tax shield for firms:

$$P_t T_t = P_t G_t + B_{t+1}(1/R_t - 1/(1+r_t)).$$

Government expenditure follows an exogenous law of motion, $\hat{g}_t = \rho_g\hat{g}_{t-1} + \sigma_g\epsilon_{g,t}$, where $\epsilon_{g,t} \sim N(0, 1)$, $\hat{g}_t = \ln(g_t/g)$, and $g_t \equiv G_t/N_t$. In the steady-state, $G/Y^G = \eta_G$.

2.4. Monetary policy

The central bank sets the nominal interest rate according to a feedback rule:

$$(1+r_t)/(1+r) = ((1+r_{t-1})/(1+r))^{\rho_r}\left[(\Pi_t/\Pi^*_t)^{\phi_\pi}(\Delta Y_t/\Delta Y)^{4\phi_{dy}}\right]^{1-\rho_r} e^{\sigma_r\epsilon_{r,t}},$$

where $1+r$, and ΔY are the steady-state values of the nominal interest rate and output growth, respectively; Π^*_t is the inflation target. The central bank responds to deviations in inflation and annualized output growth from their respective target levels. Unanticipated deviations from the interest rate rule are captured by $\epsilon_{r,t} \sim N(0, 1)$.

The target for inflation, Π^*_t, is assumed to follow an autoregressive process, $\pi^*_t = (1-\rho_\pi)\pi^* + \rho_\pi\pi^*_{t-1} + \sigma_\pi\epsilon_{\pi,t}$, where $\pi^*_t = \log(\Pi^*_t)$, $\pi^* = \log(\Pi)$ is the steady state inflation target, and $\epsilon_{\pi,t} \sim N(0, 1)$. We allow for changes in the target to accommodate the possibility that the inflationary stance of the Federal Reserve has changed over time. An alternative approach would consist of explicitly modeling changes in monetary policy as in Bianchi (2013). While we regard this as an interesting path for future research, at this stage it would add an unnecessary layer of complexity.

2.5. TFP decomposition

Imposing the symmetric equilibrium conditions, the aggregate variable output $\widetilde{Y}_t$ can be expressed as:

$$\widetilde{Y}_t = (Z_t L_t)^{1-\alpha} K_t^{\alpha},$$

where aggregate measured TFP, Z_t, is endogenous and depends on technology utilization and the knowledge stock:

$$Z_t \equiv A_t u_t^n N_t.$$

As in Comin and Gertler (2006) and Kung and Schmid (2015), the trend component in TFP, N_t, is endogenous and time-varying. For the discussion of the results below, we define $a_t \equiv \log(A_t)$ as the *exogenous* stationary shock to TFP, u_t^n is the technology utilization rate, N_t is the knowledge stock.

2.6. Solving the model

The trend component in TFP, N_t, is endogenous. In order to induce stationarity, aggregate variables, such as, consumption, R&D, investment, output and government expenditures, are normalized by N_t. Once the model is rewritten in terms of stationary variables, the nonstochastic steady state can be computed, which includes the endogenous trend growth rate, ΔN. After obtaining the non-stochastic steady state values, we log-linearly approximate the equations around the steady-state values (the linearized equations are in the Online Appendix). In the linearized approximation, we follow Jermann and Quadrini (2012) and conjecture that the enforcement constraint is always binding.[5]

3. Estimates

This section presents the main estimation results. We estimate the model using a Metropolis Hastings algorithm. As observables, we use eleven series of U.S. quarterly data: real GDP per capita, annualized quarterly inflation, the federal funds rate (FFR), real consumption per capita, physical investment in terms of consumption units, R&D investment in terms of consumption units, hours, the growth rate of real wages, the relative price of investment, net debt issuance, and net equity payout.

All macroeconomic variables, except for inflation and the FFR, enter as log differences and are downloaded from the BEA website and the Federal Reserve website. The sample spans from 1955:Q1 to 2011:Q3. To the best of our knowledge, this is the first paper that makes use of the newly released series for quarterly R&D in a structural estimation. Following Jermann and Quadrini (2012), the two financial series are calculated using data from the flow of funds accounts of the Federal Reserve Board. Net equity payout is calculated as 'Nonfinancial corporate business; net dividends paid' minus 'Nonfinancial corporate business; corporate equities; liability'. Net debt issuance is 'Nonfinancial corporate business; debt securities and loans; liability'. Both series are divided by business value added.

3.1. Parameter estimates

Table 1 reports priors, modes, and 90% error bands for the model parameters. The priors are diffuse and in line with the literature. For the parameters that characterize the endogenous growth mechanism, we choose diffuse priors and take an agnostic view on their likely values, given that there is no previous evidence to guide us. We also specify a prior on the steady-state trend growth rate: $100\Delta N \sim N(0.45, 0.05)$. Given that steady state growth in the model is a function of several model parameters, this choice translates in a joint prior on these model parameters.

The posterior parameter estimates suggest a significant degree of price stickiness and habit formation consistent with the literature (e.g., Altig et al., 2011; Del Negro et al., 2007). We find higher adjustment costs for the knowledge stock relative to the capital stock (i.e., $\Psi_n'' > \Psi_k''$), which helps to capture the fact that R&D expenditure dynamics are more persistent than physical investment dynamics. On the other hand, the low value of a_n'' implies that the technology utilization rate is very responsive to changes in the marginal return on the knowledge stock. We interpret these two findings as implying that R&D needs to be carried on consistently over time in order to produce significant results and that the important margin for technology adjustment in the short-run relies on varying the utilization rate for the knowledge stock. The estimated value for the knowledge spillover parameter, η, implies that the R&D spillover is around 2.59 times the private return, $1-\eta$, in line with microevidence from Griliches (1992) and Bloom et al. (2013).

The estimated parameters governing the debt financing shock are consistent with the values from Jermann and Quadrini (2012). Both the debt and equity financing shocks are quite persistent, however, the equity financing shock is more volatile than the debt financing shock, capturing the large swings in equity payouts and issuance over the sample. The estimated parameter governing the tax advantage of debt, τ, is similar to the calibrated value from Jermann and Quadrini (2012).

Given that in the model we have less shocks than observables (10 versus 11), we include observation errors on all variables, except for the FFR and the relative price of investment. Fig. 1 in the Online Appendix reports the path of the actual

[5] The constraint is always binding given a sufficiently large tax advantage τ and sufficiently small shocks.

Table 1
Posterior modes, 90% error bands, and priors of the model parameters.

Description	Parameter	Mode posterior	5%	95%	Type	Mean	St.dev.
Degree of indexation of wages	ι_w	0.0589	0.0324	0.0762	B	0.5	0.2
Derivative R&D adjustment	Ψ''_n	7.9215	7.5090	8.2138	G	4	3
Derivative capital adjustment	Ψ''_k	1.1678	1.0770	1.3038	G	2	1
Degree of indexation of prices	ι_p	0.2532	0.2242	0.2841	B	0.5	0.2
Monetary policy	ϕ_π	1.0563	1.0486	1.0867	N	2	0.3
Monetary policy	$\phi_{\Delta y}$	0.2852	0.2762	0.2991	G	0.3	0.15
Monetary policy	ρ_R	0.8495	0.8378	0.8588	B	0.6	0.2
Spillovers knowledge	η	0.2786	0.2623	0.2795	B	0.2	0.1
Fraction wage adjustment	ζ_w	0.8327	0.8217	0.8499	B	0.5	0.2
Consumption persistence	ρ_{ζ_c}	0.5717	0.5382	0.6266	B	0.5	0.2
Inflation target persistence	ρ_π	0.9719	0.9693	0.9739	B	0.95	0.02
R.P.I persistence	ρ_{ζ_Υ}	0.9996	0.9987	0.9999	B	0.8	0.1
Technology persistence	ρ_a	0.9667	0.9605	0.9720	B	0.5	0.2
Government persistence	ρ_g	0.9995	0.9987	0.9998	B	0.5	0.2
Labor persistence	ρ_χ	0.8761	0.8634	0.8909	B	0.5	0.2
Equity financing persistence	ρ_{ζ_D}	0.9165	0.9089	0.9365	B	0.8	0.1
Price mark-up persistence	ρ_{λ_f}	0.9992	0.9977	0.9996	B	0.8	0.1
Debt financing persistence	ρ_{ζ_B}	0.9800	0.9774	0.9799	B	0.6	0.1
Wage mark-up	$\lambda_w - 1$	0.1647	0.1640	0.1695	G	0.15	0.02
Labor steady state	$L^\star$	98.7175	98.6112	99.0717	N	100	2.5
Inflation rate steady state	$\pi^\star$	0.0044	0.0044	0.0045	N	0.5	0.05
Discount factor	$100(\beta^{-1} - 1)$	0.0164	0.0061	0.0209	B	0.2	0.095
Habit in consumption	Φ_c	0.9185	0.9046	0.9275	B	0.7	0.2
Price mark-up	$\lambda_f - 1$	0.0958	0.0919	0.1052	G	0.15	0.05
Depreciation rate capital	δ_k	0.0323	0.0315	0.0333	B	0.03	0.01
Depreciation rate R&D	δ_n	0.0026	0.0015	0.0030	B	0.02	0.01
Mean productivity shock	$a^\star$	−8.3376	−8.4933	−8.2778	U	−100	100
Capital share	α	0.2290	0.2227	0.2296	B	0.3	0.05
Elasticity of labor	σ_L	1.6546	1.4879	1.7311	G	2	0.75
Monetary policy vol.	σ_R	0.0021	0.0019	0.0022	IG	0.005	0.005
Consumption vol.	σ_{ζ_c}	0.0493	0.0473	0.0523	IG	0.02	0.02
Inflation target vol.	σ_π	0.0084	0.0070	0.0094	IG	0.02	0.02
R.P.I vol.	σ_{ζ_Υ}	0.0065	0.0061	0.0073	IG	0.02	0.02
Technology vol.	σ_a	0.0074	0.0062	0.0083	IG	0.02	0.02
Government vol.	σ_g	0.0203	0.0179	0.0219	IG	0.02	0.02
Labor vol.	σ_χ	0.0747	0.0744	0.0771	IG	0.02	0.02
Debt financing vol.	σ_{ζ_B}	0.0123	0.0113	0.0135	IG	0.02	0.02
Equity financing vol.	σ_{ζ_D}	0.0783	0.0764	0.0800	IG	0.03	0.03
Price mark-up vol.	σ_{λ_f}	0.0066	0.0058	0.0076	IG	0.02	0.02
Mean debt financing shock	ζ_B	0.3081	0.3039	0.3173	B	0.3	0.08
Derivative capital utilization	a''_k	0.0546	0.0530	0.0555	G	0.02	0.01
Derivative R&D utilization	a''_n	0.0033	0.0031	0.0034	G	0.004	0.002
Price adjustment cost	ϕ_R	8.7184	7.8264	8.9855	IG	5	5
Equity payout cost	ϕ_D	1.2782	1.0866	1.5966	IG	5	5
Tax advantage	τ	0.3212	0.3191	0.3291	B	0.3	0.05
Wage obs. error vol.	σ_{OW}	0.0066	0.0058	0.0073	IG	0.005	0.005
Inflation obs. error vol.	$\sigma_{O\pi}$	0.0031	0.0029	0.0031	IG	0.0005	0.001
Capital inv. obs. error vol.	σ_{OI}	0.0026	0.0020	0.0028	IG	0.005	0.005
R&D inv. obs. error vol.	σ_{OS}	0.0035	0.0024	0.0038	IG	0.005	0.005
Debt issuance obs. error vol.	$\sigma_{O\Delta B}$	0.0077	0.0074	0.0086	IG	0.01	0.01
Equity payout obs. error vol.	σ_{OE}	0.0073	0.0069	0.0074	IG	0.0025	0.0015
Output obs. error vol.	σ_{OY}	0.0133	0.0127	0.0141	IG	0.01	0.01
Labor obs. error vol.	σ_{OL}	0.0022	0.0020	0.0025	IG	0.01	0.01
Consumption obs. error vol.	σ_{OC}	0.0019	0.0017	0.0024	IG	0.01	0.01

variables together with the path implied by the model. We find that observation errors play a minor role for all variables. Their importance is more visible for the net equity payout series, but even in this case, the majority of the fluctuations are explained well by the model, and only very high frequency fluctuations are explained by the observation error.

3.2. Impulse responses

This section illustrates the key model mechanisms through impulse response functions. This analysis provides a foundation for analyzing the 2001 and 2008 recessions through the lens of our model (explored below in Section 4). Before proceeding, recall that the model-implied TFP consists of three different components: The *stationary technology shock*, the

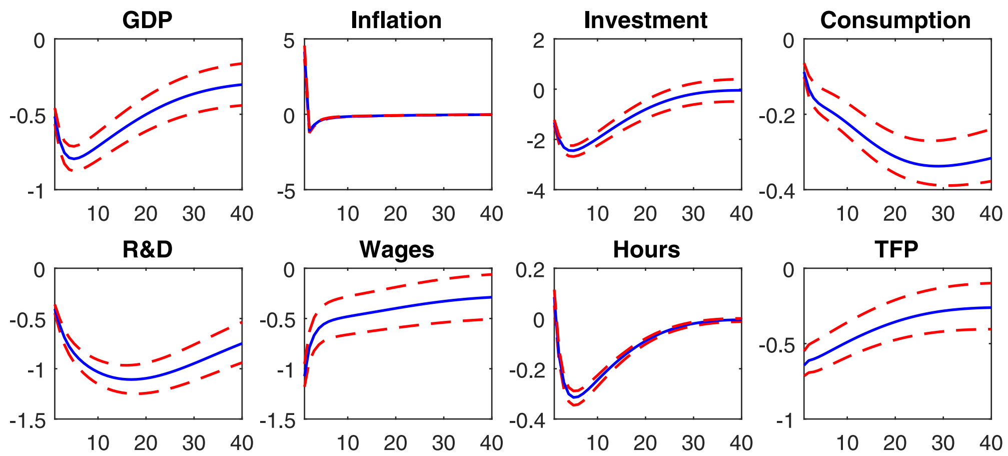


Fig. 1. Debt financing shock. This figure displays impulse response functions for GDP, inflation, investment, consumption, R&D, change in wages, hours, and TFP to a negative innovation to the debt financing shock. The solid line corresponds to the median while the dashed lines correspond to the 90% error bands.

technology utilization rate, and the *knowledge stock*. Namely:

$$TFP_t = \underbrace{A_t}_{\text{Tech. Shock}} * \underbrace{u_t^n}_{\text{Utilization}} * \underbrace{N_t}_{\text{Knowledge}} .$$

The product of technology utilization and adopted knowledge is labeled as the *endogenous component of TFP*, $N_{e,t} = u_t^n N_t$, which includes the endogenous trend component. The stationary technology shock, A_t, is the *exogenous component of TFP*. These definitions imply that TFP growth and the endogenous component of TFP can be expressed as:

$$\Delta tfp_t = \underbrace{\Delta a_t}_{\Delta\text{Exogenous}} + \underbrace{\Delta n_{e,t}}_{\Delta\text{Endogenous}} ,$$
$$\Delta n_{e,t} = \underbrace{\Delta u_t^n}_{\Delta\text{Utilization}} + \underbrace{\Delta n_t}_{\Delta\text{Knowledge}} ,$$

where we have used lower case letters to denote the logs of the corresponding economic variables.

Fig. 1 displays impulse response functions from a negative debt financing shock (contraction in debt financing). A negative shock reduces the collateral value of physical capital and tightens the enforcement constraint. Given the frictions in substituting between debt and equity, tighter financial constraints reduce demand for factor inputs and utilization rates, which is reflected in the fall in physical investment, R&D investment, and eventually, in labor hours. The fall in R&D and technology utilization reduces measured TFP, and lowers trend growth due to the presence of aggregate knowledge spillovers. The sizable and immediate drop in TFP makes the debt financing shock act as a cost-push shock, increasing inflation on impact. Overall, the decline in production inputs reduces output and consumption. Importantly, the decline in physical investment is more substantial than the fall in R&D. This is due to the assumption that only physical capital, and not knowledge capital, is collateralizable. Therefore, the marginal value of an additional unit of physical investment is directly tied to its impact on the enforcement constraint through the *ex-post* liquidation value of the firm, in contrast to R&D investment, which does not impact liquidation values directly. Consequently, physical investment is more responsive to shocks affecting liquidation values.

The model also produces positive comovement in consumption and investment, which is a challenge for standard medium-size DSGE models such as Christiano et al. (2005). For example, after a negative debt financing shock, the drop in R&D and technology utilization magnify the output response by affecting both the level and trend components of TFP persistently. Lower current and future levels of output consequently induce a similar consumption response. The positive comovement of macroeconomic quantities to debt financing shocks allow these shocks to be an important driver of business cycles movements.

Fig. 2 plots impulse response functions to a positive equity financing shock (contraction in equity financing). This shock induces a different response of the macroeconomy compared to the debt financing shock that unfolds over a significantly longer period of time. A positive shock to the net equity payout target (in the adjustment cost function) increases equity payouts to households. An increase in equity payouts reduces the resources available to the firm for production inputs, and is exacerbated by costs affecting the substitution between debt and equity. As a result, demand falls for production inputs, reflected by a drop in physical investment, R&D investment, labor hours, and utilization rates. The fall in production inputs translates into a decline in TFP and output.

In contrast to a contractionary debt financing shock, consumption increases on impact to a contractionary equity financing shock due to the large initial increase in financial income from higher equity payouts. However, consumption eventually declines as aggregate income declines persistently. Furthermore, R&D investment is affected more by an equity financing

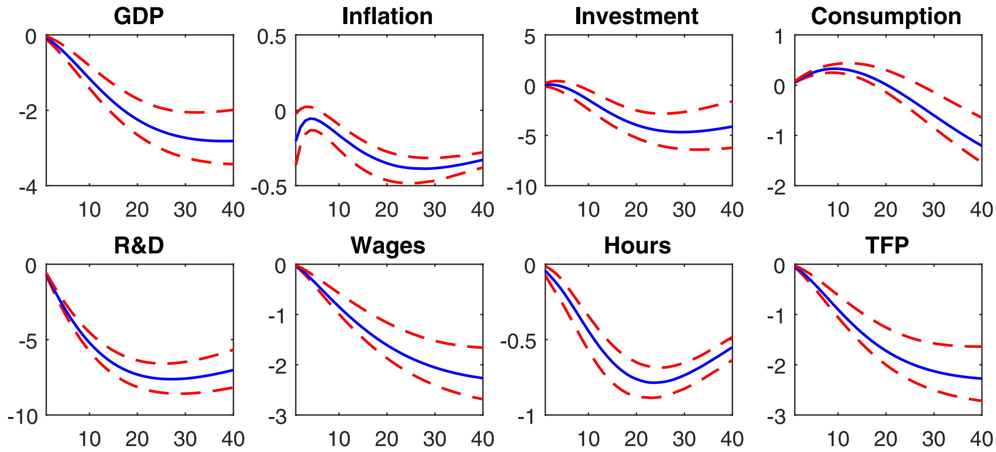


Fig. 2. Equity financing shock. This figure displays impulse response functions for GDP, inflation, investment, consumption, R&D, change in wages, hours, and TFP to a positive innovation to the equity financing shock. The solid line corresponds to the median while the dashed lines correspond to the 90% error bands.

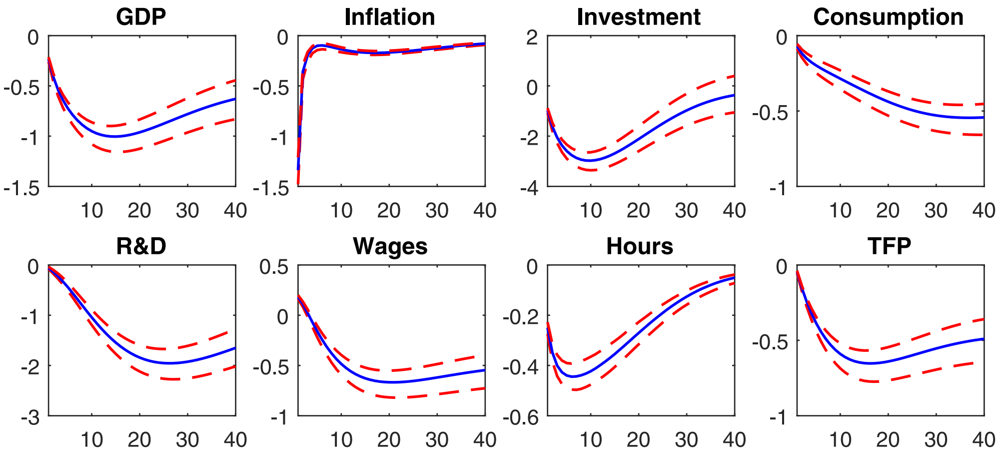


Fig. 3. Monetary policy shock. This figure displays impulse response functions for GDP, inflation, investment, consumption, R&D, change in wages, hours, and TFP to a contractionary monetary policy shock. The solid line corresponds to the median while the dashed lines correspond to the 90% error bands.

shock than physical investment, which is the opposite relation of the responses to a debt financing shock. Given that the dynamics of physical investment are closely tied to debt through the enforcement constraint, but not R&D investment, R&D is more responsive to shocks affecting equity financing (and internal cash flows). As the equity financing shock has a larger impact on R&D, the effect on trend growth is also more pronounced due to the presence of spillover effects from R&D. Thus, the equity financing shock has an effect that grows over the time horizon, which is in contrast to the debt financing shock which generates an immediate contraction in the macroeconomy. These key differences in the responses to the equity and debt financing shocks are important for capturing salient features of the 2001 and 2008 recessions, which are explored in Section 4.

Fig. 3 displays the impulse response functions to a contractionary monetary policy shock. A tightening of monetary policy increases the FFR and lowers the price level. Due to sticky prices, aggregate demand falls and the real rate rises, which discourages investment in physical capital and R&D. The decline in R&D and the endogenous component of TFP leads to a decline in TFP after a contractionary monetary policy shock, consistent with empirical evidence from Evans and dos Santos (2002). Further, the drop in R&D lowers the trend component of TFP due to the endogenous growth channel.

4. A tale of two recessions

The most recent recession has generated concerns about the possibility of a prolonged slowdown. Following the speech delivered by Summers (2013), some economists have become interested in the possibility of a “secular stagnation” similar to the one that characterized the aftermath of the Great Depression according to Hansen (1939). Eggertsson and Mehrotra (2014) build a model that can deliver secular stagnation as a result of household deleveraging or a decline in the population growth rate. Gordon (2014) argues that the US might be heading toward a prolonged period of reduced growth. On

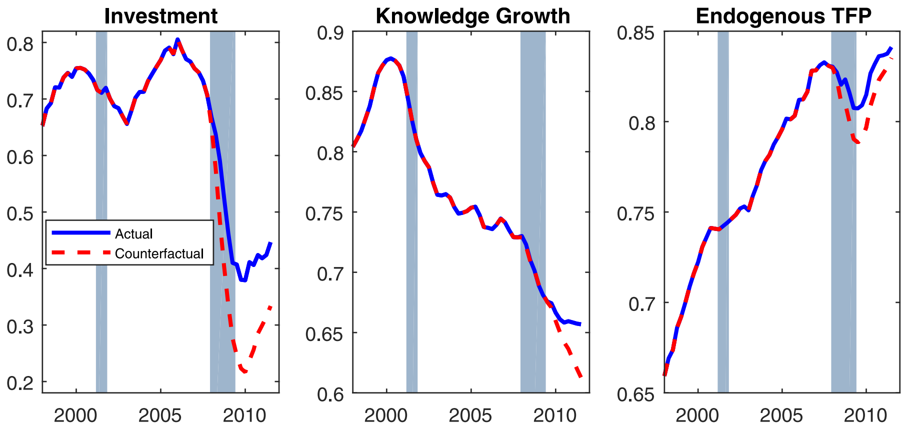


Fig. 4. Impact of the Great Recession. This figure analyzes the Great Recession through the lens of our model. The solid blue line reports smoothed estimates at the posterior mode for Investment, knowledge growth, and the endogenous part of TFP over the past 14 years. The red dashed line corresponds to a counterfactual simulation in which monetary and fiscal shocks are removed starting from the first quarter of 2008. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the other hand, using projections from a calibrated model, Fernald (2014) finds that trend growth remained stable after the Great Recession.

Our model provides a useful framework to address these concerns from a quantitative point of view, given the strong linkages between business cycle fluctuations and long term growth. Thus, in this section we use our model to understand the differences between the two most recent recessions in 2001 and 2008. Fig. 4 analyzes the Great Recession through the lens of our model. The solid blue line reports smoothed estimates at the posterior mode for investment, knowledge growth, and the endogenous component of TFP over the past 15 years. The red dashed line describes a counterfactual simulation in which all policy shocks are set to zero since the beginning of the financial crisis. Specifically, starting from the first quarter of 2008 we set the filtered government expenditure shocks, monetary policy shocks, and inflation target shocks to zero.

The first aspect that emerges from this analysis is that while the 2008 recession implied a significant fall in physical investment, the growth rate for the knowledge stock was less affected. Instead, the fall in investment was associated with a significant and persistent decline in the technology utilization rate to account for the decline in the marginal return of the knowledge input. As a result, the endogenous component of TFP fell significantly. Interestingly, this pattern was reversed during the 2001 recession. In the 2001 recession, the economy experienced a relatively small fall in physical investment, a substantial fall in the growth rate of knowledge (after the large accumulation of R&D during the IT boom in the 1990's), and only a relatively modest decline in endogenous TFP. The knowledge growth rate did not fully recover, but instead, stabilized at a lower level until the 2008 recession. The decline in the growth rate of knowledge during the 2008 recession is relatively smaller when taking into account that the 2008 recession was significantly more severe. Specifically, over the period 2001:Q1-2001:Q4, R&D investment declined by -6.99%, while over the period 2007:Q4-2009:Q2 the decline in R&D investment was -3.35%. The difference in these figures appears even larger when considering that during the 2001 recession the decline in Capital investment was around a tenth of its decline over the 2008 recession (-2.52% vs. -29.70%).

In what follows, we show that these events can be interpreted from the perspective of changes in the market conditions to external equity and debt financing. The 2001 recession coincided with the end of the IT boom and significant contraction in the supply of equity finance. Notably, this event particularly affected young tech firms (i.e., high R&D intensity firms that were the main driver of the 90's R&D boom) that primarily use external equity as a marginal source of funds. Our model captures this fact through the behavior of the equity financing shock. Fig. 5 compares the actual data with a counterfactual simulation in which all shocks are set to zero starting from 2000:Q1 except for the equity financing shocks that are instead left unchanged. Note that the counterfactual simulation captures remarkably well the decline in knowledge growth that started with the 2001 recession.

As illustrated in the previous section through impulse responses, contractionary shocks to equity financing lead to a persistent decline in the accumulation of knowledge that unfolds over several periods. Since R&D projects are often characterized by a high degree of asymmetric information and low asset tangibility, debt financing is more limited – this dimension is captured in the model by the assumption that the knowledge stock cannot be used as collateral in the debt contract. The large adverse shocks to equity financing that coincided with the 2001 recession led to a persistent decline in R&D, which implies a long-lasting adverse effect on trend growth.

In contrast, the 2008 recession originated from a severe financial crisis that more significantly impacted debt capital markets.[6] Fig. 6 considers a similar exercise as above, but instead focuses on the 2008 recession in the context of the debt

[6] Net debt issuance decreased 150% while net equity payouts decreased by 80%.

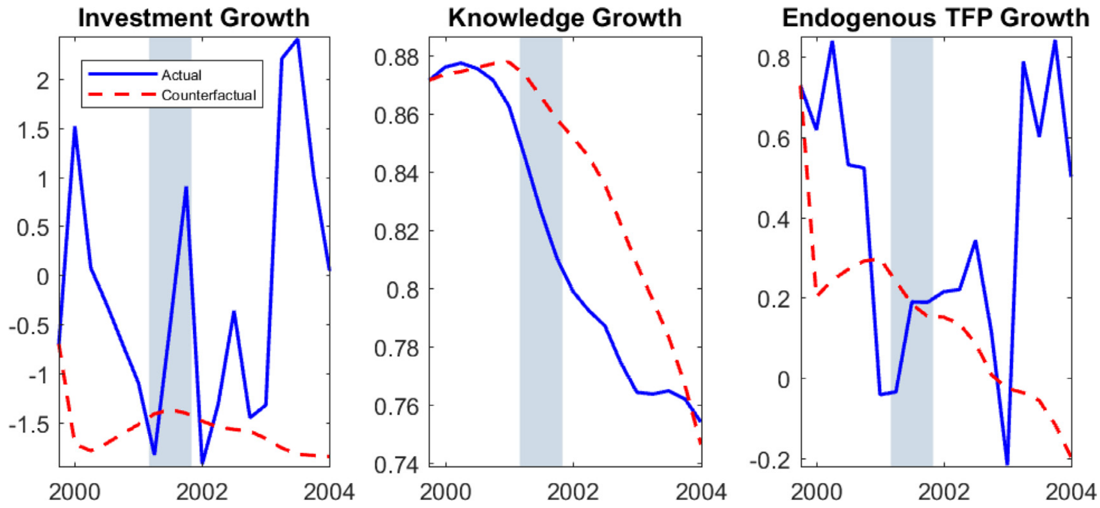


Fig. 5. The 2001 Recession and equity financing. This figure analyzes the 2001 Recession through the lens of our model. The solid blue line reports smoothed estimates at the posterior mode for investment growth, knowledge growth, and the growth of the endogenous part of TFP from 1999 to 2004. The red dashed line corresponds to a counterfactual simulation in which all shocks are set to zero starting from 2000:Q1, except for the shocks to equity financing. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

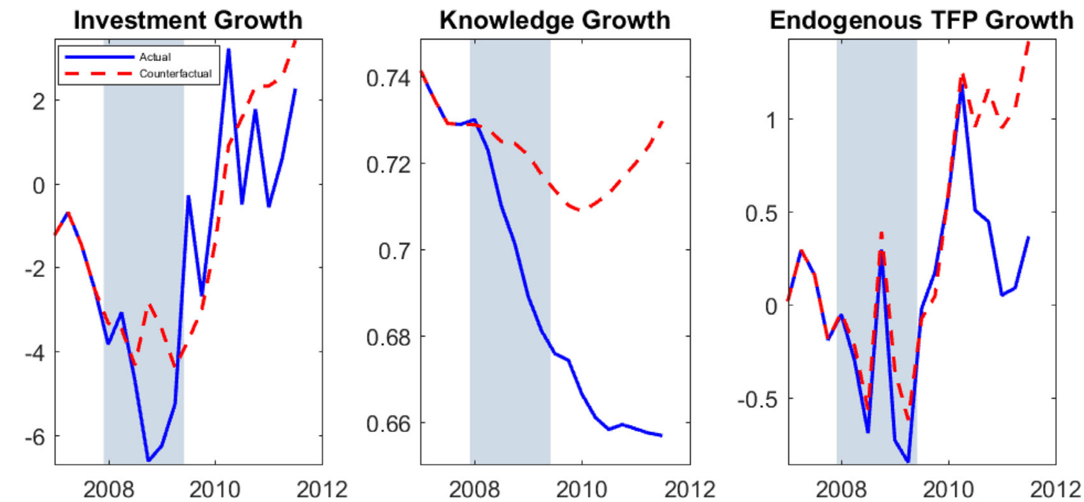
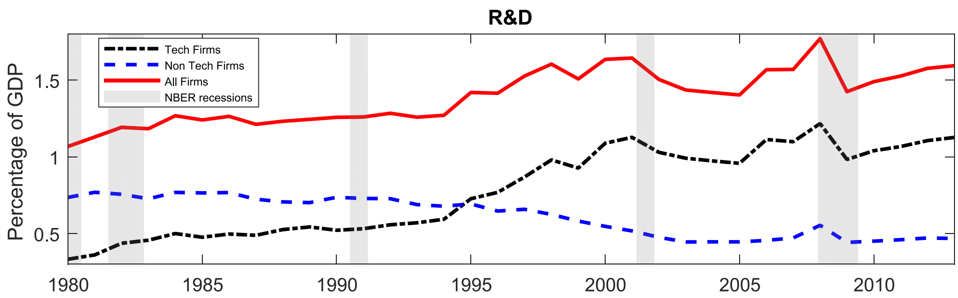


Fig. 6. The Great Recession and debt financing. This figure analyzes the Great Recession through the lens of our model. The solid blue line reports smoothed estimates at the posterior mode for investment growth, knowledge growth, and the growth of the endogenous part of TFP from 2007 to 2012. The red dashed line corresponds to a counterfactual simulation in which all shocks are set to zero starting from 2008:Q1, except for the shocks to debt financing. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

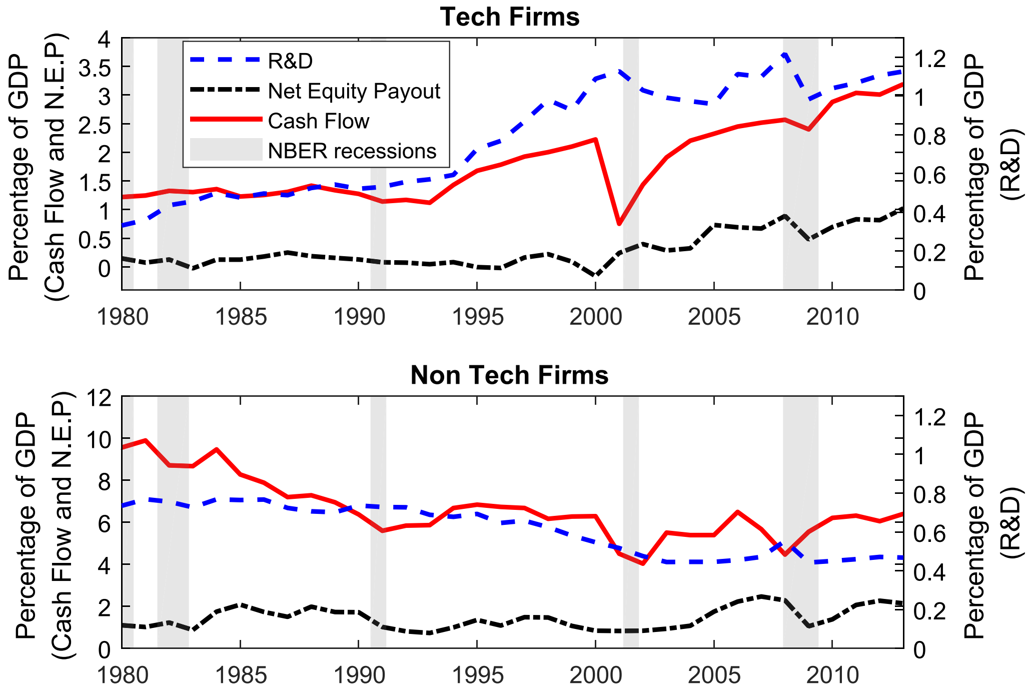
financing shock. The solid blue line corresponds to the actual data, while the red dashed line reports a counterfactual in which all shocks are set to zero starting from 2008:Q1, except for the debt financing shock. Note that the counterfactual series captures very well the behavior of the growth of the investment in physical capital and the growth of the endogenous component of TFP. On the other hand, it misses the large decline in knowledge growth. As discussed in the impulse responses, debt financing shocks have a smaller effect on R&D investment relative to physical investment. As a consequence, the decline in the marginal return for the technology input (from the decline in investment) was mostly absorbed by sharp decline technology utilization rather than a reduction in R&D. Accordingly, the *level* of endogenous TFP fell precipitously, but the *trend* component of endogenous TFP was not as adversely affected by the shock.

Therefore, our estimated model delivers two distinct interpretations for the 2001 and 2008 recessions. The results are disciplined by the fact that we use measures of debt and equity financing as in Jermann and Quadrini (2012), in addition to macroeconomic variables, including R&D flows. Nevertheless, it is interesting to show that our story lines up with the evidence that can be extracted from series not directly used in our estimation exercise.

The top panel of Fig. 7 plots the R&D series for high tech firms (dash-dot black line), non-high tech firms (dashed blue line), and all firms (solid red line) as a percentage of GDP. Observe that the R&D of the tech firms drive most of the



(a) R&D for all firms, tech firms, and non tech firms



(b) R&D, cash flow, and new shares issues for tech and non tech firms

Fig. 7. Financing of R&D for High Tech and Non-High Tech Firms. This figure depicts the financing and R&D patterns for tech firms and non tech firms. In Panel (a), the solid red line reports R&D investment as percentage of GDP for all firms. The dash-dot black line and dashed blue line show R&D investment as percentage of GDP for tech and non tech firms, respectively. Panel (b) reports cash flow, R&D and net equity payout for tech firms (first figure) and non tech firms (second figure). The red solid line shows cash flow as percentage of GDP, the dashed blue line depicts R&D investment (as percentage of GDP) and the dash-dot black line shows net equity payout (as percentage of GDP). Tech firms are firms with the SIC code: 283, 357, 366, 367, 382, 384 or 737. Section 3 of the Online Appendix describes the data employed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

fluctuations in aggregate R&D dynamics and these firms have steadily increased their share of R&D expenditures relative to non-tech firms since the 1980's. Thus, shocks to the financial constraints of high tech firms have important consequences for aggregate innovation dynamics. The middle panel plots R&D expenditures (dashed blue line), cash flow (solid red line), and net equity payout (dash-dot black line) as a percentage of GDP for tech firms, while the bottom panel plots the same series for non-tech firms.[7] From the middle panel, we can see that the persistent decline in R&D for tech firms following the 2001 recession coincides with a sharp decline in cash flow and an increase in net equity payout. In contrast, the drop in R&D after the 2008 recession was only short-lived as there was a quick rebound in R&D, cash flows fell significantly less than during the 2001 recession, and net equity payout was less volatile. For non-tech firms, the three series are relatively

[7] Section 3 in the Online Appendix provides details on the construction of the data series. Tech firms are defined as firms with the following SIC code: 283, 357, 366, 367, 382, 384 or 737.

stable compared to the tech firms, reaffirming the fact that tech firms are the key drivers of innovation over the past three to four decades.

This analysis above has important implications for assessing the long-term consequences of the Great Recession. The decline in TFP experienced during the 2008 recession is largely explained by a reduction in technology utilization, as opposed to a fall in knowledge accumulation. However, while the adverse effects of the Great Recession on knowledge accumulation was not commensurate to its sizable impact on the rest of the economy, such as physical investment, the relatively moderate contraction in R&D investment still exacerbated a pre-existing decline in trend growth that started with the 2001 recession. Furthermore, as shown by our impulse responses, a slowdown in the technology utilization rate persists for many years, suggesting that a significant amount of time is required for economic growth prospects to return to steady-state. During this time, incentives for engaging in R&D are also affected, and therefore, a longer recession exacerbates the long-term consequences on growth. Thus, our analysis should not be interpreted as saying that the 2008 recession was inconsequential for long-term dynamics.

In this respect, it is interesting to analyze the role of policymakers' behavior. Modeling unconventional monetary policy or changes in policy rules is beyond the scope of the paper. However, it is still instructive to study the implications of policy shocks. Given that we do not explicitly model the zero lower bound and forward guidance, our model captures the prolonged period of near zero interest rates as expansionary monetary policy. The counterfactual simulation reported in Fig. 4 shows that absent monetary and fiscal policy shocks, the growth rate of knowledge would have been only mildly affected, but the extent of the recovery in investment and technology utilization would have been much more contained.

These results have important implications for the role of policy interventions during recessions. In models with exogenous growth, TFP and trend growth does not depend on policymakers' actions. As a result, these models generally predict a steady and relatively fast return to the long-term trend, independent from the actions undertaken by the fiscal and monetary authorities. Instead, in the present model sustaining demand during a severe recession can deeply affect the medium- and long-term consequences for the economy. Of course, policymakers cannot intervene each period to permanently alter the trend growth rate of the economy. This would violate the notion of the equilibrium steady-state and be subject to the Lucas critique. However, policymakers can substantially reduce the long-term consequences of a recession.

5. Additional implications

In this section, we decompose the behavior of the different components of TFP, provide external validity for the technology utilization margin, and show that our model mechanisms are robust to alternative model specifications and in different data samples.

5.1. Different TFP components

The endogenous component of TFP ($N_{e,t} \equiv u_t^n * N_t$) captures the bulk of the fluctuations in the model-implied measured TFP growth, through changes in the stationary technology utilization margin (u_t^n), while the long-term trend growth component, the knowledge stock (N_t), is quite stable and persistent. The level of technology utilization is a persistent stationary process, but the growth rate exhibits business cycle fluctuations that are able to explain a significant portion of the high-frequency TFP growth fluctuations. Therefore, technology utilization provides a growth propagation mechanism at higher frequencies while knowledge accumulation provides a growth propagation mechanism at lower frequencies. In principle, the exogenous component of TFP (a_t) could account for all business cycle fluctuations in TFP growth. However, our estimation favors the endogenous technology utilization margin over the exogenous TFP shock for explaining business cycle fluctuations in TFP growth. Evidently, the data prefers the positive co-movement between TFP and business cycle dynamics induced by changes in technology utilization.

Table 2 decomposes the model-implied variance of the observed variables and the components of the model-implied TFP across three frequency intervals. Long-term frequencies correspond to cycles of more than 50 years, medium-term frequencies are associated with cycles between 8 and 50 years, whereas business cycle frequencies correspond to cycles of a duration between 0.5 and 8 years. For all the observed variables, the volatility at medium-term frequencies plays a significant role. In fact, for the FFR, labor hours, and R&D growth more than 50% of volatility is explained by medium-term fluctuations. Furthermore, for consumption growth, investment growth, and GDP growth, the variance of the medium-term and business cycle components are quite similar in magnitude, providing further evidence of the importance of studying jointly business cycle and lower frequency fluctuations. Quite interestingly, medium-term fluctuations are also important for explaining financial cycles. Not surprisingly, a large fraction of the estimated variation for net equity payouts occurs at low frequencies, in line with the observed behavior of this variable over the sample (see Fig. 1 in the Online Appendix).

For the model-implied TFP, the decomposition across frequencies varies mostly because of the dynamics of its endogenous components, technology utilization and the knowledge stock. The growth rate of TFP and the endogenous component of TFP exhibit fluctuations mostly at business cycle frequencies primarily through variation in the technology utilization margin. On the other hand, the fluctuations in the growth rate of the knowledge stock occur mostly at low frequencies, and to some extent, at medium-term frequencies, which is attributed to the high R&D adjustment costs.

Overall, most of the variation in the model-implied TFP is attributed to the movements in the endogenous TFP component, and the fraction is more significant at lower frequencies. Fig. 8 provides a visual characterization of this result by

Table 2
Median and 90% error bands for the model-implied variance across different frequency intervals. Long term: Cycles of more than 50 years. Medium term cycle: Cycles between 8 and 50 years, Business cycle: Cycles between 0.5 and 8 years.

	Long	Medium	Business
GDP growth	5.80 (4.7,7.0)	41.94 (33.5,49.4)	52.25 (46.8,58.6)
Inflation	25.11 (21.4,29.6)	29.07 (24.8,33.4)	45.83 (37.9,53.5)
FFR	40.15 (33.8,46.9)	51.23 (42.7,59.3)	8.62 (7.1,10.0)
Investment growth	1.17 (1.0,1.3)	42.30 (37.0,48.3)	56.53 (51.4,63.9)
Consumption growth	12.30 (9.9,15.2)	35.18 (28.7,42.7)	52.52 (41.2,61.0)
R&D growth	7.72 (6.6,8.9)	62.96 (53.5,72.4)	29.32 (25.1,33.9)
Wages growth	3.71 (3.0,4.5)	14.55 (10.8,17.4)	81.74 (65.8,96.7)
Hours	38.58 (33.0,46.7)	54.95 (48.0,61.5)	6.48 (5.8,7.2)
Net debt issuance	18.28 (14.7,22.2)	73.51 (64.3,84.7)	8.20 (7.2,9.2)
Net equity payout	63.85 (55.6,73.7)	34.93 (27.5,41.8)	1.22 (0.8,1.6)
Knowledge growth	58.39 (45.3,72.7)	40.89 (28.9,50.8)	0.73 (0.5,0.9)
R&D utilization growth	4.12 (3.2,5.0)	33.45 (23.2,40.2)	62.43 (47.3,73.4)
TFP growth	5.82 (4.4,7.3)	26.43 (18.2,32.2)	67.75 (52.8,78.5)
Endogenous TFP growth	6.49 (4.9,8.2)	30.10 (20.2,36.8)	63.41 (48.0,74.6)

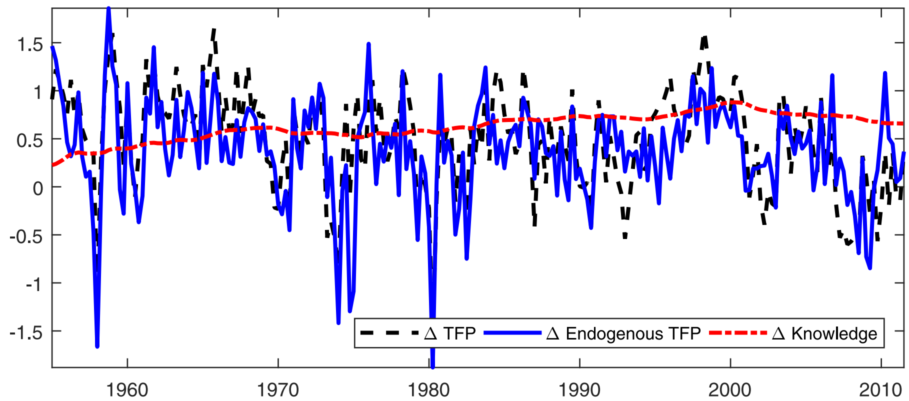


Fig. 8. TFP growth. This figure describes the evolution of TFP growth, knowledge growth, and endogenous TFP growth. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

plotting the evolution of the model-implied TFP growth (dashed black line), the endogenous component of TFP (solid blue line), and knowledge growth (dash-dot red line). These series are obtained by extracting the corresponding smoothed series based on the posterior mode estimates. Consistent with the variance decomposition, measured TFP growth appears substantially more volatile than the growth rate of knowledge itself. In principle, such large fluctuations could be explained by changes in the exogenous component of TFP. However, from visual inspection, it is evident that changes in the endogenous component of TFP capture the bulk of the fluctuations in TFP growth mainly through adjustments in technology utilization. In particular, the endogenous component tracks quite closely the medium-term fluctuations in TFP, whereas the exogenous fluctuations are significantly smaller and are more important at higher frequencies. In sum, this figure provides support for the finding that the most important margin for explaining TFP growth dynamics consists of changes in endogenous TFP – primarily through adjustments in technology utilization rates – as opposed to exogenous disturbances to technology captured by the stationary technology shock.

5.2. External validity

We provide corroborating evidence for the important role played by the endogenous technology utilization channel by comparing our latent utilization series with two empirical proxies, software expenditures and investment in information processing equipment, both of which are obtained from the Bureau of Economic Analysis (BEA). As explained above, changes in technology utilization represent the most important margin for producing significant variation in the endogenous component of TFP growth, especially at business cycle and medium-term frequencies. We find that the correlation between our technology utilization measure and software expenditures is 0.84 at business cycle and medium-term frequencies while the correlation with investment in information processing equipment is 0.50.[8] Given that these two empirical measures are not directly used in our estimation, these correlations provide external validity for our technology utilization margin.

Our technology utilization series also qualitatively replicates the low-frequency patterns of the two empirical measures. Namely, the growth rate of software expenditures and information processing equipment are higher in the first half of the sample. Despite not using these two data series as observables, technology utilization in our model is also higher in the beginning of the sample, to partially account for the opposing low-frequency trends in R&D and measured TFP (i.e., TFP growth is higher in the first half of the sample while R&D growth is higher in the second half). The finding that technology utilization is above trend over the first half of the sample is consistent with several contributions that have studied US macroeconomic dynamics over the post World-War II period. A popular narrative argues that the US economy was, on average, above potential in the 1960s and 1970s, and that this resulted in a progressive increase in inflation (e.g., Orphanides, 2002). In our model, technology utilization responds positively to the state of the economy. Thus, our finding that technology utilization contributed to higher TFP at the beginning of the sample is internally consistent.

5.3. Alternative specifications

Section 4 of the Online Appendix considers the estimation of an extension of the benchmark model where the technology utilization rate is modeled as a slow-moving accumulation process, $\bar{u}^n_{j,t} = (1-\rho_n)u^n_{j,t} + \rho_n \bar{u}^n_{j,t-1}$, where $u^n_{j,t}$ are firm expenditures towards technology utilization and $(1-\rho_n)$ captures the depreciation rate of utilized technology. In our benchmark model, we assume a flow specification for technology utilization. Therefore, this extension assumes that technology utilization depreciates partially rather than fully each period. Figs. 3–5 in the Online Appendix compare the impulse response functions from an estimated version of this extended model and from the benchmark model. Overall, both model specifications imply a similar propagation of financial and macroeconomic shocks. Importantly, technology utilization is the main driver of business cycle fluctuations in TFP growth in this extension, consistent with the benchmark model.

We favor the more parsimonious specification for technology utilization in the benchmark for two primary reasons. First, given that the implications of the two models are quite similar, the streamlined specification helps us to emphasize the role of the financial constraints and financial shocks, which are the focal points of the paper. Second, the data prefers the flow specification for technology utilization over the stock specification in our likelihood-based estimation. We reach this conclusion as the marginal data density is larger and the observation errors are smaller in the benchmark model relative to the extended model.

Given that there was an important Securities Exchange Committee (SEC) regulatory change in 1982 that affected payout policy (e.g., Grullon and Michaely, 2002), we also estimate our benchmark model in the post-1982 sample. Figs. 6–8 in the Online Appendix compare the impulse response functions from the post-1982 estimation and the full sample estimation. The responses, including that of the equity financing shock, are qualitatively similar between the two samples, suggesting the robustness of our estimation results to the regulatory change. We also compare our latent equity financing shock (the key driver of payout fluctuations in our model) with an aggregate measure of external equity issuance costs from Belo et al. (2016) to provide corroborating evidence.[9] A higher value of their measure corresponds to lower equity issuance costs. The correlation between our shock and the inverse of their measure is 0.69 over the entire sample and 0.64 in the post-1982 sample.

6. Conclusions

In this paper, we build and estimate a medium-size DSGE model that features endogenous technological progress and financial frictions. Total factor productivity in our model consists of two endogenous components, the knowledge stock and technology utilization, that drive macroeconomic fluctuations across different frequencies. Positive externalities from knowledge accumulation provide an economic channel linking macroeconomic and financial shocks to persistent movements in long-term growth prospects. In contrast, endogenous technology utilization provides a strong business cycle propagation mechanism. Due to differences in the liquidation values of physical versus knowledge capital, we find that debt financing shocks have large and immediate impact on the macroeconomy through physical investment, whereas equity financing shocks have long-lasting effects on growth that build over time through the sizable effects on R&D investment.

We use our estimated model to interpret the two most recent recessions in 2001 and 2008, and to quantitatively assess their long-run consequences on economic growth. First, we identify large contractionary shocks to debt financing in the 2008 recession that led to a significant decline in physical investment and endogenous TFP, however knowledge accumulation was less affected. In the context of our growth model, this implies that the most recent recession had severe consequences in the short- and medium-term, but long-run growth prospects remained *relatively* stable. The opposite was true during the 2001 recession, which was milder in the short term, as physical investment and technology utilization were

[8] The volatility of our utilization measure is also quantitatively similar to that of software expenditures both at business cycle and medium-term frequencies.

[9] They construct their external equity issuance cost measure by relating it to the volume of external equity issuance and the debt-to-capital ratio in a factor structure.

less affected, but large contractionary shocks to equity financing triggered a sizable and persistent decline in knowledge growth.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at 10.1016/j.jmoneco.2018.07.001.

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