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Macroeconomic linkages between monetary policy and the term structure of interest rates

Howard Kung *

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Abstract

This paper studies the equilibrium term structure of nominal and real interest rates and time-varying bond risk premia implied by a stochastic endogenous growth model with imperfect price adjustment. The production and price-setting decisions of firms drive low-frequency movements in growth and inflation rates that are negatively related. With recursive preferences, these growth and inflation dynamics are crucial for rationalizing key stylized facts in bond markets. When calibrated to macroeconomic data, the model quantitatively explains the means and volatilities of nominal bond yields and the failure of the expectations hypothesis.

JEL Classification: E43, E44, G12, G18

Keywords: Term structure of interest rates, asset pricing, recursive preferences, monetary policy, endogenous growth, inflation, productivity.

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1 Introduction

Explaining key features of the term structure of interest rates is a challenge for standard macroeconomic models. Backus, Gregory, and Zin (1989), den Haan (1995), and Donaldson, Johnsen, and Mehra (1990) show that workhorse macroeconomic models have difficulty in rationalizing the average term spread and failure of the expectations hypothesis. Empirical evidence suggests a tight link between bond yields and macroeconomic fluctuations. Ang, Piazzesi, and Wei (2006) and Estrella (2005) show that the slope of the yield curve forecasts output growth and inflation. Further, monetary policy rules [e.g., Taylor (1993)] provide a channel connecting interest rates and aggregate variables. This paper proposes a general equilibrium production-based framework to explain term structure facts jointly with the dynamics of monetary policy and the macroeconomy.

The model embeds an endogenous growth framework of vertical innovations [e.g., Grossman and Helpman (1991), Aghion and Howitt (1992), and Peretto (1999)] into a standard New Keynesian DSGE model.¹ This model has several distinguishing features. First, households have recursive preferences so that they are sensitive to uncertainty about long-term growth prospects [e.g., Epstein and Zin (1989) and Bansal and Yaron (2004)]. Second, the central bank sets the short-term nominal interest rate targeting inflation and output deviations [i.e., a Taylor rule]. Third, expected inflation and growth prospects are related to firms' production decisions. Fourth, productivity uncertainty is time-varying.

When calibrated to match the time series properties of macroeconomic variables, such as consumption, output, investment, labor, inflation, and wage dynamics, the model can quantitatively explain the means, volatilities, and autocorrelations of nominal bond yields. The model also captures the empirical failure of the expectations hypothesis. Namely, excess bond returns can be forecasted by the forward spread [e.g., Fama and Bliss (1987)] and by a linear combination of forward rates [e.g., Cochrane and Piazzesi (2005)].

Three key ingredients allow the model to rationalize these bond market facts. First, the endogenous growth channel generates long-run risks through firms' innovation decisions as in Kung and Schmid (2014). Second, the presence of nominal rigidities helps to generate a negative rela-

¹See Woodford (2003) and Galí (2008) for textbook treatments of New Keynesian models.

tionship between expected growth and inflation. Imperfect nominal price adjustment implies that equilibrium inflation is linked to the present discounted value of current and future real marginal costs. A positive productivity shock lowers marginal costs and therefore inflation. Also, firms invest more after an increase in productivity which raises expected growth prospects. With recursive preferences, a negative growth-inflation relationship leads to a positive and sizeable nominal term premium. Third, fluctuating productivity uncertainty leads to time-varying bond risk premia.

The model links monetary policy to asset prices through the Taylor rule. For example, more aggressive inflation targeting reduces nominal risks, which lowers the average nominal term spread. On the other hand, a negative growth-inflation link implies that more aggressive inflation smoothing amplifies real risks and thus, increases the equity premium. Similarly, more aggressive output stabilization lowers the equity premium but increases the nominal term spread.

This paper relates to consumption- and production-based models of the term structure. Backus, Gregory, and Zin (1989) show that a standard consumption-based model with power utility fails to account for sign, magnitude, and volatility of the term spread. Consumption-based models with richer preference specifications and model dynamics, such as Wachter (2006), Piazzesi and Schneider (2007), Gallmeyer, Hollifield, Palomino, and Zin (2007), and Bansal and Shaliastovich (2013) find more success. The bond pricing mechanisms of this paper are most closely related to Piazzesi and Schneider (2007) and Bansal and Shaliastovich (2013). The present model endogenizes the inflation and consumption growth dynamics from Piazzesi and Schneider (2007) and Bansal and Shaliastovich (2013) and connects them to firms' production decisions.

Linking the term structure explicitly to investment and production relates to Jermann (2013), who uses a pure production-based framework to explain the average yield curve and failure of the expectations hypothesis. However, previous literature demonstrates that integrating the consumption- and production-based frameworks in a general equilibrium setting have difficulty in accounting for both term structure facts and macroeconomic dynamics. Donaldson, Johnsen, and Mehra (1990) and den Haan (1995) show that extensions of the real business cycle model with power utility cannot rationalize the sign and magnitude of the average term spread, which is related to the equity premium puzzle. Rudebusch and Swanson (2008) and Palomino (2010) show that introducing habit preferences with labor market frictions can generate a sizeable nominal term premium but only with

counterfactual macroeconomic implications (i.e., consumption and real wage volatility are dramatically larger than the data). Rudebusch and Swanson (2012) and Binsbergen, Fernandez-Villaverde, Kojien, and Rubio-Ramirez (2012) demonstrate that introducing recursive preferences produces a large term premium but only with a very high coefficient of relative risk aversion (i.e., over 100). In contrast, this paper provides a production framework that can explain the nominal term premium along with macroeconomic fluctuations without relying on high risk aversion.

More broadly, this paper relates to general equilibrium production-based asset pricing models studying the equity premium. Jermann (1998), Lettau and Uhlig (2000), and Boldrin, Christiano, and Fisher (2001) analyze production-based asset models with habit preferences. Ai (2009), Croce (2012), Kuehn (2008), Kaltenbrunner and Lochstoer (2008), Favilukis and Lin (2012), and Kung and Schmid (2014) explore how long-run risks arise in production economies. Barro (2006), Gourio (2012), and Petrosky-Nadeau, Zhang, and Kuehn (2013) consider rare disasters. Given the positive results of this literature, it is encouraging to extend this paradigm to study the term structure of interest rates.

The paper is organized as follows. Section 2 outlines the benchmark model. Section 3 explores the quantitative implications of the model. Section 4 concludes.

2 Model

2.1 Households

Assume a representative household that has recursive utility over streams of consumption C_t and leisure $\bar{L} - L_t$:

$$U_t = \left\{ (1 - \beta)(C_t^*)^{\frac{1-\gamma}{\theta}} + \beta \left(E_t \left[U_{t+1}^{1-\gamma} \right] \right)^{\frac{1}{\theta}} \right\}^{\frac{\theta}{1-\gamma}}, \quad (1)$$

$$C_t^* \equiv C_t(\bar{L} - L_t)^\tau, \quad (2)$$

where γ is the coefficient of risk aversion, ψ is the elasticity of intertemporal substitution,² $\theta \equiv \frac{1-\gamma}{1-1/\psi}$ is a parameter defined for convenience, β is the subjective discount rate, and \bar{L} is the agent's time

²The parameters γ and ψ are defined over the composite good C_t^* .

endowment. The time t budget constraint of the household is

$$\mathcal{P}_t C_t + \frac{\mathcal{B}_{t+1}}{\mathcal{R}_{t+1}} = \mathcal{D}_t + \mathcal{W}_t L_t + \mathcal{B}_t, \quad (3)$$

where \mathcal{P}_t is the nominal price of the final goods, \mathcal{B}_{t+1} is the quantity of nominal one-period bonds, \mathcal{R}_{t+1} is the gross one-period nominal interest rate set at time t by the monetary authority, \mathcal{D}_t is nominal dividend income received from the intermediate firms, \mathcal{W}_t is the nominal wage rate, and L_t is labor hours supplied by the household.

The household's intertemporal condition is

$$1 = E_t \left[M_{t+1} \frac{\mathcal{P}_t}{\mathcal{P}_{t+1}} \right] \mathcal{R}_{t+1}, \quad (4)$$

where

$$M_{t+1} = \beta \left(\frac{C_{t+1}^*}{C_t^*} \right)^{\frac{1-\gamma}{\theta}} \left(\frac{C_{t+1}}{C_t} \right)^{-1} \left(\frac{U_{t+1}^{1-\gamma}}{E_t[U_{t+1}^{1-\gamma}]} \right)^{1-\frac{1}{\theta}} \quad (5)$$

is the real stochastic discount factor. The intratemporal condition is

$$\frac{\mathcal{W}_t}{\mathcal{P}_t} = \frac{\tau C_t}{\bar{L} - L_t}. \quad (6)$$

2.2 Firms

Production is comprised of a final goods and an intermediate goods sector.

2.2.1 Final Goods

A representative firm produces the final (consumption) goods Y_t in a perfectly competitive market. The firm uses a continuum of differentiated intermediate goods $X_{i,t}$ as input in a constant elasticity of substitution (CES) production technology:

$$Y_t = \left(\int_0^1 X_{i,t}^{\frac{\nu-1}{\nu}} di \right)^{\frac{\nu}{\nu-1}}, \quad (7)$$

where ν is the elasticity of substitution between intermediate goods. The profit maximization problem of the firm yields the following isoelastic demand schedule with price elasticity ν :

$$X_{i,t} = Y_t \left(\frac{\mathcal{P}_{i,t}}{\mathcal{P}_t} \right)^{-\nu}, \quad (8)$$

where \mathcal{P}_t is the nominal price of the final goods and $\mathcal{P}_{i,t}$ is the nominal price of intermediate goods i . The inverse demand schedule is

$$\mathcal{P}_{i,t} = \mathcal{P}_t Y_t^{\frac{1}{\nu}} X_{i,t}^{-\frac{1}{\nu}}.$$

2.2.2 Intermediate Goods

The intermediate goods sector is characterized by a continuum of monopolistic firms. Each intermediate goods firm produces $X_{i,t}$ with physical capital $K_{i,t}$, R&D capital $N_{i,t}$, and labor $L_{i,t}$ inputs using the following technology, similar to Peretto (1999),

$$X_{i,t} = K_{i,t}^\alpha (Z_{i,t} L_{i,t})^{1-\alpha}, \quad (9)$$

and measured total factor productivity (TFP) is

$$Z_{i,t} \equiv A_t N_{i,t}^\eta N_t^{1-\eta}, \quad (10)$$

where A_t represents a stationary aggregate productivity shock, $N_t \equiv \int_0^1 N_j dj$ is the aggregate stock of R&D and $(1 - \eta) \in [0, 1]$ captures the degree of technological spillovers. Thus, firm-level TFP is comprised of two aggregate components, A_t and N_t , and a firm-specific component $N_{i,t}$. The firm can upgrade its technology directly by investing in R&D. Furthermore, there are spillover effects from innovating: Firm-level investments in R&D also improve aggregate technology. These spillover effects are crucial for generating sustained growth in the economy and are a standard feature in endogenous growth models.³

³See, for example, Romer (1990) and Aghion and Howitt (1992).

Log productivity, $a_t \equiv \log(A_t)$, follows an AR(1) process with time-varying volatility:

$$a_t = (1 - \rho)a^* + \rho a_{t-1} + \sigma_{t-1}\epsilon_t, \quad (11)$$

$$\sigma_t^2 = \bar{\sigma}^2 + \lambda(\sigma_{t-1}^2 - \bar{\sigma}^2) + \sigma_e e_t, \quad (12)$$

where $\epsilon_t, e_t \sim N(0, 1)$ are uncorrelated and iid. Croce (2012) and Bloom, Floetotto, Jaimovich, Saporta-Eksten, and Terry (2012) provide empirical support for conditional heteroscedasticity in aggregate productivity.

The law of motion for $K_{i,t}$ is

$$K_{i,t+1} = (1 - \delta_k)K_{i,t} + \Phi_k \left(\frac{I_{i,t}}{K_{i,t}} \right) K_{i,t}, \quad (13)$$

$$\Phi_k \left(\frac{I_{i,t}}{K_{i,t}} \right) = \frac{\alpha_{1,k}}{1 - \frac{1}{\zeta_k}} \left(\frac{I_{i,t}}{K_{i,t}} \right)^{1 - \frac{1}{\zeta_k}} + \alpha_{2,k}, \quad (14)$$

where $I_{i,t}$ is capital investment (using the final goods) and the function $\Phi_k(\cdot)$ captures capital adjustment costs as in Jermann (1998). The parameter ζ_k represents the elasticity of new capital investments relative to the existing stock of capital.

The law of motion for $N_{i,t}$ is

$$N_{i,t+1} = (1 - \delta_n)N_{i,t} + \Phi_n \left(\frac{S_{i,t}}{N_{i,t}} \right) N_{i,t}, \quad (15)$$

$$\Phi_n \left(\frac{S_{i,t}}{N_{i,t}} \right) = \frac{\alpha_{1,n}}{1 - \frac{1}{\zeta_n}} \left(\frac{S_{i,t}}{N_{i,t}} \right)^{1 - \frac{1}{\zeta_n}} + \alpha_{2,n}, \quad (16)$$

where $S_{i,t}$ is R&D investment (using the final goods) and the function $\Phi_n(\cdot)$ captures adjustment costs in R&D investments. The parameter ζ_n represents the elasticity of new R&D investments relative to the existing stock of R&D.⁴

Substituting the production technology into the inverse demand function yields the following

⁴For $j \in \{k, n\}$, the parameters $\alpha_{1,j}$ and $\alpha_{2,j}$ are set to values so that there are no adjustment costs in the deterministic steady state. Specifically, $\alpha_{1,j} = (\Delta N_{ss} - 1 + \delta_j)^{\frac{1}{\zeta_j}}$ and $\alpha_{2,j} = \frac{1}{\zeta_j - 1} (1 - \delta_j - \Delta N_{ss})$.

expression for the nominal price for intermediate goods i :

$$\mathcal{P}_{i,t} = \mathcal{P}_t Y_t^{\frac{1}{\nu}} \left[K_{i,t}^\alpha \left(A_t N_{i,t}^\eta N_t^{1-\eta} L_{i,t} \right)^{1-\alpha} \right]^{-\frac{1}{\nu}}. \quad (17)$$

Further, nominal revenues for intermediate firm i can be expressed as

$$\mathcal{P}_{i,t} X_{i,t} = \mathcal{P}_t Y_t^{\frac{1}{\nu}} \left[K_{i,t}^\alpha \left(A_t N_{i,t}^\eta N_t^{1-\eta} L_{i,t} \right)^{1-\alpha} \right]^{1-\frac{1}{\nu}}.$$

Each intermediate firm also faces a cost of adjusting its nominal price à la Rotemberg (1982), measured in terms of the final goods as

$$G(\mathcal{P}_{i,t}, \mathcal{P}_{i,t-1}; \mathcal{P}_t, Y_t) = \frac{\phi_R}{2} \left(\frac{\mathcal{P}_{i,t}}{\Pi_{ss} \mathcal{P}_{i,t-1}} - 1 \right)^2 Y_t, \quad (18)$$

where $\Pi_{ss} \geq 1$ is the gross steady-state inflation rate and ϕ_R is the magnitude of the costs.

The source of funds constraint for intermediate firm i is

$$\mathcal{D}_{i,t} = \mathcal{P}_t Y_t^{\frac{1}{\nu}} \left[K_{i,t}^\alpha \left(A_t N_{i,t}^\eta N_t^{1-\eta} L_{i,t} \right)^{1-\alpha} \right]^{1-\frac{1}{\nu}} - \mathcal{W}_{i,t} L_{i,t} - \mathcal{P}_t I_{i,t} - \mathcal{P}_t S_{i,t} - \mathcal{P}_t G(\mathcal{P}_{i,t}, \mathcal{P}_{i,t-1}; \mathcal{P}_t, Y_t), \quad (19)$$

where $\mathcal{D}_{i,t}$ and $\mathcal{W}_{i,t}$ are the nominal dividend and wage rate, respectively.

Firm i takes the pricing kernel M_t and the vector of aggregate states $\mathbf{\Upsilon}_t \equiv [\mathcal{P}_t, K_t, N_t, Y_t, A_t]$ as given and solves the following recursive problem to maximize shareholder value, $V_{i,t} \equiv V^{(i)}(\cdot)$:

$$V^{(i)}(\mathcal{P}_{i,t-1}, K_{i,t}, N_{i,t}; \mathbf{\Upsilon}_t) = \max_{\mathcal{P}_{i,t}, I_{i,t}, S_{i,t}, K_{i,t+1}, N_{i,t+1}, L_{i,t}} \frac{\mathcal{D}_{i,t}}{\mathcal{P}_t} + E_t \left[M_{t+1} V^{(i)}(\mathcal{P}_{i,t}, K_{i,t+1}, N_{i,t+1}; \mathbf{\Upsilon}_{t+1}) \right]$$

subject to Eqs. 13, 15, 17, and 19.⁵

⁵The corresponding first-order conditions are derived in Appendix B.

2.3 Central Bank

The central bank follows a modified Taylor rule that depends on the lagged interest rate, and output and inflation deviations:

$$\ln\left(\frac{\mathcal{R}_{t+1}}{\mathcal{R}_{ss}}\right) = \rho_r \ln\left(\frac{\mathcal{R}_t}{\mathcal{R}_{ss}}\right) + (1 - \rho_r) \left(\rho_\pi \ln\left(\frac{\Pi_t}{\Pi_{ss}}\right) + \rho_y \ln\left(\frac{\hat{Y}_t}{\hat{Y}_{ss}}\right) \right) + \sigma_\xi \xi_t, \quad (20)$$

where \mathcal{R}_{t+1} is the gross nominal short rate, $\hat{Y}_t \equiv \frac{Y_t}{N_t}$ is detrended output, and $\xi_t \sim N(0, 1)$ is a monetary policy shock. Variables with an *ss*-subscript denote steady-state values.

2.4 Symmetric Equilibrium

In the symmetric equilibrium, all intermediate firms make identical decisions: $\mathcal{P}_{i,t} = \mathcal{P}_t$, $X_{i,t} = X_t$, $K_{i,t} = K_t$, $L_{i,t} = L_t$, $N_{i,t} = N_t$, $I_{i,t} = I_t$, $S_{i,t} = S_t$, $D_{i,t} = D_t$, $V_{i,t} = V_t$. Also, $\mathcal{B}_t = 0$. The aggregate resource constraint is

$$Y_t = C_t + S_t + I_t + \frac{\phi_R}{2} \left(\frac{\Pi_t}{\Pi_{ss}} - 1 \right)^2 Y_t, \quad (21)$$

where $\Pi_t \equiv \frac{\mathcal{P}_t}{\mathcal{P}_{t-1}}$ is the gross inflation rate.

2.5 Bond Pricing

The price of an n -period nominal bond $\mathcal{P}_t^{(n)\$}$ can be written recursively as:

$$\mathcal{P}_t^{(n)\$} = E_t \left[\mathcal{M}_{t+1}^{\$} \mathcal{P}_{t+1}^{(n-1)\$} \right], \quad (22)$$

where $\mathcal{M}_{t+1}^{\$} \equiv \frac{M_{t+1}}{\Pi_{t+1}}$ is the nominal stochastic discount factor and $\mathcal{P}_t^{(0)\$} = 1$ and $\mathcal{P}_t^{(1)\$} = \frac{1}{\mathcal{R}_{t+1}}$.

Assuming that $\mathcal{M}_t^{\$}$ is conditionally lognormally distributed, then Eq. (22) can be expressed in logs as

$$p_t^{(n)\$} = E_t \left[p_{t+1}^{(n-1)\$} + m_{t+1}^{\$} \right] + \frac{1}{2} \text{var}_t \left[p_{t+1}^{(n-1)\$} + m_{t+1}^{\$} \right],$$

and recursively substituting out prices,

$$p_t^{(n)\$} = E_t \left[\sum_{j=1}^n m_{t+j}^{\$} \right] + \frac{1}{2} \text{var}_t \left[\sum_{j=1}^n m_{t+j}^{\$} \right]. \quad (23)$$

The yield-to-maturity on the n -period nominal bond is defined as

$$y_t^{(n)\$} \equiv -\frac{1}{n} p_t^{(n)\$},$$

which after substituting in Eq. (23) can be expressed as

$$y_t^{(n)\$} = -\frac{1}{n} E_t \left[\sum_{j=1}^n m_{t+j}^{\$} \right] - \frac{1}{2n} \text{var}_t \left[\sum_{j=1}^n m_{t+j}^{\$} \right]. \quad (24)$$

As evident from Eq. (24), movements in nominal yields are driven by the conditional mean and variance of the nominal stochastic discount factor, which in turn depends on inflation and consumption growth.

Similarly, the price of a n -period real bond can be written as

$$P_t^{(n)} = E_t \left[M_{t+1} P_{t+1}^{(n-1)} \right],$$

and the corresponding yield-to-maturity is defined as

$$\begin{aligned} y_t^{(n)} &\equiv -\frac{1}{n} p_t^{(n)} \\ &= -\frac{1}{n} E_t \left[\sum_{j=1}^n m_{t+j} \right] - \frac{1}{2n} \text{var}_t \left[\sum_{j=1}^n m_{t+j} \right]. \end{aligned}$$

2.6 Equilibrium Growth and Inflation

The model endogenously generates (i) low-frequency movements in growth and inflation and (ii) a negative relationship between expected growth and inflation, which have important implications for the term structure. In particular, a negative link between growth and inflation implies that long-maturity nominal bonds have lower payoffs than short-maturity ones when long-term growth is expected to be low. With recursive preferences, these dynamics lead to a positive and sizeable

average nominal term spread.

Low-frequency movements in growth rates (i.e., long-run risks) arise endogenously through the firms' R&D investments as in Kung and Schmid (2014). Imposing the symmetric equilibrium conditions implies that the aggregate production function is

$$Y_t = K_t^\alpha (Z_t L_t)^{1-\alpha},$$

where $Z_t \equiv A_t N_t$ is measured aggregate productivity. Second, assuming that A_t is a persistent process in logs, expected log productivity growth can be approximated as

$$E_{t-1}[\Delta z_t] \approx \Delta n_t.$$

Thus, low-frequency movements in growth are driven by the accumulation of R&D.

As standard in New Keynesian models, inflation dynamics depend on real marginal costs and expected inflation:

$$\tilde{\pi}_t = \gamma_1 \tilde{m}c_t + \gamma_2 E_t[\tilde{\pi}_{t+1}],$$

where $\gamma_1 = \frac{\nu-1}{\phi_R} > 0$, $\gamma_2 = \beta \Delta Y_{ss}^{1-\frac{1}{\psi}} > 0$, and lowercase tilde variables denote log deviations from the steady-state (see Appendix C for the derivation). Recursively substituting out future inflation terms implies that inflation is related to current and discounted expected future real marginal costs. Hence, persistence in marginal costs leads to low-frequency movements in inflation.

To understand the negative long-run relationship between growth and inflation, first consider a positive productivity shock. In response to this, firms increase investment, which boosts expected productivity growth persistently. Also, the prolonged increase in productivity lowers real marginal costs for an extended period of time so that inflation declines persistently as well. In sum, the model endogenizes the consumption growth and inflation dynamics specified in Piazzesi and Schneider (2007) and Bansal and Shaliastovich (2013).

3 Quantitative Results

This section discusses the quantitative implications of the model. The model is solved in Dynare++ using a third-order approximation. The policies are centered around a fix-point that takes into account the effects of volatility on decision rules. A description of the data is in Appendix A.

3.1 Calibration

Table 1 presents the quarterly calibration. Panel A reports the values for the preference parameters. The elasticity of intertemporal substitution ψ is set to 2.0 and the coefficient of relative risk aversion γ is set to 10.0, which are standard values in the long-run risks literature.⁶ The subjective discount factor β is calibrated to 0.997 to be consistent with the level of the real (risk-free) short-term rate.

Panel B reports the calibration of the technological parameters. The price elasticity of demand ν is set to 6 (corresponds to a markup of 20%), the capital share α is set to 0.33, and the depreciation rate of capital δ_k is set to 0.02. These three parameters are calibrated to standard values in the macroeconomics literature (i.e., Comin and Gertler (2006)). The price adjustment cost parameter ϕ_R is set to 30, and is calibrated to match the impulse response of output to a monetary policy shock. This value of ϕ_R implies that the average magnitude of the price adjustment costs are small (0.22% of output), consistent with empirical estimates.⁷ The capital adjustment cost parameter ζ_k is set at 4.8 to match the relative volatility of investment growth to consumption growth (reported in panel B of Table 2). This value of ζ_k implies that the average magnitude of capital adjustment costs are quite small (0.08% of the capital stock), as in the data.⁸

The parameters related to R&D are calibrated to match R&D data. The depreciation rate of the R&D capital stock δ_n is calibrated to a value of 0.0375 which corresponds to an annualized depreciation rate of 15%, and is the value used by the Bureau of Labor Statistics (BLS) in the

⁶This parametrization is also supported empirically by the GMM estimates from Bansal, Kiku, and Yaron (2007).

⁷For example, in a log-linear approximation, the parameter ϕ_R can be mapped directly to a parameter that governs the average price duration in a Calvo pricing framework. In this calibration, $\phi_R = 30$ corresponds to an average price duration of 3.3 months, which accords with micro evidence from Bils and Klenow (2004). See Appendix C for details of this mapping.

⁸For example, Cooper and Haltiwanger (2006) find that the average magnitude of capital adjustment costs is 0.91% using micro-data.

R&D stock calculations. The R&D capital adjustment cost parameter ζ_n is set at 3.3 to match the relative volatility of R&D investment growth to consumption growth (reported in panel B of Table 2). This value of ζ_n implies that the average magnitude of R&D adjustment costs are small (0.05% of the R&D capital stock). The degree of technological appropriability η is set to match the steady-state value of the R&D investment rate.

Panel C reports the parameter values for the productivity process. The unconditional volatility parameter $\bar{\sigma}$ is set at 1.20% to match the unconditional volatility of measured productivity growth. The persistence parameter ρ is calibrated to 0.983 to match the first autocorrelation of expected productivity growth. Furthermore, the first autocorrelations of key macroeconomic aggregates are broadly consistent with the data (presented in panel C of Table 2). The parameters λ and σ_e of the volatility process are calibrated to match the first autocorrelation and standard deviation of realized consumption volatility, respectively (reported in Table 2).

Panel D reports the calibration of the policy rule parameters. The parameter governing the sensitivity of the interest rate to inflation ρ_π is set to 1.5. The parameter determining the sensitivity of the interest rate to output ρ_y is set to 0.10. The persistence of the interest rate rule ρ_R is calibrated to 0.70. The volatility of interest shocks σ_ξ is set to 0.3%. These values are consistent with the calibration from Smets and Wouters (2007) and are in the range of estimates from the literature. For example, in reduced-form estimates of the interest rate rule using the Federal Funds rate, Clarida, Gali, and Gertler (2000) obtain values of ρ_π , ρ_y , and ρ_R equal to 0.83, 0.068, and 0.68, respectively, in the pre-Volcker era and values equal to 2.15, 0.23, and 0.79, respectively, in the Volcker-Greenspan era. Steady-state inflation Π_{ss} is calibrated to match the average level of inflation. Overall, the nominal short rate dynamics (one-quarter nominal rate) implied by this calibration closely match the data, as shown in the first column of panel A in Table 3.

3.2 Bond Market Implications

Panel A of Table 3 reports the means, volatilities, and first autocorrelations of nominal bond yields of different maturities and the five-year minus one-quarter yield spread. The model matches the slope of the nominal yield curve from the data very closely. The average five-year minus one-quarter nominal yield spread is around 1% in both the model and the data. Note that in panel A of Table

8, in the columns labeled ‘Model $\sigma_e = 0$ ’ and ‘Model $\sigma_e, \sigma_\xi = 0$ ’, monetary policy shocks and uncertainty shocks play a small role in determining the average slope of the yield curve.

The positive nominal yield spread in the model is due to inflation risk premia increasing with maturity. As described in Section 2.6, firms’ price-setting and investment decisions in the model lead to a negative long-run relationship between inflation and consumption growth. This mechanism is illustrated in the impulse response functions from Fig. 1. Panel D of Table 2 shows that the negative short-run and long-run correlations between inflation and consumption growth from the model closely match the empirical counterparts. The long-run correlation is computed by isolating the low-frequency components of inflation and consumption growth using a bandpass filter. This negative inflation-growth link implies that long-maturity nominal bonds have lower payoffs than short-maturity ones when long-term growth is expected to be low. Since agents with recursive preferences are strongly averse to low expected growth states, these dynamics lead to a positive and sizeable term premium.

The volatilities and first autocorrelations of nominal yields from the model match the data reasonably well (panel A of Table 3). However, the volatilities of the longer maturity bonds are moderately lower than in the data, which is a common problem in the literature.⁹ As highlighted in Section 2.5, nominal yield dynamics are dictated by fluctuations in the conditional mean and volatility of the nominal pricing kernel. In the model, the conditional mean is primarily driven by productivity shocks (via the endogenous growth and inflation channels) while the conditional volatility is driven by volatility shocks. Quantitatively, the impulse response functions from Fig. 2 illustrate that the productivity shocks are the key drivers of bond yields of different maturities while monetary policy shocks primarily influence short maturity yields and volatility shocks are relatively more important for long maturity ones.

Panel B of Table 3 displays the means, volatilities, and first autocorrelations of real bond yields of different maturities and the five-year minus one-quarter yield spread from the model. The average slope of the real yield curve is negative, as in standard long-run risks models.¹⁰ A downward sloping real yield curve is due to positive autocorrelation in consumption growth, which

⁹This issue is also documented, for example, in den Haan (1995) and Jermann (2013).

¹⁰For example, see Piazzesi and Schneider (2007) and Bansal and Shaliastovich (2013).

implies that long-maturity real bonds have higher payoffs than short-maturity ones when expected consumption growth is low. Empirical evidence for the slope of the real yield curve is varied. Evans (1998) and Bansal, Kiku, and Yaron (2012) show that the real yield curve in the UK is downward sloping for the 1984-1995 and 1996-2008 samples, respectively. On the other hand, Beeler and Campbell (2012) report that real yield curve data in the US is upward sloping in the 1997-2012 sample.

According to the expectations hypothesis, excess bond returns are not predictable. However, there is strong empirical evidence showing that excess bond returns are in fact forecastable by a single factor, such as the forward premium and a linear combination of forward rates. Panel A of Table 4 reports the Fama and Bliss (1987) regressions of n -period excess bond returns on n -period forward premiums. The model produces slope coefficients that are positive and statistically significant as in the data. While the slope coefficients are smaller than the empirical estimates, they are comparable to the production-based estimates from Jermann (2013).

Panel B of Table 4 shows the Cochrane and Piazzesi (2005) regressions of n -period excess bond returns on a single linear combination of forward rates. The model is able to replicate the empirical slope coefficients and corresponding standard errors closely while the R^2 s are sizeable. The slope coefficients are positive and increasing with horizon. In sum, the model is able to produce quantitatively significant bond return predictability.

Time-varying bond risk premia in the model is driven by fluctuating economic uncertainty. A positive uncertainty shock to productivity increases uncertainty in real marginal costs. Since equilibrium inflation depends on real marginal costs, this implies an increase in inflation uncertainty. As shown in Bansal and Shaliastovich (2013), when agents prefer an early resolution of uncertainty (i.e., $\psi > 1/\gamma$), an increase in inflation uncertainty raises nominal bond risk premia, consistent with empirical evidence.¹¹ When shutting down the time-varying uncertainty channel (Column ‘Model $\sigma_e = 0$ ’, Table 8), the Fama-Bliss slope coefficients are essentially zero and the expectations hypothesis holds.

¹¹Bansal and Shaliastovich (2013) find empirically that future bond returns load positively on inflation uncertainty.

3.3 Yield Curve and Macroeconomic Activity

The slope of the nominal yield curve is empirically a strong predictor of economic growth and inflation at business-cycle frequencies.¹² Panel A of Table 5 reports output growth forecasts using the five-year minus one-quarter nominal yield spread for horizons of one, four, and eight quarters. The slope coefficients are positive and statistically significant while the R^2 s are sizeable and comparable to the empirical counterparts. Similarly, Panel B and Panel C show that the slope of the yield curve also forecasts consumption growth and inflation, respectively. The slope coefficients, standard errors, and R^2 s from the model are similar to the empirical estimates.

The positive relationship between the slope of the yield curve and expected growth is linked to the Taylor rule. In the model, a positive productivity shock increases expected consumption growth and decreases inflation. The monetary authority responds to the decline in inflation by lowering the nominal short rate aggressively. A temporary decrease in the short rate implies that future short rates are expected to rise. Consequently, the slope of the nominal yield curve increases.

Piazzesi and Schneider (2007) show that the high- and low-frequency components of the nominal yield spread and inflation are closely related. Panel C of Table 6 shows that there is a strong negative correlation between the yield spread and inflation at both high and low frequencies, and the model is able to match the empirical correlations quite well. The negative correlations are a reaffirmation of the inflation forecasting regressions. Fig. 3 provides a visual depiction of the negative relationship between the term spread (thin line) and inflation (thick line). During periods of high inflation, such as the late 1970s/early 1980s, the term spread is negative. Similarly, episodes of high inflation in model simulations are also associated with a negative term spread. In the model, when inflation rises sharply, the monetary authority aggressively increases the short rate, which decreases the slope of the yield curve. If the rise in inflation is high enough, the yield curve slopes downwards.

The model predicts a strong positive long-run relationship between R&D and the nominal yield spread. As displayed in panel C of Table 6, both the model and the data exhibit a strong positive low-frequency correlation between the R&D rate and the term spread. A positive productivity shock increases R&D and decreases inflation persistently. Furthermore, a drop in inflation leads to a decline in the short rate, which implies an increase in the slope of the yield curve. Anecdotally,

¹²For example, see Estrella (2005) and Ang, Piazzesi, and Wei (2006).

the R&D boom of the 1990s was preceded by a persistent rise in the nominal term spread from the late 1980s through the early 1990s.

3.4 Additional Implications

This section explores additional results of the model. Panels A and B of Table 6 reports the means and volatilities of the equity premium and the short-term real rate. As in Kung and Schmid (2014), the growth channel generates endogenous long-run risks, which allows the model to generate a sizeable equity premium and a low and stable real short rate. While return volatility falls short of the empirical estimate, incorporating real wage rigidities generates substantially more volatility, as in Favilukis and Lin (2012). Following Blanchard and Galí (2007), assume the following real wage process:

$$\ln \left(\frac{W_t}{P_t} \right) = \kappa \ln \left(\frac{W_{t-1}}{P_{t-1}} \right) + (1 - \kappa) \ln \left(\frac{\tau C_t}{\bar{L} - L_t} \right), \quad (25)$$

where $\kappa \in [0, 1]$ captures the degree of wage rigidity. In this extension, equity return volatility increases from 6.68% to 9.18% (reported in the column ‘Model WR’ of Table 8).

Fama and French (1989) empirically document that the term spread forecasts excess stock returns. Panel A of Table 7 reports excess stock return forecasts using the five-year minus one-quarter nominal yield spread. The model regressions produce positive slope coefficients and sizeable R^2 s, as in the data. While the slope coefficients are smaller than in the data, they are consistent with the model estimates from Jermann (2013), a production-based benchmark. Furthermore, Cochrane and Piazzesi (2005) show that a linear combination of forward rates can also forecast excess stock returns. Panel B of Table 7 reports excess stock return forecasts using the Cochrane-Piazzesi factor for horizons of one to five years. The model forecasts produce positive slope coefficients that match the empirical estimates closely. Additionally, the slope coefficients are statistically significant and the R^2 s are sizeable.

As in the pure production-based framework of Jermann (2013),¹³ capital depreciation rates and adjustment costs play an important role for the nominal term premium. In Jermann (2013),

¹³Jermann (2013) introduces exogenous inflation dynamics to the two-sector production-based asset pricing framework of Jermann (2010) to analyze term structure implications.

depreciation rates and the curvature of the adjustment costs affect the term premium through the short rate. In the present model, these parameters impact the term premium through consumption and inflation. In the column ‘Model $\delta_k = .01$ ’ of Table 8, the capital depreciation rate is lowered from the benchmark calibration of .02 to .01. Lower depreciation rates make it easier for households to smooth consumption. Lower consumption volatility decreases the quantity of risk and therefore results in a lower term premium and equity premium. Similarly, in column ‘Model $\delta_n = .02$ ’ reducing the R&D capital depreciation rate from the benchmark value of 0.0375 to 0.02 reduces consumption volatility and risk premia.

In the column ‘Model $\zeta_n, \zeta_k = 2.0$ ’ of Table 8 the R&D and capital adjustment cost parameters are reduced from the benchmark values of 4.8 and 3.3, respectively, to 2.0. Increasing the curvature (i.e., lowering ζ_n and ζ_k) dampens the response of capital and R&D investment to productivity shocks, which weakens the negative link between consumption growth and inflation significantly (from -0.64 to -0.38). A weaker negative correlation reduces the riskiness of long nominal bonds. On the real side, higher adjustment costs decrease investment volatility.

In the column ‘Model $\eta = 0.2$ ’ of Table 8, the parameter η is increased from the benchmark value of 0.1 to 0.2. A larger value for η diminishes the degree of technological appropriability and increases firm-level returns to innovation. Higher incentives to innovate raise the sensitivity of R&D to productivity shocks, which enhances the negative link between inflation and growth moderately (from -0.64 to -0.75). A stronger negative correlation increases the nominal term premium. On the real side, higher incentives to innovate increase investment volatility.

The growth channel plays an important role in explaining the average nominal term spread. In addition to generating endogenous long-run risks, the endogenous growth framework is also crucial for generating a negative long-term relationship between inflation and growth. To highlight the importance of this channel, consider a specification without R&D accumulation but with exogenous long-run productivity risks (e.g., Rudebusch and Swanson (2012)):

$$\begin{aligned}\Delta n_t &= \mu + x_{t-1}, \\ x_t &= \rho_x x_{t-1} + \sigma_x \epsilon_{x,t},\end{aligned}$$

where measured productivity is $Z_t = A_t N_t$ and A_t is defined as before. The average nominal term spread in this specification is -0.41% (reported in column ‘Model EXG’ of Table 8). The downward sloping nominal yield curve is attributed to the positive correlation between expected consumption growth and inflation (0.36 compared to -0.93 in the benchmark model). A positive long-run productivity shock induces a very large wealth effect that decreases the incentives to work, and in equilibrium, real wages increase. A rise in real wages raises real marginal costs and therefore inflation. Also, a positive long-run productivity shock increases expected consumption growth.

In the benchmark model, expected productivity growth is endogenous and affected by labor decisions. An increase in labor hours raises the marginal productivity of R&D. Higher incentives to innovate boost expected growth prospects. When productivity is high, agents supply more labor in order to increase the level, but more importantly, the trend profile of their income. Thus, the growth channel dampens the incentives to consume leisure when expected growth is high. This mechanism maintains the strong negative relationship between expected growth and inflation in the endogenous growth model.

The monetary policy parameters are also important for the nominal term premium. Fig. 4 illustrates the effects of varying inflation stabilization. More aggressive inflation smoothing (i.e., higher ρ_π) decreases the quantity of nominal risks, which lowers the term premium. This is consistent with empirical evidence from Wright (2011) who finds that inflation uncertainty and the term premium declined significantly in countries that adopted more aggressive inflation targeting in the 1990s. On the other hand, as inflation and growth are negatively related, higher inflation smoothing amplifies growth dynamics.¹⁴ In US evidence, Bansal and Shaliastovich (2013) document that during the post-Volcker period (more aggressive inflation targeting), real uncertainty increased relative to inflation uncertainty. Fig. 5 shows that increasing output stabilization (i.e., higher ρ_y) decreases the equity premium but increases the term premium.¹⁵

¹⁴A larger value of ρ_π implies that the nominal short rate, and therefore the real rate (due to sticky prices), will rise more after an increase in inflation. Since inflation and R&D rates are negatively correlated, a larger rise in the real rate will further depress R&D and thus, amplify R&D rates. More volatile R&D amplifies growth.

¹⁵Croce, Kung, Nguyen, and Schmid (2012) and Croce, Nyugen, and Schmid (2012) are related papers that explore how fiscal policy distorts expected growth rates.

4 Conclusion

This paper relates the term structure of interest rates to macroeconomic fundamentals using a stochastic endogenous growth model with imperfect price adjustment. The model matches the means and volatilities of nominal bond yields reasonably well and captures the failure of the expectations hypothesis. The production and price-setting decisions of firms generate a negative long-term relationship between expected growth and inflation. Consequently, the positive nominal term premium is attributed to inflation risks increasing with maturity. Monetary policy plays a crucial role in reconciling the empirical growth and inflation forecasts with the slope of the yield curve. In short, this paper highlights the importance of the growth channel in explaining the term structure of interest rates.

Appendix A. Data

Annual and quarterly data for consumption, capital investment, and GDP are from the Bureau of Economic Analysis (BEA). Annual data on private business R&D investment is from the survey conducted by the National Science Foundation (NSF). Annual data on the stock of private business R&D is from the Bureau of Labor Statistics (BLS). Annual productivity data is obtained from the BLS and is measured as multifactor productivity in the private nonfarm business sector. Quarterly total wages and salaries data are from the BEA. Quarterly hours worked data are from the BLS. The wage rate is defined as the total wages and salaries divided by hours worked. The sample period is for 1953-2008, since R&D data is only available during that time period. Consumption is measured as expenditures on nondurable goods and services. Capital investment is measured as private fixed investment. Output is measured as GDP. The variables are converted to real using the Consumer Price Index (CPI), which is obtained from the Center for Research in Security Prices (CRSP). The inflation rate is computed by taking the log return on the CPI index.

Monthly nominal return and yield data are from CRSP. The real market return is constructed by taking the nominal value-weighted return on the New York Stock Exchange (NYSE) and American Stock Exchange (AMEX) and deflating it using the CPI. The real risk-free rate is constructed by using the nominal average one-month yields on treasury bills and taking out expected inflation.¹⁶ Nominal yield data for maturities of 4, 8, 12, 16, and 20 quarters are from the CRSP Fama-Bliss discount bond file. The 1 quarter nominal yield is from the the CRSP Fama risk-free rate file.

Appendix B. Intermediate goods firm problem

The Lagrangian for intermediate firm i 's problem is¹⁷

$$\begin{aligned}
 V^{(i)}(\mathcal{P}_{i,t-1}, K_{i,t}, N_{i,t}; \mathbf{r}_t) &= F(K_{i,t}, N_{i,t}, L_{i,t}; A_t, N_t, Y_t) - \frac{W_{i,t}}{\mathcal{P}_t} L_{i,t} - I_{i,t} - S_{i,t} - G(\mathcal{P}_{i,t}, \mathcal{P}_{i,t-1}; \mathcal{P}_t, Y_t) \\
 &+ E_t \left[M_{t+1} V^{(i)}(\mathcal{P}_{i,t}, K_{i,t+1}, N_{i,t+1}; \mathbf{r}_{t+1}) \right] \\
 &+ \Lambda_{i,t} \left\{ \frac{\mathcal{P}_{i,t}}{\mathcal{P}_t} - J(K_{i,t}, N_{i,t}, L_{i,t}; A_t, N_t, Y_t) \right\} \\
 &+ Q_{i,k,t} \left\{ (1 - \delta_k) K_{i,t} + \Phi_k \left(\frac{I_{i,t}}{K_{i,t}} \right) K_{i,t} - K_{i,t+1} \right\} \\
 &+ Q_{i,n,t} \left\{ (1 - \delta_n) N_{i,t} + \Phi_n \left(\frac{S_{i,t}}{N_{i,t}} \right) N_{i,t} - N_{i,t+1} \right\},
 \end{aligned}$$

¹⁶The monthly time series process for inflation is modeled using an AR(4).

¹⁷Note that for the real revenue function $F(\cdot)$ to exhibit diminishing returns to scale in the factors $K_{i,t}$, $L_{i,t}$, and $N_{i,t}$ requires the following parameter restriction $[\alpha + (\eta + 1)(1 - \alpha)] \left(1 - \frac{1}{\nu}\right) < 1$ or $\eta(1 - \alpha)(\nu - 1) < 1$.

where $J(K_{i,t}, N_{i,t}, L_{i,t}; A_t, N_t, Y_t) \equiv Y_t^{\frac{1}{\nu}} \left[K_{i,t}^\alpha \left(A_t N_{i,t}^\eta N_t^{1-\eta} L_{i,t} \right)^{1-\alpha} \right]^{-\frac{1}{\nu}}$ and $F(K_{i,t}, N_{i,t}, L_{i,t}; A_t, N_t, Y_t) \equiv Y_t^{\frac{1}{\nu}} \left[K_{i,t}^\alpha \left(A_t N_{i,t}^\eta N_t^{1-\eta} L_{i,t} \right)^{1-\alpha} \right]^{1-\frac{1}{\nu}}$.

The first-order conditions are

$$\begin{aligned}
0 &= -G_{i,1,t} + E_t[M_{t+1}V_{p,t+1}^{(i)}] + \frac{\Lambda_{i,t}}{\mathcal{P}_t} \\
0 &= -1 + Q_{i,k,t}\Phi'_{i,k,t} \\
0 &= -1 + Q_{i,n,t}\Phi'_{i,n,t} \\
0 &= E_t[M_{t+1}V_{k,t+1}^{(i)}] - Q_{i,k,t} \\
0 &= E_t[M_{t+1}V_{n,t+1}^{(i)}] - Q_{i,n,t} \\
0 &= F_{i,l,t} - \frac{\mathcal{W}_{i,t}}{\mathcal{P}_t} - \Lambda_{i,t}J_{i,l,t}
\end{aligned}$$

The envelope conditions are

$$\begin{aligned}
V_{p,t}^{(i)} &= -G_{i,2,t} \\
V_{k,t}^{(i)} &= F_{i,k,t} - \Lambda_{i,t}J_{i,k,t} + Q_{i,k,t} \left(1 - \delta_k - \frac{\Phi'_{i,k,t}I_{i,t}}{K_{i,t}} + \Phi_{i,k,t} \right) \\
V_{n,t}^{(i)} &= F_{i,n,t} - \Lambda_{i,t}J_{i,n,t} + Q_{i,n,t} \left(1 - \delta_n - \frac{\Phi'_{i,n,t}S_{i,t}}{N_{i,t}} + \Phi_{i,n,t} \right)
\end{aligned}$$

where $Q_{i,k,t}$, $Q_{i,n,t}$, and $\Lambda_{i,t}$ are the shadow values of physical capital, R&D capital and price of intermediate goods, respectively. Define the following terms from the equations above:

$$\begin{aligned}
G_{i,1,t} &= \phi_R \left(\frac{\mathcal{P}_{i,t}}{\Pi_{ss}\mathcal{P}_{i,t-1}} - 1 \right) \frac{Y_t}{\Pi_{ss}\mathcal{P}_{i,t-1}} \\
G_{i,2,t} &= -\phi_R \left(\frac{\mathcal{P}_{i,t}}{\Pi_{ss}\mathcal{P}_{i,t-1}} - 1 \right) \frac{Y_t\mathcal{P}_{i,t}}{\Pi_{ss}\mathcal{P}_{i,t-1}^2} \\
\Phi_{i,k,t} &= \frac{\alpha_{1,k}}{1 - \frac{1}{\zeta_k}} \left(\frac{I_{i,t}}{K_{i,t}} \right)^{1-\frac{1}{\zeta_k}} + \alpha_{2,k} \\
\Phi_{i,n,t} &= \frac{\alpha_{1,n}}{1 - \frac{1}{\zeta_n}} \left(\frac{S_{i,t}}{N_{i,t}} \right)^{1-\frac{1}{\zeta_n}} + \alpha_{2,n}
\end{aligned}$$

$$\begin{aligned}
\Phi'_{i,k,t} &= \alpha_{1,k} \left(\frac{I_{i,t}}{K_{i,t}} \right)^{-\frac{1}{\zeta_k}} \\
\Phi'_{i,n,t} &= \alpha_{1,n} \left(\frac{S_{i,t}}{N_{i,t}} \right)^{-\frac{1}{\zeta_n}} \\
F_{i,k,t} &= \frac{\alpha \left(1 - \frac{1}{\nu}\right) Y_t^{\frac{1}{\nu}} X_{i,t}^{1-\frac{1}{\nu}}}{K_{i,t}} \\
F_{i,n,t} &= \frac{\eta(1-\alpha) \left(1 - \frac{1}{\nu}\right) Y_t^{\frac{1}{\nu}} X_{i,t}^{1-\frac{1}{\nu}}}{N_{i,t}} \\
F_{i,l,t} &= \frac{(1-\alpha) \left(1 - \frac{1}{\nu}\right) Y_t^{\frac{1}{\nu}} X_{i,t}^{1-\frac{1}{\nu}}}{L_{i,t}} \\
J_{i,k,t} &= \frac{-\left(\frac{\alpha}{\nu}\right) Y_t^{\frac{1}{\nu}} X_{i,t}^{-\frac{1}{\nu}}}{K_{i,t}} \\
J_{i,n,t} &= \frac{-\left(\frac{\eta(1-\alpha)}{\nu}\right) Y_t^{\frac{1}{\nu}} X_{i,t}^{-\frac{1}{\nu}}}{N_{i,t}} \\
J_{i,l,t} &= \frac{-\left(\frac{1-\alpha}{\nu}\right) Y_t^{\frac{1}{\nu}} X_{i,t}^{-\frac{1}{\nu}}}{L_{i,t}}
\end{aligned}$$

Substituting the envelope conditions and definitions above, the first-order conditions can be expressed as:

$$\begin{aligned}
\frac{\Lambda_{i,t}}{\mathcal{P}_t} &= \phi_R \left(\frac{\mathcal{P}_{i,t}}{\Pi_{ss} \mathcal{P}_{i,t-1}} - 1 \right) \frac{Y_t}{\Pi_{ss} \mathcal{P}_{i,t-1}} - E_t \left[M_{t+1} \phi_R \left(\frac{\mathcal{P}_{i,t+1}}{\Pi_{ss} \mathcal{P}_{i,t}} - 1 \right) \frac{Y_{t+1} \mathcal{P}_{i,t+1}}{\Pi_{ss} \mathcal{P}_{i,t}^2} \right] \\
Q_{i,k,t} &= \frac{1}{\Phi'_{i,k,t}} \\
Q_{i,n,t} &= \frac{1}{\Phi'_{i,n,t}} \\
Q_{i,k,t} &= E_t \left[M_{t+1} \left\{ \frac{\alpha \left(1 - \frac{1}{\nu}\right) Y_{t+1}^{\frac{1}{\nu}} X_{i,t+1}^{1-\frac{1}{\nu}}}{K_{i,t+1}} + \frac{\Lambda_{i,t+1} \left(\frac{\alpha}{\nu}\right) Y_{t+1}^{\frac{1}{\nu}} X_{i,t+1}^{-\frac{1}{\nu}}}{K_{i,t+1}} \right\} \right] \\
&+ E_t \left[M_{t+1} Q_{i,k,t+1} \left(1 - \delta_k - \frac{\Phi'_{i,k,t+1} I_{i,t+1}}{K_{i,t+1}} + \Phi_{i,k,t+1} \right) \right] \\
Q_{i,n,t} &= E_t \left[M_{t+1} \left\{ \frac{\eta(1-\alpha) \left(1 - \frac{1}{\nu}\right) Y_{t+1}^{\frac{1}{\nu}} X_{i,t+1}^{1-\frac{1}{\nu}}}{N_{i,t+1}} + \frac{\Lambda_{i,t+1} \left(\frac{\eta(1-\alpha)}{\nu}\right) Y_{t+1}^{\frac{1}{\nu}} X_{i,t+1}^{-\frac{1}{\nu}}}{N_{i,t+1}} \right\} \right] \\
&+ E_t \left[M_{t+1} Q_{i,n,t+1} \left(1 - \delta_n - \frac{\Phi'_{i,n,t+1} S_{i,t+1}}{N_{i,t+1}} + \Phi_{i,n,t+1} \right) \right] \\
\frac{W_{i,t}}{\mathcal{P}_t} &= \frac{(1-\alpha) \left(1 - \frac{1}{\nu}\right) Y_t^{\frac{1}{\nu}} X_{i,t}^{1-\frac{1}{\nu}}}{L_{i,t}} + \Lambda_{i,t} \frac{\left(\frac{1-\alpha}{\nu}\right) Y_t^{\frac{1}{\nu}} X_{i,t}^{-\frac{1}{\nu}}}{L_{i,t}}
\end{aligned}$$

Appendix C. Derivation of the new keynesian phillips curve

Define $MC_t \equiv \frac{W_t}{MPL_t}$ and $MPL_t \equiv (1 - \alpha)\frac{Y_t}{L_t}$ for real marginal costs and the marginal product of labor, respectively. Rewrite the price-setting equation of the firm in terms of real marginal costs

$$\nu MC_t - (\nu - 1) = \phi_R \left(\frac{\Pi_t}{\Pi_{ss}} - 1 \right) \frac{\Pi_t}{\Pi_{ss}} - E_t \left[M_{t+1} \phi_R \left(\frac{\Pi_{t+1}}{\Pi_{ss}} - 1 \right) \frac{\Delta Y_{t+1} \Pi_{t+1}}{\Pi_{ss}} \right]$$

Log-linearizing the equation above around the nonstochastic steady-state gives

$$\tilde{\pi}_t = \gamma_1 \tilde{m}c_t + \gamma_2 E_t[\tilde{\pi}_{t+1}]$$

where $\gamma_1 = \frac{\nu-1}{\phi_R}$, $\gamma_2 = \beta \Delta Y_{ss}^{1-\frac{1}{\psi}}$, and lowercase variables with a tilde denote log deviations from the steady-state.¹⁸

Substituting in the expression for the marginal product of labor and imposing the symmetric equilibrium conditions, real marginal costs can be expressed as

$$MC_t = \frac{W_t L_t}{(1 - \alpha) K_t^\alpha (A_t N_t L_t)^{1-\alpha}}$$

Define the following stationary variables: $\bar{W}_t \equiv \frac{W_t}{K_t}$ and $\bar{N}_t \equiv \frac{N_t}{K_t}$. Thus, we can rewrite the expression above as

$$MC_t = \frac{\bar{W}_t L_t^\alpha}{(1 - \alpha) (A_t \bar{N}_t)^{1-\alpha}}$$

Log-linearizing this expression yields

$$\tilde{m}c_t = \tilde{w}_t + \alpha \tilde{l}_t - (1 - \alpha) \tilde{a}_t - (1 - \alpha) \tilde{n}_t$$

where lowercase variables with a tilde denote log deviations from the steady-state.

¹⁸In a log-linear approximation, the relationship between the price adjustment cost parameter ϕ_R and the fraction of firms resetting prices $(1 - \theta_c)$ from a Calvo pricing framework is given by: $\phi_R = \frac{(\nu-1)\theta_c}{(1-\theta_c)(1-\beta\theta_c)}$. Further, the average price duration implied by the Calvo pricing framework is $\frac{1}{1-\theta_c}$ quarters.

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Table 1: Quarterly calibration

Parameter	Description	Model
A. Preferences		
β	Subjective discount factor	0.997
ψ	Elasticity of intertemporal substitution	2.0
γ	Risk aversion	10.0
B. Technology		
ν	Price elasticity for intermediate goods	6.0
α	Capital share	0.33
δ_k	Depreciation rate of capital stock	0.02
ϕ_R	Magnitude of price adjustment costs	30.0
ζ_k	Capital adjustment cost parameter	4.8
η	Degree of technological appropriability	0.1
δ_n	Depreciation rate of R&D stock	0.0375
ζ_n	R&D capital adjustment cost parameter	3.3
C. Productivity		
ρ	Persistence of a_t	0.983
$\bar{\sigma}$	Volatility of productivity shock ϵ	1.20%
λ	Persistence of squared volatility process σ_t^2	0.997
σ_e	Volatility of volatility shock e_t	0.008%
D. Policy		
ρ_r	Degree of monetary policy inertia	0.7
ρ_π	Sensitivity of interest rate to inflation	1.5
ρ_y	Sensitivity of interest rate to output	0.10
σ_ξ	Volatility of ξ_t	0.3%

This table reports the parameter values used in the quarterly calibration of the model. The table is divided into four categories: Preferences, Technology, Productivity, and Policy parameters.

Table 2: Macroeconomic moments

	Data	Model
A. Means		
$E(\Delta y)$	2.20%	2.20%
$E(\pi)$	3.74%	3.74%
B. Standard Deviations		
$\sigma(\Delta c)$	1.42%	1.60%
$\sigma(Vol_{t,t+4})$	1.03%	1.00%
$\sigma(\Delta z)$	2.59%	2.59%
$\sigma(E[\Delta z])$	1.10%	1.05%
$\sigma(\pi)$	1.64%	1.92%
$\sigma(w)$	2.04%	2.72%
$\sigma(\Delta c)/\sigma(\Delta y)$	0.64	0.60
$\sigma(\Delta l)/\sigma(\Delta y)$	0.92	0.95
$\sigma(\Delta i)/\sigma(\Delta c)$	4.38	4.31
$\sigma(\Delta s)/\sigma(\Delta c)$	3.44	3.30
C. Autocorrelations		
$AC1(\Delta c)$	0.37	0.43
$AC1(Vol_{t,t+4})$	0.18	0.18
$AC1(\Delta y)$	0.32	0.17
$AC1(\Delta z)$	0.04	0.02
$AC1(E(\Delta z))$	0.93	0.93
$AC1(s - n)$	0.93	0.93
$AC1(i - k)$	0.86	0.92
$AC1(\pi)$	0.73	0.75
D. Correlations		
$\text{corr}(\pi, \Delta c)$	-0.56	-0.64
$\text{corr}(\pi, \Delta c)$ (low-freq)	-0.85	-0.86

This table presents the means, standard deviations, autocorrelations, and cross-correlations for key macroeconomic variables from the data and the model. The model is calibrated at a quarterly frequency and the reported statistics are annualized. The empirical measure of expected productivity growth $E[\Delta z]$ is obtained via MLE estimates from Croce (2012). The series for realized consumption growth volatility is computed following Beeler and Campbell (2012) and Bansal, Kiku, and Yaron (2012). First, the consumption growth series is fitted to an AR(1): $\Delta c_t = \beta_0 + \beta_1 \Delta c_{t-1} + u_t$. Then, annual (four-quarter) realized volatility is computed as $Vol_{t,t+4} = \sum_{j=0}^{4-1} |u_{t+j}|$. Low-frequency components are obtained using a bandpass filter and isolating frequencies between 20 and 50 years.

Table 3: Term structure

	Maturity						
	1Q	1Y	2Y	3Y	4Y	5Y	5Y - 1Q
A. Nominal yields							
Mean (Model)	5.05%	5.26%	5.45%	5.64%	5.82%	5.99%	0.96%
Mean (Data)	5.03%	5.29%	5.48%	5.66%	5.80%	5.89%	1.02%
Std (Model)	3.09%	2.87%	2.68%	2.51%	2.35%	2.20%	1.08%
Std (Data)	2.97%	2.96%	2.91%	2.83%	2.78%	2.72%	1.05%
AC1 (Model)	0.96	0.97	0.98	0.98	0.98	0.98	0.76
AC1 (Data)	0.93	0.94	0.95	0.95	0.96	0.96	0.74
B. Real yields							
Mean (Model)	1.07%	0.98%	0.91%	0.85%	0.80%	0.76%	-0.31%
Std (Model)	1.36%	0.78%	0.66%	0.63%	0.62%	0.62%	1.13%
AC1 (Model)	0.52	0.77	0.90	0.94	0.96	0.97	0.43

This table presents summary statistics for the term structure of interest rates. Panel A presents the annual mean, standard deviation, and first autocorrelation of the one-quarter, one-year, two-year, three-year, four-year, and five-year nominal yields and the 5-year and one-quarter spread from the model and the data. Panel B presents the annual mean, standard deviation, and first autocorrelation of the real yields from the model. The model is calibrated at a quarterly frequency and the moments are annualized.

Table 4: Bond return predictability

	Maturity (Years)			
	2	3	4	5
A. Fama-Bliss				
$\beta^{(n)}$ (Data)	1.076	1.476	1.689	1.150
S.E. (Data)	0.239	0.321	0.407	0.619
R ² (Data)	0.175	0.190	0.185	0.068
$\beta^{(n)}$ (Model)	0.279	0.409	0.454	0.475
S.E. (Model)	0.112	0.148	0.160	0.164
R ² (Model)	0.031	0.046	0.051	0.054
B. Cochrane-Piazzesi				
$\beta^{(n)}$ (Data)	0.455	0.862	1.229	1.449
S.E. (Data)	0.027	0.014	0.011	0.030
R ² (Data)	0.379	0.415	0.446	0.421
$\beta^{(n)}$ (Model)	0.423	0.833	1.204	1.540
t-stat (Model)	0.019	0.008	0.006	0.020
R ² (Model)	0.109	0.119	0.123	0.125

This table presents forecasts of one-year excess returns on bonds of maturities of two to five years from the data and the model. Panel A reports forecasts of excess bond returns using the forward spread (i.e., Fama-Bliss regressions): $rx_{t+1}^{(n)} = \alpha + \beta(f_t^{(n)} - y_t^{(1)}) + \epsilon_{t+1}^{(n)}$. Panel B reports forecasts of excess bond returns using the Cochrane-Piazzesi factor. First, the factor is obtained by running the regression: $\frac{1}{4} \sum_{n=2}^5 rx_{t+1}^{(n)} = \gamma' \mathbf{f}_t + \bar{\epsilon}_{t+1}$, where $\gamma' \mathbf{f}_t \equiv \gamma_0 + \gamma_1 y_t^{(1)} + \gamma_2 f_t^{(2)} + \dots + \gamma_5 f_t^{(5)}$. Second, use the factor $\gamma' \mathbf{f}_t$ obtained in the previous regression to forecast bond excess returns of maturity n : $rx_{t+1}^{(n)} = b_n(\gamma' \mathbf{f}_t) + \epsilon_{t+1}^{(n)}$. The forecasting regressions use overlapping quarterly data and Newey-West standard errors are used to correct for heteroscedasticity.

Table 5: Forecasts with the yield spread

	Horizon (Quarters)		
	1	4	8
A. Output			
β (Data)	1.023	0.987	0.750
S.E. (Data)	0.306	0.249	0.189
R ² (Data)	0.067	0.148	0.147
β (Model)	0.263	0.880	1.504
S.E. (Model)	0.118	0.103	0.109
R ² (Model)	0.015	0.103	0.183
B. Consumption			
β (Data)	0.731	0.567	0.373
S.E. (Data)	0.187	0.163	0.153
R ² (Data)	0.092	0.136	0.088
β (Model)	0.904	0.773	0.684
S.E. (Model)	0.204	0.175	0.182
R ² (Model)	0.103	0.155	0.161
C. Inflation			
β (Data)	-1.328	-1.030	-0.649
S.E. (Data)	0.227	0.315	0.330
R ² (Data)	0.180	0.157	0.071
β (Model)	-0.770	-0.955	-0.984
S.E. (Model)	0.208	0.273	0.303
R ² (Model)	0.081	0.118	0.136

This table presents output growth, consumption growth, and inflation forecasts for horizons of one, four, and eight quarters using the five-year nominal yield spread from the data and the model. The n -quarter regressions, $\frac{1}{n}(x_{t,t+1} + \dots + x_{t+n-1,t+n}) = \alpha + \beta(y_t^{(5)} - y_t^{(1Q)}) + \epsilon_{t+1}$, are estimated using overlapping quarterly data and Newey-West standard errors are used to correct for heteroscedasticity.

Table 6: Asset pricing moments

	Data	Model
A. Means		
$E(r_d - r_f)$	5.84%	3.17%
$E(r_f)$	1.62%	1.07%
$E(y^{(5)} - y^{(1Q)})$	1.02%	0.96%
$E(y^{(1Q)})$	5.03%	5.05%
B. Standard deviations		
$\sigma(r_d - r_f)$	17.87%	6.68%
$\sigma(r_f)$	0.67%	0.68%
$\sigma(y^{(5)} - y^{(1Q)})$	1.05%	1.08%
$\sigma(y^{(1Q)})$	2.96%	3.09%
C. Correlations		
$\text{corr}(y^{(5)} - y^{(1Q)}, \pi)$	-0.40	-0.46
$\text{corr}(y^{(5)} - y^{(1Q)}, \pi)$ (low-freq)	-0.69	-0.54
$\text{corr}(y^{(5)} - y^{(1Q)}, s - n)$ (low-freq)	0.72	0.77

This table reports the means, standard deviations, and correlations for key asset pricing variables, such as the return on the equity claim r_d , the real riskfree rate r_f , the five-year minus one-quarter yield spread $y^{(5)} - y^{(1Q)}$, and the nominal short rate $y^{(1Q)}$, for the data and the model. The model is calibrated at a quarterly frequency and the reported statistics are annualized. Low-frequency components are obtained using a bandpass filter and isolating frequencies between 20 and 50 years.

Table 7: Stock Return Predictability

	Horizon (Years)				
	1	2	3	4	5
A. Yield Spread					
$\beta^{(n)}$ (Data)	2.958	4.606	6.084	9.889	14.656
S.E. (Data)	1.491	1.993	1.936	1.784	1.656
R ² (Data)	0.040	0.048	0.050	0.080	0.106
$\beta^{(n)}$ (Model)	0.664	1.316	1.978	2.677	3.369
S.E. (Model)	0.199	0.379	0.564	0.754	0.958
R ² (Model)	0.044	0.070	0.088	0.102	0.112
B. CP Factor					
$\beta^{(n)}$ (Data)	1.718	3.177	3.220	4.433	6.975
S.E. (Data)	0.815	0.868	1.074	1.279	1.757
R ² (Data)	0.078	0.131	0.081	0.094	0.140
$\beta^{(n)}$ (Model)	1.847	3.324	4.657	5.748	6.682
t-stat (Model)	0.606	1.093	1.537	1.950	2.333
R ² (Model)	0.113	0.176	0.216	0.237	0.248

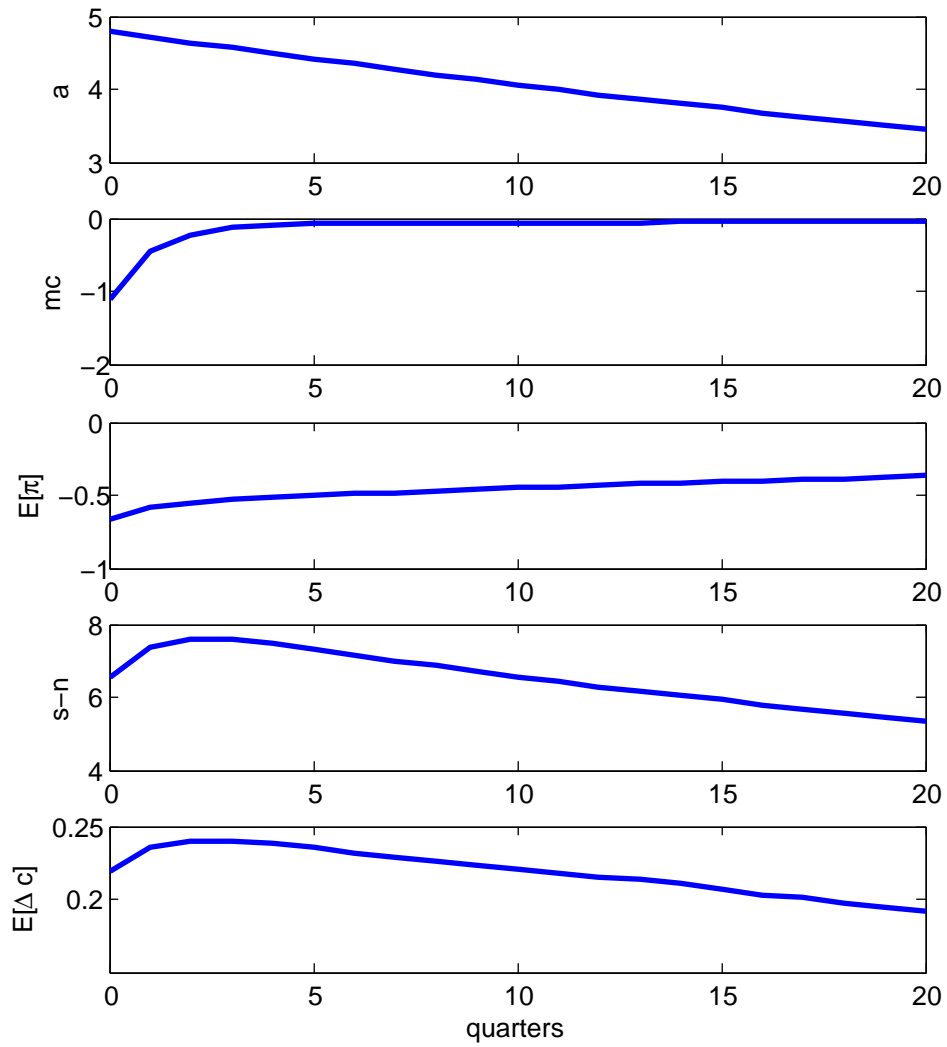
This table reports excess stock return forecasts for horizons of one to five years. Panel A presents the forecasting regressions using the five-year minus one-quarter nominal yield spread: $r_{t,t+n}^{ex} - y_t^{(n)} = \beta(y_t^{(5)} - y_t^{(1Q)}) + \epsilon_{t+1}$. Panel B presents the forecasting regressions using the Cochrane-Piazzesi factor. First, the factor is obtained by running the regression: $\frac{1}{4} \sum_{n=2}^5 rx_{t+1}^{(n)} = \gamma' \mathbf{f}_t + \bar{\epsilon}_{t+1}$, where $\gamma' \mathbf{f}_t \equiv \gamma_0 + \gamma_1 y_t^{(1)} + \gamma_2 f_t^{(2)} + \dots + \gamma_5 f_t^{(5)}$. Second, use the factor $\gamma' \mathbf{f}_t$ obtained in the previous regression to forecast excess stock returns of horizon n : $r_{t,t+n}^{ex} - y_t^{(n)} = b_n \gamma' \mathbf{f}_t + \epsilon_{t+1}^{(n)}$. The forecasting regressions use overlapping quarterly data. Newey-West standard errors are used to correct for heteroscedasticity.

Table 8: Alternative specifications

	Model BEN	Model $\delta_k = .01$	Model $\delta_n = .02$	Model $\zeta_k, \zeta_n = 2.0$	Model $\eta = 0.2$	Model $\sigma_e = 0$	Model $\sigma_e, \sigma_\xi = 0$	Model WR	Model EXG
A. Asset prices									
$E(y^{(5)} - y^{(1Q)})$	0.96%	0.81%	0.88%	0.78%	1.03%	0.94%	0.92%	1.51%	-0.41%
$\sigma(y^{(5)} - y^{(1Q)})$	1.08%	1.03%	1.06%	1.05%	1.17%	0.75%	0.38%	1.72%	0.89%
$E(r_d - r_f)$	3.17%	2.35%	1.96%	2.70%	2.91%	3.14%	3.10%	4.10%	2.86%
$\sigma(r_d - r_f)$	6.68%	5.68%	5.13%	6.61%	5.84%	5.94%	5.71%	9.18%	6.89%
B. Fama-Bliss									
$\beta^{(2)}$	0.28	0.22	0.26	0.25	0.28	0.00	-0.01	0.37	0.09
$\beta^{(3)}$	0.41	0.32	0.38	0.38	0.41	-0.03	-0.04	0.47	0.18
$\beta^{(4)}$	0.45	0.36	0.41	0.43	0.45	-0.05	-0.07	0.49	0.23
$\beta^{(5)}$	0.48	0.37	0.43	0.45	0.47	-0.07	-0.08	0.51	0.26
C. Macro									
$\sigma(\Delta c)$	1.60%	1.46%	1.29%	1.50%	1.71%	1.12%	1.12%	1.92%	1.60%
$\sigma(\pi)$	1.92%	1.85%	2.21%	1.67%	2.19%	1.61%	1.53%	2.69%	3.95%
$\sigma(\Delta i)/\sigma(\Delta c)$	4.31	4.88	4.71	2.52	4.46	5.50	3.08	4.58	3.88
$\sigma(\Delta s)/\sigma(\Delta c)$	3.30	3.58	3.70	2.36	3.38	4.36	2.98	3.56	-
$\text{corr}(\Delta c, \pi)$	-0.64	-0.65	-0.59	-0.38	-0.75	-0.69	-0.70	-0.82	-0.04
$\text{corr}(E[\Delta c], E[\pi])$	-0.93	-0.86	-0.90	-0.92	-0.92	-0.96	-0.99	-0.94	0.36

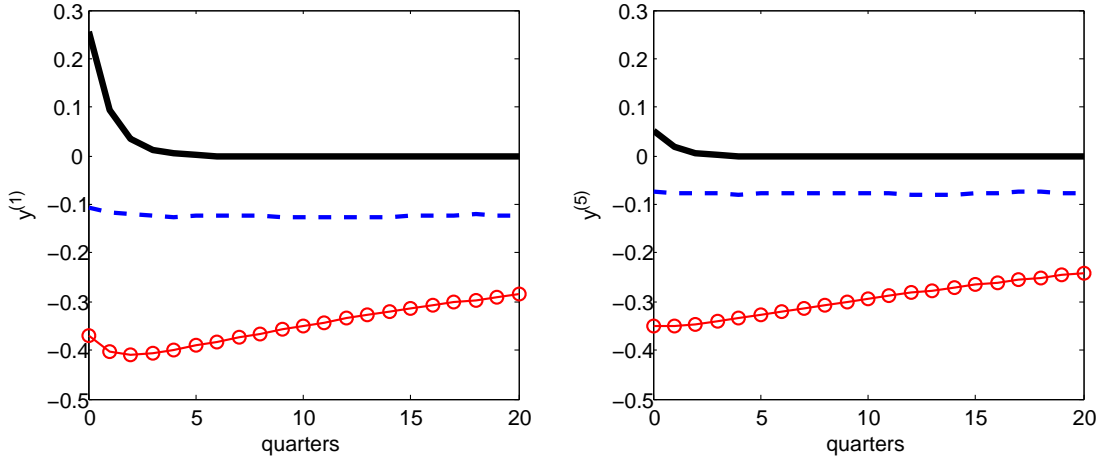
This table compares alternative calibrations and specifications of the benchmark model for key asset pricing moments, the slope coefficients from the Fama-Bliss regressions for maturities of two to five years, and key macroeconomic moments. Model (BEN) is the benchmark model. Model ($\delta_k = .01$) lowers the physical capital depreciation rate from the benchmark value of .02 to .01. Model ($\delta_n = .02$) lowers the R&D capital depreciation rate from the benchmark value of .0375 to .02. Model ($\zeta_k, \zeta_n = 2.0$) reduces the capital adjustment costs parameters from $\zeta_k = 4.8$ and $\zeta_n = 3.3$ to 2.0 and 2.0, respectively. Model ($\eta = 0.2$) increases the degree of technological appropriability from 0.1 to 0.2. Model ($\sigma_e = 0$) shuts down the stochastic volatility channel. Model ($\sigma_e, \sigma_\xi = 0$) shuts down both the stochastic volatility and policy uncertainty channels. Model (WR) incorporates wage rigidities to the benchmark model. Model (EXG) is the model with exogenous growth.

Figure 1: Expected inflation-growth link



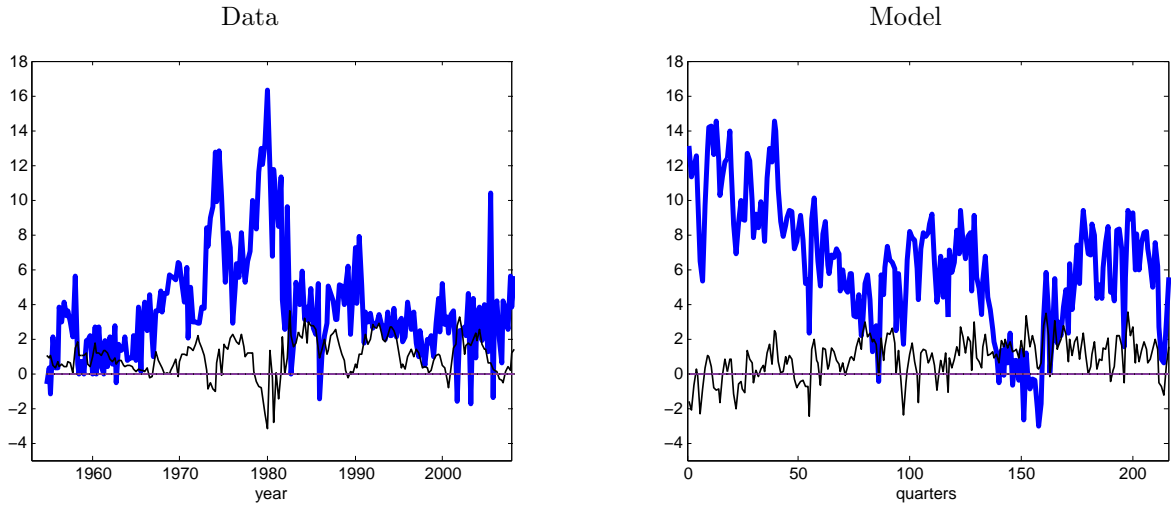
This figure plots impulse response functions of productivity, real marginal costs, expected inflation, the log R&D rate, and expected consumption growth to a positive productivity shock (ϵ_t).

Figure 2: Bond yield dynamics



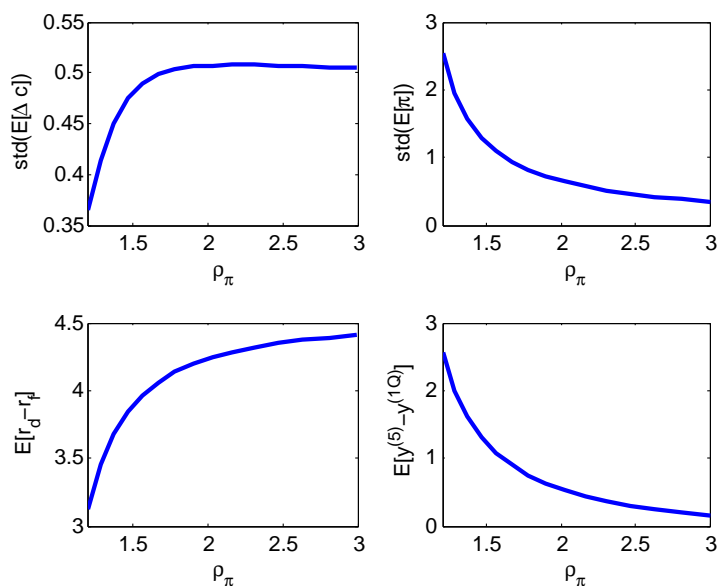
This figure plots the impulse response functions for the 1-year nominal bond yield (left panel) and 5-year nominal yield (right panel) from the model. The thick bold line corresponds to a positive monetary policy shock (ξ_t), the dashed line corresponds to a positive volatility shock (e_t), and the line with circles corresponds to a positive productivity shock (ϵ_t).

Figure 3: Inflation and yield spread dynamics



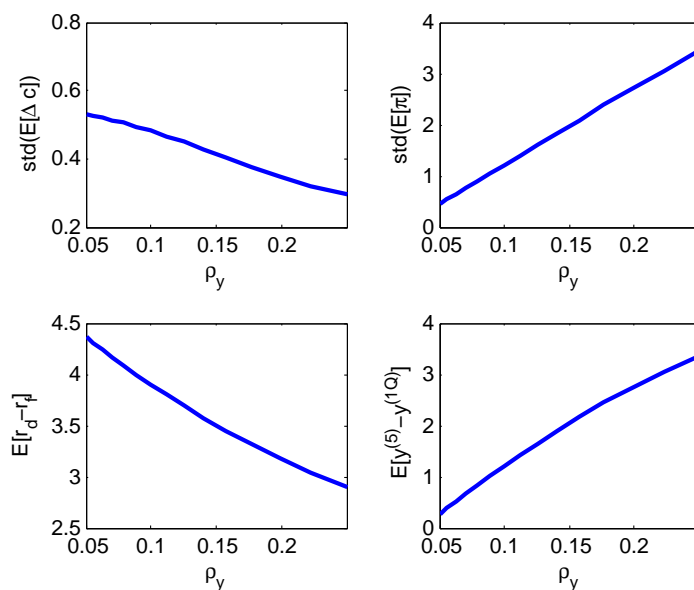
This figure plots inflation (thick line) and the five-year nominal yield spread (thin line) for the data (left panel) and the model (right panel). Data are quarterly and the values of the series are in annualized percentage units.

Figure 4: Varying inflation stabilization



This figure plots the impact of varying the policy parameter ρ_π on the volatility of expected consumption growth, volatility of expected inflation, equity premium, and average nominal yield spread in the model. Values on y-axis are in annualized percentage units.

Figure 5: Varying output stabilization



This figure plots the impact of varying the policy parameter ρ_y on the volatility of expected consumption growth, volatility of expected inflation, equity premium, and average nominal yield spread in the model. Values on y-axis are in annualized percentage units.