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Real and Nominal Equilibrium Yield Curves: Wage Rigidities and Permanent Shocks *

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Abstract

The links between real and nominal bond risk premia and macroeconomic dynamics are explored quantitatively in a model with nominal rigidities and monetary policy. The estimated model captures macroeconomic and yield curve properties of the U.S. economy, implying significantly positive real term and inflation risk bond premia. In contrast to previous literature, both premia are positive and generated by wage rigidities as a compensation for permanent productivity shocks. Stronger policy-rule responses to inflation (output) increase (decrease) both premia, while policy surprises generate negligible risk premia. Empirical evidence of the economic mechanism is provided.

JEL Classification: D51, E43, E44, E52, G12.

Keywords: Term structure of interest rates, bond risk premia, monetary policy, nominal rigidities.

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1 Introduction

What are the economic drivers and sources of risk in real and nominal long-term bonds? Are these bonds risky or hedging instruments with positive or negative risk premia, respectively? Answering these questions will help us to better understand important asset pricing dynamics, the portfolio diversification benefits of bonds, and the transmission of monetary policy, among others. Some answers have been recently provided using dynamic stochastic general equilibrium (DSGE) models.[1] Most of these models imply risk premia that are (i) small or negative in real bonds (or real term premia), (ii) significantly positive in nominal bonds, and (iii) mainly a compensation for transitory shocks. Thus, positive risk premia in nominal bonds result from substantial positive inflation risk premia offsetting the implied negative real term premia. In this paper, we investigate an alternative characterization in a DSGE framework, and provide supporting empirical evidence: Both real term and inflation risk premia are significantly positive as a compensation for permanent productivity shocks in the presence of nominal wage rigidities.

While there is significant empirical support for positive nominal bond risk premia, our knowledge of the sign and size of real term premia is limited. Inflation-linked government bonds are imperfect substitutes of real bonds, their data are affected by illiquidity and mispricing, and evidence on their risk properties is mixed across countries and sub-periods.[2] For instance, while 1999-2008 data support significantly negative and positive real term premia in the United Kingdom and the United States, respectively, data for 1985-2008 suggest small positive real term premia in the U.K. A theoretical model then can help us shed light into the properties of real term premia.

[1] See, for instance, Rudebusch and Swanson (2012), Dew-Becker (2014), and Kung (2014).

[2] See Garcia and van Rixtel (2007) for recent history on inflation-linked bond markets, D'Amico, Kim and Wei (2014) for evidence on significant time-varying liquidity premia in United States and United Kingdom inflation-linked bonds, and Fleckenstein, Longstaff and Lustig (2014) for evidence on mispricing in the TIPS market.

To our knowledge, this is the first paper emphasizing the important quantitative role of wage rigidities in combination with permanent productivity shocks to determine bond risk premia. Christiano, Eichenbaum and Evans (2005) show that nominal wage rigidities are both a salient feature of the data and an important element to capture some fundamental dynamics in economic models. Evidence on the relevance of permanent shocks in the economy, however, is mixed. While Campbell and Mankiw (1987) suggest that shocks to GDP are permanent, Christiano and Eichenbaum (1990) find it difficult to conclude whether economic shocks are transitory or permanent given data limitations. To overcome this difficulty, we estimate impulse responses of macroeconomic variables to permanent shocks in the data and show that their model couterparts only agree with these responses in the presence of wage rigidities. This evidence provides support to the underlying economic mechanism generating positive real term and inflation risk premia in the model.

Our model contains the standard elements of the New Keynesian framework, adding to the household's preferences external habit formation in consumption and recursive utility over (habit-adjusted) consumption and labor. Andreasen (2012) and Rudebusch and Swanson (2012), among others, use these ingredients to study bond risk premia with relative quantitative success.[3]

Our analysis is focused on understanding the contribution of three key elements to real and nominal bond risk premia. First, nominal price and wage rigidities. Both frictions generate real effects in monetary policy, but have different implications for economic dynamics, as highlighted in Christiano, Eichenbaum and Evans (2005). Second, productivity, monetary policy, and inflation-target shocks. Productivity shocks contain permanent (difference-stationary) and transitory (trend-stationary) components. As shown by Campbell (1986) and Labadie (1994), these two components have different implications for bond

[3]See Rudebusch and Swanson (2008, 2012) for differences in the ability of habit formation and recursive preferences, respectively, to capture macroeconomic and term structure dynamics simultaneously.

risk premia. Third, a nominal interest-rate policy rule. The response to economic conditions in this rule has important implications for the joint dynamics of real variables and inflation, and then for the link between real term and inflation risk premia.[4] To assess the contribution of these elements, we use a Generalized Method of Moments (GMM) estimation of the model that matches key U.S. macroeconomic moments and nominal term premia well.

There are two main implications from the model. The first implication is that permanent productivity shocks, in combination with wage rigidities, are crucial to generating large and positive real term and inflation risk premia. Permanent productivity shocks contribute to almost all the variability in the pricing kernel, and thus bond risk premia are mainly a compensation for this risk. Positive real term premia are the result of a negative autocorrelation in the pricing kernel induced by wage rigidities. Without rigidities, prices and wages decline after a negative permanent shock, labor supply increases to partially offset the effect of the shock, and habit-adjusted consumption growth drops persistently. The positive autocorrelation in habit-adjusted consumption growth is inherited by the pricing kernel. In the presence of wage rigidities, wages remain high after a negative shock, leading to a lower increase in labor and lower consumption compared to the no rigidity case. As wages gradually decrease, labor improves and mitigates the negative effect of the shock on next period's consumption. As a result, the habit-adjusted consumption growth (and the pricing kernel) become negatively autocorrelated, leading to positive real term premia. In addition, due to the higher wages in the presence of wage rigidities, producers set a higher product price to maintain their markups. Inflation then increases after a negative permanent shock and generates positive inflation risk premia.

[4]Alternatively, a more structural approach to monetary policy is to consider the monetary authority as a social planner that maximizes welfare, as in Palomino (2012). This approach may have different implications and is not explored in this paper.

The second implication from the model is that bond risk premia are considerably affected by the response to economic conditions in the interest-rate policy rule, but almost unaltered by surprises in monetary policy. A stronger response to inflation in the policy rule increases real term and inflation risk premia by increasing the sensitivity of the real rate (and pricing kernel) to permanent shocks. A stronger response to the output gap, or an increase in the interest-rate smoothing coefficient, has the opposite effect. In contrast, monetary policy and inflation-target shocks have negligible effects on bond risk premia given their transitory effects on the marginal utility of consumption

Finally, we provide empirical support to our model mechanism by comparing data and model impulse responses to permanent productivity shocks for macroeconomic variables of interest. In particular, the response of inflation in the model changes sign in the presence of wage rigidities. We show that the the response of inflation in the data agrees with that of the model under wage rigidities.

This paper contributes to the literature in which New Keynesian models (see Woodford 2003 for the standard framework) are used to analyze the term structure of interest rates.[5] Rudebusch and Swanson (2012) rely on transitory productivity shocks and price rigidities to capture nominal yield curve properties, and do not study real yield curve implications. These elements, although present in our model, are not as quantitatively important as wage rigidities and permanent shocks. Andreasen (2012) incorporates both permanent and transitory components in productivity, and Dew-Becker (2014) adds wage rigidities. These studies focus on the time-variation in bond risk premia by fitting macroeconomic and yield dynamics. Our focus is different. The GMM approach allows us to target unconditional moments, provide quantitative comparisons across model specifications, and

[5] Buraschi and Jiltsov (2005) studies real and nominal bond risk premia in a monetary real business cycle model. This model also generates endogenous consumption growth and inflation. Their monetary policy and friction specifications are substantially different from those of a standard New Keynesian model.

focus on explaining the economic mechanisms behind bond risk premia. Kung (2014) uses an endogenous growth channel that is complementary to our model structure.

Our paper is also related to term structure models with exogenous inflation.[6] As an advantage, our model generates an endogenous negative correlation of consumption growth and inflation, and links real and nominal bond risk premia from first principles. This allows us to predict changes in the yield curve dynamics that are related to structural economic and policy changes.

The paper is organized as follows. Section 2 describes the data and reports the descriptive statistics for nominal and inflation-linked bonds in the U.S. and the U.K. Section 3 describes the model. Section 4 provides details of the model estimation and its quantitative performance, presents its main implications, and explores the economic mechanism behind the results. Section 5 validates the impulse responses of the baseline model in the data, and Section 6 concludes.

2 Empirical Evidence

This section presents descriptive statistics of inflation-linked and nominal government bonds in the U.K. and U.S. Inflation-linked government bonds are, at best, imperfect substitutes of real bonds, and have only been traded in the U.K. and U.S. since 1981 and 1997, respectively.[7] There are several difficulties with exploring the properties of real bonds from the available data, motivating the joint theoretical analysis of real and nominal yields

[6]The endowment economy models with recursive preferences in Piazzesi and Schneider (2007) and Bansal and Shaliastovich (2013) imply negative real term premia, while the habit model in Wachter (2006) implies the opposite. The producton economy model in Van Binsbergen et al. (2012) implies negative real term premia and positive inflation risk premia.

[7]Their inflation protection is limited by a lagged indexation to price levels and the embedded deflation optionality they provide. In addition, pricing in these markets has been affected by liquidity concerns and potential unexploited arbitrage opportunities. See D'Amico, Kim and Wei (2014) for evidence on significant time-varying liquidity premia in U.S. and U.K. inflation-linked bonds. See Fleckenstein, Longstaff and Lustig (2014) for evidence of mispricing in the TIPS and inflation swaps markets.

that follows.[8]

We use quarterly data from January 1985 to September 2008.[9] This data period is motivated by two reasons. First, British inflation-linked Gilts are only available since 1985. Second, the period September - December 2008 coincides with the collapse of Lehman Brothers and a switch to unconventional monetary policy given the zero interest-rate bound. We stop in September 2008, since we want to focus on understanding the effects of a monetary authority setting the level of a short-term rate (conventional monetary policy) on bond yields. We report statistics for the whole sample and for the subsample January 1999 to September 2008, during which TIPS are actively traded in the U.S. The consumption growth and inflation series were constructed using quarterly data from the Bureau of Economic Analysis, following the methodology in Piazzesi and Schneider (2007). These series capture only consumption of non-durables and services and its related inflation. These data are consistent with the variables of the economic model below. The data on zero-coupon nominal bond and TIPS yields are constructed following the procedure in Gurkaynak, Sack and Wright (2006) and Gurkaynak, Sack and Wright (2008), respectively. The data are obtained from the Federal Reserve website. The short-term nominal interest rate is the 3-month T-bill from the Fama risk-free rates database. Data for British Gilts are obtained from the Bank of England website.[10]

[8]There is an extensive empirical literature on the real term and inflation risk premia with and without inflation-linked bonds using no-arbitrage term structure models. This literature shows a wide range for the sign and size of inflation risk premia in the U.K. and in the U.S. An incomplete list includes Barr and Campbell (1997) Evans (1998), and Joyce, Lildholdt and Sorensen (2010) for the U.K., and Ang, Bekaert and Wei (2008), D'Amico, Kim and Wei (2014), Chen, Liu and Cheng (2010), Christensen, Lopez and Rudebusch (2010), Chernov and Mueller (2012), Grishchenko and Huang (2013), and Abrahams et al. (2013) for the U.S. Hördahl and Tristani (2012) provide a similar study for the eurozone.

[9]Results using comparable monthly data are similar. We present results for quarterly data to be consistent with the model estimation.

[10]Consumption and inflation data are constructed from Bureau of Economic Analysis (2015). "Personal Consumption Expenditures and "Price Indexes for Personal Consumption Expenditures." Accessed January, 2015. http://www.bea.gov/. Nominal bond and TIPS yields are obtained from FEDS Working Papers (2006, 2008). Accessed January, 2015. http://www.federalreserve.gov/pubs/feds/2006/200628/200628abs.html, and

Table 1: **Descriptive Statistics of U.K. and U.S. Government Indexed and Nominal Bond Yields and Excess Returns, Consumption Growth, and Inflation**
Yields are annualized rates. Statistics are quarterly, non-annualized. Consumption growth is denoted by Δc, inflation by π_t, and the 3-month nominal rate by i_t. Excess returns on inflation-linked bonds are computed as $\log P_{indexed,t+1} - \log P_{indexed,t} + \pi_{t+1} - i_t$. Excess returns on nominal bonds are computed as $\log P_{nom,t+1} - \log P_{nom,t} - i_t$. Data sources: BEA (2015), FEDS (2015), CRSP (2015), and Bank of England (2015).

	United Kingdom				United States		
	1985:Q1 - 2008:Q3		1999:Q1 - 2008:Q3		1985:Q1 - 2008:Q3	1999:Q1 - 2008:Q3	
	Indexed	Nominal	Indexed	Nominal	Nominal	TIPS	Nominal
Panel A: Bond Yields							
Average							
2.5 years	2.85	7.07	2.15	4.77	5.37		3.70
5 years	2.88	7.14	2.04	4.81	5.92	2.27	4.24
10 years	2.94	7.13	1.91	4.76	6.48	2.64	4.92
Standard Deviations							
2.5 years	0.94	2.54	0.80	0.73	2.07		1.54
5 years	0.86	2.43	0.49	0.60	1.93	1.14	1.10
10 years	0.98	2.38	0.40	0.38	1.75	0.88	0.76
Panel B: Bond Excess Returns							
Average							
2.5 years	-0.22	0.15	0.00	0.06	0.34		0.26
5 years	-0.17	0.72	-0.04	0.08	0.74	0.79	0.53
10 years	-0.03	0.36	-0.01	0.02	1.22	1.02	0.77
Sharpe Ratios							
2.5 years	-0.18	0.11	0.00	0.05	0.29		0.24
5 years	-0.10	0.12	-0.03	0.04	0.25	0.33	0.20
10 years	-0.01	0.12	-0.01	0.00	0.24	0.30	0.18
Panel C:Correlations with Macroeconomic Variables and Stock Returns							
Yields and Consumption Growth							
2.5 years	0.28	0.54	0.06	0.47	0.30		0.51
5 years	0.39	0.54	0.16	0.44	0.28	0.42	0.54
10 years	0.48	0.56	0.28	0.39	0.24	0.42	0.51
Yields and Inflation							
2.5 years	0.19	0.46	-0.18	-0.35	0.24		-0.08
5 years	0.27	0.46	-0.14	-0.33	0.23	-0.34	-0.18
10 years	0.33	0.47	-0.13	-0.28	0.24	-0.37	-0.27

	Δc	π	Δc	π	Δc	π	Δc	π
Panel D: Macroeconomic Variables								
Average	1.47	0.77	1.10	0.57	0.43	0.78	0.36	0.78
Std. Deviation	0.90	0.62	0.72	0.49	0.37	0.33	0.37	0.32
Autocorrelation	0.45	0.40	0.11	-0.22	0.40	0.43	0.61	0.18
corr($\Delta c, \pi$)	0.26		-0.21		-0.24		-0.32	

https://www.federalreserve.gov/pubs/feds/2008/200805/200805abs.html. The U.S. 3-month T-bill rate is from The Center for Research in Security Prices (2015). "Fama Risk-Free Rates Database." Accessed January, 2015. http://www.crsp.com/. British Gilts yields are from Bank of England (2015). "Interest and Exchange Rates." Accessed January, 2015. http://www.bankofengland.co.uk/statistics/.

The properties of bond risk premia are frequently characterized by the average slope of a yield curve, the average excess bond returns relative to a risk-free rate, or the correlation of excess bond and stock returns. Panel A of Table 1 reports a slightly and a significantly upward-sloping average nominal yield curves in the U.K. and the U.S., respectively, indicating positive risk premia in nominal bonds. The picture is less clear for inflation-linked bonds. The average yield curve for these bonds is slightly upward sloping for the U.K. 1985-2008 sample, but becomes drastically downward sloping for the 1999-2008 sample. During the latter period, the comparable average yield curve in the U.S. is significantly upward sloping. These findings suggest negative and positive risk premia in inflation-linked bonds in the U.K. and the U.S. respectively. The average excess returns in Panel B support these claims.[11] Nominal bonds exhibit positive average excess returns for both the U.K. and U.S., and inflation-linked bonds in the U.K. and the U.S. have negative and positive average excess returns, respectively.

However, the correlations between excess bond and stock returns in Panel C suggest a different story. While inflation-linked bond excess returns in the U.K. have shown positive correlations with stock excess returns in both samples, U.K. nominal bonds switch from a positive correlation for 1985-2008 to a negative one for 1999-2008. The opposite occurs for U.S. nominal bonds, while the correlation between TIPS and stock excess returns is negative for 1999-2008. According to the CAPM, the evidence for the recent sample implies negative risk premia for U.K. and U.S. nominal and inflation-linked bonds, at odds with evidence from panels A and B.[12]

Panel C in Table 1 shows that the correlations of U.K. and U.S. inflation-linked and nominal bond yields with consumption growth are significantly positive during both sam-

[11] Excess bond returns are computed as the difference of realized nominal returns on inflation-linked and nominal bonds with the respective 3-month nominal rate for each country.

[12] The time-varying nature of the correlation between nominal bond and stock returns is highlighted and studied by Viceira (2012) and Campbell, Sunderam and Viceira (2013).

ple periods. On the other hand, the correlations of these yields with inflation change from positive for 1985-2008 to negative for 1999-2008. These changes are accompanied by a reduced autocorrelation of inflation in both the U.K. and the U.S., higher and lower autocorrelations of consumption growth in the U.S. and the U.K respectively, and a correlation between consumption growth and inflation that is negative in the U.S. and switching from positive to negative in recent years in the U.K. This evidence can be linked to bond risk premia through a standard equilibrium model.[13]

In summary, the descriptive statistics do not provide a clear pattern to describe the salient properties of real bond risk premia and their links to macroeconomic variables. The theoretical model in Section 3 allows us to analyze the link between real and nominal bond risk premia and macroeconomic variables. This analysis can provide testable implications to better understand the dynamics of real bond yields.

3 Model

The model is an extension of the standard New-Keynesian framework with price and wage rigidities (e.g. Woodford (2003)) to capture bond pricing dynamics. It incorporates recursive preferences with habit formation for the representative household. Recursive preferences, as in Rudebusch and Swanson (2012) and Li and Palomino (2014), are used to disentangle risk aversion from the elasticity of intertemporal substitution of consumption. This separation is useful to match observed macroeconomic dynamics, while a high degree

[13]Under constant relative risk aversion (CRRA) preferences, a positive autocorrelation of consumption growth implies negative premia for real bonds, and a negative correlation between consumption growth and inflation implies positive inflation risk premia. Campbell (1986) shows the link between the autocorrelation of consumption growth and the real yield curve under CRRA. The same intuition applies under recursive preferences on consumption, as shown in Bansal and Shaliastovich (2013). The Campbell and Cochrane (1999) habits model can imply the opposite, as shown by Wachter (2006). Piazzesi and Schneider (2007) highlight the link between positive inflation risk premia and the negative correlation between (expected) consumption growth and inflation under recursive preferences.

of risk aversion captures large expected excess returns. Nominal price and wage rigidities generate price and wage distortions that affect production decisions. Monetary policy in this setting affects inflation and real activities, thus impacting the riskiness of real and nominal bonds.

3.1 Household

A representative household chooses consumption C_t and labor supply N_t^s to maximize the Epstein and Zin (1989) recursive utility function

$$V_t = (1-\beta)U(C_{h,t}, N_t^s)^{1-\varphi} + \beta \mathbb{E}_t \left[V_{t+1}^{\frac{1-\gamma}{1-\varphi}} \right]^{\frac{1-\varphi}{1-\gamma}}, \tag{1}$$

where $\beta > 0$ is the subjective discount factor, φ and γ determine the elasticity of intertemporal substitution (EIS) and the coefficient of relative risk aversion, respectively, and $C_{h,t}$ is the habit-adjusted consumption, defined as $C_{h,t} \equiv C_t - b_h \tilde{C}_{t-1}$.[14] The external habit is represented by lagged aggregate consumption $\tilde{C}_{t-1}$, equal to C_{t-1} in equilibrium, but not determined directly by the household. This is a simplified Campbell and Cochrane (1999) habit specification. The intra-temporal utility depends on the habit-adjusted consumption and labor supply as

$$U(C_{h,t}, N_t^s) = \left(\frac{C_{h,t}^{1-\varphi}}{1-\varphi} - \kappa_t \frac{(N_t^s)^{1+\omega}}{1+\omega} \right)^{\frac{1}{1-\varphi}}, \tag{2}$$

where $\omega^{-1} > 0$ captures the Frisch elasticity of labor supply and the process κ_t (specified below) is chosen to ensure balanced growth. The consumption good is a basket of differentiated goods produced by a continuum of firms. Labor supply is the aggregate of a

[14] The elasticity of intertemporal substitution of the utility bundle of consumption and labor is φ^{-1}. The coefficient of relative risk aversion is defined in Section 4.

continuum of different labor types supplied to the production sector.[15]

The representative consumer is subject to the intertemporal budget constraint

$$\mathbb{E}_t\left[\sum_{s=0}^{\infty} M^{\$}_{t,t+s} P_{t+s} C_{t+s}\right] \leq \mathbb{E}_t\left[\sum_{s=0}^{\infty} M^{\$}_{t,t+s} P_{t+s}\left(LI_{t+s} + D_{t+s}\right)\right], \tag{3}$$

where $M^{\$}_{t,t+s}$ is the nominal discount factor for cashflows at time $t+s$, P_t is the nominal price of a unit of the basket of goods, and LI_t and D_t are the real labor income and dividends from the production sector, respectively. The online Appendix shows that optimality implies the one-period real and nominal discount factors

$$M_{t,t+1} = \beta\left(\frac{C_{h,t+1}}{C_{h,t}}\right)^{-\varphi}\left(\frac{V_{t+1}^{1/(1-\varphi)}}{\mathbb{E}_t\left[V_{t+1}^{(1-\gamma)/(1-\varphi)}\right]^{1/(1-\gamma)}}\right)^{\varphi-\gamma}, \tag{4}$$

and $M^{\$}_{t,t+1} = M_{t,t+1}\left(\frac{P_{t+1}}{P_t}\right)^{-1}$, respectively. The one-period (continuously compounded) real and nominal interest rates satisfy

$$r_t = -\log \mathbb{E}_t\left[M_{t,t+1}\right], \quad \text{and} \quad i_t = -\log \mathbb{E}_t\left[M^{\$}_{t,t+1}\right], \tag{5}$$

respectively. The nominal interest rate i_t is the instrument of monetary policy.

Wage rigidities follow Schmitt-Grohe and Uribe (2007). The representative household monopolistically provides a continuum of labor types indexed by $k \in [0,1]$, subject to a demand schedule from the production sector.[16] The household chooses wages $W_t(k)$ for all

[15] A detailed presentation of the model is given in the online Appendix. We omit these details here since they are standard in the literature.

[16] This approach is different from the standard heterogeneous households approach to model wage rigidities in Erceg, Henderson and Levin (2000), where each household supplies a differentiated type of labor. In the presence of recursive preferences, this approach introduces heterogeneity into the marginal rate of substitution of consumption across households since it depends on labor. We avoid this difficulty and obtain a unique marginal rate of substitution by modeling a representative agent who provides all different types of labor.

labor types k under Calvo (1983) staggered wage setting: At each time t, the household is only able to adjust wages optimally for a fraction $1-\alpha_w$ of labor types. The remaining fraction α_w of labor types adjust their previous period wages by the wage indexation factor $\Lambda_{w,t-1,t}$. The online Appendix shows that the household chooses the same optimal wage W_t^* for all labor types subject to an optimal wage change at time t. This wage satisfies

$$\frac{W_t^*}{P_t} = \mu_w \kappa_t \left(N_t^s\right)^{\omega} C_{h,t}^{\varphi} \frac{G_{w,t}}{H_{w,t}}, \tag{6}$$

where $\mu_w \equiv \frac{\theta_w}{\theta_w - 1}$, and θ_p is the elasticity of substitution across labor types. The recursive equations describing $G_{w,t}$ and $H_{w,t}$ are presented in the Appendix. Equation (6) can be interpreted as follows: In the absence of wage rigidities ($\alpha_\omega = 0$), the marginal rate of substitution between labor and consumption is $\kappa_t \left(N_t^s\right)^{\omega} C_{h,t}^{\varphi}$, and the optimal wage is this rate adjusted by the optimal markup μ_w. Wage rigidities generate the time-varying markup $\mu_w \frac{G_{w,t}}{H_{w,t}}$, since the wages of some labor types are not adjusted optimally.

3.2 Production Sector

A continuum of firms indexed by $j \in [0,1]$ set the prices of their differentiated goods in a Calvo (1983) staggered price setting. At each time t, with probability α_p, a firm sets the price of its good as the previous period price adjusted by the price indexation factor $\Lambda_{p,t-1,t}$. With probability $1-\alpha_p$, the firm sets the product price to maximize the present value of expected profits, subject to a household's demand function and the production function

$$Y_{t+s|t}(j) = A_{t+s} N_{t+s|t}^d(j). \tag{7}$$

The output $Y_{t+s|t}(j)$ is the production of firm j at time $t+s$ given that the last optimal price change was at time t. The labor demand $N^d_{t+s|t}(j)$ has a similar interpretation. The production function depends on labor productivity A_t and labor. We assume that labor productivity contains difference- and trend-stationary components.[17] Specifically, $A_t = A^p_t Z_t$, where $a_t \equiv \log A^p_t$ and $z_t \equiv \log Z_t$, are the difference- and trend-stationary components of productivity, respectively. These components follow the processes

$$\Delta a_{t+1} = (1-\phi_a)g_a + \phi_a \Delta a_t + \sigma_a \varepsilon_{a,t+1}, \quad \text{and} \quad z_{t+1} = \phi_z z_t + \sigma_z \varepsilon_{z,t+1}, \tag{8}$$

where Δ is the difference operator, g_a is the average growth rate in the economy, and innovations $\varepsilon_{a,t}$ and $\varepsilon_{z,t} \sim \text{IID}\mathcal{N}(0,1)$. For simplicity, we refer to the difference- and trend-stationary components as the permanent and transitory shocks to productivity, respectively. Labor demand is a composite of a continuum of differentiated labor types. All firms that set prices optimally are identical and set the optimal price P^*_t. The online Appendix shows that this price satisfies

$$\left(\frac{P^*_t}{P_t}\right) H_{p,t} \quad = \quad \frac{\mu_p}{A_t}\frac{W_t}{P_t} G_{p,t}, \tag{9}$$

where $\mu_p = \frac{\theta_p}{\theta_p - 1}$, θ_p is the elasticity of substitution across goods, and W_t is the aggregate wage. The recursive equations for $H_{p,t}$ and $G_{p,t}$ are presented in the Appendix. Equation (9) can be interpreted as follows: In the absence of price rigidities, the product price is the markup-adjusted marginal cost of production, with optimal markup μ_p. Price rigidities generate the time-varying markup $\mu_p \frac{G_{p,t}}{H_{p,t}}$, since some firms do not adjust their prices optimally.

[17] The two components are incorporated given the different effects on bond risk premia of these two processes for consumption in endowment economies. A difference-stationary process for consumption with a positive autocorrelation coefficient generates negative term premia. A trend-stationary process for consumption with positive autocorrelation coefficient generates positive term premia.

3.3 Monetary Policy

Monetary policy is described by the interest-rate policy rule

$$i_t = \rho i_{t-1} + (1-\rho)\left[\bar{\imath} + \imath_\pi(\pi_t - \pi^\star_{t-1}) + \imath_x(x_t - x_{ss})\right] + u_t\,. \tag{10}$$

The policy rule has an interest-rate smoothing component, captured by the sensitivity ρ to i_{t-1}, and responds to aggregate inflation $\pi_t \equiv \log \frac{P_t}{P_{t-1}}$, the output gap x_t, and the policy shock u_t. The output gap $x_t \equiv \log \frac{Y_t}{Y_t^f}$ is the deviation of total output, Y_t, from the output in an economy under flexible prices and wages, Y_t^f. The coefficients $\imath_\pi$ and $\imath_x$ capture the response of the monetary authority to the deviations of inflation and the output gap from their targets, $\pi^\star_t$ and x_{ss}, respectively. The inflation target is time-varying as in Ireland (2007) and Rudebusch and Swanson (2012).[18] Its process is

$$\pi^\star_t = (1-\phi_{\pi^\star})g_\pi + \phi_{\pi^\star}\pi^\star_{t-1} + \sigma_{\pi^\star}\varepsilon_{\pi^\star,t}, \tag{11}$$

where $\varepsilon_{\pi^\star,t} \sim \text{IID}\mathcal{N}(0,1)$. The policy shocks u_t follow the process

$$u_{t+1} = \phi_u u_t + \sigma_u \varepsilon_{u,t+1}, \tag{12}$$

where $\varepsilon_{u,t} \sim \text{IID}\mathcal{N}(0,1)$.

3.4 Equilibrium

Equilibrium requires product, labor, and financial market clearing. Product market clearing implies that consumption is equal to the production of differentiated and final goods. Labor market clearing requires that the supply and demand for all labor types are equal.

[18] The inflation target has also been used in the macro finance literature by Bekaert, Cho and Moreno (2010), Campbell, Pflueger and Viceira (2014) and Dew-Becker (2014).

As shown in the online Appendix, this implies the aggregate labor market clearing condition $N_t^s = N_t^d F_{w,t}$ where $N_t^d = \frac{Y_t}{A_t} F_{p,t}$. The distortions $F_{w,t}$ and $F_{p,t}$, described in the Appendix, are caused by wage and price rigidities, respectively. Equilibrium in the financial market implies that the nominal interest rate from the household maximization problem in equation (5) is equal to the interest rate set by the monetary policy rule in equation (10). Bond market clearing implies the absence of arbitrage opportunities in bond markets. The preference shock in equation (1) is defined as $\kappa_t \equiv (A_t^p)^{1-\varphi}$ to preserve balanced growth. The online Appendix provides a summary of the equilibrium conditions.

3.5 Expected Excess Bond Returns and Risk Premia

Real and nominal default-free zero-coupon bonds with maturity at $t+n$ pay a unit of real and nominal consumption, respectively, at maturity. Their prices are

$$B_t^{c,(n)} = \mathbb{E}_t[M_{t,t+n}], \quad \text{and} \quad B_t^{\$,(n)} = \mathbb{E}_t[M_{t,t+n}^{\$}], \tag{13}$$

for real and nominal bonds, respectively, where $M_{t,t+n}$ and $M_{t,t+n}^{\$}$ are the real and nominal discount factors for payoffs at $t+n$.[19] The associated real and nominal yields are $r_t^{(n)} = -\frac{1}{n}\log B_t^{c,(n)}$ and $i_t^{(n)} = -\frac{1}{n}\log B_t^{\$,(n)}$, respectively.

Real term and inflation risk premia are useful to decompose bond yields and expected excess returns into compensations for real and nominal risks. The one-period real term premium of an n-period (real) bond is defined as

$$rTP_t^{(n)} \quad \equiv \quad \log \mathbb{E}_t\left[R_{t,t+1}^{c,(n)}\right] - r_t, \tag{14}$$

where $R_{t,t+1}^{c,(n)}$ is the one-period gross real bond return. The online Appendix shows that

[19] Notice that $B_t^{c,(n)}$ is the real price of the real bond, while $B_t^{\$,(n)}$ is the nominal price of the nominal bond.

this premium captures the correlation between the marginal utility of consumption and the bond's one-period return. A positive correlation between marginal utility and the bond yield implies low bond real returns during periods of high marginal utility and, therefore, positive expected excess bond returns. The Appendix also shows that the unconditional yield spread $r_t^{(n)} - r_t$ can be approximated as an average of one-period real term premia during the life of the bond.[20]

The one-period inflation risk premium $\pi TP_t^{(n)}$ is the difference in (log) real return for investing in an n-period nominal bond over an n-period real bond for one-period. That is,

$$\pi TP_t^{(n)} \equiv \log \mathbb{E}_t \left[R_{t,t+1}^{\$,(n)} P_t / P_{t+1} \right] - \log \mathbb{E}_t \left[R_{t,t+1}^{c,(n)} \right], \tag{15}$$

where $R_{t,t+1}^{\$,(n)}$ is the one-period gross nominal bond return. The online Appendix shows that this premium is then an expected return compensation in nominal bonds for the correlation between the marginal utility of consumption and inflation. If this correlation is positive, the expected real returns of nominal bonds are higher than for real bonds: during periods of high marginal utility, high inflation has a negative impact on nominal bond returns. The Appendix also shows that the unconditional expectation of the spread $i_t^{(n)} - r_t^{(n)}$ between nominal and real rates captures average inflation and inflation risk premia.

4 Model Implications and Analysis

This section describes the model estimation and its ability to capture macroeconomic and yield curve dynamics. It presents the main findings and highlights the underlying economic mechanisms by comparing different model specifications for nominal rigidities, shocks, and

[20]As shown in the Appendix, this derivation relies on the the assumption of joint normality for the log-pricing kernel and bond yields. This is used only for illustration purposes, since the economic model is solved using a second-order perturbation method, which does not imply log-normality. Equation (14) is used for the computation of real term premia in the quantitative analysis.

monetary policy.

4.1 Estimation Strategy

The model estimation examines the ability of the model to simultaneously capture observed macroeconomic and nominal yield curve dynamics, and provides a quantitative framework for the economic analysis of the real yield curve and bond risk premia. Model parameters are chosen to capture key quarterly properties of U.S. data for the period 1982:Q1 to 2008:Q3 using the Generalized Method of Moments (GMM). The sample period is chosen to focus on a monetary policy with a stable response to economic conditions. Clarida, Galí and Gertler (2000) provide empirical evidence of a change in monetary policy after 1979. The monetary experiment period 1979-1981 is excluded since the short-term rate was replaced by monetary aggregates as the policy instrument during this period. Data after the third quarter of 2008 are not included since the ability to conduct policy using the Federal Funds rate was limited by the zero bound after December 2008. The data series are described in Section 2.

Table 2 reports the parameter values for the baseline model. The model estimation involves three sets of parameters.[21] For the first set, parameter values are assigned to match a direct empirical counterpart or to be consistent with the literature. The average productivity growth rate g_a is chosen to match the average consumption growth during the period. Non-optimal changes in prices and wages are assumed to be perfectly indexed to the inflation target, such that $\log \Lambda_{p,t,t+1} = \pi_t^\star$, and $\log \Lambda_{w,t,t+1} = g_a + \pi_t^\star$. The wage indexation implies no deviation from real wages on average. The price duration of $-1/\log(\alpha_p) \approx 2.4$ quarters is consistent with the empirical evidence in Bils and Klenow (2004). The wage

[21] The parametrization has elements of both estimation and calibration. For simplicity, we refer to it as "estimation" throughout the paper. The method is similar to that in Andreasen, Fernández-Villaverde and Rubio-Ramírez (2014). The model is solved using the Dynare package, available from www.dynare.org.

Table 2: **Model Parameter Values**

Parameter values for the baseline estimation of the economic model.

Parameter	Description	Value
Panel A: Preferences		
β	Subjective discount factor	0.92107
φ	Inverse of elasticity of intertemporal substitution	20
γ	Risk aversion parameter	600
ω	Inverse of Frisch labor elasticity	0.50
b_h	External habit parameter	0.42
Panel B: Product and Labor Rigidities and Elasticities		
α_p	Price rigidity parameter	0.66
θ_p	Elasticity of substitution of differentiated goods	6
α_w	Wage rigidity parameter	0.78
θ_w	Elasticity of substitution of labor types	6
Panel C: Interest Rate Rule		
ρ	Interest-rate smoothing coefficient in policy rule	0.60
$\imath_\pi$	Response to inflation in the policy rule	1.8
$\imath_x$	Response to output gap in the policy rule	0.125
Panel D: Policy and Productivity Shocks		
ϕ_u	Autocorrelation of policy shock	0.515
$\sigma_u \times 10^2$	Conditional vol. of policy shock	0.44
ϕ_a	Autocorrelation of permanent productivity shock	0.194
$\sigma_a \times 10^2$	Conditional vol. of permanent productivity shock	0.42
ϕ_z	Autocorrelation of transitory productivity shock	0
$\sigma_z \times 10^2$	Conditional vol. of transitory productivity shock	1.89
Panel E: Growth Rates and Inflation Target		
$g_a \times 10^2$	Unconditional mean of productivity growth	0.4695
$g_{\pi^\star}$	Unconditional mean of inflation target	0.2251
$\phi_{\pi^\star}$	Autocorrelation of inflation target	0.9999
$\sigma_{\pi^\star} \times 10^2$	Conditional volatility of inflation target	0.0010

duration of $-1/\log(\alpha_w) \approx 4$ quarters is consistent with the evidence in Barattieri, Basu and Gottschalk (2014). The elasticity parameters θ_p and θ_w imply price and wage markups of 20%. The value chosen for ω implies a Frisch labor elasticity of $1/\omega = 2$, which is in the lower range of the values used in the macro literature to capture labor and wage dynamics. The policy responses to inflation $\imath_\pi = 1.8$ and the output gap $\imath_x = 0.125$ are standard in the literature. The persistence $\phi_{\pi^\star} = 0.9999$ and volatility $\sigma_{\pi^*} = 0.001\%$ of the inflation target process are chosen to maximize the model's ability to capture the high volatility of long-term yields, and are in line with the ones used by Rudebusch and Swanson (2012), and the unit root process in Campbell, Pflueger and Viceira (2014).

For a second set of parameters, values are estimated using GMM. This procedure focuses on maximizing the model's ability to capture macroeconomic dynamics. Nine parameter values are chosen to minimize the percentage deviations of nine model moments from their data counterparts.[22] The moments are the volatilities and autocorrelations of consumption growth, inflation, wage growth, and the short-term nominal interest rate, and the correlation of consumption growth and inflation. The estimated parameters are φ, b_h, ρ, and the persistence and volatility parameters of productivity and monetary policy shocks.[23] The elasticity of intertemporal substitution $1/\varphi = 0.05$, is in the lower range of values in the macroeconomic literature. The habit parameter value $b_h = 0.42$ is lower than those reported in habit models, but not directly comparable given the recursive utility specification. The interest-rate smoothing coefficient $\rho = 0.6$ in the policy rule is slightly lower than the one estimated by Clarida, Galí and Gertler (2000) for the period, but in line with the literature. The persistence of policy shocks $\phi_u \approx 0.5$ is in the upper range of values estimated in the literature. The persistence parameters for both permanent and transitory productivity components are lower than those in Andreasen (2012).

Finally, values for the subjective discount factor β, the average inflation target g_π, and the risk aversion parameter γ are chosen to match the average (annualized) inflation rate of 3.26%, the short-term nominal (annualized) interest rate of 5.20%, and the Sharpe ratio and average spread implied by excess returns of the 5-year bond simultaneously.[24] The

[22] The estimation is restricted within a range of parameter values that are economically sensible.

[23] Allowing ω, $\phi_{\pi^\star}$, and $\sigma_{\pi^\star}$ to be estimated implies a very similar performance matching these moments.

[24] The model is solved using a second-order approximation around the non-stochastic steady state. The high value for γ generates large precautionary savings terms that affect the means of inflation and the short-term interest rate. The precautionary savings terms are offset by a large values for g_π, reducing its interpretation as a long-term inflation target. The approach does not generate distortions in expected excess bond returns.

policy rule constant $\bar{\imath} \equiv -\log\beta + \psi g_a + g_\pi$ is the nominal rate when both inflation and the output gap are at their respective targets. The average coefficient of risk aversion in the presence of leisure preferences, as shown by Swanson (2012), is given by[25]

$$\frac{\varphi}{1+\frac{\varphi}{\omega}\frac{\mu_w}{\mu_p}} + \frac{\gamma-\varphi}{1-\frac{1-\varphi}{1+\omega}\frac{\mu_w}{\mu_p}} \approx 44.$$

This value is comparable to those used in term structure models with recursive preferences. For instance, Piazzesi and Schneider (2007) estimate a value of 59 in an endowment economy, and Rudebusch and Swanson (2012) and Andreasen (2012) use values between 75 and 110 in models with price rigidities.[26]

4.2 Quantitative Performance of the Model

This section describes the model's ability to simultaneously match macroeconomic and yield curve properties of the economy. The estimation centers almost entirely on matching macroeconomic moments, and uses only yield curve information to match the Sharpe ratio and average yield spread of the 5-year nominal bond. It is then important to verify that the estimation can capture other properties of the nominal yield curve and provide a reasonable baseline for the analysis of the implied real yield curve.

Table 3 reports moments for the baseline model and their empirical counterparts in columns (2) and (1), respectively. Panel A reports the macroeconomic moments. The

[25] In the presence of recursive preferences on consumption and labor, the coefficient of relative risk aversion is not solely determined by γ, since the ability to smooth consumption using labor changes the representative agent's attitudes towards risk. The coefficient is computed relative to intertemporal gambles on consumption-related wealth, since the coefficient related to total wealth (including the value of leisure) is not well defined.

[26] This value could be reduced by incorporating persistent sources of long-run risk as in Bansal and Shaliastovich (2013), or Kung (2014). Bansal and Shaliastovich (2013) achieve this in an endowment economy with exogenous inflation. Kung (2014) introduces endogenous growth to a New Keynesian model and generates an endogenous persistent source of long-run risk. We do not follow this approach to highlight the different effects of price and wage rigidities and different shocks in a standard New Keynesian framework.

Table 3: **Data and Baseline Model Implied Statistics - The Effect of Rigidities and Shocks**

The data statistics are for the 1982:Q1 to 2008:Q3 period. The parameter values of the baseline model are reported in Table 2. The operators $\mathbb{E}[\cdot]$, $\sigma(\cdot)$, and AC$(\cdot)$ denote the unconditional mean, volatility, and first-order autocorrelation, respectively. $rTP^{(20)}$ and $\pi TP^{(20)}$ are the 5-year bond real term and inflation risk premia, respectively. "Baseline" indicates an economy with both price and wage rigidities and all four exogenous shocks. "WR" indicates no price rigidities ($\alpha_p = 0$). "PR" indicates no wage rigidities (α_w=0). "NR" indicates no price and wage rigidities ($\alpha_p = \alpha_w = 0$). "Only A^p" indicates only permanent productivity shocks ($\sigma_z = \sigma_u = \sigma_{\pi^\star} = 0$). "Only Z" indicates only transitory productivity shocks ($\sigma_a = \sigma_u = \sigma_{\pi^\star} = 0$). "Only u" indicates only policy shocks ($\sigma_a = \sigma_z = \sigma_{\pi^\star} = 0$). "Only $\pi^\star$" indicates only shocks to the inflation target ($\sigma_a = \sigma_z = \sigma_u = 0$). The baseline model statistic corresponds to the closed-form average of the second-order approximation of the solution. Volatilities, yields, and (excess) returns are in percentage terms. The inflation rate, yields, excess returns, and risk premia are annualized. The data statistics related to the real rate r are obtained from the estimated real rate. Values not reported are not available. The values of β and g_π are adjusted across columns to match the average inflation and short-term nominal rate. Data sources: BEA (2015), FEDS (2015), and CRSP (2015).

		Model							
		Rigidities				Shocks			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Statistic	Data	Baseline	WR	PR	NR	Only A^p	Only Z	Only u	Only $\pi^\star$
Panel A: Macroeconomic Variables									
$\sigma(\Delta c)$	0.38	0.34	0.35	0.32	0.32	0.34	0.01	0.05	0.00
$\sigma(\pi)$	1.36	1.83	10.80	3.13	12.38	0.16	1.02	0.89	0.65
$\sigma(\Delta w)$	0.66	0.52	2.71	2.59	2.71	0.36	0.21	0.14	0.00
$\sigma(x)$	0.00	0.13	0.10	0.09	0.00	0.07	0.08	0.10	0.02
$AC(\Delta c)$	0.42	0.41	0.35	0.44	0.48	0.42	0.01	0.25	0.00
$\text{corr}(\Delta c, \pi)$	-0.15	-0.08	-0.29	0.35	0.01	-0.99	-0.96	0.41	0.00
Panel B: Real and Nominal Yield Curves									
$\mathbb{E}[i]$	5.20	5.20	5.20	5.20	5.20	5.20	5.20	5.20	5.20
$\mathbb{E}[i^{(20)} - i]$	1.38	1.28	2.46	-4.78	-13.20	1.08	0.00	0.05	0.00
$\mathbb{E}[r]$	1.98	1.37	-0.64	5.57	17.71	1.51	1.93	1.94	1.93
$\mathbb{E}[r^{(20)} - r]$		0.99	3.42	-5.41	-20.63	0.71	0.00	0.05	0.00
$\sigma(i)$	2.59	2.34	6.16	1.96	7.49	0.18	0.79	2.31	0.65
$\sigma(r)$	2.09	3.17	12.98	2.87	12.97	0.12	1.03	3.00	0.01
$\sigma(r)/\sigma(i)$	0.81	1.36	2.11	1.47	1.73	0.69	1.31	1.30	0.01
$\text{corr}(i, r)$	0.99	0.96	0.99	0.88	0.98	0.89	1.00	1.00	0.00
$\sigma(i^{(20)})/\sigma(i)$	1.02	0.30	0.11	0.34	0.10	0.17	0.07	0.15	1.00
$\sigma(r^{(20)})/\sigma(r)$		0.13	0.04	0.11	0.05	0.20	0.08	0.15	0.10
Panel C: Expected Excess Returns									
$\mathbb{E}[XR^{\$,(20)}]$	4.28	2.27	4.05	-7.69	-20.03	1.90	0.00	0.09	0.00
$\mathbb{E}[XR^{c,(20)}]$		1.47	4.59	-7.06	-25.49	1.05	0.01	0.11	0.00
$SR^{\$,(20)}$	0.32	0.34	0.67	-1.69	-1.73	3.04	0.00	0.02	0.00
$SR^{c,(20)}$		0.19	0.36	-1.16	-1.60	3.04	0.00	0.02	0.00
$\mathbb{E}[rTP^{(20)}]$		1.23	3.84	-5.96	-21.74	0.88	0.01	0.11	0.00
$\mathbb{E}[\pi TP^{(20)}]$		0.86	1.58	-2.91	-7.64	0.82	0.00	-0.04	0.00

model captures well the volatilities and autocorrelations of consumption and wage growth and inflation, as well as the negative correlation between consumption growth and inflation. This correlation is important in explaining a positive inflation risk premium.

Panels B and C of Table 3 report yield curve and bond excess return statistics, respectively. The baseline model implies an average 5-year nominal bond spread of 128 bps. vs. 138 bps. in the data, and a positive 5-year real bond spread of 99 bps. The model does a reasonable job at capturing the volatility of the short-term nominal interest rate but fails to reproduce the high volatility of long-term nominal yields. This is a well-known shortcoming of most equilibrium models. The Sharpe ratio of the 5-year nominal bond is higher than the implied Sharpe ratio for the comparable real bond. The one-quarter expected bond excess return in the model is small relative to the average realized excess return in the data. This reflects the model's limitation to capture the high volatility of bond returns. The positive 5-year real bond spread implies a real term premium of 1.23%. The higher expected excess return for the comparable nominal bond reflects a positive inflation risk premium of 86 bps. In summary, the baseline model provides a reasonable description of U.S. macroeconomic and yield dynamics, and thus it provides a good framework for the quantitative analysis of the real term structure.

4.3 Bond Risk Premia

This section describes the contribution of nominal rigidities and shocks to real and nominal bond risk premia in the baseline model. The findings are illustrated using the results of alternative model specifications in Table 3. This table presents statistics of models that share the same parameter values with the baseline estimation, except for rigidity or shock parameters. It highlights the contribution of each rigidity and shock to the quantitative results. Columns (2)-(5) in this table are related to parameterizations where price or wage rigidities or both are shut down, but all shocks affect the economy. Columns (6)-(9) are related to parameterizations where the economy is exposed only to one source of risk, but both rigidities are active.[27]

The main finding is that positive real term and inflation risk premia are mostly a compensation for permanent productivity shocks as a result of wage rigidities. Permanent productivity shocks generate most of the variability in consumption growth and the real and nominal pricing kernels.[28] Consistent with this, column (6) in Table 3 shows that the 5-year real term and inflation risk premia for permanent productivity shocks are 88 and 82 bps., respectively, while columns (7)-(9) show that these premia are minor or negligible for the other shocks. A similar pattern is seen in bond spreads and expected excess returns. Columns (2)-(4) show that only wage rigidities generate significantly positive real and nominal risk premia in the baseline model.

4.4 The Mechanism Behind Bond Risk Premia

Permanent productivity shocks, in combination with wage rigidities, lead to positive real term and inflation risk premia. The mechanism behind these results can be illustrated using model's impulse responses. Figure 1 presents the impulse responses of different endogenous variables in the baseline model after a negative one-standard deviation permanent shock under four specifications: no nominal rigidities, only price rigidities, only wage rigidities, and both price and wage rigidities.

Positive inflation risk premia can be understood from the responses of habit-adjusted consumption growth and inflation to permanent productivity shocks. After a negative shock, the supply of labor increases to mitigate the negative effect of productivity on

[27] For comparison purposes, β and g_π are adjusted across parametrizations to match the average inflation and short-term nominal rates. This adjustment has a minor effect on second moments.

[28] A variance decomposition of the pricing kernels shows that more than 99% of their variability is the result of permanent productivity shocks.

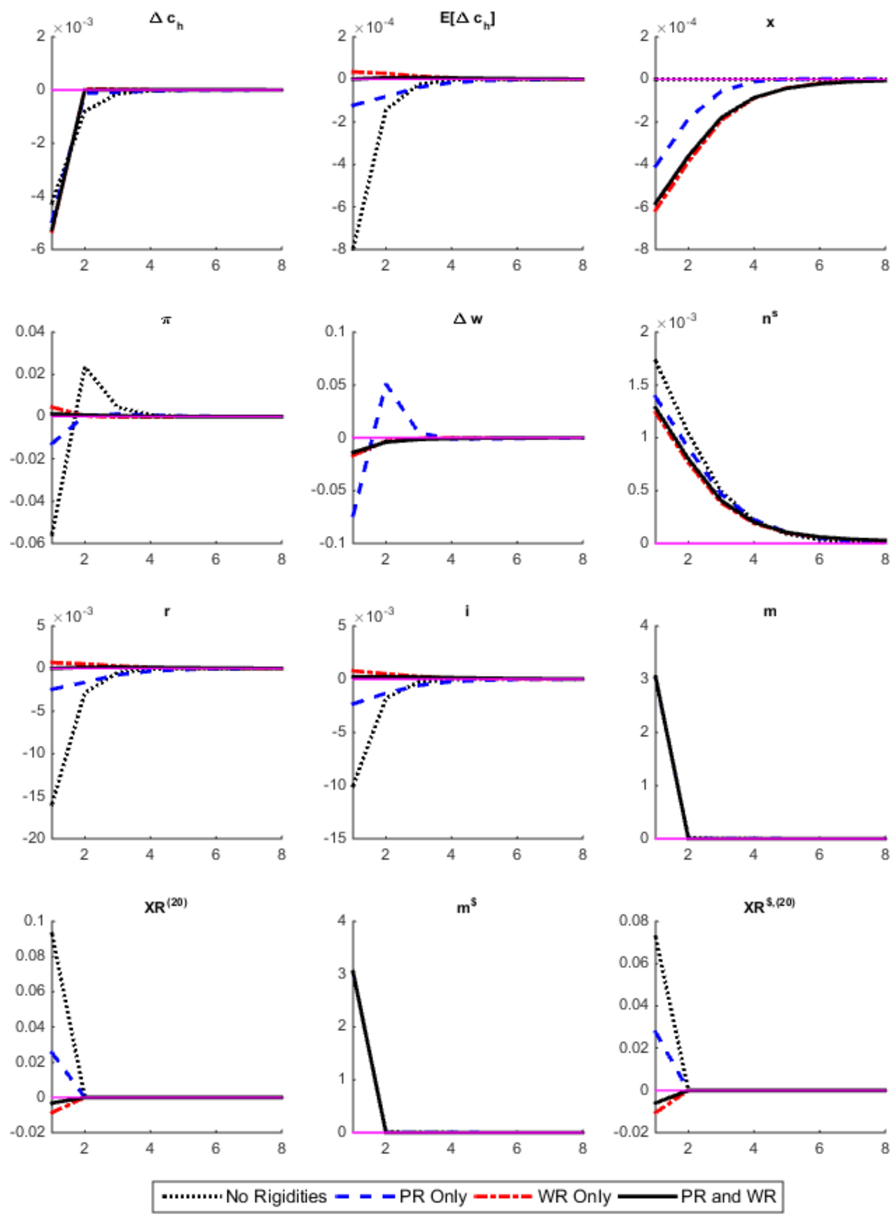

Figure 1: Impulse responses to a one-standard deviation negative permanent productivity shock. The parameter values of the baseline model are reported in Table 2.

consumption. In the absence of wage rigidities, wages drop sharply and firms adjust product prices downwards to get closer to their optimal markups, resulting in lower inflation. With wage rigidities, wages do not decline as much, and increase relative to labor productivity. Firms increase product prices in response to higher marginal costs and inflation goes up. Therefore, inflation increases after a negative permanent shock only in the presence of wage rigidities, as shown in Figure 1. Inflation is high then in states of high marginal utility, resulting in positive inflation risk premia.

Positive real term premia can be understood from the effect of wage rigidity on the autocorrelation of the habit-adjusted consumption growth. The magnitude of the labor response to permanent shocks is critical to understand their effect on habit-adjusted consumption. The labor increase after a negative permanent shock is more significant in the absence of rigidities than under price or wage rigidities. With price rigidities, some firms cannot reduce prices which reduces the demand of output and labor. With wage rigidities, the wages of some labor types cannot be adjusted down, which leads to lower labor demand. The impulse response of labor, n in Figure 1, indicates that the dampening effect of wage rigidities on labor is quantitatively stronger than that of price rigidities. Therefore, consumption and habit-adjusted consumption decline by more in the presence of wage rigidities after the negative productivity shock.

To understand the effect of wage rigidity on the autocorrelation of habit-adjusted consumption growth, consider a shock at time t. The permanent nature of the negative shock implies that consumption continues to drop after the shock, leading to a positively autocorrelated consumption growth rate. However, the autocorrelation of the habit-adjusted consumption growth rate, $\Delta c_{h,t+1}$, could be positive or negative, depending on the magnitude of the reduction in C_t. A lower C_t leads to lower $\Delta c_{h,t}$ but higher $\Delta c_{h,t+1}$, which decreases the autocorrelation of the habit-adjusted consumption growth rate. If the reduction in C_t is large enough, its positive impact on $\Delta c_{h,t+1}$ outweighs the negative effect of the permanent shock. Consequently, after the negative permanent shock, current habit-adjusted consumption growth declines, but the next period's habit-adjusted consumption growth is expected to rise, consistent with the impulse responses of Δc_h and $\mathbb{E}[\Delta c_h]$ in Figure 1, respectively. Therefore, the autocorrelation of $\Delta c_{h,t}$ becomes negative.

Consistent with the response of labor, the impulse responses of Δc_h in Figure 1 show that the habit-adjusted consumption in the presence of wage rigidities returns more quickly to its steady state after the initial drop. In our calibration, habit-adjusted consumption growth becomes negatively autocorrelated. The autocorrelation of the real pricing kernel largely depends on the autocorrelation of $\Delta c_{h,t}$. It then becomes negatively autocorrelated, real interest rates rise, as shown in Figure 1, and real term premia are positive.

It is important to notice the role of the habit in the results. In the absence of habit formation, the autocorrelation of the pricing kernel largely depends on the autocorrelation of consumption growth. Wage rigidities and permanent shocks lead to procyclical labor in this setting, and consumption growth becomes counterfactually negatively autocorrelated. The model, however, is still able to generate positive real term premia under wage rigidities.[29] Habit formation is hence critical to simultaneously match the positive autocorrelation of consumption growth in U.S. data and obtain positive real term premia.

4.5 Bond Risk Premia and Monetary Policy

The response to economic conditions in the policy rule affect both real term and inflation risk premia. Comparative statics for policy rule parameters are computed to quantify the sensitivity of these premia. The parameters are modified individually, keeping the remaining parameters at their baseline model levels. Selected moments are computed

[29] The results of the model without habit are presented in Section C of the online Appendix.

Table 4: **Data and Baseline Model Implied Statistics - The Effects of Monetary Policy**

The data statistics are for the 1982:Q1 to 2008:Q3 period. The parameter values of the baseline model are reported in Table 2. The model columns report statistics for the baseline model estimation and for parametrizations where individual parameters in the policy rule

$$i_t = \rho i_{t-1} + (1-\rho)\left[\bar{\imath} + \imath_\pi(\pi_t - \pi^\star_{t-1}) + \imath_x(x_t - x_{ss})\right] + u_t$$

are modified to the values reported in each column. The operators $\mathbb{E}[\cdot]$, $\sigma(\cdot)$, and AC$(\cdot)$ denote the unconditional mean, volatility, and first-order autocorrelation, respectively. $rTP^{(20)}$ and $\pi TP^{(20)}$ are the 5-year bond real term and inflation risk premia, respectively. The model statistic corresponds to the closed-form average of the second-order approximation of the solution. Volatilities, yields, and (excess) returns are in percentage terms. The inflation rate, yields, excess returns, and risk premia are annualized. The data statistics related to the real rate r are obtained from the estimated real rate. Values not reported are not available. The values of β and g_π are adjusted across columns to match the average inflation and short-term nominal rate. Data sources: BEA (2015), FEDS (2015), and CRSP (2015).

		Model			
	(1)	(2)	(3)	(4)	(5)
Statistic	Data	Baseline	$\imath_\pi = 1.9$	$\imath_x = 0.25$	$\rho = 0.7$
Panel A: Macroeconomic Variables					
$\sigma(\Delta c)$	0.38	0.34	0.34	0.34	0.34
$\sigma(\pi)$	1.36	1.83	1.79	1.82	2.19
$\sigma(\Delta w)$	0.66	0.52	0.52	0.52	0.56
$\sigma(x)$		0.13	0.13	0.13	0.15
$AC(\Delta c)$	0.42	0.41	0.41	0.41	0.41
corr$(\Delta c, \pi)$	-0.15	-0.08	-0.09	-0.09	-0.04
Panel B: Real and Nominal Yield Curves					
$\mathbb{E}[i]$	5.20	5.20	5.20	5.20	5.20
$\mathbb{E}[i^{(20)} - i]$	1.38	1.28	1.37	1.20	1.11
$\mathbb{E}[r]$	1.98	1.37	1.36	1.35	1.39
$\mathbb{E}[r^{(20)} - r]$		0.99	1.07	0.87	0.91
$\sigma(i)$	2.59	2.34	2.34	2.33	2.37
$\sigma(r)$	2.09	3.17	3.15	3.16	3.63
$\sigma(r)/\sigma(i)$	0.81	1.36	1.35	1.35	1.53
corr(i, r)	0.99	0.96	0.96	0.96	0.96
$\sigma(i^{(20)})/\sigma(i)$	1.02	0.30	0.29	0.30	0.31
$\sigma(r^{(20)})/\sigma(r)$		0.13	0.13	0.13	0.15
Panel C: Expected Excess Returns					
$\mathbb{E}[XR^{\$,(20)}]$	4.28	2.27	2.37	2.13	2.02
$\mathbb{E}[XR^{c,(20)}]$		1.47	1.58	1.31	1.42
$SR^{\$,(20)}$	0.32	0.34	0.36	0.32	0.27
$SR^{c,(20)}$		0.19	0.21	0.17	0.15
$\mathbb{E}[rTP^{(20)}]$		1.23	1.33	1.10	1.19
$\mathbb{E}[\pi TP^{(20)}]$		0.86	0.87	0.91	0.70

and compared with the baseline estimation in Table 4. Column (3) reports results when the response to inflation in the policy rule $\imath_\pi$ is increased from 1.8 to 1.9 in the baseline estimation. Similarly, column (4) reports results when the response to the output gap $\imath_x$ is increased from 0.125 to 0.25. A comparison of both columns with the baseline estimation in column (2) shows opposite effects of the two policy changes. While a stronger response to inflation increases real and nominal bond spreads, expected excess returns and Sharpe ratios, a stronger response to the output gap has the opposite effect. For instance, the 0.1 increase in $\imath_\pi$ is reflected in an increase in expected excess returns on real and nominal 5-year bonds of 8 and 9 bps., respectively. An increase in $\imath_x$ of 0.125 reduces these expected returns by 14 and 16 bps., respectively. Changes in expected excess returns are explained by the effects of the policy rule on labor dynamics and then on interest rates. An increase in the response to inflation increases the response of labor to productivity shocks and real term premia. An increase in the response to the output gap has the opposite effect. Column (5) presents results for a policy that increases the interest-rate smoothing coefficient ρ from the baseline value of 0.6 to 0.7. Similar to a reduction in the response to inflation, this policy decreases real and nominal bond spreads, expected excess returns, and Sharpe ratios. Finally, reducing the autocorrelation of the inflation target from 0.9999 to 0.9 (not shown in the table) does not have any significant effects on bond risk premia, given the small price of risk of inflation target shocks.

4.6 Model Extensions

This section extends the model to incorporate (i) capital accumulation in the economy, and (ii) time variation in bond risk premia.

4.6.1 Capital Accumulation and Bond Risk Premia

The baseline model economy has an only-labor production function. It is of interest to learn whether the bond risk premia mechanism and the results above hold under capital accumulation. Table 5 reports results for an estimation of a model with capital K_t and the production function $Y_t = (A_t N_t^d)^{1-\alpha} K_t^{\alpha}$. Capital follows the process

$$K_{t+1} = (1-\delta)K_t + \Phi\left(\frac{J_t}{K_t}\right)K_t, \quad \text{where} \quad \Phi\left(\frac{J_t}{K_t}\right) = b_1 + \frac{b_2}{1-1/\zeta}\left(\frac{J_t}{K_t}\right)^{1-1/\zeta}$$

captures capital adjustment costs through $\zeta \geq 0$, J_t is investment, δ is the depreciation rate, and b_1 and b_2 are parameters chosen to preserve balanced growth.[30] The model has a reasonable macroeconomic performance using an adjustment cost $\zeta = 4$, similar to values reported in the literature. It matches the volatility of output and investment growth, the positive autocorrelation of consumption growth, and the negative correlation of consumption growth and inflation. The output gap is highly volatile, and the correlations between real and nominal yields are lower. As in the baseline estimation, the real and nominal average yield curves are upward sloping, but with substantially smaller and larger, respectively, real term and inflation risk premia.

4.6.2 Stochastic Volatility and Time-Varying Bond Risk Premia

The low volatility in bond risk premia in the baseline model is at odds with the well-documented empirical evidence on deviations from the expectations hypothesis and bond return predictability. Adding time-varying volatility to productivity shocks captures substantial variation in bond risk premia. Consider the modified specifications for productivity

[30]The complete model specification, equilibrium conditions and estimated parameters are available under request.

Table 5: **Data and Model Implied Statistics - Capital Accumulation**

The data statistics are for the 1982:Q1 to 2008:Q3 period. The parameter values of the baseline model are reported in Table 2. The operators $\mathbb{E}[\cdot]$, $\sigma(\cdot)$, and AC$(\cdot)$ denote the unconditional mean, volatility, and first-order autocorrelation, respectively. $rTP^{(20)}$, and $\pi TP^{(20)}$ are the 5-year bond real term and inflation risk premia, respectively. "Baseline" indicates an economy with both price and wage rigidities and all four exogenous shocks. "Capital" indicates an economy with capital accumulation. The model statistic corresponds to the closed-form average of the second-order approximation of the solution. Volatilities, yields, and (excess) returns are in percentage terms. The inflation rate, yields, excess returns, and risk premia are annualized. The data statistics related to the real rate r are obtained from the estimated real rate. Values not reported are not available. All estimations use $\gamma = 400$. The objective value is the sum of squared percentage differences between the model- and data-implied moments targeted in the estimation. Data sources: BEA (2015), FEDS (2015), and CRSP (2015).

		Model	
Statistic	Data	Baseline	Capital
Panel A: Parameter values			
b_h		0.42	0.90
ζ		-	4.00
Panel A: Macroeconomic Variables			
Objective value		0.29	0.67
$\sigma(\Delta c)$	0.38	0.35	0.34
$\sigma(\pi)$	1.36	1.73	1.90
$\sigma(\Delta w)$	0.66	0.51	0.29
$\sigma(\Delta y)$	0.65	0.35	0.82
$\sigma(\Delta j)$	2.45	-	2.46
$\sigma(x)$		0.14	1.55
$AC(\Delta c)$	0.42	0.41	0.40
$AC(\Delta c_h)$	0.00	0.00	-0.23
corr$(\Delta c, \pi)$	-0.15	-0.08	-0.12
Panel B: Real and Nominal Yield Curve			
$\mathbb{E}[i]$	5.20	5.20	5.20
$\mathbb{E}[i^{(20)} - i]$	1.38	0.65	0.58
$\mathbb{E}[r]$	1.98	1.61	1.65
$\mathbb{E}[r^{(20)} - r]$		0.11	0.05
$\sigma(i)$	2.59	2.36	1.49
$\sigma(r)$	2.09	2.91	1.23
$\sigma(r)/\sigma(i)$	0.81	1.24	0.83
corr(i, r)	0.99	0.93	0.35
$\sigma(i^{(20)})/\sigma(i)$	1.02	0.39	0.88
$\sigma(r^{(20)})/\sigma(r)$		0.13	0.08
Panel C: Expected Excess Returns			
$\mathbb{E}[XR^{\$,(20)}]$	4.28	1.14	0.94
$\mathbb{E}[XR^{(20)}]$		0.64	0.21
$SR^{\$,(20)}$	0.32	0.18	0.31
$SR^{(20)}$		0.10	0.11
$\mathbb{E}[rTP^{(20)}]$		0.56	0.20
$\mathbb{E}[\pi TP^{(20)}]$		0.54	0.98

shocks in equation (30) given by

$$\Delta a_{t+1} = (1-\phi_a)g_a + \phi_a \Delta a_t + \sigma_a e^{\nu_a \Delta a} \varepsilon_{a,t+1}, \quad \text{and} \quad z_{t+1} = \phi_z z_t + \sigma_z e^{\nu_z z_t} \varepsilon_{z,t+1},$$

Table 6: **Data and Model Implied Statistics - The Effects of Stochastic Volatility in Shocks**

The operators $\mathbb{E}[\cdot]$, and $\sigma(\cdot)$ denote the unconditional mean and volatility, respectively. $rTP^{(20)}$, and $\pi TP^{(20)}$ are the 5-year bond real term and inflation risk premia, respectively. The parameter values of the baseline model are reported in Table 2. "Baseline" indicates an economy with both price and wage rigidities and all four exogenous shocks. "Capital" indicates an economy with capital accumulation. Columns labeled as "No SV" corresponds to the case $\nu_a = \nu_z = 0$. Columns labeled $\nu_a = -100$ and $\nu_z = 100$ correspond to the specifications with stochastic volatility in the permanent and transitory components in productivity, respectively. The model statistic corresponds to the simulated average statistics for a sample of 1,000 periods of the third-order approximation of the solution. Volatilities, yields, (excess) returns, and risk premia are in percentage terms. The excess returns, and risk premia are annualized. All estimations use $\gamma = 400$. Data sources: BEA (2015), FEDS (2015), and CRSP (2015).

	Baseline			Capital		
	No SV	$\nu_a = -100$	$\nu_z = -100$	No SV	$\nu_a = -100$	$\nu_z = -100$
Panel A: Means						
$\mathbb{E}[XR^{\$,(20)}]$	1.15	1.15	1.15	0.94	0.94	0.94
$\mathbb{E}[XR^{c,(20)}]$	0.64	0.64	0.64	0.20	0.20	0.21
$\mathbb{E}[rTP^{c,(20)}]$	0.56	0.56	0.56	0.20	0.20	0.21
$\mathbb{E}[\pi TP^{c,(20)}]$	0.54	0.54	0.54	0.98	0.98	0.98
Panel B: Standard Deviations						
$\sigma(XR^{\$,(20)})$	0.03	0.40	0.17	0.12	0.13	0.12
$\sigma(XR^{c,(20)})$	0.02	0.18	0.21	0.01	0.10	0.08
$\sigma(rTP^{(20)})$	0.02	0.16	0.18	0.01	0.10	0.08
$\sigma(\pi TP^{(20)})$	0.02	0.22	0.08	0.13	0.15	0.13

where $\nu_a \neq 0$ and $\nu_z \neq 0$ capture time-variation in the conditional volatility of the shocks. Volatility depends on the level of the productivity component, avoiding the need for new state variables. Table 6 reports results for two specifications with only time-varying volatility in only one productivity component at a time: $\nu_a = -100$, or $\nu_z = -100$, respectively. The negative signs capture the fact that volatility tends to increase during periods of high marginal utility. The magnitude implies that the level of volatility is 40% higher if a positive shock of size σ_a or σ_z, respectively, hits the economy. The table shows that bond risk premia become time-varying in specifications with stochastic volatility.[31] In particular, volatility in permanent shocks in the model with habit persistence generates the largest variability in bond risk premia. Real term premia are more or less volatile than inflation risk premia depending on whether the stochastic volatility is in the permanent or transitory

[31] A third-order perturbation of the model solution is required to capture the effects of time-varying volatility. The model moments are computed based on simulations that use the pruning method described in Andreasen, Fernández-Villaverde and Rubio-Ramírez (2014).

productivity components, respectively.

5 Permanent Shocks in the Data

We construct empirical impulse responses to permanent shocks of several macroeconomic variables, and compare them with their model counterparts. The purpose of this exercise is to provide empirical support to the model mechanism generating bond risk premia. We expect to see an increase in inflation after a negative permanent shock to productivity. This only occurs in the model as a result of wage rigidities. Empirically, the first challenge is to determine a methodology that allows us to separately identify the permanent component and the transitory component of the productivity shock. Our identification strategy for the permanent productivity shock follows Altig, Christiano, Eichenbaum and Linde (2011) (ACEL henceforth), among others, where a ten-variable VAR is used to separate innovations to neutral and capital embodied technology growth. We use a modified seven-variable VAR to identify neutral shocks to productivity growth by making the first difference of log GDP per hour the first element in the VAR. The remaining six variables, in order, are: inflation, labor hours, wage growth, consumption growth, the output gap, and the Fed funds rate. The sample period spans from 1982:Q1 to 2008:Q3 to match the estimation sample. Specifically, the VAR is:

$$\begin{bmatrix} \Delta ln(GDP/Hours) \\ \Delta ln(GDP \text{ deflator}) \\ ln(Hours) \\ \Delta ln(Wage) \\ \Delta ln(Consumption) \\ OutputGap \\ FFR \end{bmatrix}_t = \bar{B} + B(L) \begin{bmatrix} \Delta ln(GDP/Hours) \\ \Delta ln(GDP \text{ deflator}) \\ ln(Hours) \\ \Delta ln(Wage) \\ \Delta ln(Consumption) \\ OutputGap \\ FFR \end{bmatrix}_{t-1} + \varepsilon_{VAR,t},$$

where $\Delta ln(GDP$ deflator) is inflation and L is the lag operator. We choose to include four lags in the VAR, consistent with ACEL. The permanent component of productivity shock is the identified shock to the first element of the VAR, which means it impacts all the remaining variables without delay. For all details on the estimation strategy, see ACEL.

Figure 2 shows the impulse responses of the VAR estimation. The left column shows that the empirical impulse responses agree with the theoretical IRs after a negative permanent productivity shock is realized: per hour output growth declines, inflation and hours increase, while wage growth, consumption growth, and the output gap all decrease, and the Fed funds rate nudges up slightly. Inflation increases after the negative shock, consistent with the model response under wage rigidities. However, the 95% confidence band is too wide after the initial shock to definitively report that this is the case. This is not surprising given the fact that there is some tension from price and wage rigidities on inflation. The theoretical impulse response of inflation in the figure also shows that inflation increases only slightly after a negative permanent shock when both types of rigidities are activated in the model.

Finally, the right column of Figure 2 provides further evidence that our proposed esti-

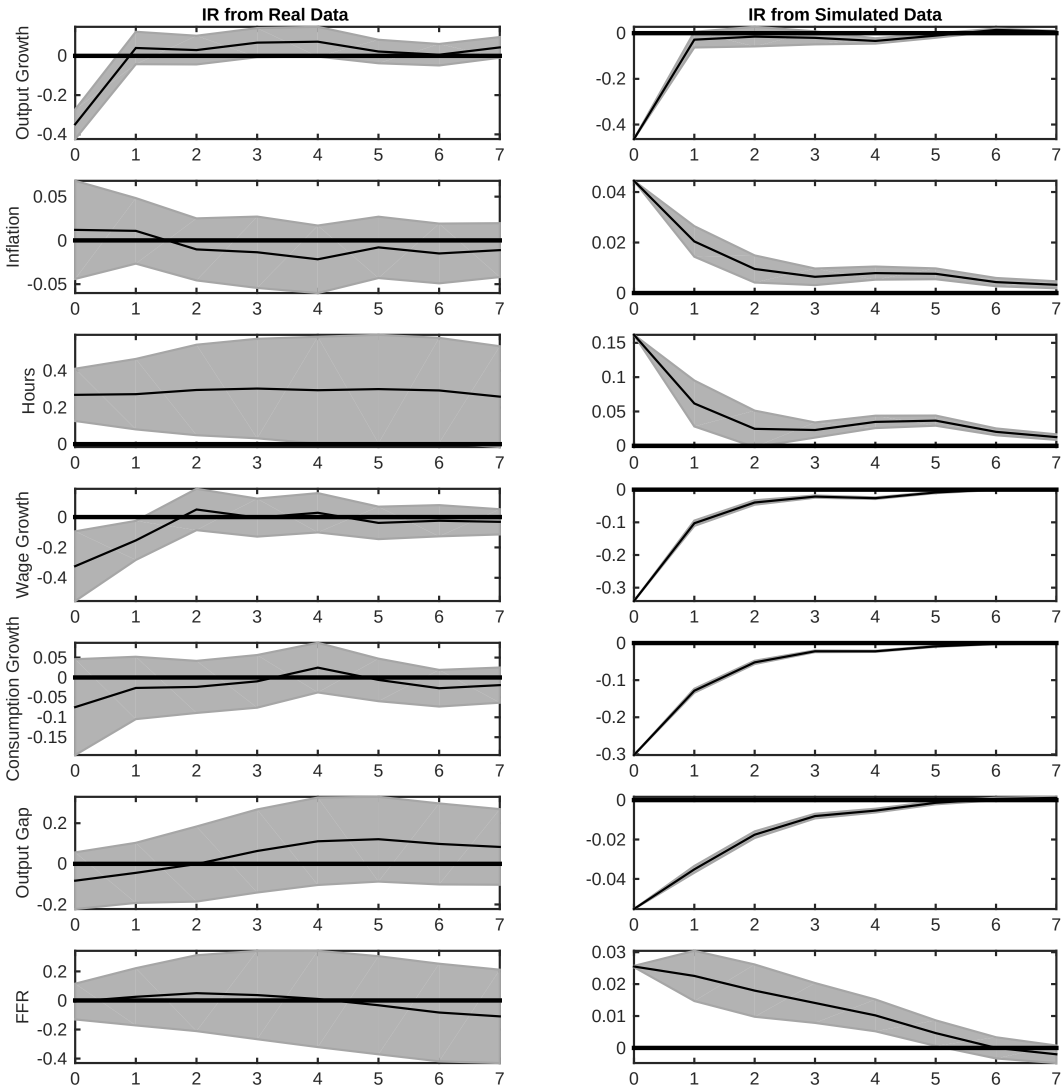

Figure 2: Impulse responses to a one-standard deviation negative permanent productivity shock constructed from a seven-variable VAR employing data from Altig, Christiano, Eichenbaum and Linde (2011) and a similar identification strategy. The left column uses real macroeconomic data, and the right column uses corresponding simulated data from the baseline model. The parameter values of the baseline model are reported in Table 2.

mation strategy is capturing the permanent shock to productivity as all simulated variables respond in the same fashion as we would expect from the theoretical impulse responses. Moreover, a comparison between the two sets of impulse responses indicates that the estimated reactions following the negative shock are much more precise on the simulated data as evidenced by the narrow confidence bands. Overall, the empirical exercise provides quantitative support to the model mechanism of permanent productivity shocks in combination with wage rigidities generating positive real term and inflation risk premia.

6 Conclusion

This paper provides a quantitative analysis of bond risk premia in the presence of nominal rigidities, permanent shocks, and monetary policy. The model estimation implies positive real term and inflation risk premia for permanent productivity shocks as a result of wage rigidities. These properties are (i) consistent with those observed in the U.S. for inflation-linked and nominal bonds in recent years, (ii) different from previous literature where real term premia are negative, and (iii) supported by empirical evidence on macroeconomic variable responses to permanent shocks.

The results have implications for the riskiness of nominal bonds and the effects of monetary policy on bond risk premia. Nominal bonds are risky not only because they involve a substantial positive compensation for inflation risk, but also because of positive real term premia. Regarding the interest-rate policy rule, a stronger response to inflation or a weaker response to output increase real term and inflation risk premia.

The analysis can be extended in several dimensions. For instance, an empirical study of the model's testable implications across countries. The model predicts lower real yield curve slopes in economies with more flexible wages. This is consistent with the average inverted real yield curve in the U.K., and the findings in Smith (2000) and Dickens et al.

(2007) of less rigid wages in the U.K. than in U.S. Also, the framework can be used to learn about the effects of optimal monetary policy on real rates and their economic content.

A U.S. and U.K. Inflation-Linked Bonds and Macroeconomic Data

We use quarterly data from January 1985 to September 2008 for the U.S. and the U.K., and report statistics for the periods 1985-2008 and 1999-2008. The data sample periods are motivated by two reasons. First, TIPS data in the U.S. and inflation-linked gilts data in the U.K. are only available since 1999 and 1985, respectively.[32] Second, the period September-December 2008 coincides with the collapse of Lehman Brothers that drove short-term interest rates close to zero, and triggered a switch to unconventional monetary policies. The period after September 2008 is then not covered to focus on the effects on bond yields of a (conventional) monetary policy conducted using an interest-rate rule.

The consumption growth and inflation series for the U.S. are constructed using quarterly data from the Bureau of Economic Analysis, following the methodology in Piazzesi and Schneider (2007). These series capture only consumption of non-durables and services and its related inflation, and then consistent with the model variables. Wages are real wages per hour of non-farm business from the Federal Reserve Economic Data (FRED) database from the Federal Reserve Bank of St. Louis. The data on U.S. zero-coupon nominal bond and TIPS yields are constructed following the procedure in Gurkaynak, Sack and Wright (2006, 2008), respectively. These data are obtained from the Federal Reserve website. The short-term nominal interest rate is the 3-month T-bill rate from the Fama risk-free rates database. The three-month real rate is estimated using the methodology described in Pflueger and Viceira (2011).[33] Dividends and stock market returns correspond to the market portfolio obtained from the Center for Research in Security Prices (CRSP). For the U.K., consumption growth and inflation are obtained directly from the FRED database. The historical yields for U.K. real and nominal bonds are taken from the Bank of England website. The three-month real rate in the U.K. is estimated using the same methodology used to estimate the U.S. real rate. Stock returns are for the UK FTSE All-Shares Index. The bond yields under study correspond to maturities from 2 to 10 years. The long end of the curves has been excluded for comparison purposes across countries. Greenwood and Vayanos (2010) document a significant effect on long-term inflation-linked bond yields in the U.K, resulting from the increased demand from pension funds to meet the Minimum Funding Requirements. Table 1 summarizes the empirical evidence.

B Model

We model a production economy with a representative household, a production sector for differentiated goods, and monetary policy. The representative household derives utility from the consumption of a basket of goods and disutility from supplying differentiated labor to the production sector. Labor and product markets are characterized by monopolistic competition and nominal wage and price rigidities, respectively. Monetary policy is modeled as an interest-rate policy rule that reacts to economic conditions. All markets are complete. Default-free real and nominal bonds are in zero net supply. The model can be seen as an extension of the standard New-Keynesian framework (see Woodford (2003), for instance) to capture bond pricing dynamics. It incorporates recursive preferences with habit formation for the representative

[32]Results using comparable monthly data are very similar. We present results for quarterly data to be consistent with the model estimation. The same macroeconomic and term structure data for the United States are used to estimate the model, for the longer period January 1982 to September 2008.

[33]Specifically, the computation is based on the regression

$$i_t - \pi_{t+1} = \text{constant} + \beta_i i_t + \beta_r (i_{t-1} - \pi_t) + \varepsilon_t,$$

where i_t is the three-month nominal rate and π_t is the three-month inflation rate. The real rate is then computed as $r_t = i_t - \mathbb{E}_t[\pi_{t+1}]$ under the assumption that the inflation risk premium in three-month nominal bonds is negligible.

household. Recursive preferences, as in Rudebusch and Swanson (2012) and Li and Palomino (2014), are used to disentangle risk aversion from the elasticity of intertemporal substitution of consumption. This separation allows us to match observed macroeconomic dynamics by choosing an appropriate level for the elasticity of intertemporal substitution, while increasing the degree of risk aversion to capture large expected excess returns. Nominal prices and/or wages that are not adjusted optimally generate relative price and wage distortions that affect production decisions. In this setting, different monetary policy rules have different implications on inflation and real activity. As a result, the dynamics and riskiness of real and nominal bond yields are affected by both nominal rigidities and monetary policy. This section describes the characteristics of the model economy.

B.1 Household

A representative agent chooses consumption C_t and labor supply N_t^s to maximize the Epstein and Zin (1989) recursive utility function

$$V_t = (1-\beta)U(C_{h,t}, N_t^s)^{1-\varphi} + \beta \mathbb{E}_t \left[V_{t+1}^{\frac{1-\gamma}{1-\varphi}} \right]^{\frac{1-\varphi}{1-\gamma}}, \tag{16}$$

where $\beta > 0$ is the subjective discount factor, φ and γ determine the elasticity of intertemporal substitution (EIS) and the coefficient of relative risk aversion, respectively, and $C_{h,t}$ is the habit-adjusted consumption, defined as $C_{h,t} \equiv C_t - b_h \tilde{C}_{t-1}$.[34] The external habit is represented by lagged aggregate consumption $\tilde{C}_{t-1}$, equal to C_{t-1} in equilibrium, but not determined directly by the household. This is a simplified Campbell and Cochrane (1999) habit specification. The recursive utility formulation relaxes the strong assumption of $\gamma = \varphi$ implied by constant relative risk aversion. The intra-temporal utility is defined over the habit-adjusted consumption and labor supply as

$$U(C_{h,t}, N_t^s) = \left(\frac{C_{h,t}^{1-\varphi}}{1-\varphi} - \kappa_t \frac{(N_t^s)^{1+\omega}}{1+\omega} \right)^{\frac{1}{1-\varphi}}, \tag{17}$$

where $\omega^{-1} > 0$ captures the Frisch elasticity of labor supply, and the process κ_t is chosen to ensure balanced growth (it is specified in the production sector section below).

The consumption good is a basket of differentiated goods produced by a continuum of firms. Specifically, the consumption basket is

$$C_t = \left[\int_0^1 C_t(j)^{\frac{\theta_p - 1}{\theta_p}} dj \right]^{\frac{\theta_p}{\theta_p - 1}}, \tag{18}$$

where $\theta_p > 1$ is the elasticity of substitution across differentiated goods, and $C_t(j)$ is the consumption of the differentiated good j. Labor supply is the aggregate of a continuum of different labor types supplied to the production sector, such that

$$N_t^s = \int_0^1 N_t^s(k) dk, \tag{19}$$

where $N_t^s(k)$ is the supply of labor type k.

[34] The elasticity of intertemporal substitution of the utility bundle of consumption and labor is φ^{-1}. The coefficient of relative risk aversion is defined in Section 4 of the paper.

The representative consumer is subject to the intertemporal budget constraint

$$\mathbb{E}_t\left[\sum_{s=0}^{\infty} M^{\$}_{t,t+s} P_{t+s} C_{t+s}\right] \leq \mathbb{E}_t\left[\sum_{s=0}^{\infty} M^{\$}_{t,t+s} P_{t+s}\left(LI_{t+s} + D_{t+s}\right)\right], \tag{20}$$

where $M^{\$}_{t,t+s}$ is the nominal discount factor for cash flows at time $t+s$, P_t is the nominal price of a unit of the basket of goods, LI_t is the real labor income from supplying labor to the production sector, and D_t is the real dividend from owning the production sector.

It can be shown that the household's optimality conditions imply that the one-period real and nominal discount factors are

$$M_{t,t+1} = \beta\left(\frac{C_{h,t+1}}{C_{h,t}}\right)^{-\varphi}\left(\frac{V_{t+1}^{1/(1-\varphi)}}{\mathbb{E}_t\left[V_{t+1}^{(1-\gamma)/(1-\varphi)}\right]^{1/(1-\gamma)}}\right)^{\varphi-\gamma}, \quad \text{and} \quad M^{\$}_{t,t+1} = M_{t,t+1}\left(\frac{P_{t+1}}{P_t}\right)^{-1}, \tag{21}$$

respectively. The one-period (continuously compounded) real and nominal interest rates are obtained from

$$r_t = -\log \mathbb{E}_t\left[M_{t,t+1}\right], \quad \text{and} \quad i_t = -\log \mathbb{E}_t\left[M^{\$}_{t,t+1}\right], \tag{22}$$

respectively. The nominal interest rate i_t is the instrument of monetary policy.

B.1.1 Wage Setting

Following Schmitt-Grohe and Uribe (2007), an imperfectly competitive labor market is modeled where the representative household monopolistically provides a continuum of labor types indexed by $k \in [0,1]$.[35] The supply of labor type k satisfies the demand equation

$$N_t^s(k) = \left(\frac{W_t(k)}{W_t}\right)^{-\theta_w} N_t^d, \tag{23}$$

where N_t^d is the aggregate labor demand of the production sector, $W_t(k)$ is the wage for labor type k, and W_t is the aggregate wage index given by

$$W_t = \left[\int_0^1 W_t^{1-\theta_w}(k)\, dk\right]^{\frac{1}{1-\theta_w}}. \tag{24}$$

The labor demand equation (23) is obtained from the production sector problem presented in the section below. The household chooses wages $W_t(k)$ for all labor types k under Calvo (1983) staggered wage setting. Specifically, at each time t, the household is only able to adjust wages optimally for a fraction $1-\alpha_w$ of labor types. The remaining fraction α_w of labor types adjust their previous period wages by the wage indexation factor $\Lambda_{w,t-1,t}$. The specific functional form of this factor is presented in Section 4 of the paper. The optimal wage maximizes (16), subject to demand functions (23) for all labor types k, and the budget

[35] This approach is different from the standard heterogeneous households approach to model wage rigidities in Erceg, Henderson and Levin (2000), where each household supplies a differentiated type of labor. In the presence of recursive preferences, this approach introduces heterogeneity in the marginal rate of substitution of consumption across households since it depends on labor. We avoid this difficulty and obtain a unique marginal rate of substitution by modeling a representative agent who provides all different types of labor.

constraint (20). Notice that real labor income is given by

$$LI_t = \int_0^1 \frac{W_t(k)}{P_t} N_t^s(k) dk\,. \tag{25}$$

Since the demand curve and the cost of labor supply are identical across different labor types, the household chooses the same wage W_t^* for all labor types subject to an optimal wage change at time t. It can be shown that the optimal wage satisfies

$$\frac{W_t^*}{P_t} \quad = \quad \mu_w \kappa_t \left(N_t^s\right)^{\omega} C_{h,t}^{\varphi} \frac{G_{w,t}}{H_{w,t}}\,, \tag{26}$$

where $\mu_w \equiv \frac{\theta_w}{\theta_w - 1}$. The recursive equations describing $G_{w,t}$ and $H_{w,t}$ are presented in the appendix. Equation (26) can be interpreted as follows: In the absence of wage rigidities ($\alpha_\omega = 0$), the marginal rate of substitution between labor and consumption is $\kappa_t \left(N_t^s\right)^{\omega} C_{h,t}^{\varphi}$, and the optimal wage is this rate adjusted by the optimal markup μ_w. Wage rigidities generate the time-varying markup $\mu_w \frac{G_{w,t}}{H_{w,t}}$, since the wage of some labor types is not adjusted optimally.

B.2 Production Sector

The production of differentiated goods is characterized by monopolistic competition and price rigidities in a continuum of firms. Firms set the price of their differentiated goods in a Calvo (1983) staggered price setting: At each time t, with probability α_p, a firm sets the price of the good as the previous period price adjusted by the price indexation factor $\Lambda_{p,t-1,t}$. The specific functional form of this factor is presented in Section 4 of the paper. With probability $1 - \alpha_p$, the firm sets the product price to maximize the present value of profits. The maximization problem for firm j can be written as

$$\max_{\{P_t(j)\}} \mathbb{E}_t \left\{ \sum_{s=0}^{\infty} \alpha_p^s M_{t,t+s}^{\$} \left[\Lambda_{p,t,t+s} P_t(j) Y_{t+s|t}(j) - W_{t+s|t}(j) N_{t+s|t}^d(j) \right] \right\}, \tag{27}$$

subject to the production function

$$Y_{t+s|t}(j) = A_{t+s} N_{t+s|t}^d(j), \tag{28}$$

and the demand function

$$Y_{t+s|t}(j) = \left(\frac{P_t(j) \Lambda_{p,t,t+s}}{P_{t+s}} \right)^{-\theta} Y_{t+s}. \tag{29}$$

The output $Y_{t+s|t}(j)$ is the production of firm j at time $t+s$ given that the last optimal price change was at time t. The wage $W_{t+s|t}(j)$ and the labor demand $N_{t+s|t}^d(j)$ have a similar interpretation. The production problem takes into account the probability of not being able to adjust the price optimally in the future, and the corresponding indexation $\Lambda_{p,t,t+s}$.

The production function depends on labor productivity A_t and labor. We assume that labor productivity contains difference- and trend-stationary components.[36] Specifically, $A_t = A_t^p Z_t$, where $a_t \equiv \log A_t^p$ and $z_t \equiv \log Z_t$, are the difference- and trend-stationary components of productivity, respectively. These

[36]The two components are incorporated given the different effects on bond risk premia of these two processes for consumption in endowment economies. A difference-stationary process for consumption with positive autocorrelation coefficient generates negative term premia. A trend-stationary process for consumption with positive autocorrelation coefficient generates positive term premia.

components follow the processes

$$\Delta a_{t+1} = (1-\phi_a)g_a + \phi_a \Delta a_t + \sigma_a \varepsilon_{a,t+1}, \quad \text{and} \quad z_{t+1} = \phi_z z_t + \sigma_z \varepsilon_{z,t+1}, \tag{30}$$

where Δ is the difference operator, g_a is the average growth rate in the economy, and innovations $\varepsilon_{a,t}$ and $\varepsilon_{z,t} \sim \text{IID}\mathcal{N}(0,1)$. For simplicity, throughout the paper we refer to the difference- and trend-stationary components as the permanent and transitory shocks to productivity, respectively.

Labor demand is a composite of a continuum of differentiated labor types indexed by $k \in [0,1]$ via the aggregator

$$N_t^d(j) = \left[\int_0^1 N_t^d(j,k)^{\frac{\theta_w - 1}{\theta_w}} dj\right]^{\frac{\theta_w}{\theta_w - 1}}, \tag{31}$$

where $\theta_w > 1$ is the elasticity of substitution across differentiated labor types.

All firms that set prices optimally are identical and set the same optimal price P_t^*. Appendix **??** shows that the optimal price satisfies

$$\left(\frac{P_t^*}{P_t}\right) H_{p,t} \quad = \quad \frac{\mu_p}{A_t} \frac{W_t}{P_t} G_{p,t}, \tag{32}$$

where $\mu_p = \frac{\theta_p}{\theta_p - 1}$. The recursive equations for $H_{p,t}$ and $G_{p,t}$ are presented in the appendix. Equation (32) can be interpreted as follows: In the absence of price rigidities, the product price is the markup-adjusted marginal cost of production, with optimal markup μ_p. Price rigidities generate the time-varying markup $\mu_p \frac{G_{p,t}}{H_{p,t}}$, since some firms do not adjust their prices optimally.

We define $\kappa_t \equiv (A_t^p)^{1-\varphi}$ to preserve balanced growth. It can be shown from equation (26) that wages and consumption share the same average trend as long as $\kappa_t \propto (A_t^p)^{1-\varphi}$, and implies stationary labor.

B.3 Monetary Policy

Monetary policy is described by the interest-rate policy rule

$$i_t = \rho i_{t-1} + (1-\rho)\left[\bar{\imath} + \imath_\pi(\pi_t - \pi_{t-1}^\star) + \imath_x(x_t - x_{ss})\right] + u_t \,. \tag{33}$$

The policy rule has an interest-rate smoothing component captured by the sensitivity ρ to the lagged term, i_{t-1}, and responds to aggregate inflation $\pi_t \equiv \log \frac{P_t}{P_{t-1}}$, the output gap x_t, and a policy shock u_t. The output gap is defined as the log deviation of total output, Y_t, from the output in an economy under flexible prices and wages, Y_t^f. That is, $X_t \equiv \frac{Y_t}{Y_t^f}$, and $x_t \equiv \log X_t$. The coefficients $\imath_\pi$ and $\imath_x$ capture the response of the monetary authority to the deviations of inflation and the output gap from their targets, respectively. The constant $\bar{\imath}$ is defined as the nominal rate when the inflation rate and the output gap are at their targets, i.e., $\bar{\imath} \equiv -\log\beta + \varphi g_a + g_\pi$. The process $\pi_t^\star$ denotes the time-varying inflation target. The inflation target is time-varying as in Ireland (2007) and Rudebusch and Swanson (2012).[37] Its process is

$$\pi_t^\star = (1-\phi_{\pi^\star})g_\pi + \phi_{\pi^\star}\pi_{t-1}^\star + \sigma_{\pi^\star}\varepsilon_{\pi^\star,t}, \tag{34}$$

where $\varepsilon_{\pi^\star,t} \sim \text{IID}\mathcal{N}(0,1)$. The output gap target x_{ss} corresponds to the output gap in steady state. The policy shocks u_t follow the process

$$u_{t+1} = \phi_u u_t + \sigma_u \varepsilon_{u,t+1}, \tag{35}$$

[37] The inflation target has also been used in the macro finance literature by Bekaert, Cho and Moreno (2010), Campbell, Pflueger and Viceira (2014) and Dew-Becker (2014).

where $\varepsilon_{u,t} \sim \text{IID}\mathcal{N}(0,1)$.

B.4 Bond Prices and Yields

Real and nominal default-free zero-coupon bonds with maturity at $t+n$ pay a unit of real and nominal consumption, respectively, at maturity. Their prices are

$$B_t^{c,(n)} = \exp\left(-nr_t^{(n)}\right) = \mathbb{E}_t[M_{t,t+n}], \quad \text{and} \quad B_t^{\$,(n)} = \exp\left(-ni_t^{(n)}\right) = \mathbb{E}_t[M_{t,t+n}^{\$}], \tag{36}$$

for real and nominal bonds, respectively, where $r_t^{(n)}$ and $i_t^{(n)}$ are the associated real and nominal bond yields, and $M_{t,t+n}$ and $M_{t,t+n}^{\$}$ are the real and nominal discount factors for payoffs at $t+n$.[38]

B.5 Equilibrium

Equilibrium requires product, labor, and financial market clearing. Product market clearing is characterized by $C_t(j) = Y_t(j)$ for all $j \in [0,1]$, and then $C_t = Y_t$. Labor market clearing requires that supply and demand of labor type k employed by firm j are equal, $N_t^s(j,k) = N_t^d(j,k)$. It implies the aggregate labor market clearing condition $N_t^s = N_t^d F_{w,t}$ where $N_t^d = \frac{Y_t}{A_t} F_{p,t}$. The distortions $F_{w,t}$ and $F_{p,t}$ measure wage and price dispersion caused by wage and price rigidities, respectively, and are defined in the appendix. Equilibrium in the financial market implies that the nominal interest rate from household maximization in equation (22) is equal to the interest rate set by the monetary policy rule in equation (33). Equilibrium implies the absence of arbitrage opportunities in real and nominal bond markets.

Here we provide a summary of the equilibrium equations for the model. These conditions need to be expressed in terms of de-trended variables. In order to obtain balanced growth, $\kappa_t \equiv \kappa_0 (A_t^p)^{1-\varphi}$. This condition ensures that Y_t, W_t, W_t^*, C_t, and $C_{h,t}$ share the same average trend. Therefore, the equations can be written in stationary form in terms of $\hat{Y}_t = \frac{Y_t}{A_t^p}$, $\hat{W}_t = \frac{W_t}{A_t^p}$, $\hat{W}_t^* = \frac{W_t^*}{A_t^p}$, $\hat{C}_t = \frac{C_t}{A_t^p}$, and $\hat{C}_{h,t} = \frac{C_{h,t}}{A_t^p}$

Wage setting

$$\begin{aligned}
\frac{W_t^*}{P_t} &= \mu_w \kappa_t \left(N_t^s\right)^{\omega} C_{h,t}^{\varphi} \frac{G_{w,t}}{H_{w,t}}. \\
H_{w,t} &= 1 + \alpha_w \mathbb{E}_t \left[M_{t,t+1}^{\$} \Lambda_{w,t,t+1}^{-\theta_w} \left(\frac{N_{t+1}^d}{N_t^d}\right) \left(\frac{W_t}{W_{t+1}}\right)^{-\theta_w} H_{w,t+1} \right], \\
G_{w,t} &= 1 + \alpha_w \mathbb{E}_t \left[M_{t,t+1}^{\$} \Lambda_{w,t,t+1}^{-\theta_w} \left(\frac{P_{t+1}}{P_t}\right) \left(\frac{C_{h,t+1}}{C_{h,t}}\right)^{\varphi} \left(\frac{N_{t+1}^d}{N_t^d}\right) \left(\frac{\kappa_{t+1}}{\kappa_t}\right) \left(\frac{N_{t+1}^s}{N_t^s}\right)^{\omega} \left(\frac{W_t}{W_{t+1}}\right)^{-\theta_w} G_{w,t+1} \right].
\end{aligned}$$

Price dispersion

$$F_{p,t} = \int_0^1 \left(\frac{P_t(j)}{P_t}\right)^{-\theta_p} dj = (1-\alpha_p)\left(\frac{P_t^*}{P_t}\right)^{-\theta_p} + \alpha_p \Lambda_{p,t-1,t}^{-\theta_p} \left(\frac{P_{t-1}}{P_t}\right)^{-\theta_p} F_{p,t-1}.$$

Wage dispersion

$$F_{w,t} = \int_0^1 \left(\frac{W_t(k)}{W_t}\right)^{-\theta_w} dk = (1-\alpha_w)\left(\frac{W_t^*}{W_t}\right)^{-\theta_w} + \alpha_w \Lambda_{w,t-1,t}^{-\theta_w} \left(\frac{W_{t-1}}{W_t}\right)^{-\theta_w} F_{w,t-1}.$$

[38] Notice that $B_t^{c,(n)}$ is the real price of the real bond, while $B_t^{\$,(n)}$ is the nominal price of the nominal bond.

Wage aggregator

$$\left(\frac{W_t}{P_t}\right)^{1-\theta_w} = \int_0^1 \left(\frac{W_t(k)}{P_t}\right)^{1-\theta_w} dk = (1-\alpha_w)\left(\frac{W_t^*}{P_t}\right)^{1-\theta_w} + \alpha_w \Lambda_{w,t-1,t}^{1-\theta_w}\left(\frac{P_{t-1}}{P_t}\right)^{1-\theta_w}\left(\frac{W_{t-1}}{P_{t-1}}\right)^{1-\theta_w},$$

Price setting

$$\begin{aligned}
\left(\frac{P_t^*}{P_t}\right) H_{p,t} &= \frac{\mu_p}{A_t}\frac{W_t}{P_t} G_{p,t}\,, \\
H_{p,t} &= 1 + \alpha_p \mathbb{E}_t\left[M_{t,t+1}^{\$}\Lambda_{p,t,t+1}^{1-\theta_p}\left(\frac{Y_{t+1}}{Y_t}\right)\left(\frac{P_t}{P_{t+1}}\right)^{-\theta_p} H_{p,t+1}\right], \\
\text{and} \quad G_{p,t} &= 1 + \alpha_p \mathbb{E}_t\left[M_{t,t+1}^{\$}\Lambda_{p,t,t+1}^{-\theta_p}\left(\frac{Y_{t+1}}{Y_t}\right)\left(\frac{P_t}{P_{t+1}}\right)^{-\theta_p}\left(\frac{W_{t+1}}{W_t}\right)\left(\frac{A_t}{A_{t+1}}\right) G_{p,t+1}\right].
\end{aligned}$$

Price aggregator

$$1 = (1-\alpha_p)\left(\frac{P_t^*}{P_t}\right)^{1-\theta_p} + \alpha_p \Lambda_{p,t-1,t}^{1-\theta_p}\left(\frac{P_{t-1}}{P_t}\right)^{1-\theta}.$$

Aggregate labor supply and demand

$$N_t^s = F_{w,t} N_t^d, \qquad N_t^d = \frac{Y_t}{A_t} F_{p,t}.$$

Pricing kernel

$$\begin{aligned}
M_{t,t+1} &= \left[\beta\left(\frac{C_{h,t+1}}{C_{h,t}}\right)^{-\varphi}\right]^{\frac{1-\gamma}{1-\varphi}}\left(\frac{1}{R_{Q,t+1}}\right)^{1-\frac{1-\gamma}{1-\varphi}}, \\
R_{Q,t+1} &= (1-\nu_t) R_{C_h,t+1} + \nu_t R_{LI^*,t+1}, \\
R_{C_h,t+1} &= \frac{C_{h,t+1} + S_{C_h,t+1}}{S_{C_h,t}}, \qquad R_{LI^*,t+1} = \frac{LI_{t+1}^* + S_{LI^*,t+1}}{S_{LI^*,t}}, \\
\nu_t &= \frac{\bar{\nu} S_{LI^*,t}}{\bar{\nu} S_{LI^*,t} - S_{C_h,t}}.
\end{aligned}$$

Real and nominal bond yields

$$\exp\left(-n r_t^{(n)}\right) = \mathbb{E}_t\left[M_{t,t+1}\exp\left(-(n-1) r_{t+1}^{(n-1)}\right)\right], \quad \exp\left(-n i_t^{(n)}\right) = \mathbb{E}_t\left[M_{t,t+1}^{\$}\exp\left(-(n-1) i_{t+1}^{(n-1)}\right)\right].$$

Indexation

$$\log \Lambda_{p,t,t+1} = \pi_t^\star, \quad \log \Lambda_{w,t,t+1} = g_a + \pi_t^\star.$$

Policy rule

$$i_t = \rho i_{t-1} + (1-\rho)\left[\bar{\imath} + \imath_\pi(\pi_t - \pi_{t-1}^\star) + \imath_x(x_t - x_{ss})\right] + u_t.$$

Goods market clearing

$$Y_t = C_t.$$

Habit

$$C_{h,t} = C_t - b_h C_{t-1},$$

Flexible price and wage economy

$$\begin{aligned} C^f_{h,t} &= C^f_t - b_h C^f_{t-1}, \\ Y^f_t &= C^f_t, \\ \left(Y^f_t\right)^{\omega} \left(C^f_{h,t}\right)^{\varphi} &= \frac{A_t^{1+\omega}}{\mu_p \mu_w \kappa_t}. \end{aligned}$$

Output steady state

$$\begin{aligned} 1 &= \mu_p \mu_w \kappa_t \left(Y_{ss}\right)^{\omega} \left(C_{ss} - b_h C_{ss}\right)^{\varphi} \frac{G_{w,ss}}{H_{w,ss}}, \\ 1 &= \mu_p \mu_w \kappa_t \left(Y^f_{ss}\right)^{\omega} \left(C^f_{ss} - b_h C^f_{ss}\right)^{\varphi}, \\ Y_{ss} &= C_{ss}, \\ x_{ss} &= y_{ss} - y^f_{ss}. \end{aligned}$$

B.6 Expected Excess Bond Returns and Risk Premia

Risk differences between short- and long-term bonds, and between real and nominal bonds are analyzed in terms of differences in their expected returns, risk premia, or implied yields. The link between these measures is presented in this section. It allows us to decompose and quantify the compensations for real and nominal risks in real and nominal bond yields. In particular, real term and inflation risk premia are useful to decompose bond yields into compensations for real and nominal risks, respectively. The model determinants of these premia are analyzed in Section 4 of the paper.

One-period gross bond returns are $R^{\ell,(n)}_{t,t+1} \equiv \frac{B^{\ell,(n-1)}_{t+1}}{B^{\ell,(n)}_t}$, for $\ell = \{c, \$\}$. Real and nominal gross risk-free rates are $R^c_{f,t} \equiv \exp(r_t)$ and $R^{\$}_{f,t} \equiv \exp(i_t)$, respectively. One-period expected excess returns relative to the risk-free rate are $\mathbb{E}_t\left[XR^{\ell,(n)}_{t,t+1}\right] = \mathbb{E}_t\left[R^{\ell,(n)}_{t,t+1}\right] - R^{\ell}_{f,t}$, and Sharpe ratios are $SR^{\ell,(n)}_t \equiv \frac{\mathbb{E}_t\left[XR^{\ell,(n)}_{t,t+1}\right]}{\sigma_t\left(XR^{\ell,(n)}_{t,t+1}\right)}$, for $\ell = \{c, \$\}$. In equilibrium, $\mathbb{E}_t\left[XR^{\ell,(n)}_{t,t+1}\right] = -R^{\ell}_{f,t}\text{cov}_t\left(M^{\ell}_{t,t+1}, XR^{\ell,(n)}_{t,t+1}\right)$, where $M^c_{t,t+1} \equiv M_{t,t+1}$. Expected excess bond returns capture the compensation for macroeconomic risk in long-term bonds. This compensation depends on the correlation between bond returns and the marginal utility of consumption.

The one-period real term premium of an n-period (real) bond is defined as

$$rTP^{(n)}_t \equiv \log \mathbb{E}_t\left[R^{c,(n)}_{t,t+1}\right] - \log R^c_{f,t}. \tag{37}$$

Appendix C shows that this premium and the average spread $r^{(n)}_t - r_t$ can be approximated as[39]

$$rTP^{(n)}_t = \text{cov}_t\left(m_{t,t+1}, (n-1) r^{(n-1)}_{t+1}\right), \quad \text{and} \quad \mathbb{E}\left[r^{(n)}_t - r_t\right] = \text{J.I.}^{(n)}_r + \frac{1}{n}\sum_{s=0}^{n-2} \mathbb{E}\left[rTP^{(n-s)}_{t+s}\right], \tag{38}$$

[39]As shown in the appendix, this derivation relies on the the assumption of joint normality for the log-pricing kernel and bond yields. This is used only for illustration purposes, since the economic model is solved using a second-order perturbation method, which does not imply log-normality. Similar approximations are used throughout the paper for illustration purposes only. Equation (37) is used for the computation of real term premia in the quantitative analysis.

respectively, where $m_{t,t+1} \equiv \log M_{t,t+1}$, and J.I. denotes Jensen's inequality terms not important for the analysis. The real term premium captures the correlation between the marginal utility of consumption and the bond one-period return. This return depends on the bond yield at the end of the period. A positive correlation between marginal utility and the bond yield implies low bond real returns during periods of high marginal utility and, therefore, positive expected excess bond returns. The unconditional yield spread can be seen as an average of one-period real term premia during the life of the bond.

The one-period inflation risk premium $\pi TP_t^{(n)}$ is the difference in (log) real return for investing in an n-period nominal bond over an n-period real bond for one-period. That is,

$$\pi TP_t^{(n)} \quad \equiv \quad \log \mathbb{E}_t \left[R_{t,t+1}^{\$,(n)} P_t / P_{t+1} \right] - \log \mathbb{E}_t \left[R_{t,t+1}^{c,(n)} \right], \tag{39}$$

Appendix C shows that this premium and the average spread $i_t^{(n)} - r_t^{(n)}$ can be approximated as

$$\pi TP_t^{(n)} = \text{cov}_t \left(m_{t,t+1}, \sum_{s=1}^{n} \pi_{t+s} \right), \text{ and } \mathbb{E}\left[i_t^{(n)} - r_t^{(n)} \right] = \mathbb{E}[\pi_t] + \text{J.I.}_\pi^{(n)} + \frac{1}{n} \sum_{s=0}^{n} \mathbb{E}\left[\pi TP_{t+s}^{(n-s)} \right], \tag{40}$$

The inflation risk premium is then an expected return compensation in nominal bonds for the correlation between the marginal utility of consumption and inflation. If this correlation is positive, the expected real returns of nominal bonds are higher than for real bonds: during periods of high marginal utility, high inflation has a negative impact on nominal bond returns. The unconditional spread between nominal and real rates captures average inflation and inflation risk premia.

C Bond Risk Premia

C.1 Real Term and Inflation Risk Premia

Consider the no arbitrage equation for the n-period real bond:

$$B_t^{c,(n)} \quad = \quad e^{-nr_t^{(n)}} = \mathbb{E}_t \left[M_{t,t+1} B_{t+1}^{c,(n-1)} \right] = \mathbb{E}_t \left[e^{m_{t,t+1} - (n-1) r_{t+1}^{(n-1)}} \right],$$

where $m_{t,t+1} \equiv \log M_{t,t+1}$. Assuming normality and homoskedasticity for the log-pricing kernel and bond yields, it follows that

$$e^{-nr_t^{(n)}} \quad = \quad \mathbb{E}_t \left[e^{m_{t,t+1}} \right] \mathbb{E}_t \left[e^{-(n-1) r_{t+1}^{(n-1)}} \right] e^{-\text{cov}_t (m_{t,t+1}, (n-1) r_{t+1}^{(n-1)})}.$$

The equation above also implies

$$nr_t^{(n)} = r_t - \frac{1}{2} \text{var}_t \left((n-1) r_{t+1}^{(n-1)} \right) + rTP_t^{(n)} + \mathbb{E}_t \left[(n-1) r_{t+1}^{(n-1)} \right].$$

Solving for the last term iteratively and applying unconditional expectations, we get

$$rTP_t^{(n)} = \text{cov}_t \left(\log M_{t,t+1}, (n-1) r_{t+1}^{(n-1)} \right). \tag{41}$$

Consider the inflation risk premium in equation (43) for $n = 1$,

$$\pi TP_t^{(1)} = \text{cov}_t (m_{t,t+1}, \pi_{t+1}) = i_t - r_t + \log \mathbb{E}_t [\exp(-\pi_{t,t+1})]. \tag{42}$$

In general, the inflation risk premium in equation (43) can be written in terms of bond yields as

$$\begin{aligned}\pi TP_t^{(n)} &= n(i_t^{(n)} - r_t^{(n)}) + \log \mathbb{E}_t\left[e^{\left(-(n-1)i_{t+1}^{(n-1)}\right)}\right] - \log \mathbb{E}_t\left[e^{\left(-(n-1)r_{t+1}^{(n-1)}\right)}\right] \\ &+ \log \mathbb{E}_t[e^{(-\pi_{t,t+1})}] + \text{cov}_t\left((n-1)i_{t+1}^{(n-1)}, \pi_{t+1}\right).\end{aligned}$$

From equation (42), the recursive bond pricing equation

$$e^{-ni_t^{(n)}} = e^{-i_t}\mathbb{E}_t\left[e^{-(n-1)i_{t+1}^{(n-1)}}\right]e^{-\text{cov}_t\left(m_{t,t+1}^{\$},(n-1)i_{t+1}^{(n-1)}\right)},$$

where $m_{t,t+1}^{\$} \equiv \log M_{t,t+1}^{\$}$, and a similar equation for the comparable real bond yield, it follows that

$$\begin{aligned}\pi TP_t^{(n)} &= \pi TP_t^{(1)} + \text{cov}_t\left(m_{t,t+1}^{\$}, (n-1)i_{t+1}^{(n-1)}\right) - \text{cov}_t\left(m_{t,t+1}, (n-1)i_{t+1}^{(n-1)}\right) \\ &\quad + \text{cov}_t\left(\pi_{t+1}, (n-1)i_{t+1}^{(n-1)}\right) \\ &= \pi TP_t^{(1)} + \text{cov}_t\left(m_{t,t+1}^{\$}, (n-1)\left(i_{t+1}^{(n-1)} - r_{t+1}^{(n-1)}\right)\right),\end{aligned}$$

where the second equality follows from $m_{t,t+1} = m_{t,t+1}^{\$} + \pi_{t+1}$. Realizing that under log-normality and homoskedasticity assumptions the nominal-real bond spread is

$$(n-1)\left(i_{t+1}^{(n-1)} - r_{t+1}^{(n-1)}\right) = \sum_{s=1}^{n-1}\mathbb{E}_t[\pi_{t+s}] - \frac{1}{2}\text{var}_t\left(\sum_{s=1}^{n-1}\pi_{t+s}\right) - \text{cov}_t\left(\sum_{s=1}^{n-1}m_{t,t+s}, \sum_{s=1}^{n-1}\pi_{t+s}\right).$$

Since the variance and covariance terms are constant, it follows that

$$\pi TP_t^{(n)} = \text{cov}_t\left(m_{t,t+1}, \sum_{s=1}^{n-1}\pi_{t+s}\right).$$

Computing the unconditional expectation of the nominal-real bond spread above and replacing the covariance terms for the one-period inflation risk premia, we get

$$\pi TP_t^{(n)} \equiv \log\frac{\mathbb{E}_t\left[\exp(-\pi_{t,t+n})\right]}{B_t^{\$,(n)}} - \log\frac{1}{B_t^{(n)}} = \text{cov}_t\left(m_{t,t+n}, \pi_{t,t+n}\right), \tag{43}$$

C.2 Understanding the Mechanism

To understand the mechanism of what drives the real and nominal term structures, we derive the loglinear analytical solution of the model without habit. [40] For the model without habit, all variables can be expressed as a loglinear function of the state variables, Δa_t and z_t.

The labor-only linear production technology in equation (28) implies that aggregate consumption is

$$C_t = A_t^p Z_t \frac{N_t^d}{F_{p,t}F_{w,t}},$$

where the difference-stationary shocks $a_t \equiv \log A_t^p$ and the trend-stationary shocks $z_t \equiv \log Z_t$ follow the processes in equations (30), and $F_{p,t}$ and $F_{w,t}$ are distortions generated by price and wage rigidities, respectively. It can be shown that a first-order approximation of the distortions implies $F_{p,t} \approx 1$ and $F_{w,t} \approx 1$. We use this approximation for simplicity. It implies that $N_t^s = N_t^d = N_t$.

[40] The analytical solution of the model with habit is too complicated to illustrate the intuitions.

Notice that when prices and wages are perfectly flexible, consumption growth becomes

$$\Delta c_t = \Delta a_t + \left(\frac{1+\omega}{\omega+\varphi}\right)\Delta z_t, \quad \text{and} \quad Q_t = C_t\left[1-\left(\frac{1-\varphi}{1+\omega}\right)\left(\frac{1}{\mu_p\mu_w}\right)\right].$$

That is, the dividend of the wealth portfolio is proportional to consumption and, then, the return on wealth is a "levered" claim on the return on the consumption claim.

Consider the recursive preferences on consumption and labor in equation (16) and its associated real pricing kernel in equation (21). Under the change of variable $\tilde{v} \equiv (1-\varphi)^{-1}\log(V_t/C_t)$, these preferences can be written as

$$(1-\varphi)\tilde{v}_t = \log\left[(1-\beta)\left(1-\frac{1-\varphi}{1+\omega}e^{(\omega+\varphi)n_t-(1-\varphi)z_t}\right)+\beta e^{\left(\frac{1-\psi}{1+\omega}\right)\log\mathbb{E}_t\left[\exp((1-\gamma)(\tilde{v}_{t+1}+\Delta c_{t+1}))\right]}\right].$$

A log-linear approximation of this term implies

$$\begin{aligned}\tilde{v}_t &= \text{constant} + \eta_n n_t + \eta_z z_t + \eta_{vc}\mathbb{E}_t[\tilde{v}_{t+1}+\Delta c_{t+1}] \\ &= \text{constant} + \sum_{s=0}^{\infty}\eta_{vc}^s\mathbb{E}_t\left[\eta_{vc}\Delta c_{t+1+s}+\eta_n n_{t+1+s}+\eta_z z_{t+1+s}\right], \end{aligned} \tag{44}$$

where η_n, η_z, and η_{vc} are appropriate approximation constants, and the second equality follows from solving the first equation recursively. The term $\frac{V_{t+1}^{1/(1-\varphi)}}{\mathbb{E}_t\left[V_{t+1}^{(1-\gamma)/(1-\varphi)}\right]^{1/(1-\gamma)}}$ in the pricing kernel can be written in log-form as

$$\tilde{v}_{t+1}+\Delta c_{t+1}-\frac{1}{1-\gamma}\log\mathbb{E}_t\left[\exp((1-\gamma)(\tilde{v}_{t+1}+\Delta c_{t+1}))\right].$$

Replacing equation (44), and realizing that $\pi TP_t^{(2)} = \text{cov}_t(m_{t,t+1}, r_{t+1})$, and $r_t = \text{constant} + \varphi\mathbb{E}_t[\Delta c_{t+1}]$, we can write the real pricing kernel as

$$\log M_{t,t+1} = \log\beta - \varphi\Delta c_{t+1} - (\gamma-\varphi)\sum_{s=1}^{\infty}\eta_{vc}^s\left(\mathbb{E}_{t+1}-\mathbb{E}_t\right)\left[\Delta c_{t+1+s}+\eta_n n_{t+1+s}+\eta_z z_{t+1+s}\right], \tag{45}$$

and the one-period real term premium in a 2-period bond as

$$\begin{aligned} rTP_t^{(2)} &= -\varphi^2\text{cov}_t\left(\Delta c_{t+1}, \mathbb{E}_{t+1}[\Delta c_{t+2}]\right) \\ &- (\gamma-\varphi)\varphi\sum_{s=1}^{\infty}\eta_{vc}^s\text{cov}_t\left(\mathbb{E}_{t+1}[\Delta c_{t+1+s}+\eta_n n_{t+1+s}+\eta_z z_{t+1+s}], \mathbb{E}_{t+1}[\Delta c_{t+2}]\right). \end{aligned} \tag{46}$$

The real pricing kernel also can be written in terms of the return on wealth $R_{Q,t}$ as

$$M_{t,t+1} = \left[\beta\left(\frac{C_{t+1}}{C_t}\right)^{-\varphi}\right]^{\frac{1-\gamma}{1-\varphi}}\left[\frac{1}{R_{Q,t+1}}\right]^{1-\frac{1-\gamma}{1-\varphi}}, \quad \text{where} \quad Q_t = C_t\left[1-\left(\frac{1-\varphi}{1+\omega}\right)\kappa_0\left(\frac{N_t^{\varphi+\omega}}{Z_t^{1-\varphi}}\right)\right]$$

is the dividend associated to the wealth portfolio. The log-pricing kernel can be written as

$$m_{t,t+1} = \left(\frac{1-\gamma}{1-\varphi}\right)\log\beta - \varphi\left(\frac{1-\gamma}{1-\varphi}\right)\Delta c_{t+1} + \left(\frac{\varphi-\gamma}{1-\varphi}\right)r_{q,t+1}.$$

The log-return on wealth, $r_{q,t+1}$ can be approximated as

$$r_{q,t+1} = \bar{\eta}_q + \eta_q p_{q,t+1} + \Delta q_{t+1} - p_{q,t}, \quad \text{where} \quad \Delta q_t = \Delta c_t - \left(\frac{1-\varphi}{1+\omega}\right)(\omega+\varphi)\bar{\kappa}\Delta n_t + \frac{(1-\varphi)^2}{1+\omega}\bar{\kappa}\Delta z_t$$

is the wealth-dividend ratio for appropriate approximation constants $\bar{\eta}_q$, η_q, and $\bar{\kappa}$.

Assume that labor follows the process $n_t = \bar{n} + n_a\Delta a_t + n_z z_t$, where $\bar{n}$, n_a, and n_z are determined in equilibrium. From this process, the consumption growth processes $\Delta c_t = \Delta a_t + \Delta n_t$, and the no-arbitrage pricing equation $1 = \mathbb{E}_t[\exp(m_{t,t+1} + r_{q,t+1})]$, it can be shown that the wealth-dividend ratio can be approximated as

$$p_{q,t} = \bar{p}_q + p_{q,a}\Delta a_t + p_{q,z}z_t,$$

where

$$\begin{aligned} p_{q,a} &= \left(\frac{1-\varphi}{1-\eta_q\phi_a}\right)\left[\phi_a - (1-\phi_a)n_a\left(1-\bar{\kappa}\left(\frac{\omega+\varphi}{1+\omega}\right)\right)\right], \\ \text{and} \quad p_{q,z} &= -\frac{(1-\phi_z)(1-\varphi)}{1-\eta_q\phi_z}\left[1+n_z+\bar{\kappa}\left(\frac{1-\varphi-(\omega+\varphi)n_z}{1+\omega}\right)\right]. \end{aligned}$$

C.2.1 The real consol bond

Consider the real consol bond that pays one unit of consumption every period. The price of this bond can be written recursively as

$$B_t^{c,\infty} = \mathbb{E}_t\left[M_{t,t+1}\left(1+B_{t+1}^{c,\infty}\right)\right].$$

Its one-period log-return can be written as

$$r_{\infty,t+1}^c = \log\left(\frac{1+\exp(p_{\infty,t+1}^c)}{\exp(p_{\infty,t}^c)}\right) \approx \bar{\eta}_\infty^c + \eta_\infty^c p_{\infty,t+1}^c - p_{\infty,t}^c\,,$$

where $p_{\infty,t}^c \equiv \log B_t^{c,\infty}$, and $\bar{\eta}_\infty^c$, and $\eta_\infty^c < 1$, are appropriate approximation constants. From the pricing equation $1 = \mathbb{E}_t\left[\exp(m_{t,t+1} + r_{\infty,t+1}^c)\right]$, it can be shown that the log-bond price follows the linear function

$$p_{\infty,t}^c = \bar{p}_\infty^c + p_{\infty,a}^c\Delta a_t + p_{\infty,z}^c z_t$$

where

$$p_{\infty,a}^c = \frac{\varphi[(1-\phi_a)n_a - \phi_a]}{1-\eta_\infty\phi_a}, \quad \text{and} \quad p_{\infty,z}^c = \frac{(1-\phi_z)(1+n_z)\varphi}{1-\eta_\infty\phi_z}.$$

C.2.2 Inflation dynamics

Consider the interest-rate policy rule says that the current interest rate depends on the lagged interest rate as follows

$$i_t = \bar{\imath} + \imath_\pi(\pi_t - \pi^*) + \imath_x(x_t - x_{ss} + u_t\,,$$

where the response to the lagged interest rate i_{t-1} is $\rho = 0$. Under nominal rigidities, the output gap is given by

$$x_t = y_t - y_t^f = n_t - n_t^f + \frac{\log(\mu_w\mu_p)}{\omega+\varphi}\,,$$

where n_t^f denotes labor under no price and wage rigidities. The output gap can be written as

$$x_t = \bar{x} + n_a\Delta a_t + \left(n_z - \frac{1-\varphi}{\omega+\varphi}\right)z_t\,,$$

where $\bar{x}$ is a constant not important for the analysis, and the term $\frac{1-\varphi}{\omega+\varphi}$ is the sensitivity of labor to transitory shocks under flexible prices and wager. From the pricing equation $\mathbb{E}_t\left[\exp\left(m_{t,t+1} - \pi_{t+1} + i_t\right)\right] = 1$, and guessing that

$$\pi_t = \bar{\pi} + \pi_a \Delta a_t + \pi_z z_t,$$

it can be shown that

$$\pi_a = \frac{-\varphi[(1-\phi_a)n_a - \phi_a] - \imath_x n_a}{\imath_\pi - \phi_a}, \quad \text{and} \quad \pi_z = \frac{-\varphi(1-\phi_z)(1+n_z) - \imath_x\left(n_z - \frac{1-\varphi}{\omega+\varphi}\right)}{\imath_\pi - \phi_z}.$$

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