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MONETARY POLICY, SEGMENTATION, AND THE TERM STRUCTURE

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ABSTRACT

We develop a segmented markets model which rationalizes the effects of monetary policy on the term structure of interest rates. When arbitrageurs' portfolio features positive duration, an unexpected rise in the short rate lowers their wealth and raises term premia. A calibration to the U.S. economy accounts for the transmission of monetary shocks to long rates. We discuss the additional implications of our framework for state-dependence in policy transmission, the volatility and slope of the yield curve, and trends in term premia accompanying trends in the natural rate.

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A data appendix is available at http://www.nber.org/data-appendix/w32324
Code to solve model is available at https://github.com/KekreLenel/term

1 Introduction

The effect of a change in short rates on long rates is central to the monetary transmission mechanism. It determines how monetary policy affects mortgage rates, corporate borrowing rates, and other determinants of aggregate demand. Long rates reflect the expected path of short rates plus term premia. There is accumulating empirical evidence that contractionary monetary policy raises long rates by more than can be accounted for by the change in the expected path of short rates.[1] This implies that contractionary monetary policy operates in part by raising term premia.

This evidence poses a challenge to existing models of monetary transmission and the term structure. Representative agent models typically imply that monetary policy shocks have negligible effects on the price and quantity of interest rate and inflation risks. Market segmentation opens the door for transitory shocks to have more substantial effects on term premia if they have relatively large effects on the subset of agents pricing long-term bonds. However, existing models of this kind, most notably those in the preferred habitat tradition, counterfactually imply that a monetary tightening *lowers* term premia, as the associated rise in long yields causes habitat investors to borrow less long-term and thus exposes arbitrageurs to less risk.

In this paper, we propose a model which rationalizes the effects of monetary policy shocks on the term structure of interest rates. We build on the preferred habitat tradition by studying an environment in which habitat investors and arbitrageurs trade bonds of various maturities. We integrate this with the intermediary asset pricing tradition by studying an environment in which arbitrageur wealth is an endogenous state variable governing the price of risk. When arbitrageurs' portfolio features positive duration, an unexpected rise in the short rate lowers their wealth and raises term premia. Quantitatively, a calibration matching the portfolio duration of arbitrageurs in the data rationalizes the responses of the yield curve to monetary shocks. The endogenous price of risk further implies state-dependent effects of conventional and unconventional policies; generates endogenous price volatility which accounts for a sizable fraction of the unconditional slope of the yield curve; and helps to explain trends in term premia in recent years owing to trends in the natural rate.

Our model integrates elements of the preferred habitat and intermediary asset pric-

[1] See, e.g., Cochrane and Piazzesi (2002), Gertler and Karadi (2015), Gilchrist, Lopez-Salido, and Zakrajsek (2015), Hanson and Stein (2015), Abrahams, Adrian, Crump, Moench, and Yu (2016), and Hanson, Lucca, and Wright (2021).

ing traditions. As in existing preferred habitat models, habitat investors elastically demand bonds of each maturity.[2] This class of investors captures the government issuing debt securities net of central bank purchases, households borrowing in mortgages, and other investors who do not actively trade across maturities to maximize risk-adjusted returns. Overlapping generations of arbitrageurs, capturing financial institutions such as broker/dealers and hedge funds, trade across maturities to maximize risk-adjusted returns. Time is continuous, and the short rate and habitat demand across maturities are subject to exogenous shocks. Unlike existing preferred habitat models, arbitrageurs have CRRA (rather than CARA) preferences, and are characterized by perpetual youth (rather than living only instantaneously). The wealth of arbitrageurs is thus an endogenous state variable relevant for risk pricing, as in the intermediary asset pricing tradition.

We first study a simplified version of this environment which allows us to analytically characterize our main results. In the simplified environment, time is discrete and only one- and two-period bonds are traded. If arbitrageurs die after one period and thus their endowment is exogenous, we recover the existing result from preferred habitat models that an unexpected rise in the short rate lowers the term premium on two-period bonds: the associated increase in the two-period yield causes habitat investors to borrow less at this maturity and thus means arbitrageurs are exposed to less interest rate risk. When arbitrageurs live for more than one period, the revaluation of arbitrageurs' wealth also determines the response of the term premium to a short rate shock. In particular, if arbitrageurs' portfolio features positive duration — in this simple setting, if they are long two-period bonds — an unexpected rise in the short rate lowers their wealth. If this force is sufficiently strong relative to the demand elasticity of habitat investors, the term premium rises.

We then numerically quantify these mechanisms in the full, continuous-time model. When arbitrageur wealth is endogenous in the ways described above, bond prices no longer take an exponentially affine structure, and the model does not admit a closed form solution. We can nonetheless describe the equilibrium in terms of a parsimonious system of partial differential equations: equilibrium in the bond market implied by arbitrageurs' optimization and market clearing; the endogenous evolution of arbitrageur wealth; and the exogenous evolutions of the short rate and habitat demand. We solve

[2]We use the term "habitat investors" to be consistent with the prior literature. However, this does not require that they have positive positions in long-term bonds; indeed, in our calibration they will be borrowers in long-term bonds.

this system numerically using the Feynman-Kac formula and Monte Carlo simulation. We expect our code can be useful to other researchers who wish to study the yield curve in an environment with heterogeneous agents and an endogenous price of risk.

We confront the model with estimates of the yield curve responses to monetary policy shocks. In the data, we isolate monetary policy shocks from other shocks by using the high-frequency response of futures prices around FOMC announcements as an instrumental variable. Our baseline estimates imply that a policy-induced rise in the one-year ahead one-year real forward by $1pp$ raises the one-year real forward rate paying in five (10) years by over $0.50pp$ (nearly $0.20pp$). This economically and statistically significant increase in long-dated real forward rates is robust to a variety of specifications, including alternative measures of monetary policy shocks and samples which exclude the worst months of the financial crisis. This in turn means that a monetary tightening raises term premia (and an easing lowers term premia), since both evidence on the dynamic responses to monetary shocks as well as theoretical models imply that the expected real interest rate must be essentially unchanged within a few years after a monetary shock. Our primary quantitative question of interest is whether our model can account for this evidence.

We discipline the model to match novel evidence on the duration of arbitrageurs. Following the literature on intermediary asset pricing, we associate these arbitrageurs with broker/dealers and hedge funds. We employ two approaches to measure their aggregate duration. The first combines evidence on the average duration of individual assets such as Treasuries, mortgage-backed securities, and corporate equities with the portfolio holdings of broker/dealers and hedge funds in these asset classes. The second estimates the response of primary dealers' equity prices in tight windows around FOMC announcements. Both approaches imply that these arbitrageurs have an aggregate duration between roughly 10 and 30. The implication that arbitrageurs lose wealth upon a monetary tightening is validated by a broader set of evidence from asset prices, such as an increase in the excess bond premium and widening of CIP deviations.

Calibrated to match this evidence on arbitrageur duration, our model can account for much of the responses of long-dated real forward rates to monetary shocks in the data. In particular, in our baseline calibration with arbitrageur duration at the lower end of our estimated range in the data, a monetary tightening which raises the one-year ahead one-year real forward by $1pp$ raises the five- (10-) year real forward rate by roughly $0.30pp$ ($0.20pp$). At higher values of arbitrageur duration within our estimated range, or when habitat demand is less elastic, the model generates even more overreaction of forward rates. The overreaction of forward rates vis-à-vis the expectations hypothesis is reversed in a counterfactual economy with exogenous arbitrageur wealth, consistent with our analytical results.

The endogenous price of risk via arbitrageur wealth has several additional implications. First, it implies state-dependent effects of both conventional and unconventional policies. For instance, we simulate the Federal Reserve's March 18, 2009 announcement that it would purchase long-term Treasuries and increase the size of its agency debt and mortgage-backed security purchases. We find that the 10-year real yield would have fallen by roughly 20% less if arbitrageur wealth was initially at its average level instead of depressed by a third. Second, the model clarifies that fluctuations in arbitrageur wealth account for roughly 20% of the average slope of the yield curve, because they generate endogenous and stochastic volatility in bond prices. Finally, the revaluation of arbitrageur wealth can help account for trends in term premia in recent years via trends in the natural rate of interest. A persistent decline in the short rate recapitalizes arbitrageurs with positive duration much like a transitory monetary easing. Quantitatively, the wealth revaluation from a $1pp$ persistent decline in the short rate generates a nearly $0.20pp$ decline in the 5-year forward, 5-year term premium on impact.

In the post-pandemic period, yield curve models indicate that long yields have risen in part because of a higher real term premium. At the same time, U.S. monetary policy has tightened and there is evidence of an increase in the U.S. natural rate. Our framework provides a way to relate these developments, though we leave a quantitative exploration of the recent increase in the term premium to future work.

Related literature Our paper builds on preferred habitat models of the term structure of interest rates. The preferred habitat view was proposed by Culbertson (1957) and Modigliani and Sutch (1966) and formalized by the seminal work of Vayanos and Vila (2021). A growing theoretical literature has used this framework to study the implications for corporate finance (Greenwood, Hanson, and Stein (2010)), government debt policy (Guibaud, Nosbusch, and Vayanos (2013)), exchange rates (Gourinchas, Ray, and Vayanos (2024) and Greenwood, Hanson, Stein, and Sunderam (2023)), and the real economy (Ray (2021) and Ray, Droste, and Gorodnichenko (2024)). An enormous empirical literature has drawn on this framework to inform analyses of unconventional monetary policies. In the existing framework, the effects of the key driving force (the short rate) are counterfactual. We enrich this framework to match evidence on the response to such shocks by allowing the wealth of arbitrageurs to be an endogenous state variable relevant for risk pricing.

In doing so, our paper builds on the literature linking changes in intermediary net worth with asset prices. This is at the core of the intermediary asset pricing tradition in finance (He and Krishnamurthy (2013) and Brunnermeier and Sannikov (2014)) as well as the financial accelerator tradition in macroeconomics (Bernanke, Gertler, and Gilchrist (1999)). Our contribution is to embed this insight into a leading model of the term structure of interest rates.[3] The recent analyses of Haddad and Sraer (2020), He, Nagel, and Song (2022), and Schneider (2024) similarly apply insights from intermediary asset pricing models to the term structure, though their focus differs from ours on monetary transmission.

Our emphasis on the wealth revaluation channel in accounting for the term premium effects of monetary shocks contrasts with alternative explanations focused instead on habitat demand or changing policy rules.[4] Hanson (2014), Hanson and Stein (2015), and Hanson et al. (2021) propose models in which habitat investors have upward-sloping demand for long-term bonds in response to short rate shocks, perhaps due to mortgage refinancing, "reaching for yield", or duration matching of life insurance companies and pension funds.[5] Bianchi, Lettau, and Ludvigson (2021), Bauer, Pflueger, and Sunderam (2024), and Bianchi, Ludvigson, and Ma (2024) propose models in which investors learn about changing policy rules and thus future comovements around monetary announcements. Our model is fully complementary with these mechanisms. However, we also demonstrate that the wealth revaluation channel — disciplined by evidence on arbitrageurs' duration and reflected in the broader response of asset prices — can largely account for the yield curve responses to monetary shocks on its own.

Our paper is finally part of a broader agenda studying links between macroeconomic shocks, the wealth distribution, and the price of risk in heterogeneous agent models.

[3] In their empirical analysis of government bond supply and excess returns, Greenwood and Vayanos (2014) anticipate that if arbitrageurs' coefficient of absolute risk aversion is a declining function of their wealth, changes in their wealth will have effects on term premia. Our paper formalizes this idea and traces out its theoretical and quantitative implications.

[4] There is an additional mechanism which may be complementary to these, namely that in the presence of a lower bound on the nominal interest rate, a monetary easing lowers the amount of future interest rate risk and thus term premia, and vice-versa for a tightening. See, for instance, King (2019).

[5] See also Malkhozov, Mueller, Vedolin, and Venter (2016) and Domanski, Shin, and Sushko (2017). The cross-elasticities of demand emphasized by Jansen, Li, and Schmid (2024) behave similarly to the upward-sloping habitat demand curves in the aforementioned papers as well.

Alvarez, Atkeson, and Kehoe (2002, 2009) study monetary economies with segmented financial markets in which monetary shocks change the price of risk. Kekre and Lenel (2022) build on these insights in a conventional New Keynesian model enriched with agents having heterogeneous risk-bearing capacity. They find that a monetary easing lowers the risk premium on capital by redistributing wealth to agents who wish to invest more of their marginal wealth in capital. The present paper shows that a similar mechanism is at work for the term premium in a preferred habitat environment.[6] While we do not extend the model to feature a New Keynesian production block, we expect that the effects of policy shocks on the term premium would imply that monetary policy is more potent in affecting the real economy to the extent that aggregate demand is rising in the amount habitat investors borrow long-term.[7]

Outline In section 2 we outline the model environment. In section 3 we characterize our main results analytically in a simple version of this environment. In section 4 we estimate the effects of policy shocks on the yield curve and measure arbitrageurs' duration in the data. In section 5 we calibrate the full model and assess its ability to rationalize the data. Finally, in section 6 we conclude.

2 Model

In this section we outline our model of the term structure of interest rates. The model integrates features of the preferred habitat and intermediary asset pricing traditions.

Timing and assets Time t is continuous. At time t there is a continuum of zero coupon bonds with maturities $\tau \in (0, \infty)$. A bond trading at t with maturity τ pays one unit of the numeraire at $t + \tau$ and its price is $P_t^{(\tau)}$. The instantaneous return on

[6] We conjecture that introducing heterogeneity in risk aversion into representative agent models in which aggregate comovements deliver a positive term premium, as in Piazzesi and Schneider (2007), Rudebusch and Swanson (2012), and Campbell, Pflueger, and Viceira (2020), would lead to similar results. With a positive price on term risk, relatively risk tolerant agents would endogenously be more exposed to it, implying a redistribution of wealth which affects the price of risk on impact of policy shocks. The preferred habitat environment is effectively an extreme version of such an environment, wherein the demand of habitat investors for long-term bonds is invariant to changes in their wealth.

[7] See Caballero and Simsek (2020) for recent work linking risk premia, aggregate demand, and output in the New Keynesian environment. See Caramp and Silva (2023) for recent work linking term premia and aggregate demand in such an environment in particular.

holding such a bond is $dP_t^{(\tau)}/P_t^{(\tau)}$. The yield of the bond is given by

$$y_t^{(\tau)} = -\frac{\log\left(P_t^{(\tau)}\right)}{\tau}$$

and the short rate r_t is the limit of the yield as τ goes to zero.

Decision problems There are two types of agents: habitat investors and arbitrageurs. The former captures investors such as the government issuing debt securities net of central bank purchases and households borrowing in long-term mortgages, while the latter captures financial institutions such as broker/dealers and hedge funds which trade across maturities to maximize risk-adjusted returns.

In aggregate, habitat investors hold positions

$$Z_t^{(\tau)} = -\alpha(\tau)\log\left(P_t^{(\tau)}\right) - \theta_t(\tau) \tag{1}$$

at each maturity $\tau \in (0, \infty)$, where a positive position implies that these investors are saving in this security. The parameter $\alpha(\tau)$ controls the elasticity of demand to price. $\theta_t(\tau)$ controls the level of habitat demand and is given by

$$\theta_t(\tau) = \theta_0(\tau) + \theta_1(\tau)\beta_t, \tag{2}$$

where β_t is a demand factor, the parameter $\theta_1(\tau)$ controls the loading of demand on that factor, and the parameter $\theta_0(\tau)$ controls the time-invariant level of demand.

Arbitrageurs trade at all maturities as well as at the short rate r_t with the central bank.[8] Arbitrageurs are born and die at rate ξ, discount the future at rate ρ, and have separable CRRA preferences over consumption upon death with risk aversion γ.[9,10] Here we depart from typical preferred habitat models which assume arbitrageurs

[8]The statement that arbitrageurs trade at the short rate r_t with the central bank encodes our assumption that the short rate is exogenous, as in existing preferred habitat models. In other words, the central bank adjusts its borrowing/lending at the short rate to clear the market at that rate, so we do not specify the market clearing condition at that rate. However, as we describe later in this section, we allow the short rate to be correlated with habitat demand β_t, capturing the fact that in fully-specified general equilibrium models, they will both depend on common fundamentals.

[9]The death rate ξ acts like a discount rate in arbitrageurs' decision problem. We nonetheless account for a distinct discount rate ρ because this will control the strength of the intertemporal hedging motive in portfolio choice when $\gamma \neq 1$, as clarified in section 5.

[10]Consumption only upon death allows us to nest the environment in Vayanos and Vila (2021) when $\xi \to \infty$. However, it is straightforward to allow arbitrageurs to consume throughout life. We

are alive instantaneously and have CARA preferences over consumption upon death. Using lower case to denote the endowment and choices of an individual arbitrageur with wealth w_t, this arbitrageur chooses its sequence of financial portfolios to maximize

$$v_t(w_t) = \max_{\{\{x_{t+s}^{(\tau)}\}\}} E_t \int_0^\infty \exp(-(\xi+\rho)s)(\xi+\rho)\left(\frac{w_{t+s}^{1-\gamma}-1}{1-\gamma}\right) ds \tag{3}$$

subject to the budget constraint

$$dw_t = w_t r_t dt + \int_0^\infty x_t^{(\tau)} \left(\frac{dP_t^{(\tau)}}{P_t^{(\tau)}} - r_t dt\right) d\tau, \tag{4}$$

where $x_t^{(\tau)}$ denotes its position in bonds with maturity τ.[11] Using upper case to denote aggregates across arbitrageurs, aggregate arbitrageur wealth thus follows

$$dW_t = W_t r_t dt + \int_0^\infty X_t^{(\tau)} \left(\frac{dP_t^{(\tau)}}{P_t^{(\tau)}} - r_t dt\right) d\tau + \xi\left(\bar{W} - W_t\right) dt, \tag{5}$$

where $\bar{W}$ is the exogenous endowment of newborn arbitrageurs. When $\xi \to \infty$, this converges to the constant endowment process in Vayanos and Vila (2021). For finite ξ, W_t will be an endogenous state variable of the model as in intermediary asset pricing models such as He and Krishnamurthy (2013) and Brunnermeier and Sannikov (2014), and financial accelerator models such as Bernanke et al. (1999).

Driving forces The short rate and demand factor load on latent state variables $\{\omega_{1t}, \omega_{2t}\}$ according to

$$r_t = \bar{r} + \sigma_{r,1}\omega_{1,t} + \sigma_{r,2}\omega_{2,t}, \tag{6}$$

$$\beta_t = \sigma_{\beta,1}\omega_{1,t} + \sigma_{\beta,2}\omega_{2,t}, \tag{7}$$

where each of the latent states evolves according to an Ornstein-Uhlenbeck process

$$d\omega_{1,t} = -\kappa_1\omega_{1,t}dt + dB_{1,t}, \tag{8}$$

show in appendix C.6 that the quantitative properties of such a model are very similar to those of our baseline model with finite ξ.

[11] To simplify expressions for the equilibrium value function which follows, we include the multiplicative scalar $\xi+\rho$ in the definition of the value function. This is of course without loss of generality.

$$d\omega_{2,t} = -\kappa_2 \omega_{2,t} dt + dB_{2,t}, \tag{9}$$

with independent Wiener increments $dB_{1,t}$ and $dB_{2,t}$. Assuming $\kappa_1 \geq \kappa_2$ without loss of generality, we refer to $\omega_{1,t}$ as the transitory latent state variable and $\omega_{2,t}$ as the persistent one. The comovement of the short rate and habitat demand in response to each latent driving force allows us to capture the feature of richer general equilibrium models that shocks to fundamentals are jointly reflected in demand and the short rate. Setting $\sigma_{\beta,1} = 0$ and $\sigma_{r,2} = 0$ allows us to nest the case of an independent short rate and demand factor studied in Vayanos and Vila (2021).

Market clearing and equilibrium Bond markets must clear according to

$$Z_t^{(\tau)} + X_t^{(\tau)} = 0 \tag{10}$$

for each maturity $\tau \in (0, \infty)$ at each point in time t. The definition of an equilibrium is standard.

Interpretation We interpret the model in real terms. We do this for two reasons. First, focusing on real bonds allows us to study our mechanism focused on interest rate risk in a more parsimonious setting which can abstract away from inflation risk.[12] Second, focusing on the real term structure allows us to uncover the effects of monetary shocks on term premia purged from any effects on long-run inflation. In particular, monetary policy shocks may contain news about the long-run inflation target, which in turn will affect long-dated nominal forwards (Gurkaynak, Sack, and Swanson (2005b)). Long-dated real forwards are immune from this issue, and moreover monetary neutrality implies that expected real interest rates beyond a few years in the future should be unaffected by monetary shocks. In both model and data, this allows a tight analysis of the effects of a monetary shock on term premia by studying the response of real forwards on impact of the shock, following Hanson and Stein (2015).

It is also useful at this stage to clarify how we think of monetary shocks in the model. We view these as distinct from the "typical" shocks to the short rate $dB_{1,t}$ and $dB_{2,t}$ which arise from shocks to fundamentals like productivity, credit conditions, and demographics. This reflects that the systematic component of monetary policy, which

[12] With that said, our analysis would extend to a setting with inflation risk: a change in arbitrageurs' wealth would affect their willingness to be exposed to this risk and thus the inflation risk premium.

tracks these fundamentals, accounts for the overwhelming amount of variation in the short rate. We thus simulate a monetary shock in the model as a one-off, unanticipated shock to the short rate with speed of mean reversion κ_m. Studying unanticipated monetary shocks in both data and model is useful because, by construction, these shocks are orthogonal to the fundamentals which also affect habitat demand, allowing us to identify the effects of a change in the short rate alone. This in turn is informative about the transmission of the systematic component of monetary policy as well.

3 Analytical insights

We now study a simplified version of the model which allows us to analytically characterize our main results. When arbitrageur wealth is endogenous and their portfolio features positive duration, an unexpected rise in the short rate lowers their wealth and raises term premia.

3.1 Simplified environment

In this section we assume time is discrete and only two bonds are traded: maturities one and two periods.[13] We further assume log preferences ($\gamma = 1$) and independent short rate and habitat demand ($\sigma_{\beta,1} = 0$ and $\sigma_{r,2} = 0$). This environment captures the essential forces at play in our full model.

We now spell out the details. Arbitrageurs trade in one-period bonds at price $\exp(-r_t)$ set by the central bank and in two-period bonds at price P_t, where we now dispense with the notation for maturity τ since it is unambiguous. Habitat investors hold a position

$$Z_t = -\alpha \log P_t - \theta_t$$

in two-period bonds, as in (1). An arbitrageur with wealth w_t chooses its position in two-period bonds x_t to maximize

$$\max_{\{x_{t+s}\}} E_t \sum_{s=1}^{\infty} \exp(-(\xi+\rho)s)(\xi+\rho) \log w_{t+s}$$

[13] Note, however, that we continue to study an infinite horizon setting.

subject to the evolution of wealth

$$w_{t+1} = w_t \exp(r_t) + x_t \left(\frac{\exp(-r_{t+1})}{P_t} - \exp(r_t) \right),$$

the discrete time counterparts to (3)-(4) with $\gamma = 1$. Note that the one-period return on a two-period bond is $\exp(-r_{t+1})/P_t$ because the two-period bond at t becomes a one-period bond at $t+1$, with price $\exp(-r_{t+1})$. Aggregate arbitrageur wealth follows

$$W_{t+1} = \exp(-\xi) \left[W_t \exp(r_t) + X_t \left(\frac{\exp(-r_{t+1})}{P_t} - \exp(r_t) \right) \right] + (1 - \exp(-\xi))\bar{W},$$

the discrete time counterpart to (5). The short rate and habitat demand follow the AR(1) processes

$$r_{t+1} - \bar{r} = (1 - \kappa_r)(r_t - \bar{r}) + \sigma_r \epsilon_{r,t+1}, \tag{11}$$

$$\theta_{t+1} - \bar{\theta} = (1 - \kappa_\theta)\left(\theta_t - \bar{\theta}\right) + \sigma_\theta \epsilon_{\theta,t+1}, \tag{12}$$

where $\epsilon_{r,t+1}$ and $\epsilon_{\theta,t+1}$ are independent standard Normal innovations. $\kappa_r \in (0,1)$ and $\kappa_\theta \in (0,1)$ can be interpreted as the degree of mean reversion in these driving forces, as in (8) and (9). We dispense with β_t in this section because it is isomorphic to θ_t since there is only one long-term bond. Finally, as in (10), bond market clearing requires

$$X_t + Z_t = 0.$$

3.2 Equilibrium

Following standard arguments, arbitrageurs' optimality condition with respect to x_t is

$$E_t \left(\exp(r_t) + \frac{x_t}{w_t} \left(\frac{\exp(-r_{t+1})}{P_t} - \exp(r_t) \right) \right)^{-1} \left[\frac{\exp(-r_{t+1})}{P_t} - \exp(r_t) \right] = 0, \tag{13}$$

implying that their portfolio share $\frac{x_t}{w_t}$ is invariant to wealth. Defining the log one-period holding return on a two-period bond

$$r_{t+1}^{(2)} \equiv -r_{t+1} - \log P_t \tag{14}$$

and making use of

$$\frac{x_t}{w_t} = \frac{X_t}{W_t} \tag{15}$$

by aggregation, a second-order Taylor approximation of (13) around $r_{t+1}^{(2)} = r_t$ implies

$$E_t r_{t+1}^{(2)} - r_t + \frac{1}{2}\sigma_r^2 \approx \frac{X_t}{W_t}\sigma_r^2. \tag{16}$$

This has an intuitive interpretation. Arbitrageurs require non-zero expected excess returns to compensate them for bearing interest rate risk on two-period bonds. In particular, when $X_t > 0$, arbitrageurs are long two-period bonds and thus expected excess returns on two-period bonds must be positive; the opposite is true if $X_t < 0$. The higher is arbitrageur wealth W_t, the smaller (in absolute value) expected excess returns must be, because two-period bonds are a smaller share of their wealth and arbitrageurs have CRRA preferences. In the limit $W_t \to \infty$, arbitrageurs are effectively risk neutral and thus the (local) expectations hypothesis holds.[14] The relevance of W_t in risk pricing is the key distinction between the present model and existing preferred habitat models.

The above condition is the only approximation we use in the rest of this section; all other conditions hold exactly. Combining the above condition with market clearing in two-period bonds and habitat investors' demand yields

$$E_t r_{t+1}^{(2)} - r_t + \frac{1}{2}\sigma_r^2 = \frac{1}{W_t}\left(\alpha \log P_t + \theta_t\right)\sigma_r^2. \tag{17}$$

Combining the evolution of aggregate arbitrageur wealth with market clearing in two-period bonds and habitat investors' demand yields

$$W_{t+1} = \exp(-\xi)\left[W_t \exp(r_t) + \left(\alpha \log P_t + \theta_t\right)\left(\exp(r_{t+1}^{(2)}) - \exp(r_t)\right)\right] + (1-\exp(-\xi))\bar{W}. \tag{18}$$

The dynamical system (11)-(12), (14), and (17)-(18) is thus five equations in five unknowns r_{t+1}, θ_{t+1}, $r_{t+1}^{(2)}$, P_t, and W_{t+1}, given r_t, θ_t, and W_t. The rest of this section proceeds through our two main results studying a short rate shock $\epsilon_{r,t}$.

[14]The standard Jensen's inequality term $\frac{1}{2}\sigma_r^2$ implies that the expectations hypothesis does not hold. See Piazzesi (2010) for further discussion of this point.

3.3 Effects of short rate shock

We characterize the effects of the shock around the stochastic steady-state, denoted without time subscripts, for expositional simplicity.

Our first result describes the impact effect of the shock on arbitrageur wealth W_t:[15]

Proposition 1. *The response of arbitrageur wealth to a short rate shock is*

$$d \log W_t = -\exp(-\xi) D \sigma_r d\epsilon_{r,t},$$

where D is the duration of arbitrageurs' wealth and satisfies

$$D \propto \frac{X}{W}.$$

Intuitively, consider an unexpected rise in the short rate. When arbitrageurs' aggregate wealth is endogenous (finite ξ), their wealth will be revalued downwards if and only if their portfolio has positive duration at the stochastic steady-state, which amounts in this environment to a positive position in two-period bonds X. When arbitrageurs' aggregate wealth is exogenous ($\xi \to \infty$), this mechanism is shut down.

Our second result describes the impact effect of the shock on the one-period ahead forward rate

$$f_t \equiv -\log P_t - r_t. \tag{19}$$

We focus on this anticipating our empirical work studying the impact effect on forward rates, though it is straightforward to characterize the full impulse response of the forward rate or transformations such as bond yields. We obtain:

Proposition 2. *The response of the one-period ahead forward rate to a short rate shock is*

$$df_t = \left[\frac{1-\kappa_r - \frac{1}{W}\alpha\sigma_r^2}{1+\frac{1}{W}\alpha\sigma_r^2} + \frac{\frac{1}{W}X\sigma_r^2}{1+\frac{1}{W}\alpha\sigma_r^2}\exp(-\xi)D\right]\sigma_r d\epsilon_{r,t}.$$

Thus, if $\xi \to \infty$ (exogenous arbitrageur wealth), there is underreaction *of the forward rate relative to the expected short rate*

$$|df_t| < (1-\kappa_r)\sigma_r|d\epsilon_{r,t}| = |dE_t r_{t+1}|$$

if $\alpha\sigma_r^2 > 0$. If ξ is finite (endogenous arbitrageur wealth), there is overreaction *of the*

[15]The proofs of this result and the next one are in appendix A.

forward rate relative to the expected short rate

$$|df_t| > (1 - \kappa_r)\sigma_r|d\epsilon_{r,t}| = |dE_t r_{t+1}|$$

if $\exp(-\xi)|D|$ *is sufficiently high relative to* α*, given* $\sigma_r > 0$*.*

Thus, when $\xi \to \infty$, we recover the effects of short rate shocks in existing preferred habitat models.[16] Intuitively, consider an unexpected rise in the short rate. Holding fixed habitat investor borrowing, this raises the two-period bond yield. If habitat investors are price elastic ($\alpha > 0$), this causes them to borrow less in two-period bonds. If arbitrageurs face price risk in these bonds ($\sigma_r > 0$), this lowers the term premium, reflected in underreaction of the forward rate. To summarize: a rise in the short rate lowers the term premium because arbitrageurs must bear less risk.

When arbitrageurs' wealth is a relevant state variable for risk pricing (finite ξ), we can reverse the effects of a short rate shock on the term premium. In particular, if arbitrageurs have positive duration $D \propto \frac{X}{W}$, we know from (17) that the steady-state term premium is positive. A fall in their wealth raises their price of bearing interest rate risk. If this force is sufficiently strong relative to the decrease in the quantity of risk they bear — controlled by α, as described in the prior paragraph — the term premium will rise. This is reflected in overreaction of the forward rate.[17,18]

[16] See for instance Proposition 2 in Vayanos and Vila (2021).

[17] Proposition 2 also implies that if $D < 0$ but is sufficiently large in absolute value, there will still be overreaction of the forward rate. This is because the steady-state term premium is negative, and a rise in the short rate will revalue wealth in favor of arbitrageurs. This will make the term premium less negative, and thus cause overreaction of the forward rate. Of course, the more empirically relevant case features $D > 0$ and a positive term premium in steady-state, which is why we focus on it.

[18] We also note that the relevance of the wealth revaluation channel has applicability beyond the particular environment studied here. For instance, suppose arbitrageurs are risk neutral but face a leverage constraint which depends on their wealth

$$|x_t| \leq \kappa w_t,$$

where $\kappa > 0$ controls the tightness of this constraint. If the constraint is binding and arbitrageurs are long two-period bonds, it implies that in aggregate

$$\alpha \log P_t + \theta_t = \kappa W_t.$$

Hence, an increase in arbitrageur wealth will again raise the price of two-period bonds and thus lower the forward rate. In this sense, the wealth revaluation channel can also operate through wealth-dependent constraints, rather than preferences. We thank a referee for pointing this out.

4 Empirical analysis

Motivated by these results, we now estimate the effects of monetary shocks on the yield curve and measure arbitrageurs' duration. Our core question of interest in the balance of the paper will be whether a calibration of the full model matching arbitrageurs' duration can account for the effects of monetary shocks along the yield curve.

4.1 Effects of monetary shocks on yield curve

We first study the response of the yield curve to announcements of the Federal Open Market Committee (FOMC).

4.1.1 Approach

Given one-year real forward rates $\{f_t^{(\tau-1,\tau)}\}$ paying $\tau \in \{2, \ldots, 10\}$ years from day t, we estimate the effect of intraday monetary surprises on the daily change in $\{f_t^{(\tau-1,\tau)}\}$. These monetary surprises are measured using the response of Fed funds and Eurodollar futures contracts in 30-minute windows around FOMC announcements. We focus on variation induced by the high-frequency monetary surprise because even on days with FOMC announcements, there is news orthogonal to monetary policy which may also affects yields and other outcome variables.

To ease interpretation of our results, we implement these regressions using a two-stage least squares design: we first project the daily change in $f_t^{(1,2)}$ on the monetary surprise, and we then project the daily change in all other forward rates $f_t^{(\tau-1,\tau)}$ on the fitted daily change in $f_t^{(1,2)}$. This allows us to compare across specifications using different monetary surprises, since each specification reflects the effects of a monetary surprise which raises the one-year ahead one-year real forward by $1pp$.[19]

4.1.2 Data

We use Gurkaynak, Sack, and Wright (2008)'s interpolated yield curve, maintained and updated by the Federal Reserve, to obtain yields and forwards at a daily frequency. As previously noted, we focus on the real yield curve.[20] We focus on yields and forwards

[19]The point estimates are identical to simply scaling each specification so that the effect of the surprise on $f_t^{(1,2)}$ is $1pp$, but the instrumental variable design adjusts standard errors to account for the fact that the response of $f_t^{(1,2)}$ is itself estimated.

[20]We present empirical estimates using the nominal yield curve from Gurkaynak, Sack, and Wright (2006) in appendix B.3.

paying in two to 10 years. We exclude maturities below two years because TIPS with maturity below 18 months are excluded from the fitted yield curve in Gurkaynak et al. (2008). We exclude maturities above 10 years to minimize the concern that our results are affected by changing liquidity premia, since most TIPS are issued at 10-year and shorter maturities.[21]

Our baseline measure of monetary surprises is from Bauer and Swanson (2023a). This is the first principal component of responses in the first four quarterly Eurodollar futures contracts in the 30 minutes around FOMC announcements, parsimoniously capturing surprises to the near term path of monetary policy. We also consider alternative measures of monetary surprises using the current Fed funds contract alone (from Swanson (2021b)), three-month ahead Fed funds contract alone (from Jarocinski and Karadi (2020a)), and longer term prices alone (the "forward guidance" factor from Swanson (2021b)), as well as Nakamura and Steinsson (2018a)'s first principal component of Fed funds and Eurodollar responses which is similar to our baseline measure but uses more information from near-term contracts.

Bauer and Swanson (2023a) demonstrate that all of these measures of monetary surprises are predictable using information known prior to the FOMC announcement. They interpret this as evidence of the market learning about the Federal Reserve's reaction function to news released between FOMC meetings. Since changes in (the market's perceptions of) the reaction function may affect risk premia through a channel distinct from the one we emphasize in this paper, we orthogonalize all of our measures of monetary surprises with respect to macroeconomic and financial variables known prior to the FOMC announcement.[22] We also present sensitivity analysis to not orthogonalizing the monetary surprise in this way.

We use the January 2004 through December 2019 period for our analysis. While TIPS have been traded since the late 1990s, maturities below five years were only included in Gurkaynak et al. (2008)'s interpolated real yield curve since 2004. We end our sample in 2019 as this is the last year in Bauer and Swanson (2023a)'s sample.[23]

[21] Appendix B.1 depicts the time to maturity of all TIPS outstanding over our sample period.

[22] Following Bauer and Swanson (2023a), these are the most recent nonfarm payrolls surprise; employment growth over the past year; the change in the S&P 500, slope of the nominal yield curve, and commodity price index in the three months prior to the announcement; and implied skewness of the ten-year nominal Treasury yield over the prior month from Bauer and Chernov (2023).

[23] Our sample ends in 2016 using the Jarocinski and Karadi (2020a) surprise, and in 2014 using the Nakamura and Steinsson (2018a) surprise, given the periods studied by these papers. We use the "full sample" studied in the latter paper (that is, we do not exclude July 2008 through June 2009).

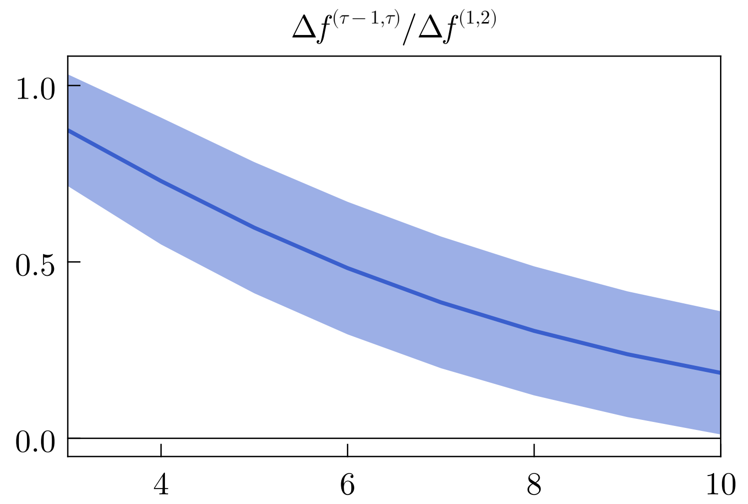

Figure 1: $\Delta f_t^{(\tau-1,\tau)}$ on $\Delta f_t^{(1,2)}$, instrumented by high-frequency surprise

Notes: at each integer τ on the x-axis, we plot coefficient and 95% confidence interval using $\Delta f_t^{(\tau-1,\tau)}$ as the outcome variable. Confidence intervals based on robust standard errors.

4.1.3 Results

Figure 1 plots the baseline estimates and associated 95% confidence intervals. We find that long-dated forward rates respond economically and statistically significantly to a monetary tightening: given a surprise which raises the one-year ahead one-year forward by $1pp$, the one-year forward paying in five years rises by more than $50bp$ and the one-year forward paying in 10 years rises by nearly $20bp$.[24]

Table 1 demonstrates that the significant responses of forwards paying in five years and beyond are not limited to announcements during the depth of the financial crisis or to those accompanied by other policy news. The first row summarizes the baseline estimates of a monetary tightening on the four-, six-, eight-, and 10-year forwards (the same as the relevant points in Figure 1). The second row drops all announcements between July 2008 and June 2009 to eliminate the most acute phase of the financial crisis. The response of the one-year forward paying in six years remains economically and statistically significant. The third row drops all announcements involving any news about asset purchases or non-standard credit operations, as classified by Cieslak and Schrimpf (2019b). In this case, the response of the one-year forward paying in eight

[24] Appendix B.1 visually depicts the relationship between the change in the real forward rate and the change in the one-year yield induced by the high-frequency monetary surprise, and makes clear that the positive relationship for long-dated forwards is not driven by any one observation.

Specification	$\Delta f_t^{(3,4)}$	$\Delta f_t^{(5,6)}$	$\Delta f_t^{(7,8)}$	$\Delta f_t^{(9,10)}$
Baseline	0.73	0.48	0.30	0.19
	(0.09)	(0.10)	(0.09)	(0.09)
Excl. 7/08-6/09	0.68	0.35	0.11	-0.05
	(0.13)	(0.11)	(0.10)	(0.11)
Excl. days w. LSAP news	0.67	0.44	0.27	0.14
	(0.12)	(0.13)	(0.12)	(0.10)
Without orthogonalizing IV	0.76	0.53	0.35	0.23
	(0.09)	(0.09)	(0.09)	(0.11)
Swanson (2021b) Fed funds IV	0.56	0.28	0.12	0.03
	(0.19)	(0.27)	(0.27)	(0.20)
Jarocinski and Karadi (2020a) IV	0.58	0.33	0.17	0.08
	(0.10)	(0.12)	(0.12)	(0.10)
Nakamura and Steinsson (2018a) IV	0.84	0.41	0.14	0.07
	(0.13)	(0.14)	(0.17)	(0.18)
Swanson (2021b) forward guidance IV	0.84	0.61	0.42	0.28
	(0.10)	(0.10)	(0.09)	(0.08)

Table 1: $\Delta f_t^{(\tau-1,\tau)}$ on $\Delta f_t^{(1,2)}$, instrumented by high-frequency surprise

Notes: robust standard errors provided in parenthesis.

years remains economically and statistically significant.

Table 1 also demonstrates that our results are robust to a variety of alternative measures for monetary surprises. We first consider the same Bauer and Swanson (2023a) monetary surprise used in the baseline specification, but no longer orthogonalize it with respect to macroeconomic news known prior to the announcement. This has minimal effects on our estimates, suggesting that changes in the perceived Fed reaction function are not the primary reason why long-dated real forwards respond to the monetary surprises that we study. We next consider the alternative monetary surprise measures described in the prior subsection. The Swanson (2021b) and Jarocinski and Karadi (2020a) surprise measures use very near term futures contracts and feature smaller responses of forward rates than our baseline specification; we interpret this as reflecting lower power among very near term futures contracts over our sample period, given that the zero lower bound was binding for much of the time. The Nakamura and Steinsson (2018a) surprise measure, which uses information from these same near term futures contracts, similarly features smaller responses of long-dated forward rates than our baseline. Even using the Jarocinski and Karadi (2020a) or Nakamura and Steinsson (2018a) measures, however, the response of the one-year forward paying in six years remains economically and statistically significant. Using the Swanson (2021b) forward guidance monetary surprise measure, we estimate an even stronger response of long-dated forwards than in our baseline.

Taken together, there are three possible interpretations of these results: that a surprise monetary tightening raises the expected real interest rate more than five years in the future; that a surprise monetary tightening in fact communicates news about the underlying state of the economy which raises expected real interest rates more than five years in the future; or that a surprise monetary tightening raises real term premia. The first interpretation is inconsistent with the dynamic effects of monetary policy shocks as well as the degree of monetary non-neutrality in New Keynesian models. For instance, the local projections or VAR-based evidence in Ramey (2016) and Bauer and Swanson (2023a) implies that the effects of monetary shocks on the Fed funds rate and short-dated Treasury yields essentially die out within three or four years.

The second interpretation — that a "Fed information effect" explains the long-horizon response of real forwards — is inconsistent with the responses of survey-based forecasts to these same monetary surprises. Following Bauer and Swanson (2023b), in appendix B.2 we study the response of professional forecasts summarized in the Blue Chip Economic Indicators around FOMC announcements. We find that a surprise monetary tightening is associated with expectations of higher unemployment, lower GDP growth, and lower CPI inflation. These are inconsistent with the interpretation that a monetary tightening conveys news about a higher natural rate of interest, as for instance driven by higher underlying growth. To be clear, this evidence does not mean that Fed information effects are unimportant; it simply suggests that the effects we estimate on long-horizon real forwards are not driven by such information effects.[25]

We thus conclude from the response of long-dated real forwards that a surprise monetary tightening raises real term premia. Our analysis echoes the basic message of Hanson and Stein (2015), but demonstrates that it is robust to an analysis using intraday monetary surprises to sharpen identification, and using data from professional forecasters to cast doubt on a "Fed information" interpretation of this result.

[25]The effects on survey expectations also help explain differences in the response of nominal and real forwards, explored further in appendix B.3. Nominal forwards exhibit a smaller response to a monetary tightening at all maturities, implying a decline in forward breakeven inflation rates. This is consistent with the decline in forecasts of expected inflation around FOMC announcements. This may reflect the effects of both a monetary tightening on inflation, as well as news about a lower inflation target (the latter likely needed to explain why forward breakevens even 10 years in the future decline).

4.2 Duration of arbitrageurs

We next study the duration of arbitrageurs. Following the literature in intermediary asset pricing, our preferred definition of arbitrageurs is broker/dealers and hedge funds. These institutions arguably trade actively across maturities to maximize risk-adjusted returns as in our model. By market clearing, this implies that households, other financial institutions such as pension funds and life insurance companies, non-financial companies, the government (including the Federal Reserve), and the rest of the world are modeled as habitat investors.

4.2.1 Balance sheets and asset class duration

Our first approach is to combine data on the balance sheets of broker/dealers and hedge funds with estimates of duration by asset class.[26] The advantage of this approach is that it allows us to characterize the aggregate duration of this broad group of institutions. The disadvantage is that it assumes that these institutions hold a representative portfolio within each asset class, and it cannot account for the effect of derivative positions on these institutions' true interest rate exposure.[27,28]

We use four data sources. We obtain the aggregate balance sheet of broker/dealers from the Financial Accounts, which includes the broker/dealer subsidiaries of commercial banks. We obtain the aggregate balance sheet of hedge funds filing Form PF to the Securities and Exchange Commission (SEC), summarized in the Enhanced Financial Accounts.[29] This data is provided since the fourth quarter of 2012 and provides substantially more information about portfolio holdings and leverage in the hedge fund sector than previously available sources such as BarclayHedge and Lipper TASS. We

[26]The approach of combining risk exposures by asset class with positions by asset class follows Begenau, Piazzesi, and Schneider (2015) and Greenwald, Leombroni, Lustig, and Van Nieuwerburgh (2023). We study the duration of broker/dealers and hedge funds, whereas these papers study the duration of commercial banks and households, respectively.

[27]Using supplementary data sources, in appendix B.5 we assess the validity of the representativeness assumption, and the potential implications of derivatives positions, for Treasuries in particular.

[28]Another disadvantage is that the measured balance sheets may not fully account for these sectors' net worth because their net worth also includes the franchise value of market-making and intermediation services. The true duration of net worth will then exceed our estimate if the duration of franchise value exceeds that of measured wealth. Estimating the duration of franchise value for these sectors requires better data on their income than we have (similar to that used by DeMarzo, Krishnamurthy, and Nagel (2024) for commercial banks), so we leave this for future research.

[29]Hedge funds must file Form PF if they are registered or are required to register with the SEC, manage private funds, and have at least $150 million in such assets under management. Importantly, this includes hedge funds both domiciled in the U.S. and abroad (such as the Cayman Islands).

obtain the effective duration of the U.S. Treasury, U.S. mortgage-backed security, and U.S. corporate bond indices computed by Bloomberg.[30] These duration measures account for the optionality embedded in the latter two classes of securities, such as the ability to prepay. Finally, we obtain valuation ratios on the S&P 500 available from Robert Shiller's website to compute the duration of equities.

Given this data, we proceed in three steps. Each quarter, we first compute the net positions of each set of financial institutions in each asset class. The sum of these positions is wealth.[31] The first three columns of Table 2 summarize their individual and aggregate balance sheets in the fourth quarter of 2012. As is evident, these institutions hold a levered position in cash, Treasuries, corporate and foreign bonds, other debt securities (primarily agency/GSE-backed securities), and corporate equities, financed by repurchase agreements and other short-term loans (primarily secured borrowing of hedge funds from prime brokerages).[32]

We next combine this data with estimates of duration by asset class. The last column of Table 2 summarizes this in the fourth quarter of 2012. We assume that Treasuries, corporate and foreign bonds, and other debt securities have the effective duration of the Bloomberg Treasury, corporate bond, and mortgage-backed security indices, respectively. We assume that cash, deposits, and money market fund shares have an average duration of one quarter, repo and other short-term loans have an average duration of one month, and loans have a duration of five years. We use the price-earnings ratio on the S&P 500 together with the Gordon growth formula to compute the duration of equities, following the approach of Greenwald et al. (2023) and further described in appendix B.4.[33]

[30]These were previously the Barclays indices, and prior to that the Lehman Brothers indices. These are among the most widely used bond indices in the literature.

[31]In the Financial Accounts (for broker/dealers), wealth is total financial assets less liabilities, less FDI and miscellaneous assets less liabilities. Since the latter largely correspond to transactions with holding and parent companies, this means we measure wealth at the level of the broker/dealer subsidiary itself. In the Form PF filings (for hedge funds), wealth is net asset value.

[32]Drechsler, Savov, and Schabl (2021) argue that commercial banks are not much exposed to interest rate risk because deposits, which constitute an important component of their liabilities, pay sticky interest rates, like long duration assets. We note that for the broker/dealers and hedge funds which are our focus, this is less relevant because deposits are not an aggregate source of funding (in fact, these sectors are net long cash, deposits, and money market fund shares, as demonstrated in Table 2). Instead, these sectors are financed using repo and other short-term loans.

[33]This approach involves making an assumption of the share of earnings which are paid out to shareholders, which we assume to be 0.5 based on the dividend to earnings ratio over 1950-1990 before share buybacks grew in importance. Appendix B.5 assesses the sensitivity of our estimated duration to alternative assumptions on equity duration.

	Balance sheet ($bn)			
	Broker/ dealers	Hedge funds	Sum	Duration (years)
Cash, deposits, MMFs	128	553	681	0.25
Repo and other short-term loans*	-448	-1,231	-1,679	0.083
Treasuries	185	654	839	5.4
Corporate and foreign bonds	40	994	1,034	7.2
Other debt securities†	302	61	363	3.2
Loans‡	-35	133	99	5
Corporate equities	127	1,148	1,275	32.9
Wealth§	299	2,313	2,612	21.2
Only fixed income	172	1,164	1,336	10.1

Table 2: duration of arbitrageurs in Q4 2012

Notes: see text for data sources and definitions of wealth-weighted duration.
* Includes cash and margin accounts of households at broker/dealers, clearing funds and receivables/payables among broker/dealers (including securities lending), and hedge fund loan liabilities (largely secured borrowing from prime brokerages).
† Includes open market paper, municipal securities, and agency/GSE-backed securities.
‡ Includes broker/dealer loans to non-financial corporates, depository institution loans to broker/dealers not elsewhere counted, and loan assets of hedge funds.
§ For broker/dealers, equals financial assets less liabilities, less FDI and miscellaneous line items (largely transactions with holding companies and parents). For hedge funds, equals net asset value less miscellaneous line items.

We finally compute wealth-weighted aggregate duration using the last two columns of Table 2. In the fourth quarter of 2012, this implies arbitrageurs' duration is 21.2. Since the duration of equities plays an important role in driving this number up, we also consider the possibility that equity and fixed income arbitrageurs are segmented, in which case we eliminate equities from our calculation and focus on fixed income duration alone. This implies arbitrageurs' duration is 10.1. Repeating this process for each quarter through 2019 (given our maintained sample period of interest) and averaging over time, arbitrageurs' duration is between 10.3 (fixed income alone) and 28.0 (also including equities). One way to make sense of these estimates is that the duration of ultimate investments of these arbitrageurs is around 5 to 10 years, and their leverage in these investments is around 2 to 3.[34]

[34] This interpretation also helps makes sense of the high duration of equities, which are themselves levered claims on long duration assets.

4.2.2 High-frequency response of dealer equity prices

Our second approach is to measure the high-frequency response of primary dealers' stock prices around FOMC announcements, paralleling our analysis of the yield curve. The advantage of this approach is that it captures the realized exposure to a macroeconomic risk factor without the assumptions required in the prior subsection. The disadvantage is that it is restricted to publicly traded primary dealers, as hedge funds are not publicly traded, and may reflect the economic exposure of other parts of dealers' holding companies rather than the dealer subsidiary itself.[35]

To construct the high-frequency response of dealers' stock prices, we use the list of primary dealers provided by the Federal Reserve and intraday quotes using TAQ.[36] For each publicly traded and active dealer around an FOMC announcement, we measure the closest prices of transactions 10 minutes prior to the FOMC announcement and 20 minutes after the FOMC announcement.[37] We then aggregate the change in dealer prices in this 30-minute window, weighting by dealers' market capitalizations at the end of the previous trading day from CRSP.

We find that a surprise monetary tightening generates an economically and statistically significant fall in dealer equity prices in this 30-minute window. In our baseline specification reported in the first row of Table 3, a $1pp$ increase in the one-year ahead one-year forward induced by a monetary tightening causes a $6.7pp$ decline in dealer equity prices.[38,39] The remaining rows of Table 3 demonstrate that across the same alternative samples and measures of monetary surprises as in Table 1, dealer equity prices fall by $2.9pp - 16.2pp$ in response to a $1pp$ rise in the one-year ahead one-year forward. In the baseline and three other specifications, the response is statistically significantly different from zero at a 95% level.

Interpreting these estimates through the lens of our estimated yield curve response to monetary shocks can shed light on dealers' duration. The price of a 20-year TIPS

[35] As noted by He, Kelly, and Manela (2017), the last point may not be a concern if internal capital markets are frictionless, in which case it is more relevant to measure the holding companies' exposure.

[36] The list of dealers for which we have stock market data is provided in appendix B.6. While we focus on data between 2004 and 2019 to be consistent with our analysis of the TIPS yield curve, we find that all of our results regarding the high-frequency response of dealers' stock prices are robust to beginning the sample in 1993, when the TAQ data becomes available.

[37] For FOMC announcements occurring outside NYSE trading hours, we use the preceding closing price and following opening price, following Gorodnichenko and Weber (2016).

[38] The change in the forward rate is still the one-day change, as throughout this section.

[39] Appendix B.6 visually depicts the relationship between the change in dealer equity prices and the change in the one-year yield induced by the high-frequency monetary surprise.

Specification	30-minute change in dealer equity prices
Baseline	-6.7
	(2.6)
Excl. 7/08-6/09	-4.9
	(4.0)
Excl. days w. LSAP news	-9.3
	(2.9)
Without orthogonalizing IV	-5.8
	(2.5)
Swanson (2021b) Fed funds IV	-6.4
	(10.7)
Jarocinski and Karadi (2020a) IV	-5.9
	(4.2)
Nakamura and Steinsson (2018a) IV	-16.2
	(6.5)
Swanson (2021b) forward guidance IV	-2.9
	(1.8)

Table 3: change in dealer prices on $\Delta f_t^{(1,2)}$, instrumented by high-frequency surprise

Notes: robust standard errors provided in parenthesis.

falls by 6.8*pp* in response to our baseline monetary surprise that raises the one-year ahead one-year real forward by 1*pp*. This is quite close to our estimated 6.7*pp* decline in dealers' stock prices, and is thus consistent with dealer duration of roughly 20 years. There are two reasons why this comparison may be inappropriate, though they push in opposite directions. On the one hand, dealers largely trade nominal fixed income assets rather than TIPS, and the prices of nominal Treasuries respond by a smaller magnitude than TIPS, as described in appendix B.3: this would suggest a higher level of duration to rationalize dealers' stock price decline. On the other hand, the cashflows earned by dealers likely fall and the equity premium might rise upon a monetary tightening (over and above the increase in the term premium): this would suggest a lower level of duration to rationalize dealers' stock price decline.[40]

[40]We also wish to emphasize that inferring dealers' duration from their stock price response is very sensitive to measurement error. For instance, in our baseline specification, we estimate that the price of a 5-year TIPS falls by 4.1*pp* given a monetary surprise that raises the one-year ahead one-year real forward by 1*pp*. Hence, the confidence interval for dealers' stock price reaction in Table 3 would admit a very wide range of estimates for duration, using this approach.

4.3 Broader evidence of wealth revaluation channel

In the next section, we use the evidence from the prior subsections to discipline and evaluate our quantitative model. Before turning to the quantification, we summarize additional evidence of the wealth revaluation channel at the core of our paper, the details of which are provided in appendix B.7.

We first provide additional evidence that a monetary tightening indeed reduces intermediation capacity in fixed income markets. In particular, we demonstrate that a surprise monetary tightening lowers the intermediary capital risk factor of He et al. (2017), which is a priced risk factor for intermediated assets as demonstrated by that paper; raises the excess bond premium of Gilchrist and Zakrajsek (2012), a widely used measure of risk appetite in the corporate bond market; raises the yield curve noise measure of Hu, Pan, and Wang (2013), which reflects diminished intermediation capacity and thus liquidity in the Treasury market; and finally widens the average five-year deviation from covered interest parity (CIP) between U.S. and G10 currency countries from Du, Im, and Schreger (2018a).

The cross-section of CIP deviations offers particularly compelling evidence of the wealth revaluation channel. Across currencies, some (typically the Australian dollar or New Zealand dollar) exhibit positive CIP deviations versus the U.S. dollar, while others exhibit negative CIP deviations versus the U.S. dollar. We demonstrate that a monetary tightening lowers the CIP deviation for currencies in which it is currently negative, and raises the CIP deviation for currencies in which it is currently positive. We then extend the model of section 3 to feature a synthetic short bond which enters into a balance sheet constraint facing arbitrageurs, effectively integrating the model of CIP deviations in Du, Tepper, and Verdelhan (2018b) with our model of the yield curve. The tightening of arbitrageurs' balance sheet constraint, as because arbitrageurs' wealth falls, can precisely rationalize this finding. By contrast, if CIP deviations respond to monetary shocks because of a change in demand for currencies from clients (the analog of the "reach for yield" mechanism in the currency market), currency flows to/from the U.S. dollar and thus CIP deviations would move in the same direction regardless of their initial sign.

Finally, these high frequency measures of intermediation capacity also provide evidence of state-dependent effects of monetary shocks on the yield curve. We demonstate that the conditional effect of a monetary surprise on long-dated forward rates is amplified when the intermediary capital ratio is low, excess bond premium is high, noise in the yield curve is high, and average CIP deviation is large in absolute value.[41] This again speaks to a distinctive prediction of the wealth revaluation channel vis-à-vis other explanations of the term premium response to monetary shocks focused on habitat demand or changing perceptions of macroeconomic comovements.

5 Quantitative analysis

We now assess the ability of our full model to rationalize the effects of monetary policy on the yield curve. Calibrated to match the evidence on arbitrageur duration, it can account for much of the responses of long-dated real forward rates in the data. We quantify the additional implications of our model for state-dependence in policy transmission, the volatility and slope of the yield curve, and trends in term premia accompanying trends in the natural rate.

5.1 Equilibrium and solution

We first summarize the equilibrium conditions of the full model environment described in section 2 and the computational algorithm we use to solve it.

Equilibrium As derived formally in appendix C.1, arbitrageurs' first-order conditions for the problem (3)-(4) imply that

$$E_t\left(\frac{dP_t^{(\tau)}}{P_t^{(\tau)}}\right) - r_t dt = \frac{\gamma}{W_t}\int_0^\infty X_t^{(s)} Cov_t\left(\frac{dP_t^{(\tau)}}{P_t^{(\tau)}}, \frac{dP_t^{(s)}}{P_t^{(s)}}\right) ds - (1-\gamma) Cov_t\left(\frac{dP_t^{(\tau)}}{P_t^{(\tau)}}, \frac{d\nu_t}{\nu_t}\right), \quad (20)$$

where ν_t defines the marginal value of wealth in the value function

$$v_t(w_t) = \frac{(\nu_t w_t)^{1-\gamma} - 1}{1-\gamma}$$

[41] We do not obtain such sharp evidence of state-dependence using our balance sheet-based measure of arbitrageur duration, which we interpret as reflecting the advantage of these price-based measures. We only observe the balance sheets at a quarterly frequency from 2012 onwards, and we assume that dealers and hedge funds hold the representative portfolio within each asset class. While this may be a reasonable assumption to measure average duration over time, it surely understates how their balance sheets change over time, as appendix B.5 illustrates for Treasuries.

solving (3). Generalizing (16) in the simple model, (20) says that arbitrageurs require non-zero expected excess returns on a bond of maturity τ to compensate them for bearing price risk on that bond. Their exposure to a bond with maturity τ depends in part on the covariance of returns on that bond with all other bonds of maturity $s \in (0, \infty)$ and the arbitrageurs' position in those bonds $\{X_t^{(s)}\}_{s=0}^{\infty}$. Away from log preferences ($\gamma \neq 1$), arbitrageurs' required risk compensation also reflects a standard intertemporal hedging motive: they require a lower expected excess return on a bond if it pays well when the (instantaneous change in the) marginal value of wealth $(1-\gamma)d\nu_t$ is positive. When arbitrageurs' discount rate $\rho \to \infty$, appendix C.1 proves that the marginal value of wealth $\nu_t \to 1$, so that the intertemporal hedging motive vanishes. We focus on this case for simplicity. This allows us to continue focusing on endogenous wealth W_t in risk pricing as the only departure from existing preferred habitat models.[42]

Substituting habitat demand (1) and market clearing (10) into (20) in the $\rho \to \infty$ limit in which the intertemporal hedging motive drops out, we obtain

$$E_t\left(\frac{dP_t^{(\tau)}}{P_t^{(\tau)}}\right) - r_t dt = \frac{\gamma}{W_t}\int_0^{\infty}\left(\alpha(s)\log\left(P_t^{(s)}\right) + \theta_0(s) + \theta_1(s)\beta_t\right) Cov_t\left(\frac{dP_t^{(\tau)}}{P_t^{(\tau)}}, \frac{dP_t^{(s)}}{P_t^{(s)}}\right) ds. \quad (21)$$

Substituting habitat demand and market clearing in arbitrageurs' aggregate evolution of wealth (5), we obtain

$$dW_t = W_t r_t dt + \int_0^{\infty}\left(\alpha(\tau)\log\left(P_t^{(\tau)}\right) + \theta_0(\tau) + \theta_1(\tau)\beta_t\right)\left[\frac{dP_t^{(\tau)}}{P_t^{(\tau)}} - r_t dt\right] d\tau + \xi(\bar{W} - W_t)dt. \quad (22)$$

These equilibrium conditions parallel (17) and (18) in the simple model. Together with the driving forces (6)-(9), this characterizes the equilibrium.

Solution In a large class of term structure models, including existing models in the preferred habitat tradition, bond prices are exponentially affine in the model's state variables. The dependence of the price of risk on arbitrageurs' wealth in our setting

[42] We relax the assumption $\rho \to \infty$ in appendix C.6 and demonstrate that our quantitative results remain very similar to those of our baseline environment.

implies that bond prices are no longer exponentially affine in this way.

We therefore characterize bond prices as a general function of the three state variables $\omega_{1,t}$, $\omega_{2,t}$ and W_t

$$P_t^{(\tau)} \equiv P^{(\tau)}(\omega_{1,t}, \omega_{2,t}, W_t). \tag{23}$$

Writing the evolution of wealth as

$$dW_t = \mu_W(\omega_{1,t}, \omega_{2,t}, W_t)dt + \eta_1(\omega_{1,t}, \omega_{2,t}, W_t)dB_{1,t} + \eta_2(\omega_{1,t}, \omega_{2,t}, W_t)dB_{2,t} \tag{24}$$

for some functions μ_W, η_1, and η_2, we can use (6)-(9) and (24) together with Ito's Lemma to write (21) as a partial differential equation (PDE) relating partial derivatives of $\{P^{(\tau)}\}_{\tau=0}^{\infty}$ and the state variables $\omega_{1,t}$, $\omega_{2,t}$, and W_t. Given conjectures for the functions μ_W, η_1, and η_2, the Feynman-Kac formula implies a solution $P^{(\tau)}$ which we numerically solve using Monte Carlo simulation. We then use (22) to characterize the implied evolution of W_t and iterate over our guesses for the functions μ_W, η_1, and η_2 until (24) is consistent with (22). Further details on the algorithm are in appendix C.2.

5.2 Calibration

We assume an exponential form for the price elasticity, intercept, and slope of habitat demand by maturity:

$$\alpha(\tau) = \alpha \exp^{-\tau},$$
$$\theta_0(\tau) = \theta_0 \exp^{-\tau},$$
$$\theta_1(\tau) = \theta_1 \exp^{-\tau},$$

for $\tau \leq 30$, and $\alpha(\tau) = \theta_0(\tau) = \theta_1(\tau) = 0$ for $\tau > 30$.[43] Since only the products $\theta_1\sigma_{\beta,1}$ and $\theta_1\sigma_{\beta,2}$ matter for the equilibrium dynamics, we normalize $\theta_1 = 1$. Since $\{\bar{W}, \theta_0, \sigma_{\beta,1}, \sigma_{\beta,2}, \alpha\}$ can each be scaled without changing the state-contingent path of prices or returns, we normalize $\theta_0 = 1$.

The calibration of remaining moments is summarized in Table 4. We calibrate the model to match three sets of moments: unconditional moments of the yield curve, the evidence on arbitrageur duration assembled in section 4, and the yield curve responses to quantitative easing studied widely in the literature. We reiterate that our calibration

[43] Adjusting the maximal duration of traded assets does not meaningfully affect our results, conditional on calibrating parameters to match our targeted moments.

	Description	Value	Moment	Target	Model
Unconditional moments of yield curve					
$\bar{r}$	mean short rate	-0.0025	$y_t^{(5)}$	0.51%	0.51%
γ	arb. risk aversion	4	$y_t^{(10)} - y_t^{(5)}$	0.52%	0.52%
κ_1	mean rev. transitory shock	0.10	$\sigma(y_t^{(5)})$	1.08%	1.06%
$\sigma_{r,1}$	short rate transitory loading	0.0087	$\sigma(\Delta y_t^{(5)})$	0.85%	0.76%
$\sigma_{\beta,1}$	demand transitory loading	-0.45	$\beta_{FB}^{(5)}$	-0.06	-0.05
κ_2	mean rev. persistent shock	0.03	$\sigma(y_t^{(10)})$	0.89%	0.94%
$\sigma_{r,2}$	short rate persistent loading	0.0054	$\sigma(\Delta y_t^{(10)})$	0.67%	0.67%
$\sigma_{\beta,2}$	demand persistent loading	0.22	$\beta_{FB}^{(10)}$	0.14	0.12
Duration of arbitrageurs					
$\bar{W}$	arb. endowment	0.05	duration	10	9.8
Yield curve responses to QE announcement on March 18, 2009					
α	habitat price elast.	4	$df_t^{(4,5)}$	-0.74%	-0.77%
ξ	persistence arb. wealth	0.1	$df_t^{(9,10)}$	-0.46%	-0.56%

Table 4: baseline calibration

Notes: Δ denotes annual change, σ denotes monthly standard deviation, d denotes instantaneous change, and moments without these symbols are simple time-series averages. Model moments are computed by averaging over 3,000 samples of 16 years. These samples are obtained from 100 simulations of 30 $\times$ 16 years, each simulated after a burn-in period of 100 years.

focuses on the real yield curve, since our model is silent about inflation.

We first set a subset of parameters to match unconditional moments of the yield curve.[44,45] We set the average level of the short rate $\bar{r}$ to match the average five-year yield. We set arbitrageur risk aversion γ to match the average 10-year/five-year yield curve slope. We set the persistence of the transitory and persistent state variables (κ_1 and κ_2), and loading of the short rate on these state variables ($\sigma_{r,1}$ and $\sigma_{r,2}$), to match the volatilities of the five- and 10-year yields in changes and levels. We set the loading

[44] All moments in the data are computed over the same January 2004 through December 2019 period studied in section 4. In the usual way, all parameters jointly determine the moments we target. For each parameter, we describe the moment we primarily target by varying that parameter.

[45] Prior work has documented large movements in TIPS liquidity premia around the global financial crisis (e.g., D'Amico, Kim, and Wei (2018)). As we later explore in the context of our results on state-dependence and stochastic volatility, our model can capture large conditional movements in TIPS yields during this period arising from low levels of arbitrageur wealth. However, for robustness purposes, we also present in appendix C.5 an alternative calibration to yield curve moments excluding the period July 2008 through June 2010.

of habitat demand on these state variables ($\sigma_{\beta,1}$ and $\sigma_{\beta,2}$) to match the relationship between the slope of the yield curve and excess returns on five- and 10-year bonds, denoted $\beta_{FB}^{(5)}$ and $\beta_{FB}^{(10)}$ with reference to Fama and Bliss (1987);[46] we later discuss why this classic evidence on return predictability is informative about the magnitude of demand shocks. For the persistent state variable which will be of particular interest in our analysis of trends in the natural rate at the end of the paper, we note that this loading has the same sign as the short rate loading, consistent with higher habitat savings reducing the persistent component of the short rate.[47]

We next set arbitrageurs' initial wealth $\bar{W}$ to match the novel evidence on arbitrageur duration assembled in section 4. Arbitrageurs' duration in the model is

$$(\text{duration})_t \equiv \frac{\int_0^\infty \tau X_t^{(\tau)} d\tau}{W_t}. \tag{25}$$

Arbitrageurs' initial wealth affects their average level of wealth and thus the denominator of (25). We set it to target duration of 10, the lower end of the range estimated in section 4. We later explore the sensitivity of our findings to a higher value.[48]

We lastly set parameters to match evidence on the yield curve responses to quantitative easing (QE) which have been widely studied in the literature. QE is a habitat demand shock in our model since the Federal Reserve is included in the set of habitat

[46]Formally, in both data and model we estimate the specification

$$r_{t,t+2}^{(\tau)} - y_t^{(2)} = \alpha_{FB}^{(\tau)} + \beta_{FB}^{(\tau)} \left(f_t^{(\tau-2,\tau)} - y_t^{(2)} \right) + \epsilon_{FB,t+2}^{(\tau)},$$

where $r_{t,t+2}^{(\tau)}$ is the two-year holding period return on a τ-year bond. We calibrate to data using a two-year holding period given that the one-year real yield is extrapolated from the TIPS yields used in estimation by Gurkaynak et al. (2008), as previously described. Note that $\beta_{FB}^{(5)}$ in the model is negative, as in the data, but the model clarifies that this is a consequence of Stambaugh (1999) bias: when running these regressions on extremely long samples of data, all $\beta_{FB}^{(\tau)}$ coefficients are positive.

[47]For the transitory state variable, the demand loading has the opposite sign as the short rate loading, which helps to quantitatively account for a high term premium when the transitory component of the short rate is low and thus the term spread is high. However, this is inconsistent with the negative relationship between changes in dealer balance sheets and changes in the term spread documented in Hanson and Stein (2015). Appendix C.5 describes how a model extension with news shocks about the future short rate, or shocks to arbitrageurs' effective risk aversion, can rationalize this evidence while still being consistent with the return predictability evidence from Fama and Bliss (1987).

[48]In appendix C.5, we present an alternative calibration of $\bar{W}$ that does not use this duration target, but instead targets the volatility of realized volatility in the 10-year yield. The baseline calibration generates some but not all of the stochastic volatility observed in the data. Because the alternative calibration achieves higher stochastic volatility, $\bar{W}$ is calibrated to be even lower and thus model-implied duration is even higher than in the baseline calibration.

investors. The yield curve responses to QE discipline both habitat investors' price elasticities, controlled by α, as well as the speed of mean reversion in arbitrageur wealth, controlled by ξ. The intuition for why QE disciplines α can be understood using the simple model of section 3, in which case the response of the two-period bond price to a demand shock is

$$\frac{d\log P_t}{d\theta_t} = -\frac{1}{\alpha + \frac{W_t}{\sigma_r^2}}. \tag{26}$$

The denominator is the price elasticity of the aggregate demand for two-period bonds; in the usual way, the more elastic it is, the smaller will be the equilibrium price response. Conditional on the price elasticity of arbitrageurs $\frac{W_t}{\sigma_r^2}$ implied by the other calibration targets above, the equilibrium price response thus disciplines the price elasticity of habitat investors α. The intuition for why QE disciplines ξ reflects the fact that — as we later demonstrate — QE revalues wealth and thus arbitrageurs' risk bearing capacity like a monetary shock. Since ξ governs the speed with which arbitrageurs' wealth returns to its long-run average, it governs the persistence of term premium responses and thus the shape of the yield curve responses on impact of QE.

We discipline both parameters using the forward rate responses to the March 18, 2009 announcement that the Federal Reserve would begin purchasing Treasuries and expand its purchases of agency/GSE-backed securities and mortgage-backed securities. Appendix C.4 motivates why we focus on this announcement and describes how we translate the announcement into model scale. We simulate it starting from arbitrageur wealth one third below its average value, consistent with the decline in total wealth among broker/dealers and hedge funds between the fourth quarter of 2007 and first quarter of 2009 (also detailed in appendix C.4).[49] We calibrate α and ξ to match the five- and 10-year forward rate responses to the announcement, respectively. Since some of the announced asset purchases may have been anticipated, this will imply a value for α in particular which is an upper bound, working against our ability to account for the term premium effects of monetary shocks as demonstrated in our analytical results. Later in this section, we assess the sensitivity of our results to a lower value of α.

[49] As we later describe, initializing arbitrageurs' wealth at a lower level than steady-state allows us to capture the fact that the price impact of QE during this period was higher than it normally would have been. That said, we also acknowledge that there are effects of QE announcements during this period, such as the repricing of of illiquid off-the-run bonds to meet their liquid on-the-run counterparts (D'Amico and King (2013)), which our model is not well suited to capture.

5.3 Effects of monetary shock

We now turn to the model's key impulse response: the effects of a monetary shock.

5.3.1 Impulses responses to monetary shock

Figure 2 depicts the impulse responses to a contractionary monetary shock, scaled to generate a 100*bp* rise in the one-year ahead one-year real forward on impact. As discussed in section 2, a monetary-induced shock to the real short rate can have a different speed of mean reversion κ_m than "typical" short rate shocks arising from underlying shocks to preferences or productivity, and is unaccompanied by any exogenous innovation to habitat demand. We set $\kappa_m = 0.6$ so that the response of the short rate five years after the shock is 5% of the impact effect on the short rate, consistent with monetary neutrality beyond five years. Monetary-induced short rate shocks are thus less persistent than typical short rate shocks, which we view as sensible.

The first row of Figure 2 depicts the short rate, the one-year ahead one-year real forward, and arbitrageur wealth. The second row depicts the 10-year real forward rate, the spread between the 10-year real forward rate and one-year yield, and expected excess returns on the 10-year bond financed by the one-year bond over the next year. The impulse responses are contrasted against those in a counterfactual economy in which $\xi \to \infty$ and thus arbitrageurs' endowment is constant.[50]

The 10-year real forward rate rises in response to the shock, in contrast to the counterfactual model in which arbitrageurs' endowment is constant. The difference in these responses is driven by the downward revaluation of arbitrageurs' wealth, which raises their price of bearing risk and raises term premia. Since term premia have risen, future excess returns on the 10-year bond are high — persistently so, reflecting the pattern of arbitrageurs' wealth.[51,52] The opposite is true in the counterfactual model.

[50] In this counterfactual economy, we leave all parameters unchanged except γ, which we recalibrate to match the same level of the yield spread as the baseline calibration (and the data). This ensures that our comparison of risk premium responses across these models does not mechanically reflect differences in the level of the risk premium itself.

[51] Notably, since the fall in the short rate is not permanent, the forward spread falls as the yield curve flattens. This implies that, at least around impact of the shock, there is a negative relationship between the slope of the yield curve and subsequent excess returns on long-term bonds. By contrast, shocks to habitat demand imply a positive relationship between the slope of the yield curve and subsequent excess returns on long-term bonds. This is why the classic evidence on return predictability of Fama and Bliss (1987) and Campbell and Shiller (1991) can be used to identify the loadings of demand on the latent driving forces in Table 4.

[52] The continued decline in arbitrageur wealth for roughly 20 months after the initial decline reflects

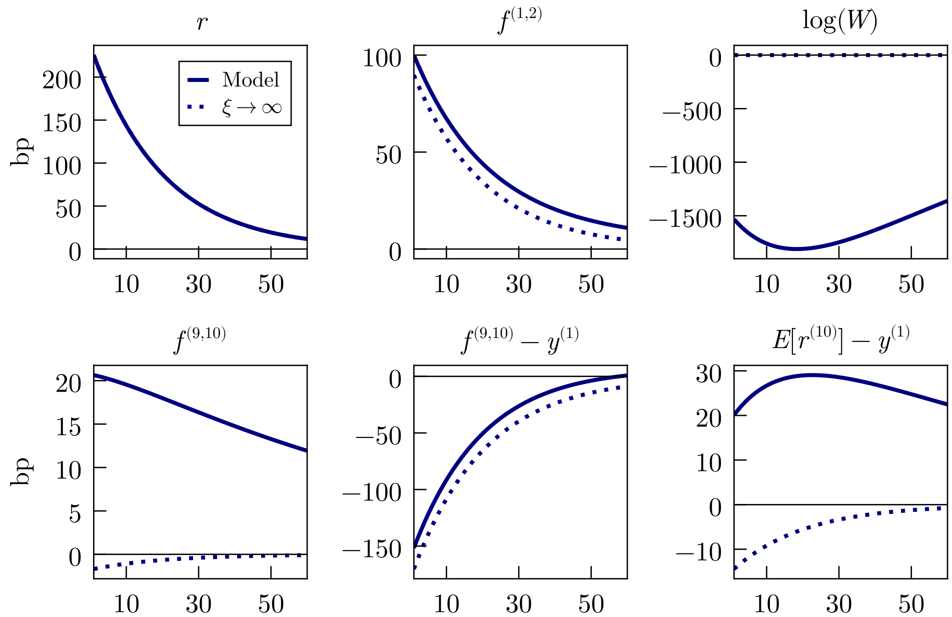

Figure 2: impulse responses to monetary shock

Notes: monetary shock is a one-time innovation to short rate with mean reversion $\kappa_m = 0.6$ as described in main text. Figure depicts responses to infinitesimal shock, scaled to generate $100bp$ fall in one-year ahead one-year forward on impact, and x-axis denotes number of months since the shock. Responses are averaged (relative to no shock) starting at 100 points drawn from the ergodic distribution of states, itself approximated by 48,000 years of data simulated as described in Table 4.

All of these results are consistent with the analytical results in section 3.

Figure 3 depicts the impact effect of the monetary shock on the forward rate across maturities and compares it to the estimates from Figure 1. The model generates responses within the empirical confidence intervals for seven- to 10-year real forwards, and in particular accounts for essentially all of the 10-year forward response. The gap between the forward rate response and expected one year yield response rises in maturity.[53] By contrast, in the counterfactual economy with $\xi \to \infty$, forward rates beyond eight years in fact fall upon a monetary tightening. We conclude that the model can successfully account for the observed overreaction of long-dated forwards to monetary shocks in the data, and that an endogenous price of risk through arbitrageur wealth is essential to this result.

that, because habitat investors seek to borrow less when long yields rise, arbitrageurs' intermediation profits in fact fall. Only after 20 months does wealth begin to return to its initial value, as the higher term premium dominates and recapitalizes arbitrageurs.

[53]Using that the spread between the forward rate and expected one year yield equals the cumulative expected return to a sequence of carry strategies, appendix C.3 demonstrates that it is the persistence of the rise in expected carry trade returns which explains why term premia rise with maturity.

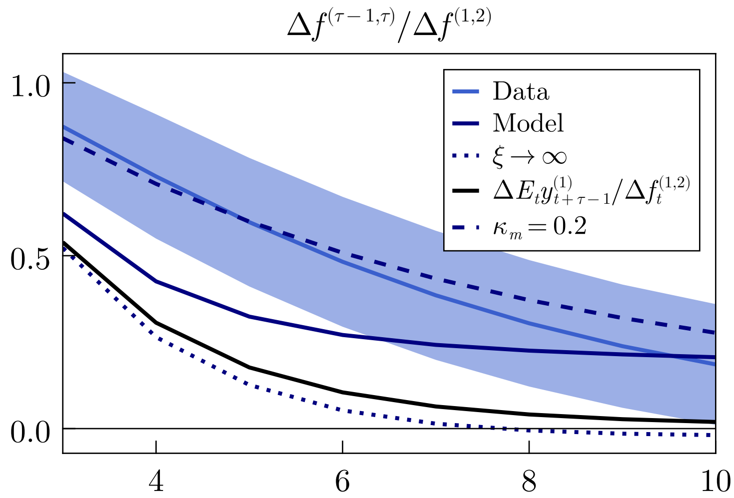

Figure 3: $f_t^{(\tau-1,\tau)}$ on $f_t^{(1,2)}$ given monetary shock: model vs. data

Notes: empirical estimates correspond to those in Figure 1. Model responses simulated as described in Figure 2.

Figure 3 also indicates that the model falls short of accounting for the observed forward rate response at maturities below seven years. This may reflect that the response of the short rate to a monetary shock is more persistent than is assumed here; that our assumptions on arbitrageurs' duration and habitat demand elasticities are too conservative; or that there are additional drivers of yield variation and thus term premia at the short end of the yield curve that our model does not capture, such as those induced by a time-varying convenience yield. While we leave the last for future work, it is straightforward to examine the consequences of the first two possibilities. The last line plotted in Figure 3 simulates a more persistent shock with $\kappa_m = 0.2$,[54] disciplined to match the response of the three-year real forward. In this case, the model-implied responses at longer maturities exceed those in the data, though they still remain within the empirical confidence intervals. In the next section, we explore the effects of higher arbitrageur duration or lower habitat demand elasticities.

5.3.2 Sensitivity to duration and demand elasticity

The empirical evidence could support higher values for arbitrageur duration and lower values of habitat demand elasticities $\alpha(\tau)$. Here we explore the sensitivity of our findings to these key parameters.

[54] Note that this is still more transitory than the typical short rate shocks anticipated by agents.

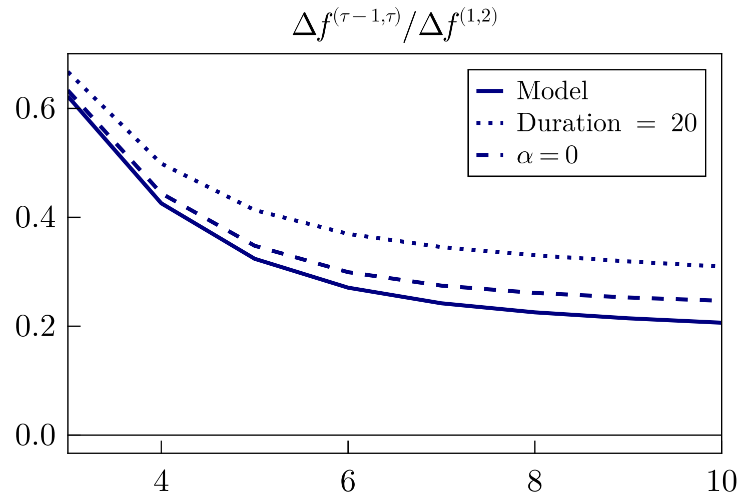

Figure 4: $f_t^{(\tau-1,\tau)}$ on $f_t^{(1,2)}$ given monetary shock: alternative calibrations

Notes: responses simulated as described in Figure 2.

We first consider a higher value for arbitrageur duration. We lower $\bar{W}$ so that arbitrageurs' duration of wealth is 20, the midpoint of the range estimated in section 4.[55] The resulting responses of forward rates around a monetary shock are summarized by the dotted line in Figure 4. The responses are everywhere higher than in the baseline calibration, and the response of the 10-year forward rate now exceeds 0.30*pp*.

We next consider lower values for the elasticities of habitat demand $\alpha(\tau)$. In particular, we assume habitat demand is completely inelastic by setting $\alpha = 0$.[56] The resulting responses of forward rates around a monetary shock are summarized by the dashed line in Figure 4. The responses are again everywhere higher than in the baseline calibration. Consistent with our analytical results, a lower elasticity of habitat demand dampens the response of the quantity of risk borne by arbitrageurs, amplifying the response of the term premium.

5.3.3 State-dependence

We finally demonstrate that the model generates state-dependent effects of monetary shocks. Figure 5 depicts the forward responses to the same monetary shock depicted in the previous figures, but starting from arbitrageur wealth one standard deviation below

[55] As in footnote 50, we recalibrate γ to target the same yield spread as our baseline calibration, and keep all other parameters fixed at their baseline values.

[56] Again, we recalibrate γ to match the same yield spread and leave all other parameters unchanged.

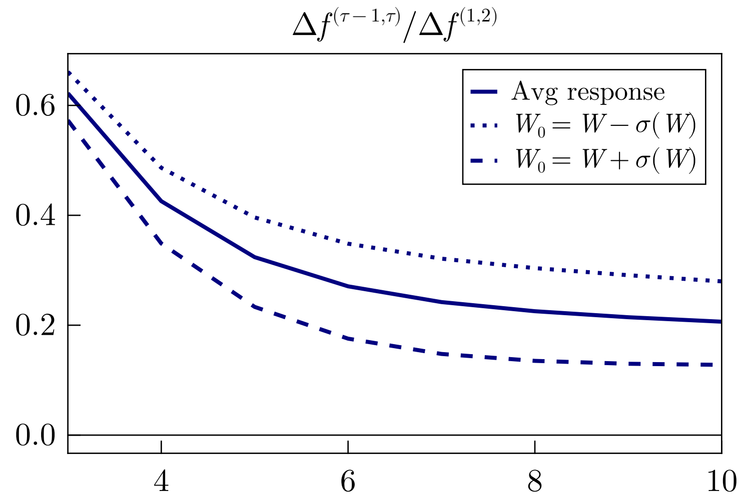

Figure 5: $f_t^{(\tau-1,\tau)}$ on $f_t^{(1,2)}$ given monetary shock: state-dependence

Notes: average response simulated as described in Figure 2. Responses with initial wealth one standard deviation above/below its average value also assume that $\omega_{1,0} = 0$ and $\omega_{2,0} = 0$ (so $r_0 = \bar{r}$ and $\beta_0 = 0$, their average values).

or above its mean of the ergodic distribution. Holding fixed the other state variables (at their mean values), the model implies that a two standard deviation lower value of initial arbitrageur wealth is associated with a roughly $0.15pp$ higher response of the 10-year forward rate to a monetary tightening which raises the one-year ahead one-year real forward by $1pp$. This is because lower initial wealth corresponds to higher duration, and thus a larger revaluation of arbitrageur wealth. Quantitatively, the degree of state-dependence is comparable to the dependence of the 10-year forward response to the initial value of intermediary leverage, excess bond premium, noise in the yield curve, and average CIP deviation studied in appendix B.7.

5.4 Implications beyond monetary shocks

The prior subsection demonstrated that the revaluation of arbitrageur wealth can account for much of the term premium responses to monetary shocks. We now trace out the broader implications of fluctuations in arbitrageur wealth for state-dependence, the slope of the yield curve, and trends in term premia from a declining natural rate.

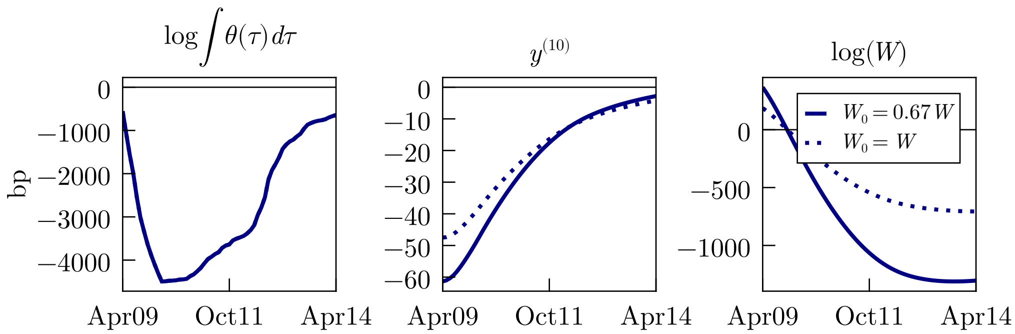

Figure 6: simulation of QE announcement at alternative levels of W_0

Notes: baseline simulation assumes W_0 is one third less than its average value. Alternative simulation assumes W_0 is equal to its average value. In both cases $\omega_{1,0} = 0$ and $\omega_{2,0} = 0$ (so $r_0 = \bar{r}$ and $\beta_0 = 0$, their average values) at time of announcement. See appendix C.4 for further details on simulation.

5.4.1 State-dependent effects of QE

Just as the model implies that the effects of monetary policy along the term structure depend on the level of arbitrageur wealth and thus duration, it implies that the effects of other shocks similarly depend on arbitrageur wealth. Here we focus on our QE experiment used to calibrate the model.

As previously noted, we simulate the March 18, 2009 announcement in the model assuming that arbitrageur wealth is initially one third less than its average value, corresponding to the decline in broker/dealer and hedge fund wealth between the fourth quarter of 2007 and first quarter of 2009. Figure 6 compares the yield curve responses of this announcement in the model to an alternative scenario in which arbitrageur wealth is initially at its average value.[57]

The model implies that the 10-year real yield would have fallen by 20% less had broker/dealers and hedge funds not been so poorly capitalized at the time of the announcement. There are two reasons for the amplified yield curve response when arbitrageurs have lower wealth. First, as is evident from the price effects of QE in the simple model characterized in (26), arbitrageurs have more inelastic demand for longer-term bonds when they have lower wealth, implying larger price responses to changes in the supply they must absorb.[58] Second, a lower level of arbitrageur wealth implies

[57] The announcement is simulated as an unexpected shock to the path of habitat demand as depicted in the first panel. It is again distinct from the "typical" shocks anticipated by agents in sample.

[58] This result is similar to Proposition 4 in Vayanos and Vila (2021) that changes in supply affect yields only when arbitrageurs are risk averse, and Proposition 4 in Greenwood and Vayanos (2014) that changes in supply have larger effects on expected returns when arbitrageurs are more risk averse.

that they have higher duration, all else equal. A given increase in bond prices thus generates a larger percentage increase in their wealth, lowering their price of bearing risk and raising bond prices further.[59]

5.4.2 Volatility and slope of yield curve

The analysis so far has focused on the role of fluctuations in arbitrageur wealth in shaping the conditional response to monetary and demand shocks. In this subsection we quantify the role of endogenous wealth in the unconditional properties of the term structure more broadly.

Table 5 demonstrates how yield volatilities and the slope of the yield curve change when $\xi \to \infty$ and thus arbitrageurs' initial wealth is constant.[60] The first row demonstrates that yield volatility falls when arbitrageurs' initial wealth is constant, consistent with the dampened responses of yields to short rate and demand shocks in the absence of the wealth revaluation channel. The second row demonstrates that while the model with endogenous wealth features stochastic volatility because short rate and demand shocks have state-dependent effects on yields as arbitrageur wealth varies, the model with exogenous wealth features constant volatilities. While the magnitude of stochastic volatility is small relative to the average volatility, it is worth noting that volatility is high precisely when wealth is low, making it particularly relevant for risk pricing ex-ante. Indeed, the final row demonstrates that endogenous wealth accounts for roughly one fifth of the unconditional slope of the yield curve. Taken together, we conclude that the time variation in arbitrageurs' wealth plays an important role in shaping the unconditional properties of the term structure.

5.4.3 Trends in natural rate

While our analysis has focused on the effects of a monetary-induced shock to the short rate, similar mechanisms operate in response to more persistent changes in the short

What is novel here is that arbitrageurs' risk-bearing capacity is endogenous to their level of wealth.

[59]The endogeneity of arbitrageurs' wealth also means that their wealth eventually falls relative to its initial value, both because QE reduces the volume of arbitrageurs' carry trade and reduces their excess return in doing so. For a similar reason, wealth falls faster when $W_0 = 0.67W$ than when $W_0 = W$, since the decline in risk premia and thus carry profits is amplified in the first case.

[60]In the latter calibration, we also set $\bar{W}$ equal to the average value of wealth in the baseline calibration, so that the only difference between the two is in the endogenous volatility of wealth. This contrasts with the $\xi \to \infty$ calibration depicted in Figure 3, in which (as described in footnote 50) we recalibrate γ (equivalently, $\bar{W}$, since only the ratio $\gamma/\bar{W}$ matters for risk pricing with exogenous wealth) to match the same yield spread and thus average term premium as the baseline model.

Moment	Model	$\xi \to \infty$
$\sigma(y_t^{(10)})$	0.94%	0.90%
$\sigma(\sigma_{t-1}(y_t^{(10)}))$	0.014%	0.000%
$y_t^{(10)} - y_t^{(5)}$	0.53%	0.42%

Table 5: unconditional moments of long yields

Notes: σ denotes monthly standard deviation and last row is simple time-series average. Model moments computed as in Table 4.

rate. We conclude by quantifying the relationship implied by our model between trends in the natural rate and trends in term premia in recent years.

We can interpret the secular decline in the natural rate in recent years as a sequence of negative shocks to the latent persistent state variable in the model, $\omega_{2,t}$. Recall that this implies a sequence of negative shocks to the short rate r_t as well as negative shocks to habitat demand β_t, consistent with general equilibrium models in which a "savings glut" generates a decline in the natural rate.[61] Figure 7 plots such a shock, scaled to imply a 1*pp* decline in the short rate. Given such a shock, the five-year forward, five-year term premium falls by roughly 0.45*pp*. As a point of comparison, D'Amico et al. (2018) estimate a 1*pp* fall in the five-year forward, five-year expected real interest rate from 2004 to 2019,[62] and a 1.7*pp* decline in the five-year forward, five-year real term premium over this period. In this sense, the model can account for a meaningful share of the secular decline in term premium estimated in the data.

The model-implied decline in the term premium reflects both the effects of higher arbitrageur wealth and the decline in habitat demand. A bit less than half of the impact response (nearly 0.20*pp*) is due to the wealth revaluation channel, as is evident from the dashed lines in Figure 7. These plot the effect of an exogenous increase in arbitrageurs' wealth matching the equilibrium increase in wealth due to the change in the latent state variable. Interestingly, relative to this counterfactual path, equilibrium wealth falls faster and in fact falls below its initial value, evident from the second panel. This is because, as arbitrageurs earn lower profits due to lower intermediation volumes, eventually their wealth is eroded in a low rate environment.

[61] Using a preferred habitat model with exogenous wealth, Kaminska and Zinna (2019) recover the latent shocks which maximize the likelihood of the observed yield curve over 2001 through 2016, and also conclude that a secular fall in habitat demand has accompanied the secular fall in the short rate.

[62] The Laubach and Williams (2003) model reported by the Federal Reserve Bank of New York also implies a 1*pp* decline in the natural rate over this period.

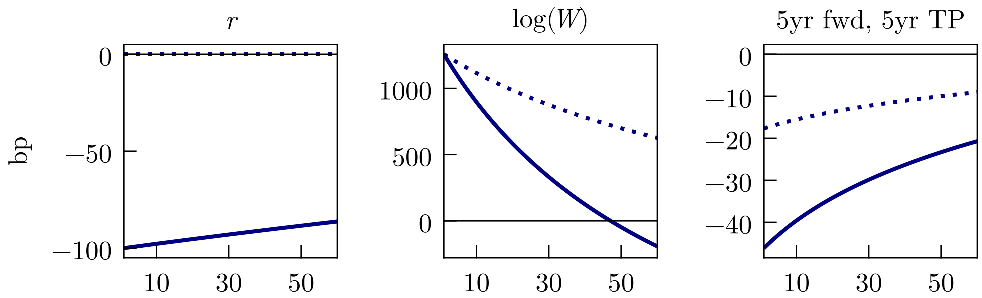

Figure 7: negative shock to persistent state variable $\omega_{2,t}$

Notes: solid lines depict responses to infinitesimal shock in $\omega_{2,t}$, scaled to generate 100*bp* fall in short rate on impact, and x-axis denotes number of months since the shock. Dashed lines simulate effect of unexpected shock to arbitrageur wealth matching the initial wealth response from shock to $\omega_{2,t}$. Responses are simulated as described in Figure 2.

Relative to the existing literature, our model thus offers a complementary but distinct explanation of declining term premia in recent years. Campbell et al. (2020) and Gourio and Ngo (2020) argue that changes in macroeconomic comovements can explain why term premia have fallen in recent years. In particular, these authors argue that because long-term bond prices no longer fall as much (and in fact rise) in bad times, the quantity of risk in long-term bonds has fallen. Our model suggests a complementary explanation in an environment with segmentation: a "savings glut" has reduced the exposure of arbitrageurs to long-term bonds and lowered the natural rate of interest. On impact of such shocks, the associated rise in long bond prices has recapitalized arbitrageurs with positive duration and further lowered their required compensation to bear risk; in the long run, however, the erosion of arbitrageurs' wealth has mitigated the decline in the term premium.

6 Conclusion

In this paper, we propose a model which rationalizes the effects of monetary policy shocks on the term structure of interest rates. As in the preferred habitat tradition, habitat investors and arbitrageurs trade bonds of various maturities; as in the intermediary asset pricing tradition, arbitrageur wealth is an endogenous state variable relevant for equilibrium risk pricing. When arbitrageurs' portfolio features positive duration, an unexpected rise in the short rate lowers their wealth and raises term premia. A calibration matching the duration of broker/dealers and hedge funds in the data rationalizes the identified effects of policy shocks along the yield curve. The revaluation of arbitrageur wealth has additional implications for the state-dependent effects of policy, endogenous price volatility and the average slope of the term structure, and trends in term premia accompanying trends in the natural rate.

Our analysis has stopped short of tracing out the consequences of changes in term premia for the real economy so as to focus on the novel mechanisms in financial markets relative to existing term structure models. Embedding our model in a New Keynesian production economy, we expect that the effects of policy on the price of risk will amplify the real effects of monetary policy, to the extent that aggregate demand is rising in the amount habitat investors borrow long-term. This seems natural if we interpret long-term borrowers as mortgagors or non-financial corporates whose marginal propensity to consume or invest is higher than the owners of financial firms. We view this as among the most interesting applications of our framework in future work.

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