Imperfect Pass-Through to Deposit Rates and Monetary Policy Transmission*

Alberto Polo†

July 13, 2022

Abstract

I document three salient features of the transmission of monetary policy shocks: imperfect pass-through to deposit rates, impact on credit spreads, and substitution between deposits and other bank liabilities. I develop a monetary model consistent with these facts, where banks have market power on deposits, a duration-mismatched balance sheet, and a dividend-smoothing motive. Deposit demand has a dynamic component, as in the literature on customer markets. A financial friction makes non-deposit funding supply imperfectly elastic. The model indicates that imperfect pass-through to deposit rates is an important source of amplification of monetary policy shocks. An alternative source of liquidity to deposits, such as a central bank digital currency, can further amplify transmission.

Keywords: Monetary Policy Transmission, Deposit Rate, Bank, Market Power.

JEL Codes: E43, E52, G21.

---

*This paper is a revised version of Chapter 1 of my PhD dissertation at NYU. I am extremely grateful to Gianluca Violante, Virgiliu Midrigan and Mark Gertler for their guidance, encouragement and patience during this project. I thank Phillipp Gnan and Francesca Vinci for their discussions of the paper. I thank Dario Bonciani, Matteo Crosignani, Federico Di Pace, Miguel Faria-e-Castro, Carlos Garriga, Simon Gilchrist, Priit Jeenas, Riccardo Masolo, Kate Reinold, Alexi Savov, Philipp Schnabl, Bálint Szőke, Ryland Thomas, and several seminar and conference participants for their insightful comments and suggestions. I thank Itamar Drechsler, Alexi Savov and Philipp Schnabl for providing the US Call Report data and Silvia Miranda-Agrippino and Giovanni Ricco for sharing their US monetary surprises and codes. I thank New York University through the Henry Mitchell MacCracken Fellowship, the Bank of England and the Federal Reserve Bank of St. Louis for financial support. All errors are my responsibility only. Declarations of interest: none. The views expressed in this paper are solely mine and should not be taken to represent those of the Bank of England.

†Bank of England and CfM. Address: Threadneedle St, London, EC2R 8AH, United Kingdom. Email: alberto.polo@bankofengland.co.uk

1 Introduction

Standard models of the transmission mechanism of monetary policy assume that banks play no role. In these models, interest rates are entirely determined by the policy rate and its expected path. There are features of the data, however, that are inconsistent with these models and suggest that banks are relevant for monetary policy transmission.

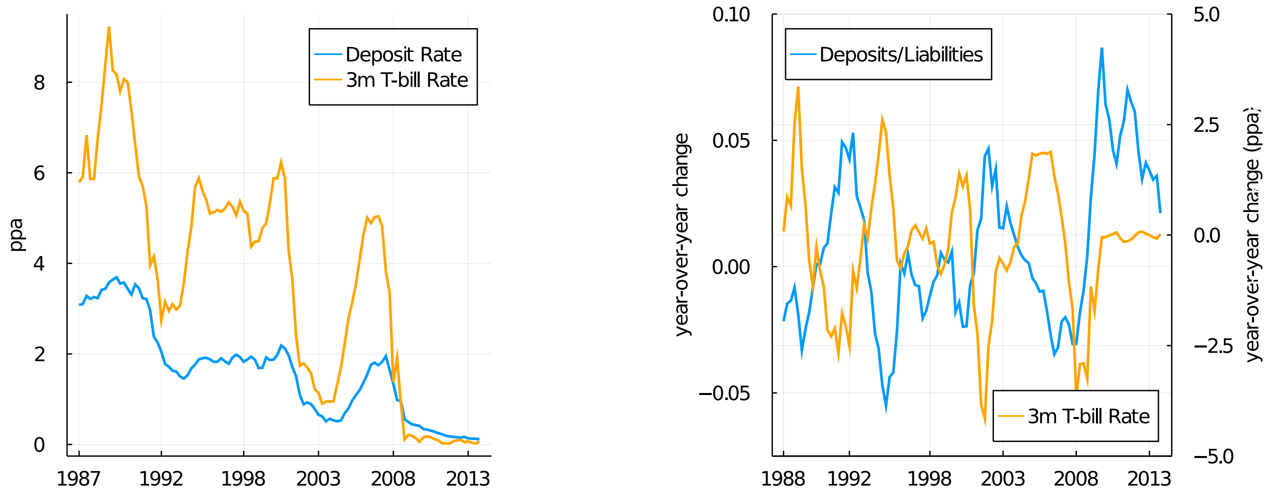
This paper investigates the monetary transmission mechanism by focusing on the effects of monetary policy changes on real activity through the banking sector and the deposit market. Specifically, I study a general equilibrium monetary model which is consistent with three key facts about monetary policy transmission. First, pass-through of the policy rate to deposit rates is imperfect[1] (see e.g. Berger and Hannan 1989 and Figure 1a). Second, with imperfect pass-through to deposit rates, the opportunity cost of holding deposits increases when the policy rate increases. Accordingly, depositors withdraw their savings from banks in order to invest them into higher yielding assets, and banks have to compensate the outflow of deposits with other liabilities. This phenomenon is described in Figure 1b, where a clear negative correlation emerges between the year-over-year change in the 3-month T-bill rate and in the share of banks' total liabilities accounted for by transaction and savings deposits. In Section 2 I show that both features of monetary policy transmission are causal, using monetary policy shocks identified through external instruments. Third, I show that credit spreads – in particular spreads on mortgages and banks' short-term non-deposit debt – increase in response to contractionary monetary policy shocks, a point also made by Gertler and Karadi (2015) using different shocks and empirical model.

I extend a borrower-saver model with housing in the tradition of Iacoviello (2005) to include banks that intermediate funds between savers and borrowers and have market power in the deposit market. Banks borrow through short-term deposits and bonds from savers and lend in fixed-rate mortgages to borrowers.[2] Savers value services from deposits in the utility function and perceive deposits at different banks as being differentiated. Borrowers derive utility from housing services and are subject to a borrowing limit. Motivated by evidence that turnover of banks' customers and depositors is limited, implying that the customer and depositor base of banks is persistent[3], I assume that banks set deposit rates considering that the deposit demand they face has a dynamic component: it depends on current and past deposit rates. In order to capture the dynamic component of deposit demand I use "deep habits" following Ravn et al. (2006). Deep habits is a common speci-

[1]Even after interest-rate ceilings on deposits have been phased-out in the 1980's.

[2]Duration mismatch is a standard feature of modern commercial banks' portfolios (e.g. Begenau et al. 2015). Banks do not appear to use interest-rate derivatives to hedge the corresponding interest-rate risk.

[3]I discuss the evidence concerning deposits in Appendix H.



(a) Risk-free Rate vs. Deposit Rate

(b) Deposits/Liabilities vs. Risk-free Rate

Figure 1

fication in macroeconomic models to represent persistence in the customer base of a firm due to switching costs or repeated purchase in customer markets. Furthermore, banks are subject to a dividend-smoothing motive, and therefore they are not indifferent about the timing of the cash flows they earn from intermediating funds. In this respect Floyd et al. (2015) argue that banks have a more stable propensity to pay dividends than industrials. Alternatively, given the relationship between net interest margin (NIM), profits and dividends, the smoothing motive can capture banks' preference for NIM stability (Drechsler et al., 2020). Dividend-smoothing is modeled through a convex cost that banks incur if dividends deviate from a target level, as assumed for instance by Jermann and Quadrini (2012) in a model with firms. Finally, savers are subject to a financial friction which limits arbitrage in the market for banks' bonds. The friction takes the form of a convex portfolio-adjustment cost. Facing this cost, savers require banks to pay a rate on bonds that is higher than the risk-free rate, and the rate increases if banks want to increase their share of assets financed through bonds. This is meant to capture the feature that banks have a limited pool of non-deposit borrowing available, and in particular that this source of funding is less stable than deposits (Hanson et al., 2015). Therefore, lenders to banks would require a higher compensation for the additional rollover risk the bank takes when it finances a larger share of its assets through non-deposit liabilities.

I propose a novel mechanism that generates imperfect pass-through of changes in the policy rate to deposit rates. The mechanism relies on three main features: i) banks have market power in the deposit market and face a deposit demand with a dynamic component, ii) they manage a duration-mismatched portfolio, and iii) they are subject to a dividend-smoothing motive. When the policy rate increases, the cost of banks' short-term debt increases. While new mortgages price-in the higher level of rates, mortgages issued before the rate change have their rate locked-in in the short run. Hence, banks face a trade-off. If a bank increases the deposit rate as much as the policy rate, it loses current profits. If it keeps the deposit rate low, the bank experiences an outflow of deposits, as depositors prefer to earn a higher rate by investing their savings elsewhere. This is costly for the bank in an environment where deposit demand has a dynamic component. If the bank loses current deposits, the demand it will face in the future will also be low. Attracting more deposits in the future will then require a higher deposit rate than otherwise. In the end, banks decide to increase the deposit rate partially, smoothing their profits without losing an excessive amount of deposits. I show that each of the three main assumptions - dynamic deposit demand, duration mismatch, and dividend smoothing - is essential in order to obtain a realistic degree of imperfect pass-through to deposit rates in this model.

Then, I use the model to investigate the implications of imperfect pass-through for monetary policy transmission. With the portfolio-adjustment cost, the trade-off faced by banks when the policy rate increases becomes more involved. As banks keep deposit rates low in order to smooth profits, deposits flow out. However, banks still have to finance the assets on their balance sheets, thus they substitute deposits with bonds. The substitution towards bond financing leads to an increase in the bond rate banks have to pay above the risk-free rate. In turn, banks pass the higher bond rate they face at the margin to the rate on new mortgages originated after the monetary policy shock. As a consequence of the stronger response in mortgage rates, borrowing demand decreases by more relative to the case with perfect pass-through – where there is no outflow of deposits because their opportunity cost is constant. Since borrowers have a high marginal propensity to consume, as they cut borrowing by more they also cut consumption by more, leading to a 9% larger decrease in output on impact (6% over the first year) relative to the case with perfect pass-through.

Relatedly, Drechsler et al. (2017) show that US counties served by banks that raise deposits in more concentrated markets – and thus have lower pass-through to deposit rates – experience a larger reduction in employment relative to other counties, following an increase in the Federal funds rate. This evidence is cross-sectional and does not necessarily imply a similar effect of imperfect pass-through to deposit rates in the aggregate. My paper fills the gap by showing that a monetary model that captures multiple dimensions of monetary policy transmission implies that imperfect pass-through to deposit rates amplifies the aggregate impact of monetary policy and offers a quantification of the effect. For simplicity the model abstracts from corporate borrowing and investment, but a financial accelerator could further amplify the effect.

I provide three main validations of the model. First, I compare non-targeted local projections of financial and real variables with a monetary policy shock vs. impulse response functions to the same shock from the model, verifying that model variables track quite closely their empirical counterparts. Second, using bank panel data, I find that banks whose balance sheets have a larger gap in duration between assets and liabilities have lower pass-through to deposit rates. This is consistent with the model implication that, if banks held all adjustable-rate mortgages i.e. assets with the same duration as liabilities, then pass-through would be full, while with long-duration assets such as fixed-rate mortgages, pass-through is imperfect. Third, I show that aggregate and panel local projections of deposit spreads with persistent monetary surprises support the theory of imperfect pass-through to deposit rates developed in this paper, as opposed to the popular alternative theory that relies on competition between bank deposits and cash (e.g. Drechsler et al. 2017, Di Tella and Kurlat 2020).

Finally, I study the implications for monetary policy transmission of introducing an alternative source of liquidity to banks' deposits, for instance in the form of a central bank digital currency (CBDC). In doing so, I add to the seminal contributions of Barrdear and Kumhof (2021) and Andolfatto (2021) by modeling in detail the deposit market and investigating dynamic responses. Given the uncertainty around parameter values, I explore the implications of the model over a wide range of values. I find that, if deposits and CBDC are substitutes for savers, the introduction of CBDC amplifies the response of output to monetary policy over most of the parameter space. Intuitively, the option of substituting deposits for CBDC leads to a larger outflow of deposits whenever banks keep deposit rates from increasing with other short term rates, reinforcing the amplification mechanism of the baseline model. However, if the return on CBDC increases less than the deposit rate and deposits are more widely held than CBDC, then monetary policy could become less effective as savers in fact substitute away from CBDC towards deposits when the policy rate rises.

Literature

This paper is related to several strands of the economics literature. In proposing a novel mechanism that generates imperfect pass-through to deposit rates, it contributes to the large literature that studies deposit pricing. Berger and Hannan (1991), Neumark and Sharpe (1992) and Driscoll and Judson (2013), among others, document the slow adjustment of deposit rates using various panel datasets and econometrics techniques. Yankov (2018) focuses on dispersion in rates offered by banks on certificate deposits and finds that market power generated by an asset-pricing model with heterogeneous search costs across savers is consistent with the evidence. Sharpe (1997), Shy (2002), Hannan and Adams (2011) and Carbo-Valverde et al. (2011) focus on switching costs as the key friction that gives banks market power and allows them to slowly adjust deposit rates in response to changes in the short-term rate. Since deep habits for deposits induce a dynamic pricing problem for the bank which is analogous to that of models with switching costs, this paper represents the first application of this pricing channel to deposit rates in a macroeconomic model.

Starting with Aliaga-Díaz and Olivero (2010), deep habits have been applied to the asset side of banks' balance sheets in order to capture the effect of hold-up problems between firms and banks on the cost of firms' external finance. Kravik and Mimir (2019) use a combination of CES demand for deposits at different banks, inertia in aggregate deposits, and cost of adjusting deposit rates. However, in their model banks do not consider the dynamic component of deposit demand when setting deposit rates. In this sense, my paper is the first to use deep habits to represent a pricing friction on the liability side of banks' balance sheets.

The mechanism developed in this paper is also related to Ravn et al. (2006) and especially Gilchrist et al. (2017), who combine deep habits and costly external finance in order to generate movements in the optimal markup chosen by firms. The most important difference relative to them is that my mechanism also relies on a peculiar feature of the banking sector, namely duration transformation, in order to generate fluctuations in profits and induce banks to change markups in the deposit market.

A number of recent papers have studied imperfect pass-through to deposit rates and monetary policy. Drechsler et al. (2017) find that stronger market power by a bank in the local deposit market reduces the degree of pass-through of the policy rate to the bank's deposit rate relative to other banks, generates a larger outflow of deposits, and a stronger contraction in lending and employment across counties. Among dynamic general equilibrium models, Gerali et al. (2010) assume that changing deposit rates is subject to convex adjustment costs in order to generate partial pass-through to deposit rates. Di Tella and Kurlat (2020) assume that banks are subject to a binding leverage constraint that requires deposit supply to be a multiple of banks' market value of net worth. Given the assumption that households derive utility from liquidity services provided by deposits, the deposit spread increases with the short-term rate as the market value of banks' long-duration assets and net worth decrease. Brunnermeier and Koby (2018) introduce variation in the degree of pass-through with the level of the short-term rate by assuming that the propensity of depositors to shop for rates across banks decreases with the level of the short-term rate. Wang (2020) shows empirically that low policy rates shift the cost of financial intermediation from depositors to borrowers and weaken monetary policy transmission as the level of rates decreases towards the effective lower-bound. These facts are rationalized by a model where banks are subject to a borrowing constraint and finance their assets through deposits and equity, and where savers can substitute between deposits and currency. Relative to these papers, my contribution is to develop a model with a different mechanism that can account for the extent of pass-through documented by Drechsler et al. (2017), while capturing substitution between deposits and non-deposit liabilities and overshooting of borrowing rates relative to the policy rate, as observed in the data. Moreover, I show that Drechsler et al. (2017)'s cross-sectional evidence on larger real effects of monetary policy with lower pass-through to deposit rates extends to the aggregate economy.

Finally, the structure of the model with borrowers, savers and mortgages analyzed in this paper is based on Greenwald (2018). In addition to the different focus on the deposits market, my main novelty is the introduction of a banking sector between borrowers and savers, which offers an endogenous channel for the term premium/mortgage spread shock studied in Greenwald (2018).

Outline

The rest of the paper is organized as follows. Section 2 shows the empirical evidence on the effects of monetary policy on bank variables and interest spreads. Section 3 develops the dynamic general equilibrium model and discusses the mechanism that generates imperfect pass-through to deposit rates. Section 4 describes the baseline parameterization of the model. Section 5 provides further illustration of the mechanisms and discusses how the assumptions of the model are essential in generating the degree of imperfect pass-through observed in the data. Section 6 studies the relationship between duration mismatch and deposit pass-through and compares the theory of deposit pass-through developed in this paper with the 'competition-with-cash' theory. Section 7 explores the implications of imperfect pass-through for monetary policy transmission. Section 8 concludes.

2 Evidence

This section presents the three facts about monetary policy transmissions which are the focus of the paper: i) imperfect pass-through to deposit rates, effect of monetary shocks on ii) deposit balances and other bank liabilities, and effect on iii) credit spreads.

First, I confirm that, in the aggregate, following a monetary shock that increases US risk-free rates, deposit rates at US banks increase only partially, deposit balances decrease and banks substitute deposits with non-deposit liabilities. Using a different identification strategy, Drechsler et al. (2017) show evidence of these patterns in the cross-section, although - as pointed out by Repullo (2020) - their panel data evidence does not necessarily translate into implications for aggregate deposits and non-deposit liabilities.

I use local projections of the variables of interest with an external instrument for monetary policy shocks, in the spirit of Jordà (2005) and Mertens and Ravn (2013). I choose the "informationally-robust" monetary policy shocks constructed by Miranda-Agrippino and Ricco (2021b) as the instrument for changes in US monetary policy. These shocks consist of surprises in the 3-month-ahead Federal funds futures over 30-minute windows around FOMC announcements, projected on Greenbook forecasts and forecast revisions for real GDP growth, inflation and unemployment and past market surprises to control for the Federal Reserve's information channel. I estimate quarterly[4] local projections between 1987 and 2013 of the form

$$y_{t+h} = \alpha_h + \beta_h i_t + \Gamma_h X_{t-1} + u^y_{t+h} \quad (1)$$

where y_{t+h} is either i) the average deposit rate for the aggregate of US commercial banks - computed as the ratio of interest expense on deposits to the stock of deposits, ii) the natural logarithm of real deposits, iii) the natural logarithm of real non-deposit liabilities, iv) the ratio of non-deposit liabilities to total liabilities of banks, all computed from US Call Report data.[5] Deposits correspond to transaction and savings deposits, consistently with how deposits are treated in the model of Section 3.

Denote by z^i_t a monetary policy shock. Then, z^i_t is the instrument for the policy indicator i_t in Equation (1), which I set as the 1-year US Treasury bond rate in order to capture also the effects of forward guidance (Gertler and Karadi, 2015). X_{t-1} collects a number of controls, chosen following Miranda-Agrippino and Ricco (2021b): four lags of industrial production, the unemployment rate, a consumer price index, a commodity price index, the Gilchrist and Zakrajšek (2012) excess bond premium, the policy indicator i_t, and the response variable y_t.[6]

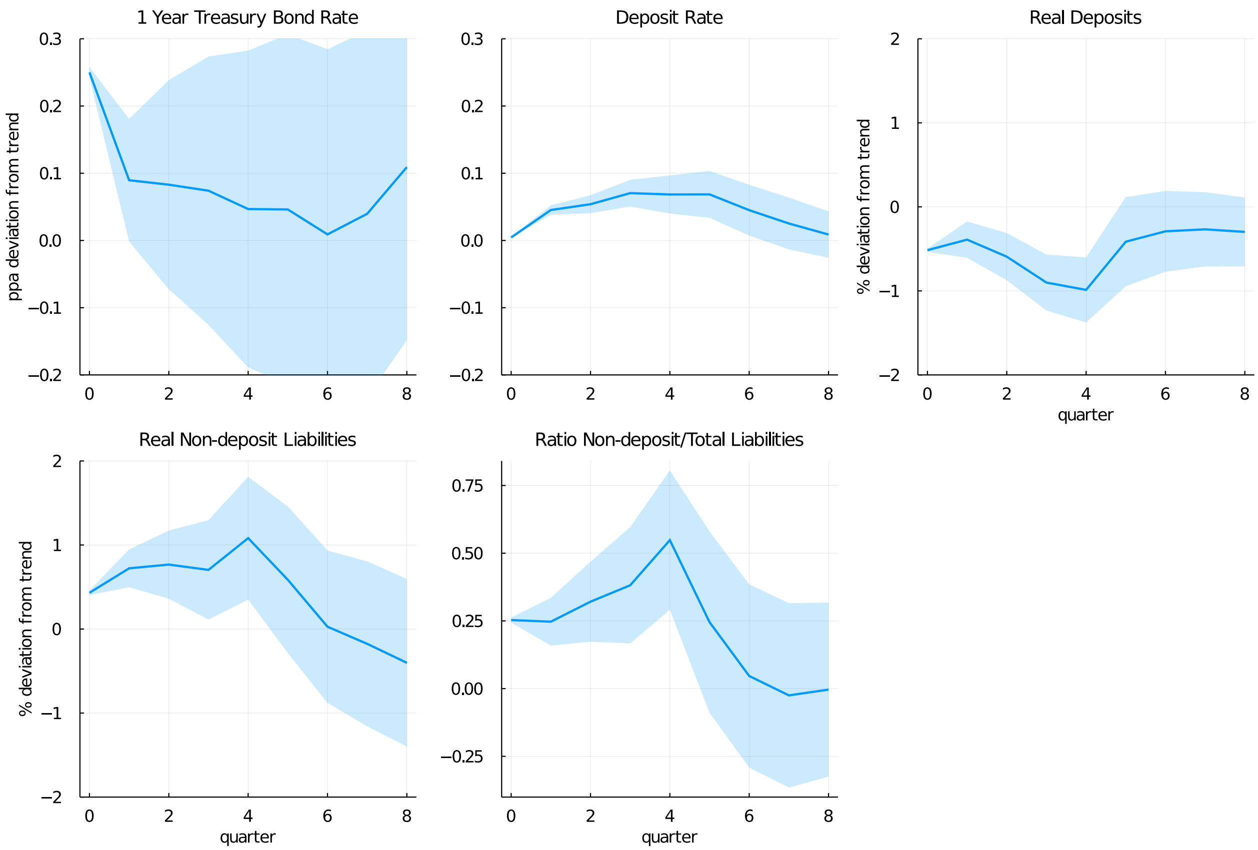
Figure 2 shows the first set of results. The first panel describes the response of the 1-year Treasury bond rate to the monetary shock, normalized to increase by 25 bps on impact. Following the exogenous increase in the policy indicator, deposit rates adjust only partially, deposits decrease and banks' non-deposit debt increases.

Next, I show that monetary policy shocks affect credit spreads, using different shocks and empirical model than Gertler and Karadi (2015), and extending the result to interbank spreads. Given the structure of the model introduced in Section 3, I focus on the mortgage

[4] Since in a given quarter there can be more than one FOMC announcement, I follow e.g. Wong (2021) and Jeenas (2018) and sum all shocks over each quarter.

[5] I use quarterly local projections since US Call Report data are only available at quarterly frequency. Real variables are obtained by deflating the corresponding nominal variables using the consumer price index for all urban consumers.

[6] Appendix B provides details on the data and shows local projections of macroeconomic variables with the monetary policy shock, which display the usual patterns.



Source: US Call Reports, various Federal Reserve releases, Miranda-Agrippino and Ricco (2021b) monetary shocks, Q1 1987 - Q4 2013. Shaded areas correspond to 90% confidence bands (with HAC standard errors).

Figure 2: Local Projections of Bank Variables with Monetary Policy Shock

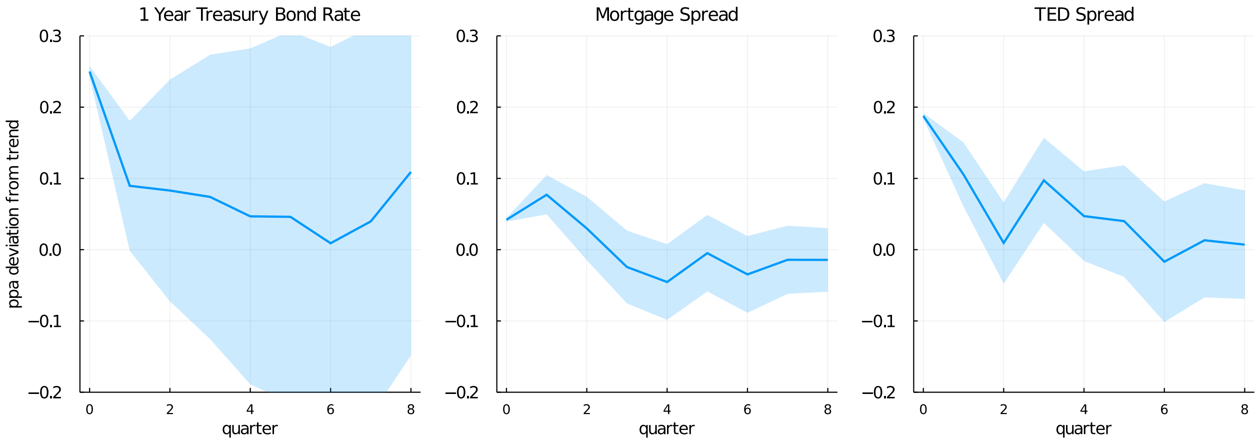
spread and the TED spread. The mortgage spread is computed as the difference between the US average 30-year mortgage rate provided by Freddie Mac and the 10-year Treasury bond rate, as in Gertler and Karadi (2015). The TED spread is the spread between the 3-month LIBOR and the 3-month Treasury bill rate, capturing the average spread on banks' non-deposit borrowing at the margin.

Figure 3 presents local projections of these variables with the same Miranda-Agrippino and Ricco (2021b) instrument used before and the same specification of Equation (1), highlighting the substantial response of the TED spread and the more muted response of the mortgage spread to the monetary policy shock.

3 Model

This section describes the model and discusses some of the agents' main first-order conditions. All equilibrium conditions are listed in Appendix A.

Time is discrete and infinite. There are four types of agents in the economy: two families



Source: Federal Reserve H.15 and Interest Rate Spreads releases, Freddie Mac Primary Mortgage Market Survey, Miranda-Agrippino and Ricco (2021b) monetary shocks, Q1 1987 - Q4 2013. Shaded areas correspond to 90% confidence bands (with HAC standard errors).

Figure 3: Local Projections of Interest Spreads with Monetary Policy Shock

of households, commercial banks and a production sector.

Each family consists of a continuum of households. One of the main differences between households in the two families is their rate of time preference: one family comprises more patient households ("savers", s) and the other comprises more impatient households ("borrowers", b). The respective measures of the two families are χ and $1-\chi$.

The economy is populated by a unit measure of banks. Banks intermediate funds between savers and borrowers, engaging in duration transformation by lending in fixed-rate mortgages to borrowers and borrowing in short-term deposits and bonds from savers. Because savers perceive deposits at different banks as being differentiated, banks enjoy market power in setting deposit rates. Since there is a continuum of banks, there is no strategic interaction among them in setting deposit rates. A unit measure of monopolistically competitive firms hire labor from households to produce intermediate goods under a nominal rigidity, while a representative final good producer transforms intermediate goods into the final good. Finally, the central bank sets the nominal risk-free rate according to a Taylor rule.

Markets are incomplete with respect to aggregate shocks: borrowers can only borrow through fixed-rate mortgages and are subject to a borrowing limit, and savers con only save in banks' deposits, banks' bonds and government bonds. All these assets are non-contingent with respect to aggregates.

The economy is subject to two monetary shocks in the Taylor rule - a standard transitory shock and a persistent inflation-target shock. The latter corresponds to persistent changes in monetary policy as in Smets and Wouters (2003), Ireland (2007), Garriga et al. (2017) and Greenwald (2018). It allows the central bank to shift long-term nominal interest rates, in addition to short-term rates, in an environment with fixed-rate mortgages.

Preferences

I represent the demand for deposits by savers using a money-in-the-utility function specification.[7] Moreover, I assume that savers are subject to "deep habits" for deposits offered by different banks. Deep habits are a common specification in macroeconomic models to represent persistence in the customer base faced by firms due to switching costs (Klemperer, 1995) or repeated purchase in customer markets (Phelps and Winter, 1970), as in Ravn et al. (2006) and Gilchrist et al. (2017) among others.

Accordingly, a saver s derives utility from consumption of the final good C_t^s and deposit holdings at banks $\{d_{jt}^s\}_{j=0}^1$, and disutility from labor N_t^s. Her period-utility function is

$$U^s\left(C_t^s, N_t^s, D_t^s\right) = \frac{\left(\frac{C_t^s}{\chi}\right)^{1-\frac{1}{\sigma}} - 1}{1-\frac{1}{\sigma}} + \psi \frac{\left(\frac{D_t^s}{\chi}\right)^{1-\frac{1}{\gamma}} - 1}{1-\frac{1}{\gamma}} - \zeta_s \frac{\left(\frac{N_t^s}{\chi}\right)^{1+\epsilon}}{1+\epsilon} \tag{2}$$

where

$$D_t^s = \left[\int_0^1 \left(d_{jt}^s S_{j,t-1}^{\theta}\right)^{1-\frac{1}{\eta}} \mathrm{d}j\right]^{\frac{\eta}{\eta-1}}, \eta > 1 \text{ and } \theta > 0 \tag{3}$$

is a CES aggregator of utility derived from the continuum of deposits held.[8] This function captures how the saver values deposits at different banks in the utility function. The parameter η governs the elasticity of substitution of deposits across banks, $S_{j,t-1}$ is bank j's deposit habit stock at the end of period $t-1$, while θ is the degree of habit formation.[9] The bank-specific habit stock is taken as given by the saver as I assume that habits are external.[10] Its law of motion is described in Section 3.2 when discussing the problem of a bank.

[7] Following Sidrauski (1967), several macroeconomic models have used this specification to capture non-pecuniary benefits enjoyed by households from holding money-like-assets. These benefits could arise due to exposure to liquidity shocks (Diamond and Dybvig, 1983) or transaction and liquidity costs (Baumol, 1952, Tobin, 1956). Feenstra (1986) shows that models with money-in-the-utility and models with transaction/liquidity costs are functionally equivalent.

[8] While these preferences represent one saver household as holding deposits at each bank, Appendix C discusses how this can be interpreted as the aggregate outcome of decisions made by individual members of a household each to hold deposits at a single bank, using a discrete choice model (Anderson et al., 1987) or a characteristics model (Anderson et al., 1989).

[9] If $\theta = 0$, the habit drops from the saver's problem.

[10] This makes the problem more tractable, as current deposit demand depends only on current rates (Ravn et al., 2006). As studied by Nakamura and Steinsson (2011), if the evolution of the habit specific to each variety is internalized by the customer, a time-inconsistency issue arises. Due to the lock-in effect, when deciding her demand, the customer takes into account not only the current price, but also future prices. Thus, the price setter has an incentive to promise low prices in the future. However, when the future comes, the price setter prefers to renege on the promise.

In the utility function (2), σ is the elasticity of intertemporal substitution, ψ and γ govern weight and curvature with respect to the CES aggregate of utility from deposits D_t^s, ζ_s is the weight on disutility from labor supply and ϵ is the inverse Frish elasticity of labor supply.

Borrowers have separable preferences over consumption of the final good C_t^b, housing services from houses purchased in the previous period H_{t-1}, and labor supply N_t^b. Their preferences take the form

$$U^b\left(C_t^b, N_t^b, H_{t-1}\right) = \frac{\left(\frac{C_t^b}{1-\chi}\right)^{1-\frac{1}{\sigma}} - 1}{1-\frac{1}{\sigma}} + \varphi \log\left(\frac{H_{t-1}}{1-\chi}\right) - \zeta_b \frac{\left(\frac{N_t^b}{1-\chi}\right)^{1+\epsilon}}{1+\epsilon}$$

where the new parameter φ governs the weight on housing services in the utility function.

Financial Assets

There are four nominal assets in the economy: government bonds, mortgages, banks' deposits and banks' bonds.

Government bonds pay the risk-free rate $1 + i_t$ in period $t + 1$ for each dollar invested in the previous period. They are available in zero-net supply.

The representation of fixed-rate mortgages follows Greenwald (2018). A mortgage is a nominal perpetuity with geometrically decaying payments, as standard in the literature. Letting q_t^* be the equilibrium coupon rate on the mortgage at origination, the bank lends one dollar to the borrower in exchange for $(1-\nu)^k q_t^*$ dollars in each future period $t + k$ until the mortgage is prepaid, where ν is the fraction of principal paid in each period. Prepayment allows the borrower to repay all remaining principal due on the mortgage, and borrow in a new mortgage. In order to have partial prepayment in any period, it is assumed that any borrower faces an *iid* transaction cost when prepaying.

In order to finance their assets, banks issue one-period nominal deposits and bonds to savers. As discussed, banks' deposits are valued for their services by savers, in addition to the return they earn. One dollar of deposits acquired in period t from bank j generates utility to savers in the same period and pays a rate $1 + i_{jt}^d$ in the following period. This implies a convenience yield on banks' deposits relative to the risk-free rate.

Bonds issued by different banks are perfectly substitutable, thus they pay the same rate $1 + i_t^B$ in period $t + 1$ per dollar invested in t. I assume that banks' bonds are *not* perfectly substitutable with government bonds due to a portfolio-adjustment cost faced by savers as e.g. in Gertler and Karadi (2013). This financial friction implies that the rate on banks' bonds will in general be higher than the risk-free rate. Finally, since bonds represent all non-deposit funding of banks, and large banks in particular are not fully deposit-funded, I assume that only non-negative holdings of bonds are admissible.

Housing

Since the housing market is not the main focus of the paper, for simplicity I assume that only borrowers obtain a service flow from holding houses and actively trade in the market. In each period, they pay a fraction δ of the market value of their housing stock as maintenance cost. Moreover, housing is in fixed supply $\bar{H}$, which implies that borrowers' demand for housing determines entirely its price.[11]

3.1 Savers

Each saver s chooses consumption C_t^s, labor supply N_t^s, holdings of government bonds A_t^s, holdings of banks' bonds B_t^s and deposits d_{jt}^s at each bank $j \in [0,1]$ to maximize the expected present discounted value of utility

$$\mathbb{E}_0 \left[\sum_{t=0}^{\infty} \beta_s^t U^s \left(C_t^s, N_t^s, D_t^s \right) \right], \beta_s \in (0,1)$$

subject to a sequence of budget constraints, which in real terms are

$$C_t^s + A_t^s + \int_0^1 d_{jt}^s \,\mathrm{d}j + B_t^s + \Theta(B_t^s, M_t) \leq (1-\tau^y) W_t N_t^s + \frac{1+i_{t-1}}{\Pi_t} A_{t-1}^s + \int_0^1 \frac{1+i_{j,t-1}^d}{\Pi_t} d_{j,t-1}^s \,\mathrm{d}j + \frac{1+i_{t-1}^B}{\Pi_t} B_{t-1}^s + T_t^s + \Xi_t^s$$

where $\Pi_t \equiv P_t / P_{t-1}$ is the gross rate of inflation between $t-1$ and t, W_t is the real wage, i_t , i_{jt}^d and i_t^B are nominal rates on government bonds, deposits and banks' bonds respectively, τ^y is a linear tax on labor income rebated to the household at the end of the period through T_t^s, and Ξ_t^s collects real profits from firms and dividends paid by banks, as they are owned by savers. $\Theta(B_t^s, M_t)$ is the convex function of bank bond holdings B_t^s which introduces the financial friction in the model, breaking no-arbitrage between government and banks' bonds. I assume the function takes the form

$$\Theta(B_t^s, M_t) = \frac{\kappa^B}{2} \left(\frac{B_t^s}{M_t} - v^B \right)^2 M_t$$

where M_t are total bank assets - taken as given by savers. The ratio B_t^s / M_t is the share of bonds the saver is supplying to banks relative to total bank assets.

Defining the saver's discount factor as

$$\Lambda_{t,t+1}^s \equiv \beta_s \frac{U_{C_{t+1}^s}^s}{U_{C_t^s}^s},$$

[11] These assumptions are common to Greenwald (2018) and Faria-e-Castro (2018).

the first-order condition for government bond holdings is the standard Euler equation

$$1 = \mathbb{E}_t \left[\frac{\Lambda^s_{t,t+1}}{\Pi_{t+1}} \right] (1 + i_t)$$

The Euler equation for the choice of banks' bonds to hold is

$$\mathbb{E}_t \left[\frac{\Lambda^s_{t,t+1}}{\Pi_{t+1}} \right] (i^B_t - i_t) = \kappa^B \left(\frac{B^s_t}{M_t} - v^B \right),$$

with a positive *rhs* in the deterministic steady state. The financial friction captures in reduced-form that savers have a limited risk-bearing capacity: they are not willing to hold any amount of banks' bonds at the risk-free rate. As savers are not able to fully absorb the demand for non-deposit funding by banks, the rate that banks need to offer on bonds has to increase above the risk-free rate, and arbitrage of asset returns is incomplete. The idea behind this friction is that the larger the share of banks' assets financed through bonds, the more the lenders become concerned about rollover risk of such short-term non-deposit liabilities - generally considered a less-stable form of funding than deposits (Hanson et al., 2015). As a result, a larger spread opens up between the bank bond rate and the risk-free rate.

The saver's problem also yields an Euler equation for deposits at a bank j, d^s_{jt}, which writes

$$\mathbb{E}_t \left[\frac{\Lambda^s_{t,t+1}}{\Pi_{t+1}} \right] \underbrace{(i_t - i^d_{jt})}_{\equiv m^d_{jt}, \text{ bank } j\text{'s deposit spread}} = \frac{U^s_{D^s_t} \frac{\partial D^s_t}{\partial d^s_{jt}}}{U^s_{C^s_t}} \tag{4}$$

This equation sets the marginal cost of holding deposits at bank j equal to its marginal benefit in equilibrium. The *lhs* is the opportunity cost of holding one dollar of deposits at bank j, in terms of forgone interest with respect to investing it at the risk-free rate i_t. This is the deposit spread offered by bank j, m^d_{jt}. Because this cost is nominal and incurred at the beginning of the following period, it is discounted to the beginning of period t using the discount factor for nominal payoffs. The *rhs* in turn is the marginal rate of substitution between consumption and deposits at bank j.

As shown in Appendix D, equation (4) allows to obtain closed-form solutions for deposit demands. Saver s's deposit demand from bank j has a standard CES form,

$$d^s_{jt} = \left(\frac{m^d_{jt}}{\tilde{m}^d_t} \right)^{-\eta} S^{\theta(\eta-1)}_{j,t-1} D^s_t \tag{5}$$

where $\tilde{m}^d_t \equiv \left[\int_0^1 \left(m^d_{jt} S^{-\theta}_{j,t-1} \right)^{1-\eta} \right]^{\frac{1}{1-\eta}}$ is the (habit-adjusted) average cost of holding deposits in the market. As expected, deposit demand is decreasing in the opportunity cost of holding deposits at bank j, $m^d_{jt}/\tilde{m}^d_t$, and increasing in the habit stock $S_{j,t-1}$ and aggregate (habit-adjusted) deposit demand D^s_t.

Because there is full insurance across saver households within the family, the solution to the problem aggregates to that of a representative saver. In particular, the saver's discount factor $\Lambda^s_{t,t+1}$ is unique. Thereafter, I will denote by s all variables that refer to the representative saver, when otherwise confusion would arise with respect to borrowers. Since government bonds, deposits and banks' bonds are only held by savers, the index s will be dropped for these variables.

3.2 Commercial Banks

As highlighted by Begenau et al. (2015) and Di Tella and Kurlat (2020), duration transformation - that is, investing in long-duration nominal assets, such as fixed-rate mortgages, and borrowing in short-duration nominal liabilities - is at the core of large modern commercial banks' business. These banks are exposed to the corresponding interest-rate risk despite the opportunity of hedging it through interest-rate derivatives.

I capture this feature by assuming that, in each period t, banks have to finance both their book of fixed-rate mortgages issued to borrowers in the past and not yet prepaid, as well as new mortgages issued to borrowers in t, by borrowing in one-period deposits and bonds from savers.

Banks are owned by savers. Each bank $j \in [0,1]$ enters period t with total principal on outstanding mortgages $M_{j,t-1}$, total payments to be collected from borrowers on outstanding mortgages $X_{j,t-1}$, and a deposit habit stock $S_{j,t-1}$. Letting μ_t be the fraction of mortgages prepaid in period t, and considering that a fraction ν of outstanding principal is repaid in each period by borrowers, the total value of mortgages that the bank has to finance in period t is

$$M_{jt} = \mu_t M^*_{jt} + (1-\mu_t)(1-\nu)\frac{M_{j,t-1}}{\Pi_t} \tag{6}$$

where M^*_{jt} are new mortgages originated to prepaying borrowers. This is the law of motion for banks' assets. As the mortgage rate is fixed, the bank operates under another similar law of motion for mortgage payments,

$$X_{jt} = \mu_t q^*_t M^*_{jt} + (1-\mu_t)(1-\nu)\frac{X_{j,t-1}}{\Pi_t} \tag{7}$$

where q^*_t is the rate on new mortgages originated in t.

The balance-sheet constraint of the bank requires that in each period the bank collects enough deposits d_{jt} and bonds B_{jt} to finance its book of mortgages M_{jt},

$$M_{jt} = d_{jt} + B_{jt} \tag{8}$$

The bank has market power in setting its deposit rate i^d_{jt}. It considers that, given the risk-free rate i_t, the deposit demand it faces is increasing in the deposit rate it offers (or equivalently, decreasing in the deposit spread $i_t - i^d_{jt}$ offered, see Equation 5). It also takes into account that savers are partially locked in: the deposit habit introduces a link between current and future deposit demand. Specifically, I assume the deposit habit stock at bank j evolves as a moving average of the past stock and current deposit demand at bank j,

$$S_{jt} = \rho_s S_{j,t-1} + (1-\rho_s) d_{jt} \tag{9}$$

The bank's objective is to maximize the expected present discounted value of net real dividends paid to savers. In doing so, the bank is subject to a friction: following e.g. Jermann and Quadrini (2012), Begenau (2020) and Elenev et al. (2021), paying a dividend div_{jt} incurs a cost $f(div_{jt})$ which is quadratic in the deviation of the dividend from a target level.[12] The total cost of paying out a dividend div_{jt} is thus $div_{jt} + f(div_{jt})$. This assumption makes banks non-indifferent about the timing of cash flows and is consistent with the evidence in Floyd et al. (2015) that banks have more stable propensity to pay dividends than US industrial firms.[13] When dividends are below the target level, the cost can capture a precautionary motive to bring profits closer to target in order to avoid expensive equity issuance. When dividends are above the target level, the cost induces the bank to sacrifice some current profits in order to pay a higher deposit rate and build a bigger deposit base, that will earn higher profits in the future when short-term rates increase again. An alternative motivation for the cost is that it represents in reduced form banks' preference for NIM stability as shown in Drechsler et al. (2020), given the mapping between NIM and dividends in the model.

In each period, the bank chooses new mortgage origination M^*_{jt}, deposit and bond issuance d_{jt} and B_{jt}, and the deposit rate to offer i^d_{jt} in order to maximize

$$\mathbb{E}_0 \left[\sum_{t=0}^{\infty} \Lambda^s_{0,t+1} div_{j,t+1} \right]$$

where

$$div_{j,t+1} = \frac{1}{\Pi_{t+1}} \left[X_{jt}(q^*_t) - \nu M_{jt} - (i^d_{jt} + \kappa) d_{jt} - i^B_t B_{jt} \right] - f(div_{j,t+1}) \tag{10}$$

$$f(div_{jt}) = \frac{\kappa^{div}}{2} \left(div_{jt} - \bar{div} \right)^2$$

subject to laws of motion (6), (7), (9), deposit demand (5) and balance sheet constraint (8).

[12] When solving the model, the target level will correspond to the steady state level of dividends.

[13] The assumption is similar to the equity-issuance costs assumed by Gilchrist et al. (2017), although my cost is two-sided and does not involve banks being exposed to uninsurable idiosyncratic shocks to their return on assets - which would be the translation of Gilchrist et al. (2017)'s setting into mine.

The term in brackets in (10) is the net interest earned by the bank at the beginning of period $t+1$ from its intermediation activity carried out in t. Since X_{jt} are total payments on outstanding mortgages, including both principal and interest, $X_{jt}(q_t^*) - \nu M_{jt}$ is the interest income earned by the bank on its book of mortgages.[14] Then, the bank has to pay interest to savers on deposits at rate i_{jt}^d and interest on bonds at rate i_t^B.[15] The parameter κ is the marginal cost incurred by the bank when offering one dollar of deposits.[16]

A discussion of the Euler equation for the deposit spread m_{jt}^d[17] is in order (Equation 17 in Appendix A), as it underpins the mechanism generating imperfect pass-through to deposit rates in the model. For the sake of exposition, I assume that the habit stock depreciates fully at the end of the period ($\rho_s = 0$). This means that current deposit demand affects next period's deposit demand only. Moreover, I suppose that the spread between the bank bond rate i_t^B and the risk-free rate i_t is 0. I re-introduce a positive spread (the empirically relevant case) below.

With these simplifying assumptions, the bank would set the sequence of deposit spreads $\{m_{jt}^d\}_{t=0}^{\infty}$ to satisfy

$$\mathbb{E}_t \left[\frac{\Lambda_{t,t+1}^s}{\Pi_{t+1}} \Omega_{j,t+1} \right] \left(\frac{\eta}{\eta - 1} - \frac{m_{jt}^d}{\kappa} \right) = \theta \mathbb{E}_t \left[\frac{\Lambda_{t,t+2}^s}{\Pi_{t+2}} \Omega_{j,t+2} \frac{m_{j,t+1}^d}{\kappa} \frac{d_{j,t+1}}{d_{jt}} \right] \tag{11}$$

in each period t, where

$$\Omega_{jt} = \frac{1}{1 + f'(div_{jt})} = \frac{1}{1 + \kappa^{div}(div_{jt} - \bar{div})}$$

is the marginal value of profits to the bank, decreasing in dividends.[18] The first-order

[14] The implicit assumption is that, in each period, the bank can convert one-for-one the unpaid part of the outstanding principal $(1-\nu)M_{jt}$ into units of the final good to be used to repay short-term deposits and bonds. This is a necessary assumption in this setting with duration mismatch, where all borrowing and saving happens between two subsequent time intervals. In reality, banks have many duration options to cover roll-over or shortage of short-term debt, which does not all mature simultaneously.

[15] Since I will use a first-order approximation of the solution to the model around the deterministic steady state, the bank does not earn any term premium from managing a duration-mismatched portfolio. The profits made by the bank on its intermediation activity come entirely from its market power in the deposit market.

[16] This cost is needed in order to have a well-defined problem. Once I assume that savers value deposits in the utility function, the bank is effectively supplying a good to the savers. Since the bank has market power, the markup would not be well-defined absent such marginal cost. This cost represents variable costs including salaries, thus I rebate it to savers in the term Ξ_t^s. In steady state, the total cost from this source is very small, as it amounts to 0.14% of output.

[17] Since all rates except the deposit rate are taken as given by the bank, setting the deposit spread or the deposit rate is equivalent for the bank.

[18] As long as $div_{jt} > \bar{div} - \frac{1}{\kappa^{div}}$.

condition equates the marginal cost of attracting one additional dollar of deposits, in terms of forgone profits, to its marginal benefit, in terms of future profits.

Notice that m^d_{jt}/κ is the time-varying markup set by the bank on deposits, as the deposit spread m^d_{jt} is the marginal cost to the saver of holding deposits at the bank and κ is the marginal cost to the bank of supplying deposits (up to time discounting). Since $\eta/(\eta-1)$ is the optimal markup that maximizes static profits given the CES demand, the *lhs* is forgone profits by the bank to attract the marginal dollar of deposits expressed in terms of deviation of the optimal markup from the markup that maximizes static profits. Given that all terms on the *rhs* are positive, the bank sets a markup below the static markup, a standard result in the deep habits literature. The *rhs* is the marginal increase in future profits expressed in markups from the additional dollar of deposits attracted in period t, which affects period $t+1$ deposit demand with elasticity θ. If $\theta = 0$, Equation (11) immediately implies

$$\frac{m^d_{jt}}{\kappa} = \frac{\eta}{\eta - 1}$$

i.e. a constant markup, or alternatively, a constant deposit spread and full pass-through to deposit rates.

Imperfect pass-through of an increase in the short-term rate i_t to the deposit rate i^d_{jt} is due to the interaction of i) rigidity in banks' interest income earned on long-duration assets relative to the interest paid on short-term debt, ii) dividend smoothing, iii) dynamic component of deposit demand from deep habits. Persistence in deposit demand implies that the bank optimally sets a deposit spread below the level that maximizes current profits, as it takes into account the positive effect on future deposit demand. However, when the short-term rate i_t increases, bank's profits and thus dividends from intermediation decrease due to its duration-mismatched portfolio: legacy assets on bank's balance sheet have a rate which is locked-in in the short term and only new assets originated price-in the new level of rates. At the same time, the bank has to continue financing its asset book. If it is too costly to finance the entire book through deposits given deposit demand[19], the bank will issue bonds at the higher rate. The resulting reduction in profits increases the marginal value of current profits $\Omega_{j,t+1}$ relative to future profits $\Omega_{j,t+2}$ in Equation (11). Holding everything else equal, this will be offset by an increase in the optimal markup towards the static markup. Hence, if the deposit spread $i_t - i^d_{jt}$ increases with i_t, it means that the deposit rate does not increase as much as the short-term rate, i.e. there is imperfect pass-through to the deposit rate.

[19]This is the case near the steady state, as the weight ψ on deposits in the utility function is set so that equilibrium deposits in steady state allow to match the allocation between deposits and other funding in the aggregate balance sheet of the US banking sector (see Section 4).

Introducing a positive bank bond spread, Equation (11) becomes

$$\mathbb{E}_t\left[\frac{\Lambda^s_{t,t+1}}{\Pi_{t+1}}\Omega_{j,t+1}\right]\left[\frac{\eta}{\eta-1}\left(1-\frac{i^B_t-i_t}{\kappa}\right)-\frac{m^d_{jt}}{\kappa}\right]=\theta\mathbb{E}_t\left[\frac{\Lambda^s_{t,t+2}}{\Pi_{t+2}}\Omega_{j,t+2}\frac{m^d_{j,t+1}}{\kappa}\frac{d_{j,t+1}}{d_{jt}}\right] \tag{12}$$

The only difference relative to Equation (11) is that the static markup $\eta/(\eta-1)$ is multiplied by the term $1-(i^B_t-i_t)/\kappa$, which is decreasing in the bond spread. Now, if $\theta=0$, Equation (12) implies

$$\frac{m^d_{jt}}{\kappa}=\frac{\eta}{\eta-1}\left(1-\frac{i^B_t-i_t}{\kappa}\right)$$

Effectively, the bond spread introduces variation in the static markup. The intuition is as follows. The marginal cost for the bank of attracting one additional dollar of deposits in terms of forgone profits still depends on the deposit spread m^d_t that the bank offers, as in order to attract deposits the bank has to sacrifice some profits and offer a higher deposit rate (i.e. a lower deposit spread). However, as the bank attracts more deposits, it can save on the additional cost that it pays if it finances its marginal dollar of assets at the bond rate, relative to the risk-free rate. Hence, everything else equal, the bank has a lower effective marginal cost of attracting deposits, the higher the bond rate i^B_t is relative to the risk-free rate i_t. As a result, it has an incentive to reduce the deposit markup m^d_{jt}/κ below the static markup $\eta/(\eta-1)$ in order to attract more deposits – in other words, to have more-than-full deposit rate pass-through.

To sum up, variation in the bond spread introduces a motive for the bank to increase pass-through to deposit rates above full pass-through, to the extent that the bank's marginal cost of funds i^B_t responds by more than the risk-free rate i_t. This is exactly the case in the data, as shown in Section 2. Therefore, deposit habits ($\theta>0$) are needed in this model in order for it to be consistent both with imperfect pass-through to deposit rates as well as with the response of the TED spread to monetary shocks. Section 5 will argue that the other features (duration mismatch and dividend-adjustment cost) are also needed to deliver the degree of imperfect pass-through seen in the data.

3.3 Borrowers

The problem of the borrowers follows Greenwald (2018). There are two main features in this problem. First, borrowers are subject to a payment-to-income (PTI) constraint (more commonly known as debt-to-income limit) which limits the borrowed amount based on interest payments due on the mortgage relative to labor income. As a result, the mortgage rate enters the constraint directly, amplifying the transmission of shocks that impact this rate. Second, there is endogenous prepayment by borrowers. At each point in time, borrowers decide whether to prepay their mortgage by comparing their *iid* transaction cost of prepayment with the benefit from prepaying. Prepayment amplifies the transmission of shocks into output.[20] As shown by Greenwald (2018), assumptions on geometrically decaying coupons, perfect insurance within the borrower family and the threshold prepayment policy greatly simplify the states that need tracking and allow aggregation.

The representative borrower chooses consumption C_t^b, labor supply N_t^b, new housing size H_t^*, new borrowing M_t^{b*}, and the fraction of mortgages to prepay μ_t to maximize the expected present discounted value of utility

$$\mathbb{E}_0\left[\sum_{t=0}^{\infty}\beta_b^t U^b\left(C_t^b, N_t^b, H_{t-1}\right)\right], \beta_b \in (0,1), \beta_b < \beta_s$$

subject to the sequence of budget constraints

$$C_t^b + \frac{(1-\tau^y)X_{t-1}^b + \tau^y \nu M_{t-1}^b}{\Pi_t} + \mu_t P_t^h (H_t^* - H_{t-1}) = (1-\tau^y)W_t N_t^b +$$
$$+ \mu_t\left[M_t^{b*} - (1-\nu)\frac{M_{t-1}^b}{\Pi_t}\right] - \delta P_t^h H_{t-1} - \{\Psi(\mu_t) - \bar{\Psi}_t\} M_t^{b*} + T_t^b$$

where P_t^h is the house price, δ is the housing maintenance cost, $\Psi(\mu_t)$ is the mortgage prepayment cost aggregated across borrower households[21], and T_t^s is the rebate of the labor income tax, net of the tax deduction on mortgage interest payment. To avoid confusion with the analogous variables in the bank's problem, I denote with X_t^b and M_t^b the mortgage payments and principal due by the borrower.

The borrower is also subject to the PTI constraint on new borrowing,

$$M_t^{b*} \leq \frac{PTI W_t N_t^b}{q_t^*}$$

Finally, the borrower is subject to laws of motion for mortgage principal and payments analogous to equations (6) and (7) for the bank, in addition to a law of motion for housing

$$H_t = \mu_t H_t^* + (1-\mu_t) H_{t-1}$$

[20]Given the nominal rigidity, shocks that change borrowing and consumption affect output only if the change is concentrated in the short run, when firms' prices are still fixed at the pre-shock level for the most part. With endogenous prepayment, an increase in mortgage rates generates a stronger contraction in borrowing, as borrowers prefer to hold onto the lower rates locked-in into mortgages and wait for rates to go down in the future before prepaying. This effect compounds the tightening of the PTI constraint due to the higher mortgage rate, leading to a larger contraction in borrowing and spending by borrowers, who have high marginal propensities to consume, eventually with additional effects on output.

[21]The exact form of the prepayment cost distribution is shown in Section 4 when discussing the parameterization. The cost is rebated lump-sum to the borrower through $\bar{\Psi}_t$ at the end of the period.

3.4 Production Sector

The production sector consists of a perfectly competitive final good producer and monopolistically competitive intermediate goods producers. The final good producer uses a continuum of differentiated inputs indexed by $\iota \in [0,1]$, purchased from intermediate goods producers at prices $P_t(\iota)$, to operate the technology

$$Y_t = \left(\int_0^1 Y_t(\iota)^{1-\frac{1}{\xi}} \, \mathrm{d}\iota \right)^{\frac{\xi}{\xi-1}}, \xi > 1 \tag{13}$$

Optimality requires that the producer minimizes total expenditure $\int_0^1 P_t(\iota) Y_t(\iota) \, \mathrm{d}\iota$ subject to (13), yielding CES demands for each intermediate good ι

$$Y_t(\iota) = \left(\frac{P_t(\iota)}{P_t} \right)^{-\xi} Y_t \tag{14}$$

where P_t is the price of the final good.

Intermediate goods producers are owned by savers. They operate a linear production function in labor,

$$Y_t(\iota) = Z N_t(\iota)$$

where Z is (fixed) TFP and $N_t(\iota)$ is labor hired to meet the final good producer's demand (14). Following Gali and Gertler (1999), a measure $1-\omega$ of intermediate good producers are "forward looking" and maximize profits by choosing prices $P_t^f(\iota)$ subject to their technology, demand and a fixed probability $1-\lambda$ of price adjustment. The remaining measure ω of intermediate good producers are "backward looking". Whenever they can reset prices (which happens with the same probability $1-\lambda$), they use a rule of thumb based on the average price set in the most recent round of price adjustments (P_{t-1}^*), corrected by realized inflation:

$$P_t^b(\iota) = P_{t-1}^* \Pi_{t-1}$$

The fraction λ of firms that do not adjust prices are assumed to just update them by the steady-state inflation rate.

Such price setting by intermediate goods producers yields a 'hybrid' Phillips curve, where current inflation depends on expected future inflation as well as past inflation. While not critical for the qualitative results, this form of the Phillips curve helps the model match the hump-shaped empirical response of inflation to a monetary policy shock, as shown in Section 6.1.

3.5 Equilibrium

I focus on a symmetric equilibrium, thus banks and intermediate goods producers choose the same deposit rate and price, respectively.

In order to close the model, I assume that the central bank sets the risk-free rate according to the Taylor rule

$$\log(1+i_t) = \log(\bar{\Pi}_t) + \rho_i \Big[\log(1+i_{t-1}) - \log(\bar{\Pi}_{t-1})\Big] + (1-\rho_i)\Big[\log(1+i_{ss}) - \log(\Pi_{ss}) + \phi_\Pi \left(\log(\Pi_t) - \log(\bar{\Pi}_t)\right)\Big] + \epsilon_t^i,\ \epsilon_t^i \sim N(0,\sigma_i)$$

where ρ_i captures the degree of interest rate smoothing, ϕ_Π captures the extent to which the central bank reacts to deviations of inflation from target, and

$$\log(\bar{\Pi}_t) = (1-\rho_{\bar{\Pi}})\log(\Pi_{ss}) + \rho_{\bar{\Pi}}\log(\bar{\Pi}_{t-1}) + \epsilon_t^{\bar{\Pi}},\ \epsilon_t^{\bar{\Pi}} \sim N(0,\sigma_{\bar{\Pi}})$$

is an AR(1) stochastic inflation target. As mentioned previously, this shock captures very persistent changes in monetary policy which affect long-term nominal rates by changing short-term rates far into the future, in addition to current short-term rates. The specification of the Taylor rule follows Greenwald (2018), with the addition of the transitory monetary policy shock ϵ_t^i.

A symmetric equilibrium of this model is a sequence of endogenous states $(M_{t-1}, X_{t-1}, H_{t-1}, S_{t-1}, \mathcal{K}_{t-1}, \Pi_{t-1}^*)$, allocations $(C_t^s, C_t^b, N_t^s, N_t^b)$ and savings A_t, mortgage origination and funding decisions (M_t^*, d_t, B_t), housing and prepayment decisions (H_t^*, μ_t), and prices $(\Pi_t, W_t, P_t^h, i_t, i_t^d, i_t^B, q_t^*)$ such that ii) given prices and the exogenous stochastic processes, borrower, saver, bank, and producer equilibrium conditions are satisfied, ii) given inflation, past rates, and exogenous processes, i_t satisfies the Taylor rule, iii) the goods, labor, housing and asset markets clear.

In particular, market clearing in final goods requires

$$C_t^b + C_t^s + \delta P_t^h H_t + f(div_t) + \Theta(B_t, M_t) = Y_t$$

while the labor, housing market, and government bond clearing conditions are $N_t^b + N_t^s = N_t$, $H_t = \bar{H}$, and $A_t = 0$ respectively.

4 Parameterization

Time is quarterly. I identify the counterpart of deposits in the model with transaction and savings deposits in the data, because these are the two types of deposits with shorter maturity[22], they have the lowest pass-through (e.g. Driscoll and Judson 2013, Drechsler et al.

[22]Time deposits typically have costs of early withdrawal.

2017, Gerlach et al. 2018), and they are the largest class of deposits. All parameter values are listed in Table 1.

Parameter	Value	Description	Moment / Source / Target
		Households' parameters	
β_s	0.998	Saver's discount factor	Real interest rate = 1% pa
β_b	0.980	Borrower's discount factor	Borrowers' house value/income = **12.25** (SCF 2004)
$1-\chi$	0.399	Fraction of borrowers	(see text) (SCF 2004)
σ	1.000	IES	Log-utility
ϵ	1.000	Inverse Frish elasticity	Standard
ζ_s	5.742	Saver's labor disutility (weight)	Saver's labor supply = **1/3**
ζ_b	7.599	Borrower's labor disutility (weight)	Borrower's labor supply = **1/3**
φ	0.316	Weight on housing in utility	Rent / income = **0.2** (Davis and Ortalo-Magné, 2011)
		Parameters related to deposits	
ψ	$6 \cdot 10^{-10}$	Weight on deposits in utility	(Transaction + saving deposits) / bank liabilities = **0.43**
γ	0.077	Utility curvature in deposits	**IRF matching** (see text)
η	1.382	CES of deposits across banks	Deposit rate markdown i^d/i = **0.58**
ρ_s	0.974	Habit stock persistence	Turnover of bank customers = 10% pa (see text)
θ	0.804	Degree of habit formation	**IRF matching** (see text)
		Parameters most relevant for banks	
ν	0.059	Share of mortgage principal repaid	Avg. duration of banks' assets = 4.26 years
κ^{div}	1291	Scale of dividend adjustment cost	**IRF matching** (see text)
κ^B	0.122	Scale of portfolio adjustment cost	**IRF matching** (see text)
κ	36 bp	Marginal cost of supplying deposits	(see text)
υ^B	0.558	Bliss point of portfolio adj. cost	Median daily TED spread = **0.49% pa**
		Other parameters	
PTI	0.430	Max DTI ratio	Dodd-Frank act
$\bar{H}$	4.399	Fixed housing supply	Normalize house price to **1**
μ_k	0.223	Mean mortgage issuance cost	Average prepayment rate = **15% pa** (Elenev, 2017)
s_k	0.070	Scale of mortgage issuance cost	Minimum prepayment rate = **4% pa** (Greenwald, 2018)
δ	0.004	Housing maintenance cost	Depreciation of housing = 1.5% pa (Kaplan et al., 2020)
τ^y	0.240	Income tax rate	Avg. marginal income tax (Mertens and Montiel Olea, 2018)
		New-Keynesian block parameters	
ξ	10.00	CES of intermediate goods	Profits = 10% of output
$1-\lambda$	0.250	Price-reset probability	Standard yearly av. price resetting
ω	0.783	Share of backward-looking firms	**IRF matching** (see text)
$\bar{Z}$	1.099	Steady state productivity	Normalize steady state output to 1
ϕ_Π	1.500	Taylor rule: inflation reaction	Standard
ρ_i	0.810	Taylor rule: interest rate smoothing	Smets and Wouters (2007)
		Shock parameters	
Π_{ss}	1.005	Trend inflation	Standard, 2% pa
$\rho_{\bar{\Pi}}$	0.990	Persistence of inflation target	Garriga et al. (2016)

Targets used to calibrate parameters internally are in **bold**

Table 1: Summary of Parameterization

Commercial Banks and Deposits

I set the bank's marginal cost of supplying deposits κ at 36 bps per quarter (1.44% annualized), as half[23] of the average non-interest expenditures excluding expenditures on premises or rent[24] per dollar of assets of commercial banks in the FFIEC Consolidated Reports of Condition and Income (US Call Reports) over 1987 to 2013. The share of mortgage principal paid in each period ν (0.059) is set to match the average duration of banks' assets in the US Call Reports between 1997 and 2013[25], equal to 4.26 years. The bliss point v^B in the savers' portfolio-adjustment cost maps directly into the steady state spread between the bank bond rate and the risk-free rate. I set it to 0.543, so that the steady state bank bond spread equals the median daily TED spread between 1987 and 2013 of 12 bps per quarter (0.49% annualized).

I choose the persistence of the habit stock ρ_s based on an annual attrition rate[26] of banks' customers. A value of 10% per year is in the middle of the values reported in the literature surveyed in Appendix H. Thus $\rho_s = (1-0.1)^{0.25} = 0.974$. The elasticity of substitution of deposits across banks is set in order to have a steady state markdown i^d/i for the deposit rate equal to its average value in the data over 1987-2007 (0.58), where the deposit rate is measured as the average rate on transaction and savings deposits in the US Call Reports. The resulting value of η is 1.382. Finally, the weight on deposits in the utility function ψ is chosen to yield an average share of deposits to bank liabilities of 0.43, as its counterpart in the Call Reports over 1987-2013.

Borrower and Saver

I set a number of parameters to standard values in the macroeconomics literature. The saver's discount factor β_s equals 0.9975, implying a steady state real rate of 1%. The IES is set to 1 (log-utility) and I choose an inverse Frish elasticity of labor supply ϵ of 1. The weights on labor disutility in the utility function, $\zeta_b = 7.599$ and $\zeta_s = 5.742$, are set such that both borrower and saver supply the same labor in steady state, equal to $1/3$.

I set the PTI ratio to 0.43, as in the Dodd-Frank act. The housing maintenance cost δ equals 0.004 to match an annual depreciation rate of 1.5% (Kaplan et al., 2020).

I define borrowers as households in the 2004 SCF who own a house, have a mortgage outstanding, and have less than six months of income in liquid assets, thus I set $1-\chi =$

[23] The division by two attributes half of the cost to assets and half to liabilities, and is a rough approximation for the fact that banks' non-interest expenses do not necessarily pertain to deposits only.

[24] Since this type of expenditure is more fixed relative to salaries, marketing, etc.

[25] See Section 6.1 for details about how duration is estimated.

[26] Interpreting the habit stock as customer base, and the law of motion of the habit stock as a function that maps demand into customer base, then $1-\rho_s$ would be the rate of attrition of the customer base.

0.399.[27] The value of these households' houses relative to their quarterly income is 12.25, and I calibrate the borrower's discount factor β_b to match this ratio, yielding $\beta_b = 0.98$. At the same time, total housing supply $\bar{H} = 4.399$ is chosen in order to get a normalized house price of 1 in steady state and the weight on housing services in the utility function, $\varphi = 0.316$, is set to match the ratio of rent to income $(U^b_H(H)/(WN^b))$ of 0.2 estimated by Davis and Ortalo-Magné (2011).

The *iid* prepayment cost distribution follows Greenwald (2018) and takes the form

$$F_k(k) = \frac{1}{4}\frac{1}{1+e^{\frac{\mu_k - k}{s_k}}}$$

where I set the location parameter $\mu_k = 0.223$ and the scale parameter $s_k = 0.070$ to match an average annual prepayment rate of 15% (Elenev, 2017) and a minimum annual prepayment rate of 4% (1% quarterly, as in Greenwald 2018) in steady state.

Other Parameters

The remaining parameters concerning policies, shocks and the production sector are taken from the literature. In the Taylor rule, interest rate smoothing $\rho_i = 0.81$ (Smets and Wouters, 2007) and inflation reaction $\phi_\Pi = 1.5$. The autocorrelation $\rho_{\bar{\Pi}}$ of the inflation target process is set to 0.99 (Garriga et al., 2016), while trend inflation Π_{ss} is set to 1.005 (2% annual inflation rate). Steady state productivity $\bar{Z} = 1.099$ is set to normalize steady-state output to 1. The linear labor tax $\tau^y = 0.24$ is set to the average marginal individual income tax estimated by Mertens and Montiel Olea (2018) over 1946-2012. The elasticity of substitution across intermediate goods ξ is 10, implying that firms' profits are 10% of output. The price-reset probability $1-\lambda$ is equal to 0.25 - equivalent to an average price reset every year.

IRF matching

Five parameters are set internally based on simulations of the model: the curvature parameter of saver's utility with respect to deposits γ, the degree of habit formation for deposits θ, the scale of the dividend adjustment cost κ^{div}, the scale of the portfolio-adjustment cost κ^B, and the share of backward-looking price setters ω. I set them jointly to minimize the weighted squared deviation between empirical responses to the monetary shock identified

[27] The total share of homeowners with a mortgage outstanding in the 2004 SCF is 0.524, while the share of homeowners with a mortgage outstanding who has less than two months of income in liquid assets is 0.308, so my value is a middle ground between the share of actual mortgagors in the data and the share of those more liquidity constrained.

in Section 2 and model responses to a similar shock[28] for: real deposits, deposit rate (impact and peak response), TED spread (impact response), inflation (peak response) and 1-year Treasury bond rate (impact and 2-year response). As a result, I set $\gamma = 0.077$, $\theta = 0.804$, $\kappa^{div} = 1291$, $\kappa^{B} = 0.122$ and $\omega = 0.783$.

Figure 4 compares the responses for targeted variables as well as non-targeted ones.[29] The model responses in the top five graphs are shown as dashed lines, as these variables are targeted. The impulse response functions to the monetary shock are reasonably close to the local projections, even if in fact not all horizons are targeted. In addition, the bottom four variables are not targeted, yet the model responses come quite close to the empirical ones, in particular for the mortgage spread and non-deposit liabilities of banks.

5 Inspection of the Mechanisms

This section illustrates the novel mechanisms of the model using a first-order approximation of the solution around the deterministic steady state.

In order to build intuition, I abstract from the portfolio-adjustment cost for the moment, and compare the resulting version of the model with deep habits for deposits against a version without habits. As discussed in Section 3.2, deep habits drop out of the problem if the degree of habit formation θ is set to 0.[30] Even with partial depreciation of the habit stock ($\rho_s > 0$), without deep habits for deposits the markup m^d_{jt}/κ is equal to the static markup, the deposit spread is constant, and changes in the risk-free rate are passed through to the deposit rate completely.

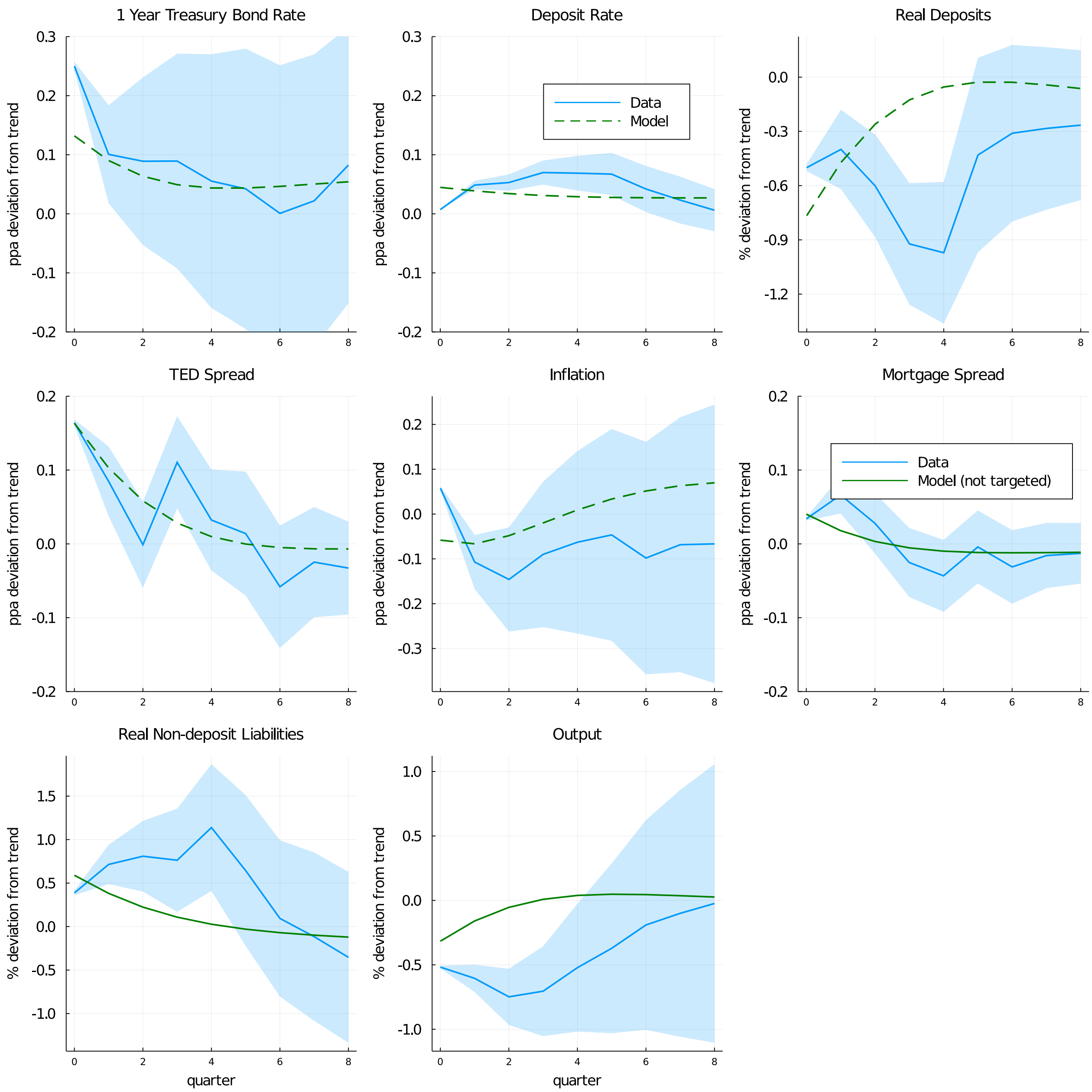
Figure 5 shows impulse response functions of various financial variables to an annualized 25 bp transitory monetary shock ϵ^i. As the risk-free rate i_t increases, the rate on new mortgages q^*_t also increases. However, most of the assets on the balance sheet of the bank pay a rate which was locked-in in the past, so the average rate earned by the bank in $t+1$ on its book of mortgages financed in t, $q_t = X_t/M_t$, increases a little, as mortgages issued in the past mature or are prepaid and new mortgages are originated at the higher rate.[31] Since the rate earned on its assets increases by less than the rate paid on – at least part of – its liabilities, the bank faces a decrease in profits from intermediation, as shown by the

[28] I include in the distance minimization the size of the IRF draws of the inflation target shock $\epsilon^{\bar{\Pi}}_0$ and the transitory shock to the Taylor rule ϵ^i_0, as they are both neeeded to bring the response of the 1-year risk-free rate in the model close to that of the 1-year Treasury bond rate.

[29] Impulse response functions of other financial and real variables to this shock are in Appendix G.

[30] All other parameters which are set based on long-run moments are reparameterized to the same targets.

[31] The more persistent the increase in risk-free rates is, the larger the response of the new mortgage rate – and consequently of the average mortgage rate – is.



Shaded areas correspond to 90% confidence bands (with HAC standard errors).

Figure 4: Data vs Model in Response to Monetary Policy Shock

decrease in the net interest margin

$$\left[X_t(q_t^*) - \nu M_t - (i_t^d + \kappa)d_t - i_t^B B_t\right]\frac{1}{M_t}$$

and dividends decrease below the steady state level. As a result, the marginal value of profits Ω_{t+1} increases.

At this point, the response of the bank in the model with deep deposit habits differs from the model without habits. With habits, the bank optimally sets a deposit rate above

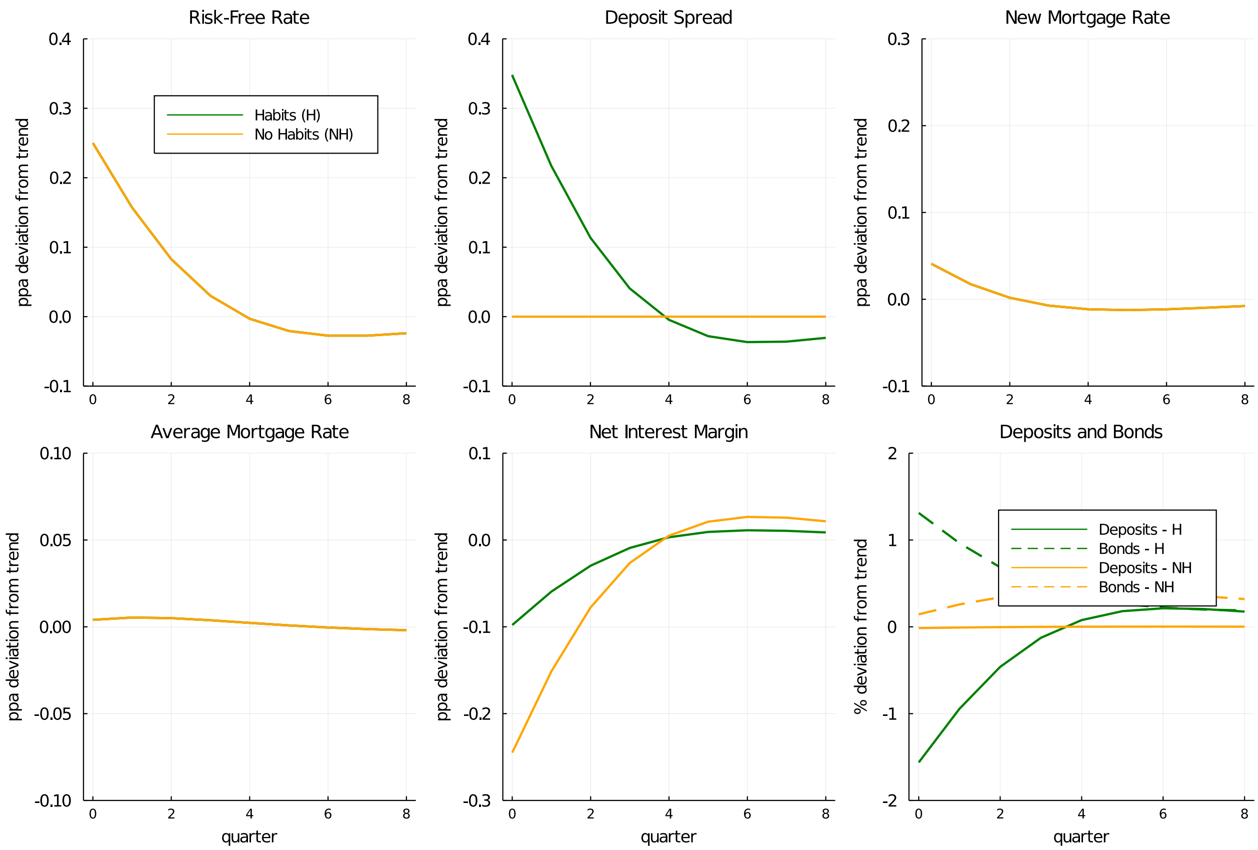


Figure 5: Impulse Response Functions to 25 bp Transitory Monetary Shock ϵ^i

the rate that maximizes static profits, considering that this will increase future deposit demand. However, since the marginal value of profits Ω_{t+1} increases, the bank increases its markup on deposits – closer to the static markup $\eta/(\eta-1)$ – by keeping the deposit rate from increasing as much as the risk-free rate. Eventually, as the deposit spread $i_t - i_t^d$ (the opportunity cost of holding deposits) has increased, savers substitute deposits for bonds, generating the correlations between deposit spread, deposit funding and banks' non-deposit liabilities described empirically in Section 2. As the orange lines in Figure 5 make clear, absent deposit habits in this simple version of the model, pass-through to deposit rates would be full and savers would not withdraw their deposits.

Still abstracting from the portfolio-adjustment cost, we can linearize the intertemporal condition for the deposit spread around the steady state[32] to disentangle three forces that affect the response of the deposit spread – or equivalently, the deposit markup. The

[32]Equation (11), but with $\rho_s > 0$.

deviation of the deposit spread from steady state can be decomposed as[33]

$$m_t^d - m^d = \underbrace{\left(m^d - \frac{\eta}{\eta-1}\kappa\right)}_{<0}\left(\sum_{j=0}^{\infty}\Gamma^j\mathbb{E}_t\text{discount}_{t+j} + \sum_{j=0}^{\infty}\Gamma^j\mathbb{E}_t\text{marg. value of dividends}_{t+j}\right) +$$

$$- m^d(1-\rho_s)\theta\Lambda^s\sum_{j=0}^{\infty}\Gamma^j\mathbb{E}_t\text{deposit demand growth}_{t+j}$$

where

$$\text{discount}_{t+j} = \hat{\Lambda}^s_{t+j+1,t+j+2} - \hat{\Pi}_{t+j+2} + \hat{\Pi}_{t+j+1}$$

$$\text{marginal value of dividends}_{t+j} = \hat{\Omega}_{t+j+2} - \hat{\Omega}_{t+j+1}$$

$$\text{deposit demand growth}_{t+j} = \hat{d}_{t+j+1} - \hat{S}_{t+j}$$

$$\Gamma = \Lambda^s[\rho_s - (1-\rho_s)\theta]$$

As usual with deep habits, a relative increase in the rate at which the price setter discounts the future (i.e. a decrease in the discount factor) leads to an increase in the current markup towards the static markup, as the price setter does not value as much future profits from accumulating demand. Moreover, if demand is shrinking (i.e. $\hat{d}_{t+1}$ is below the slow moving habit stock $\hat{S}_t$), the incentive to sacrifice current profits to build future demand is weaker, because any dollar of deposits acquired in t will generate less additional deposit demand in the future under multiplicative habits – the form of deep habits I assume in the model. This contributes to increasing the optimal markup towards the static markup. Finally, if the marginal value of current profits $\hat{\Omega}_{t+1}$ is above the future marginal value $\hat{\Omega}_{t+2}$, this will also raise the optimal markup, as discussed previously.

Figure 6 allows to compare the relative contribution of each force to the response of the deposit spread $i_t - i_t^d$ following the shock analyzed in Figure 5. While the response of discount factors (in blue) contributes marginally to the increase in the deposit spread, the marginal value of dividends (in orange) is the key force driving the increase in the deposit spread. Quantitatively, without a dividend smoothing motive, pass-through to deposit rates would be essentially full.

Hence, both deep habits for deposits ($\theta > 0$) and the dividend smoothing motive are essential in order to have imperfect pass-through in this model – at least quantitatively in the case of dividend smoothing. Section 6.1 below shows that duration mismatch between bank's assets and liabilities is also essential for this model to generate a degree of imperfect pass-through to deposit rates that matches the data.

[33]Under the transversality condition imposed by the stationary equilibrium concept.

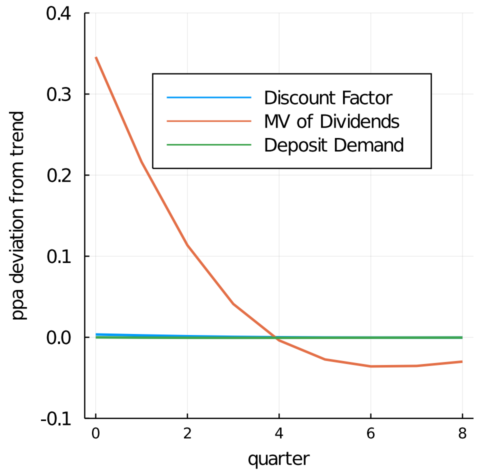


Figure 6: Impulse Response of Deposit Spread Broken Up by Component

Now I turn to discussing the portfolio-adjustment cost. In Appendix F I show that, absent such cost, the marginal value of profits Ω_t - which appears in the intertemporal condition for the deposit spread (12) - drops instead from the no-arbitrage condition[34] linking the marginal cost of funding an additional dollar of mortgages to its marginal benefit. Therefore, the effects of the dividend smoothing motive do not spill over to the mortgage market without the financial friction. The same Appendix also discusses how this result, coupled with i) banks facing a supply of non-deposit funding which is infinitely elastic at the risk-free rate and ii) deposits being separable in the utility function, implies irrelevance of the degree of deposit pass-through for the rest of the economy to a first order. In fact, the portfolio-adjustment cost introduces a financial friction that breaks i) and makes the supply of banks' funding imperfectly elastic, implying that the composition of banks' liabilities affects real outcomes.

6 Model Assessment

In this section I assess the model by testing its implications with different duration mismatch and by comparing the model against the 'competition-with-cash' theory of imperfect pass-through to deposit rates.

6.1 Implications of Duration Mismatch

Based on the description of the mechanism that produces imperfect pass-through to deposit rates, it should not come as a surprise that, if all assets of the bank had the same

[34]For a first-order approximation near the deterministic steady state.

duration as liabilities (either because they are short-term assets, or because their rate is reset every period as in the case of adjustable-rate mortgages), then the model implies that pass-through to the deposit rate would be close to perfect. This is illustrated in Figure G.3 in Appendix G, which shows impulse response functions to the monetary shock of Figure 4 when all banks' assets are assumed to be adjustable-rate mortgages (in yellow), and compares them to the baseline model with fixed-rate mortgages (in green). As Greenwald (2018) shows in the case without banks, and as shown in Appendix E using the no-arbitrage condition of the bank, the rate on adjustable-rate mortgages q_t^* is equal to $i_t^B + \nu$ in equilibrium, i.e. the mortgage rate and the marginal cost of banks' funds are perfectly correlated.

As anticipated, the deposit rate moves essentially one-for-one with the short-term rate. Absent the rigidity in the rates that the bank earns on its assets, the bank barely experiences a perturbation in its profits and dividends from a duration mismatch. Other reasons for the bank not to pass changes in the short-term rate completely to the deposit rate could arise from the other forces that affect the decision of the optimal deposit markup (or deposit spread) in Equation (12), namely movements in the discount factor, the growth rate of deposit demand, and the bond rate, as discussed in Section 5. These effects however are quantitatively small, or in the case of the bond rate go in the direction of increasing the degree of deposit rate pass-through.

Evidence from banks' panel data supports the inverse relationship between duration mismatch in banks' balance sheet and pass-through to deposit rates implied by the model. Table 2 shows that the decrease in pass-through conditional on a longer duration of banks' assets is supported by the data. The table reports bank-level panel regressions using FFIEC Consolidated Reports of Condition and Income (US Call Reports) data where the pass-through of changes in the Federal funds rate to deposit rates is interacted with either the ex-ante duration of a bank's assets or the ex-ante difference in the duration of its assets and liabilities. Specifically, I estimate

$$\Delta\text{deposit rate}_{it} = \alpha_i + \sum_{j=0}^{3} \beta_j \Delta FFR_{t-j} + \sum_{j=0}^{3} \delta_j \Delta FFR_{t-j} * Mat_{i,t-5} + \Gamma X_{i,t-5} + \epsilon_{it}$$

where $Mat_{i,t-5}$ is either the duration of a bank's assets or the gap between the duration of its assets and liabilities. I follow English et al. (2018), Di Tella and Kurlat (2020) and Drechsler et al. (2020) in measuring the duration of banks' assets and liabilities using US Call Report data on remaining maturity until payment (for fixed-rate assets/liabilities) or repricing maturity until the next rate reset (for variable-rate assets/liabilities), for different categories of assets and liabilities. Such maturities are then value-weighted in order to estimate an average duration of assets and liabilities of a bank.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
				Δdeposit rate$_t$			
$\sum_{j=0}^{3} \Delta FFR_{t-j}$	0.338	0.339	0.341	0.341	0.331	0.332	0.332
	(0.0272)	(0.0263)	(0.0257)	(0.0257)	(0.0246)	(0.0247)	(0.0247)
$AMat_{t-5}$	-0.002	-0.003	-0.002	-0.002			
	(0.0050)	(0.0050)	(0.0048)	(0.0048)			
$\sum_{j=0}^{3} \Delta FFR_{t-j} * AMat_{t-5}$	-0.017	-0.017	-0.016	-0.016			
	(0.0072)	(0.0070)	(0.0071)	(0.0071)			
$LMat_{t-5}$		-0.042	-0.057	-0.057			
		(0.0382)	(0.0428)	(0.0428)			
$DepShare_{t-5}$			-0.066	-0.066		-0.034	-0.034
			(0.0425)	(0.0427)		(0.0299)	(0.0300)
$\log(Assets)_{t-5}$				-0.002			-0.003
				(0.0028)			(0.0026)
$MatGap_{t-5}$					-0.002	-0.001	-0.001
					(0.0048)	(0.0046)	(0.0046)
$\sum_{j=0}^{3} \Delta FFR_{t-j} * MatGap_{t-5}$					-0.016	-0.016	-0.016
					(0.0072)	(0.0072)	(0.0072)
Constant	0.005	0.023	0.054	0.085	0.001	0.014	0.060
	(0.0211)	(0.0247)	(0.0416)	(0.0381)	(0.0185)	(0.0263)	(0.0315)
Bank FE	Y	Y	Y	Y	Y	Y	Y
N	431,340	431,306	431,306	431,306	431,306	431,306	431,306
R2	0.195	0.195	0.196	0.196	0.195	0.195	0.195

Standard errors in parentheses (clustered by bank)

Data is from US Call Reports and Federal Reserve H.15 Release, Q1 1997 - Q4 2013. The dependent variable is the change over a quarter in the deposit rate on transaction and saving deposits of a bank, computed as the ratio of interest expense to stock. $\sum_{j=0}^{3} \Delta FFR_{t-j}$ is the pass-through over 1 year, following Drechsler et al. (2020). $AMat_{t-5}$, $LMat_{t-5}$, $MatGap_{t-5}$ are weighted average repricing maturity of a bank's assets, liabilities, and the difference between the two, respectively. The variables are lagged before the period over which pass-through is measured. Maturities are computed as the midpoint of each maturity bin reported in the Call Reports, for each asset/liability category, weighted by the respective share of assets/liabilities for each bank-quarter (English et al., 2018). Federal funds sold and purchased, non-time deposits and cash are assumed to have maturity 0, subordinated debt is assumed to have a maturity of 5 years as in Drechsler et al. (2020). On average, 95% of assets and liabilities of a bank are accounted for. $DepShare_{t-5}$ is the share of liabilities accounted for by transaction and saving deposits. Bank variables are winsorized at the 1% level. Observations are weighted by the share of total assets in each quarter accounted for by each bank.

Table 2: Banks' Pass-through by Repricing Maturity of Assets

Since in the model the duration of assets[35] is not a choice of the bank, I condition on duration before the period over which the pass-through is measured. I measure the deposit rate as the ratio of interest expense on transaction and savings deposits to their respective stocks in the Call Reports, while $\sum_{j=0}^{3} \beta_j$ is the average pass-through of the policy rate to the

[35]Or equivalently, the duration gap between its assets and liabilities, since also banks' liabilities in the model have fixed duration.

deposit rate offered by the bank over a year, following Drechsler et al. (2020). The vector $X_{i,t-5}$ consists of other ex-ante controls.

The coefficient of interest is $\sum_{j=0}^{3}\delta_j$ which describes how much the pass-through decreases with an increase in duration. I estimate it to be approximately -0.016 in the asset-weighted regressions in Table 2, meaning that a duration of bank's assets of 4.3 years (the average aggregate duration of banks' assets) reduces the yearly pass-through by approximately 0.069, or by 21% relative to the estimates of $\sum_{j=0}^{3}\beta_j$. This is consistent with the finding in Drechsler et al. (2020) of a negative correlation between the interest expense beta[36] of a bank, averaged over time, and the duration of its assets.

6.2 Comparison with the 'Competition-with-Cash' Theory

A popular alternative theory of imperfect pass-through to deposit rates relies on competition between bank deposits and cash in the provision of liquidity services. According to this theory, the opportunity cost of holding cash increases with the short-term rate. Therefore, banks face less competitive pressure from cash and increase deposit rates by less when the short-term rate goes up, i.e. they increase deposit spreads.

As this theory is static while the theory introduced in my paper is dynamic, one way to compare them is by looking at the behavior of deposit spreads over time in response to monetary shocks that persistently move the short-term rate away from trend. Under the theory of my paper, in response to a persistent contractionary policy shock, as the rate on banks' long-duration assets is reset at a higher level, banks should eventually pass the full increase in the short-term rate through to deposit rates. In other words, deposit spreads should return to their trend. Under the 'competition-with-cash' theory, the pass-through to deposit rates should still be partial (i.e. deposit spreads should remain above trend) if the short-term rate is above trend.

To this end, I estimate Bayesian local projections[37] (Miranda-Agrippino and Ricco, 2021a) of the 3-month Treasury bill rate[38] and the aggregate deposit spread with a similar form as the local projections of Section 2 (Equation 1). There are two main differences in the specification of the projections. First, I use as instrument for i_t the change in the 5-year Treasury bond rate over a 30-minute window around FOMC announcements, in order to capture movements in expected short-term rates over a similar period to the average duration of

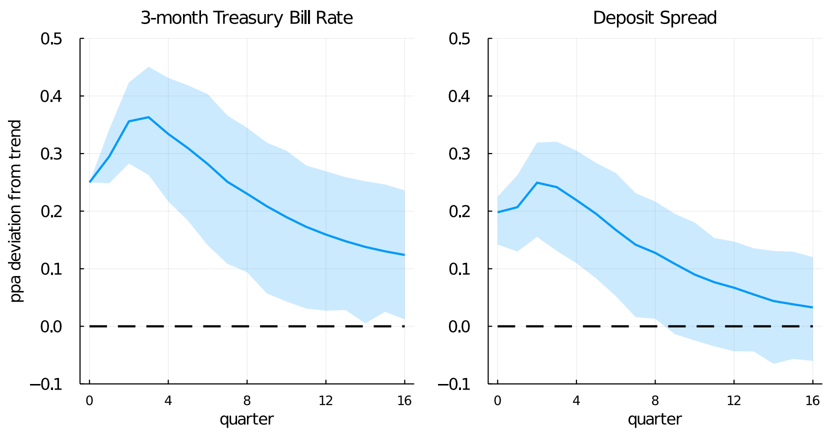
[36] The change in a bank's interest expense per 100 bp change in the Federal funds rate over one year, which includes the effect of imperfect pass-through.

[37] As explained by Miranda-Agrippino and Ricco (2021a), a Bayesian approach to local projections can optimally address the empirical bias-variance tradeoff inherent in the choice between VARs and local projections. In the estimation, I use a VAR prior for the Bayesian local projections estimated on the pre-sample Q1 1987 - Q4 1991.

[38] Which in this instance I use as the policy indicator i_t in order to zoom-in on the risk-free short-term rate.

banks' assets (4.26 years over 1997-2013). Second, the controls X_{t-1} include four lags of the Treasury bill rate, the deposit spread and the TED spread – with the latter capturing the marginal cost of banks' wholesale funding, consistently with Equation (12).

Figure 7 shows aggregate evidence in support of the mechanism of my paper. While the short-term rate remains significantly above trend for more than 4 years – by which time the rate on banks' assets will have in large part reset – the deposit spread is not significantly different from 0 after around 2.5 years.



Source: Federal Reserve H.15 and Interest Rate Spreads releases, US Call Reports, 5-year Treasury Bond high-frequency surprises (Miranda-Agrippino and Ricco, 2021b), Q1 1987 - Q4 2013. Shaded areas correspond to 95% posterior coverage bands.

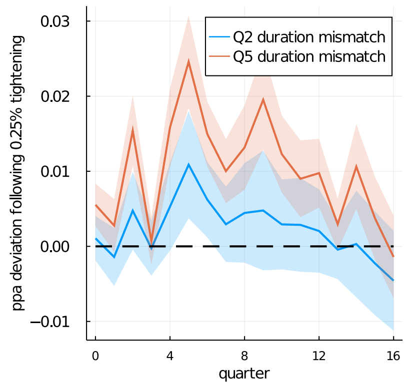
Figure 7: Bayesian Local Projections with Persistent Monetary Policy Surprise

As another comparison of the two theories, I study the dynamic response in the US Call Reports of deposit spreads of banks with different duration mismatch between assets and liabilities. Controlling for time fixed effects, and thus encompassing a surprise shift in the level of the short-term rate, my theory predicts that banks with lower duration mismatch should increase deposit spreads by less and for a shorter period of time than banks with higher duration mismatch. By contrast, the 'competition-with-cash' theory (with the addition of duration mismatch as in Drechsler et al. 2020) predicts a lower but equally persistent increase in the deposit spread for low-duration-mismatch banks.

Denoting by $\mathcal{Q}_t$ the quintiles of the distribution of duration mismatch across banks in each quarter, I estimate the following panel local projections

$$\Delta_h s_{i,t+h} = \alpha_{i,h} + \tau_{t,h} + \sum_{q \in \mathcal{Q}_{t-1}} \beta_h^q \left(i_t * \mathbb{1}_{i \in q} \right) + \Gamma_h X_{i,t-1} + u^s_{i,t+h} \text{ for } h = 0, \ldots, H$$

where i) $\Delta_h s_{i,t+h} \equiv s_{i,t+h} - s_{i,t-1}$ is the cumulative change in bank i's deposit spread between $t-1$ and $t+h$, ii) $\alpha_{i,h}$ and $\tau_{t,h}$ are bank and time fixed effects, iii) β_h^q are the coefficients of interest, as they capture the difference in the response of the deposit spread to the short-term rate at each horizon h for each quintile of duration mismatch, iv) $X_{i,t-1}$ are bank-level controls, which include four lags of the natural logarithm of bank i's assets and deposits as well as the quintile dummies $\mathbb{1}_{i \in q}$.[39] As before, i_t is the 3-month Treasury bill rate, and I instrument each $i_t * \mathbb{1}_{i \in q}$ with the interaction between the quintile dummy and the 5-year Treasury bond high-frequency surprises.



Source: Federal Reserve H.15 release, US Call Reports, 5-year Treasury Bond high-frequency surprises (Miranda-Agrippino and Ricco, 2021b), Q2 1997 - Q4 2013. Shaded areas correspond to 95% confidence bands (with bank-level clustered standard errors).

Figure 8: Panel Local Projections of Deposit Spreads

Figure 8 shows the results of the estimation for the second and fifth quintile of the duration mismatch distribution, which correspond to an average duration mismatch over 1997-2013 of 2 and 5.8 years respectively. Relative to the excluded quintile (Q1, with an average duration mismatch of 1.2 years), banks in the second quintile do not increase deposit spreads significantly more after 1.5 years. As expected, banks in the fifth quintile increase deposit spreads even more but the difference is not significant beyond approximately 3.5 years.[40] These results hold for any path of the short-term rate (absorbed by the time fixed effects), and in particular for a level shift in the rate. Accordingly, they support the prediction of the theory of imperfect pass-through to deposit rates developed in this paper vis-à-vis the 'competition-with-cash' theory.

7 Imperfect Pass-through and Monetary Transmission

A given overall effect of monetary policy on output can be split into a full pass-through effect and an additional imperfect pass-through effect.

The impulse response functions in Figure 9 compare the full-fledged model with imperfect pass-through to deposit rates against the version of the model with perfect pass-

[39] To deal with outliers, I winsorize the bottom and top 1% of all bank-level observations in each quarter.

[40] Results are robust to using a continuous interaction of the Treasury bill rate and duration mismatch.

through – i.e. no habits ($\theta = 0$) and no portfolio-adjustment cost. The graphs show responses to the monetary policy shock already used for Figure 4, which combines an inflation target shock and a transitory shock to the Taylor rule.

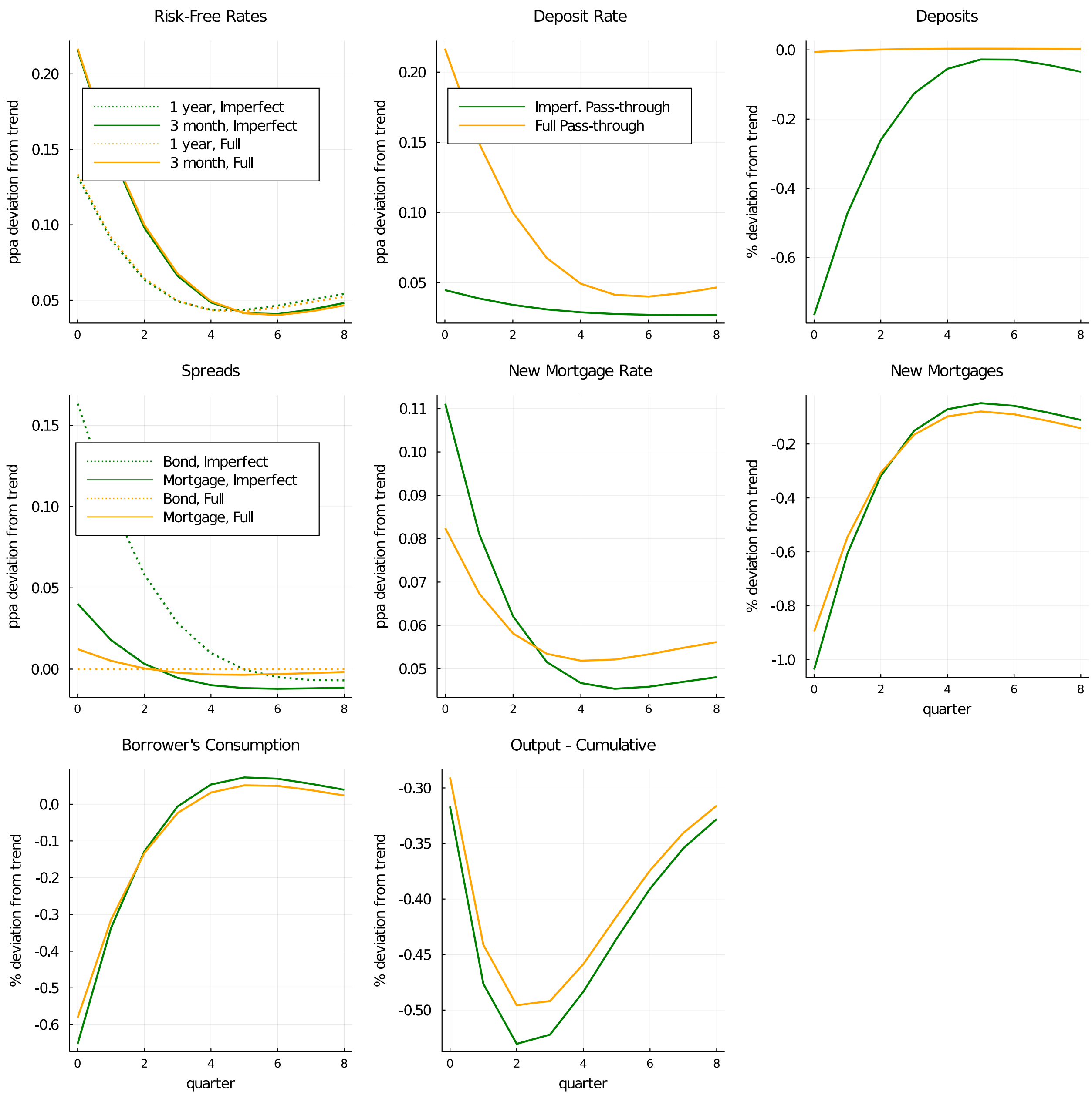


Figure 9: Imperfect vs Full Pass-through with Monetary Policy Shock

Consider first the model with imperfect pass-through, shown in green in the graphs. Faced with an increase in the short-term rate at which it finances its portfolio of mortgages, the bank decides to adjust the deposit rate partially in order to reduce the squeeze in profits from intermediation. As deposits flow out because the opportunity cost of holding them relative to the risk-free rate is higher, the ratio of bonds in total liabilities increases above the steady-state level, leading to a wider bond spread. The bank passes through part of the additional increase in its marginal cost of funds i_t^B to the rate on new mortgages q_t^*, which leads to a decrease in new mortgage origination M_t^*, relative to the case of perfect pass-through. As a consequence of the decrease in borrowing, borrower's consumption C_t^b decreases more than in the case of full pass-through, and eventually output falls by more.

Cumulating the effect of the monetary policy shock at each horizon allows to gauge the extent to which imperfect pass-through amplifies the transmission of monetary policy, as shown in the last graph of Figure 9. Imperfect pass-through – through the various endogenous channels of the model and in particular the financial friction that raises the marginal cost of funds of the bank – yields an additional 3 bp decrease in output on impact in response to the nearly 13 bp shock to the 1-year risk-free rate, which persists throughout the first year. Relative to the path of output in the economy with full pass-through, output falls by an additional 9% on impact, and 6% over the first year.

The effect is consistent with the cross-sectional evidence in Drechsler et al. (2017), who find that counties whose banks raise deposits in more concentrated markets – and thus have lower deposit-rate pass-through – see a reduction in lending and employment relative to other counties. They estimate that a one standard deviation (0.06) increase in the average deposit HHI of banks that serve a county reduces new lending by 58 bps and employment growth by 5 bps per 100 bp increase in the Federal funds rate. The model developed in this paper allows to quantify the effects of imperfect pass-through to deposit rates for the aggregate economy.

7.1 Additional Source of Liquidity

Given the relationship between deposits and monetary transmission just discussed, how would structural or policy changes that lead to a viable alternative source of liquidity to bank deposits affect monetary transmission? Examples could be the introduction of a central bank digital currency (CBDC), or widespread use by households of private digital currencies and money-market mutual fund shares for liquidity needs.

The model can be used as a laboratory to answer this question. I introduce the additional source of liquidity – let us call it CBDC – with a minimal change to the CES aggregator of utility from deposits (Equation 3):

$$D_t^s = \left\{ \left[\int_0^1 \left(d_{jt}^s S_{j,t-1}^{\theta} \right)^{1-\frac{1}{\eta}} \mathrm{d}j \right]^{\frac{\eta}{\eta-1}} \right\}^{1-\frac{1}{\varrho}} + \alpha \left\{ \Delta_t \right\}^{1-\frac{1}{\varrho}}, \eta > 1, \theta > 0, \alpha \geq 0, \varrho > 1 \text{ or } < -1$$

where Δ_t are holdings of CBDC, ϱ is the elasticity of substitution between deposits and CBDC, and α is the weight on CBDC in the utility aggregator.

The savers' problem changes as now they also choose their CBDC holdings Δ_t, earning a nominal return $1 + i_t^{\Delta}$ on each dollar invested in the previous period. Appendix J shows how the relevant FOCs change.

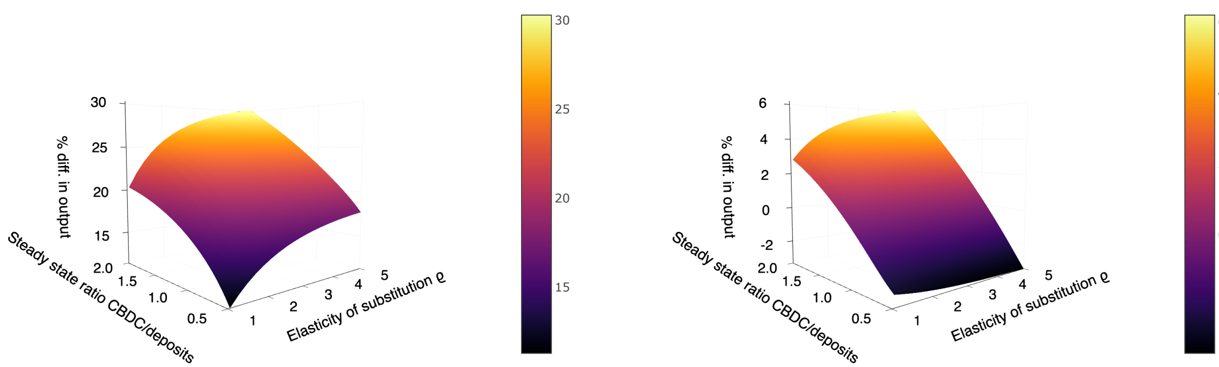
I assume that the issuer of CBDC (the central bank) sets

$$i_t^{\Delta} = i_{ss}^{d} + \phi^{\Delta}(i_t - i_{ss})$$

and supplies any quantity demanded at this rate, rebating any profits or losses to savers.

I consider below two opposite scenarios, one with full pass-through of changes in the policy rate to the CBDC rate ($\phi^{\Delta} = 1$) and one with limited pass-through ($\phi^{\Delta} = 0.01$). Given the uncertainty sorrounding the parameters ϱ and α, I consider a range of values for both.

The following figure shows the difference between the 1-year cumulative response of output to the monetary policy shock of Figure 4 in the model with CBDC relative to the baseline model without CBDC, for a range of values of ϱ and α. Since α maps to the steady state ratio of CBDC holdings to bank deposits, I show the ratio directly in the graph. Panel 10a considers the case with full pass-through to the CBDC rate i_t^{Δ}, while panel 10b corresponds to limited pass-through.



(a) Full pass-through to CBDC rate

(b) Limited pass-through to CBDC rate

Figure 10: 1-year cumulative output response to monetary shock (% diff. from baseline)

Assuming that CBDC and bank deposits are substitutes ($\varrho > 1$), the introduction of an alternative source of liquidity amplifies monetary transmission when the pass-through of the policy rate to the CBDC rate is high (panel 10a).

Figure 11 shows the IRFs to the monetary shock for the baseline model (green) and the model with CBDC (red) when $\varrho = 2$ and the steady state CBDC/deposit ratio is 1. With an alternative to bank deposits, banks lose more deposits when they increase deposit rates

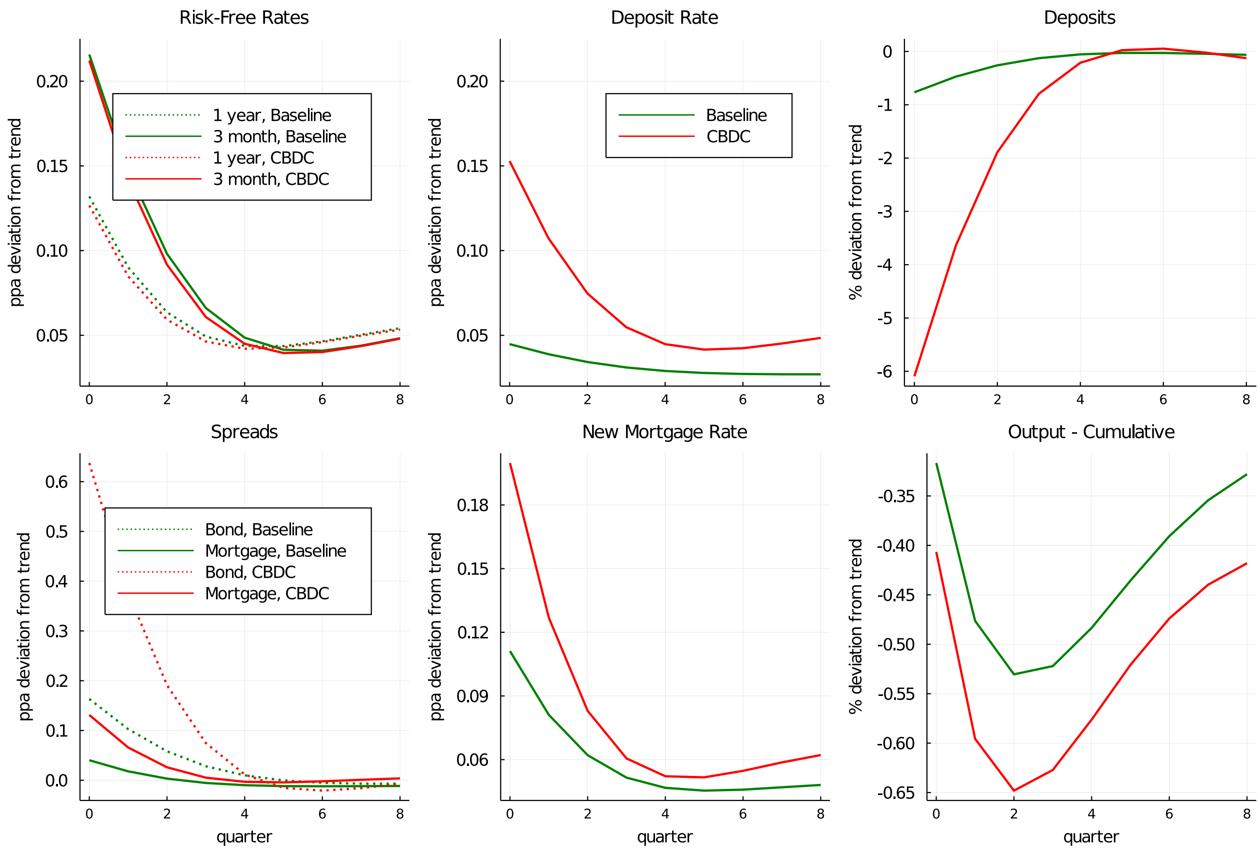


Figure 11: Impulse Response Functions to Monetary Shock

partially. Therefore, they have to issue more bonds to replace lost deposits and finance their assets, pushing up on the bond spread. Eventually, in equilibrium, banks increase deposit rate pass-through relative to the case without CBDC, but still not enough to prevent the deposit outflow. As a result, bond and mortgage spreads increase more, which translates into a larger increase in mortgage rates and a larger contraction in output.

However, as panel 10b shows, if the CBDC rate responds little to the policy rate, the effect of monetary policy on output could be dampened when CBDC holdings are low relative to deposits. In these instances, banks increase deposit rates above the CBDC rate and savers substitute CBDC with bank deposits, leading banks to issue less bonds and pushing down on spreads below the steady state level.[41]

8 Conclusion

This paper develops a general equilibrium monetary model with imperfect pass-through of changes in the short-term rate to the deposit rate. I propose a novel mechanism to generate

[41] While it is more natural to think of alternative sources of liquidity as substitutes for deposits, Appendix K shows that – if deposits and CBDC are complements for savers ($\varrho < -1$) – the results are the opposite.

the imperfect pass-through to deposit rates observed in the data. This mechanism relies on three key features: banks' activity of duration transformation, persistence in banks' deposit demand through deep habits, and costly dividend adjustment. I argue that each of these three features is essential in order to have imperfect pass-through in this framework. Then, a financial friction that breaks no-arbitrage between banks' non-deposit debt and government debt implies that imperfect pass-through to deposit rates can have real effects. With the financial friction, the model is consistent with three key facts about monetary policy transmission: partial adjustment of deposit rates to changes in the policy rate, substitution between deposits and other liabilities in banks' balance sheets following monetary policy changes, and an increase in mortgage and interbank spreads in response to contractionary monetary policy shocks.

I investigate the implications for monetary policy transmission of imperfect pass-through relative to full pass-through to deposit rates. I find that, if banks face an increase in their cost of borrowing at the margin as they finance a larger share of their assets through non-deposit liabilities, imperfect pass-through can amplify the response of output to monetary policy shocks. The introduction of an alternative source of liquidity – for instance, a central bank digital currency – which is used as a substitute for deposits strengthens transmission for a wide range of parameters.

The model allows for a quantification of the contribution of imperfect pass-through to deposit rates, which is shown to amplify the impact of a monetary shock on aggregate activity by 9% on impact and 6% over 1 year. In this way, it extends to the aggregate economy the cross-sectional finding by Drechsler et al. (2017) that lower pass-through to deposit rates leads to a larger contraction in employment across US counties. Firms' investment with a financial accelerator could further amplify the effects.

This paper opens some exciting avenues for future research. The main mechanisms of the model could be combined with an effective lower-bound on interest rates to study monetary policy transmission through the banking sector in a low-interest-rate environment. The mechanisms could also be applied in a model with heterogeneous banks such as Corbae and D'Erasmo (2021) to discipline parameters using cross-sectional bank data and explore how imperfect pass-through to deposit rates interacts with bank regulation.

References

ALIAGA-DÍAZ, R. AND M. P. OLIVERO (2010): "Macroeconomic Implications of "Deep Habits" in Banking," *Journal of Money, Credit and Banking*, 42, 1495–1521.

ANDERSON, S. P., A. DE PALMA, AND J.-F. THISSE (1989): "Demand for Differentiated Products, Discrete Choice Models, and the Characteristics Approach," *The Review of Economic Studies*, 56, 21–35.

ANDERSON, S. P., A. DEPALMA, AND J.-F. THISSE (1987): "The CES is a Discrete Choice Model," *Economics Letters*, 24, 139.

ANDOLFATTO, D. (2021): "Assessing the impact of central bank digital currency on private banks," *The Economic Journal*, 131, 525–540.

BARRDEAR, J. AND M. KUMHOF (2021): "The Macroeconomics of Central Bank Digital Currencies," *Journal of Economic Dynamics and Control*, 104148.

BAUMOL, W. J. (1952): "The Transactions Demand for Cash: An Inventory Theoretic Approach," *The Quarterly Journal of Economics*, 545–556.

BEGENAU, J. (2020): "Capital Requirements, Risk Choice, and Liquidity Provision in a Business Cycle Model," *Journal of Financial Economics*, 136, 355–378.

BEGENAU, J., M. PIAZZESI, AND M. SCHNEIDER (2015): "Banks' Risk Exposures," Working Paper 21334, National Bureau of Economic Research.

BERGER, A. N. AND T. H. HANNAN (1989): "The Price-Concentration Relationship in Banking," *The Review of Economics and Statistics*, 291–299.

——— (1991): "The Rigidity of Prices: Evidence from the Banking Industry," *American Economic Review*, 81, 938.

BERRY, S., J. LEVINSOHN, AND A. PAKES (1995): "Automobile Prices in Market Equilibrium," *Econometrica: Journal of the Econometric Society*, 841–890.

BRUNNERMEIER, M. K. AND Y. KOBY (2018): "The Reversal Interest Rate," Working Paper 25406, National Bureau of Economic Research.

CARBO-VALVERDE, S., T. H. HANNAN, AND F. RODRIGUEZ-FERNANDEZ (2011): "Exploiting Old Customers and Attracting New Ones: the Case of Bank Deposit Pricing," *European Economic Review*, 55, 903–915.

CORBAE, D. AND P. D'ERASMO (2021): "Capital Buffers in a Quantitative Model of Banking Industry Dynamics," *Econometrica*, forthcoming.

Davis, M. A. and F. Ortalo-Magné (2011): "Household Expenditures, Wages, Rents," *Review of Economic Dynamics*, 14, 248–261.

Di Tella, S. and P. Kurlat (2020): "Why are Banks Exposed to Monetary Policy?" *American Economic Journal: Macroeconomics*, forthcoming.

Diamond, D. W. and P. H. Dybvig (1983): "Bank Runs, Deposit Insurance, and Liquidity," *Journal of Political Economy*, 91, 401–419.

Dick, A. A. (2008): "Demand Estimation and Consumer Welfare in the Banking Industry," *Journal of Banking & Finance*, 32, 1661–1676.

Drechsler, I., A. Savov, and P. Schnabl (2017): "The Deposit Channel of Monetary Policy," *The Quarterly Journal of Economics*, 132, 1819–1876.

——— (2020): "Banking on Deposits: Maturity Transformation without Interest Rate Risk," *Journal of Finance*, forthcoming.

Driscoll, J. and R. Judson (2013): "Sticky Deposit Rates," SSRN 2241531.

Egan, M., A. Hortaçsu, and G. Matvos (2017a): "Deposit Competition and Financial Fragility: Evidence from the US Banking Sector," *American Economic Review*, 107, 169–216.

Egan, M., S. Lewellen, and A. Sunderam (2017b): "The Cross Section of Bank Value," Working Paper 23291, National Bureau of Economic Research.

Elenev, V. (2017): "Mortgage Credit, Aggregate Demand, and Unconventional Monetary Policy," SSRN 2951397.

Elenev, V., T. Landvoigt, and S. Van Nieuwerburgh (2021): "A Macroeconomic Model with Financially Constrained Producers and Intermediaries," *Econometrica*, 89, 1361–1418.

English, W. B., S. J. Van den Heuvel, and E. Zakrajšek (2018): "Interest Rate Risk and Bank Equity Valuations," *Journal of Monetary Economics*, 98, 80–97.

Faria-e-Castro, M. (2018): "Fiscal Multipliers and Financial Crises," Research Division Working Paper 2018-023A, FRB of St. Louis.

Favara, G., S. Gilchrist, K. F. Lewis, and E. Zakrajsek (2016): "Recession Risk and the Excess Bond Premium," FEDS Notes 2016-04-08, Board of Governors of the Federal Reserve System.

Feenstra, R. C. (1986): "Functional Equivalence between Liquidity Costs and the Utility of Money," *Journal of Monetary Economics*, 17, 271–291.

FLOYD, E., N. LI, AND D. J. SKINNER (2015): "Payout policy through the financial crisis: The growth of repurchases and the resilience of dividends," *Journal of Financial Economics*, 118, 299–316.

GALI, J. AND M. GERTLER (1999): "Inflation Dynamics: A Structural Econometric Analysis," *Journal of monetary Economics*, 44, 195–222.

GARRIGA, C., F. E. KYDLAND, AND R. ŠUSTEK (2017): "Mortgages and Monetary Policy," *The Review of Financial Studies*, 30, 3337–3375.

GARRIGA, C., F. E. KYDLAND, AND R. ŠUSTEK (2016): "Nominal Rigidities in Debt and Product Markets," Working Paper 22613, National Bureau of Economic Research.

GERALI, A., S. NERI, L. SESSA, AND F. M. SIGNORETTI (2010): "Credit and Banking in a DSGE Model of the Euro Area," *Journal of Money, Credit and Banking*, 42, 107–141.

GERLACH, J. R., N. MORA, AND P. UYSAL (2018): "Bank Funding Costs in a Rising Interest Rate Environment," *Journal of Banking & Finance*, 87, 164 – 186.

GERTLER, M. AND P. KARADI (2013): "QE 1 vs. 2 vs. 3...: A Framework for Analyzing Large-scale Asset Purchases as a Monetary Policy Tool," *International Journal of Central Banking*, 9, 5–53.

——— (2015): "Monetary Policy Surprises, Credit Costs, and Economic Activity," *American Economic Journal: Macroeconomics*, 7, 44–76.

GILCHRIST, S., R. SCHOENLE, J. SIM, AND E. ZAKRAJŠEK (2017): "Inflation Dynamics during the Financial Crisis," *American Economic Review*, 107, 785–823.

GILCHRIST, S. AND E. ZAKRAJŠEK (2012): "Credit Spreads and Business Cycle Fluctuations," *American economic review*, 102, 1692–1720.

GOURIO, F. AND L. RUDANKO (2014): "Customer Capital," *The Review of Economic Studies*, 81, 1102–1136.

GREENWALD, D. (2018): "The Mortgage Credit Channel of Macroeconomic Transmission," Research Paper 5184–16, MIT Sloan.

HAENLEIN, M., A. M. KAPLAN, AND A. J. BEESER (2007): "A Model to Determine Customer Lifetime Value in a Retail Banking Context," *European Management Journal*, 25, 221–234.

HANNAN, T. H. AND R. M. ADAMS (2011): "Consumer Switching Costs and Firm Pricing: Evidence from Bank Pricing of Deposit Accounts," *The Journal of Industrial Economics*, 59, 296–320.

HANSON, S. G., A. SHLEIFER, J. C. STEIN, AND R. W. VISHNY (2015): "Banks as Patient Fixed-income Investors," *Journal of Financial Economics*, 117, 449–469.

HE, B., Y. SHI, Q. WAN, AND X. ZHAO (2014): "Prediction of Customer Attrition of Commercial Banks Based on SVM Model," *Procedia Computer Science*, 31, 423–430.

HONKA, E., A. HORTAÇSU, AND M. A. VITORINO (2017): "Advertising, Consumer Awareness, and Choice: Evidence from the US Banking Industry," *The RAND Journal of Economics*, 48, 611–646.

IACOVIELLO, M. (2005): "House Prices, Borrowing Constraints, and Monetary Policy in the Business Cycle," *American Economic Review*, 95, 739–764.

IRELAND, P. N. (2007): "Changes in the Federal Reserve's Inflation Target: Causes and Consequences," *Journal of Money, credit and Banking*, 39, 1851–1882.

JEENAS, P. (2018): "Monetary Policy Shocks, Financial Structure, and Firm Activity: A Panel Approach," SSRN 3043579.

JERMANN, U. AND V. QUADRINI (2012): "Macroeconomic Effects of Financial Shocks," *American Economic Review*, 102, 238–71.

JORDÀ, Ò. (2005): "Estimation and Inference of Impulse Responses by Local Projections," *American Economic Review*, 95, 161–182.

KAPLAN, G., K. MITMAN, AND G. L. VIOLANTE (2020): "The Housing Boom and Bust: Model Meets Evidence," *Journal of Political Economy*, 128, 3285–3345.

KLEMPERER, P. (1995): "Competition when Consumers Have Switching Costs: an Overview with Applications to Industrial Organization, Macroeconomics, and International Trade," *The Review of Economic Studies*, 62, 515–539.

KRAVIK, E. M. AND Y. MIMIR (2019): "Navigating with NEMO," Staff Memo 5/2019, Norges Bank.

MERTENS, K. AND J. L. MONTIEL OLEA (2018): "Marginal Tax Rates and Income: New Time Series Evidence," *The Quarterly Journal of Economics*, 133, 1803–1884.

MERTENS, K. AND M. O. RAVN (2013): "The Dynamic Effects of Personal and Corporate Income Tax Changes in the United States," *American Economic Review*, 103, 1212–47.

MIRANDA-AGRIPPINO, S. AND G. RICCO (2021a): "Bayesian Local Projections," Tech. rep.

——— (2021b): "The Transmission of Monetary Policy Shocks," *American Economic Journal: Macroeconomics*, 13, 74–107.

NAKAMURA, E. AND J. STEINSSON (2011): "Price Setting in Forward-looking Customer Markets," *Journal of Monetary Economics*, 58, 220–233.

NEUMARK, D. AND S. A. SHARPE (1992): "Market Structure and the Nature of Price Rigidity: Evidence from the Market for Consumer Deposits," *The Quarterly Journal of Economics*, 107, 657–680.

PACIELLO, L., A. POZZI, AND N. TRACHTER (2019): "Price Dynamics with Customer Markets," *International Economic Review*, 60, 413–446.

PHELPS, E. S. AND S. G. WINTER (1970): "Optimal Price Policy under Atomistic Competition," in *Microeconomic Foundations of Employment and Inflation Theory*, ed. by E. S. Phelps et al., New York: Norton.

RAVN, M., S. SCHMITT-GROHÉ, AND M. URIBE (2006): "Deep Habits," *The Review of Economic Studies*, 73, 195–218.

REPULLO, R. (2020): "The Deposits Channel of Monetary Policy: A Critical Review," Discussion Paper DP15553, CEPR.

SHARPE, S. A. (1997): "The Effect of Consumer Switching Costs on Prices: a Theory and its Application to the Bank Deposit Market," *Review of Industrial Organization*, 12, 79–94.

SHY, O. (2002): "A Quick-and-easy Method for Estimating Switching Costs," *International Journal of Industrial Organization*, 20, 71–87.

SIDRAUSKI, M. (1967): "Inflation and Economic Growth," *Journal of Political Economy*, 75, 796–810.

SMETS, F. AND R. WOUTERS (2003): "An Estimated Dynamic Stochastic General Equilibrium Model of the Euro Area," *Journal of the European Economic Association*, 1, 1123–1175.

——— (2007): "Shocks and Frictions in US Business Cycles: a Bayesian DSGE Approach," *American Economic Review*, 97, 586–606.

TOBIN, J. (1956): "The Interest-elasticity of Transactions Demand for Cash," *The Review of Economics and Statistics*, 38, 241–247.

WANG, O. (2020): "Banks, Low Interest Rates, and Monetary Policy Transmission," Working Paper 20202492, ECB.

WONG, A. (2021): "Refinancing and The Transmission of Monetary Policy to Consumption," Mimeo.

YANKOV, V. (2018): "In Search of a Risk-Free Asset: Search Costs and Sticky Deposit Rates," SSRN 2044882.

Appendix

A List of Equilibrium Conditions

Saver

Euler equation for government bonds

$$1 = \mathbb{E}_t \left[\frac{\Lambda^s_{t,t+1}}{\Pi_{t+1}} \right] (1 + i_t) \text{ where } \Lambda^s_{t,t+1} = \beta_s \frac{U^s_{C^s_{t+1}}}{U^s_{C^s_t}}$$

Euler equation for bank bonds

$$\mathbb{E}_t \left[\frac{\Lambda^s_{t,t+1}}{\Pi_{t+1}} \right] (i^B_t - i_t) = \kappa^B \left(\frac{B_t}{M_t} - v^B \right)$$

Intratemporal condition

$$-U^s_{N^s_t} = U^s_{C^s_t} W_t (1 - \tau^y)$$

Euler equation for deposits

$$\mathbb{E}_t \left[\frac{\Lambda^s_{t,t+1}}{\Pi_{t+1}} \right] (i_t - i^d_t) = \frac{U^s_{D^s_t} S^\theta_{t-1}}{U^s_{C^s_t}} \tag{15}$$

Budget constraint (redundant by Walras' law)

$$\begin{aligned} C^s_t + A_t + d_t + B_t + \frac{\kappa^B}{2} \left(\frac{B_t}{M_t} - v^B \right)^2 M_t = (1 - \tau^y) W_t N^s_t + \frac{1 + i_{t-1}}{\Pi_t} (d_{t-1} + A_{t-1}) \\ + \frac{1 + i^B_{t-1}}{\Pi_t} B_{t-1} - \frac{\tilde{m}^d_{t-1}}{\Pi_t} D_{t-1} + T^s_t + \Xi^s_t \end{aligned} \tag{16}$$

where

$$D^s_t = d_t S^\theta_{t-1}$$

$$T^s_t = \tau^y W_t N^s_t$$

$$\Xi^s_t = div_t + \frac{\kappa}{\Pi_t} d_{t-1} + \underbrace{Y_t - W_t N_t}_{\text{profits from firms}}$$

$$\tilde{m}^d_t = m^d_t S^{-\theta}_{t-1}$$

Bank

Euler equation for deposit spread

$$\mathbb{E}_t \left[\frac{\Lambda^s_{t,t+1}}{\Pi_{t+1}} \Omega_{t+1} \right] \left(\frac{\eta}{\eta - 1} \left(1 - \frac{i^B_t - i_t}{\kappa} \right) - \frac{m^d_t}{\kappa} \right) = \tag{17}$$

$$= \mathbb{E}_t \left[\frac{\Lambda^s_{t,t+2}}{\Pi_{t+2}} \Omega_{t+2} \left[\rho_s \left(\frac{\eta}{\eta - 1} \left(1 - \frac{i^B_{t+1} - i_{t+1}}{\kappa} \right) - \frac{m^d_{t+1}}{\kappa} \right) + (1-\rho_s)\theta \frac{m^d_{t+1}}{\kappa} \frac{d_{t+1}}{S_t} \right] \right]$$

No-arbitrage condition

$$\mathbb{E}_t \left[\frac{\Lambda^s_{t,t+1}}{\Pi_{t+1}} \Omega_{t+1} \right] i^B_t = \mathbb{E}_t \left[\Lambda^s_{t,t+1} (\Omega^X_{t+1} q^*_t + \Omega^M_{t+1}) \right]$$

where

$$\Omega^M_t = -\mathbb{E}_t \left[\Lambda^s_{t,t+1} \Omega^X_{t+1} \right] \frac{q^*_t (1-\nu)(1-\mu_t)}{\Pi_t} - \nu \frac{\Omega_t}{\Pi_t}$$

$$\Omega^X_t = \mathbb{E}_t \left[\Lambda^s_{t,t+1} \Omega^X_{t+1} \right] \frac{(1-\nu)(1-\mu_t)}{\Pi_t} + \frac{\Omega_t}{\Pi_t}$$

Marginal value of profits

$$\Omega_t = \frac{1}{1 + \kappa^{div}(div_t - \bar{div})}$$

Dividends

$$div_t = \frac{1}{\Pi_t} \left[X_{t-1} - \nu M_{t-1} - (i^d_{t-1} + \kappa) d_{t-1} - i^B_{t-1} B_{t-1} \right] - \frac{\kappa^{div}}{2} (div_t - \bar{div})^2 \tag{18}$$

Balance-sheet constraint

$$M_t = d_t + B_t \tag{19}$$

Law of motion of deposit habit stock

$$S_t = \rho_s S_{t-1} + (1-\rho_s) d_t \tag{20}$$

Law of motion of mortgage principal

$$M_t = \mu_t M^*_t + (1-\mu_t)(1-\nu) \frac{M_{t-1}}{\Pi_t}$$

Law of motion of mortgage payments

$$X_t = \mu_t q^*_t M^*_t + (1-\mu_t)(1-\nu) \frac{X_{t-1}}{\Pi_t}$$

Borrower

Intratemporal condition

$$-U^b_{N^b_t} = U^b_{C^b_t} \left[W_t (1-\tau^y) + \mu_t \lambda_t \frac{PTIW_t}{q^*_t} \right]$$

Euler equation for new housing

$$P^h_t = \mathbb{E}_t \left[\Lambda^b_{t,t+1} \left\{ \frac{U^b_{H_t}}{U^b_{C^b_{t+1}}} + P^h_{t+1}(1-\delta) \right\} \right]$$

where $\Lambda^b_{t,t+1} = \beta_b U^b_{C^b_{t+1}} / U^b_{C^b_t}$ and λ_t is the multiplier on the borrowing constraint
Euler equation for new borrowing

$$1 = \Omega^b_{Mt} + \Omega^b_{Xt} q^*_t + \lambda_t$$

where

$$\Omega^b_{Mt} = \mathbb{E}_t \left[\frac{\Lambda^b_{t,t+1}}{\Pi_{t+1}} \{ \nu \tau^y + (1-\nu)\mu_{t+1} + (1-\mu_{t+1})(1-\nu)\Omega^b_{M,t+1} \} \right]$$

$$\Omega^b_{Xt} = \mathbb{E}_t \left[\frac{\Lambda^b_{t,t+1}}{\Pi_{t+1}} \{ 1 - \tau^y + (1-\mu_{t+1})(1-\nu)\Omega^b_{X,t+1} \} \right]$$

Euler equation for prepayment

$$\mu_t = F_k \left((1 - \Omega^b_{Mt} - \Omega^b_{Xt} q_{t-1}) \left[1 - \frac{(1-\nu)M_{t-1}}{M^*_t \Pi_t} \right] - \Omega^b_{Xt}(q^*_t - q_{t-1}) \right)$$

where $q_t \equiv \frac{X_t}{M_t}$ and F_k is the cdf of the *iid* idiosyncratic cost of taking a new loan after prepayment
Law of motion of housing stock

$$H_t = \mu_t H^*_t + (1-\mu_t) H_{t-1}$$

Borrowing limit

$$M^*_t = \frac{PTI W_t N^b_t}{q^*_t}$$

Budget constraint

$$C^b_t + \frac{(1-\tau^y)X_{t-1} + \tau^y \nu M_{t-1}}{\Pi_t} + \mu_t P^h_t (H^*_t - H_{t-1}) = (1-\tau^y) W_t N^b_t +$$
$$+ \mu_t \left[M^*_t - (1-\nu)\frac{M_{t-1}}{\Pi_t} \right] - \delta P^h_t H_{t-1} - \{ \Psi(\mu_t) - \bar{\Psi}_t \} \mu_t M^*_t + T^b_t$$

where

$$T^b_t = \tau^y \left(W_t N^b_t - \frac{X_{t-1} - \nu M_{t-1}}{\Pi_t} \right)$$
$$\bar{\Psi}_t = \Psi(\mu_t)$$

Producers

Inflation index

$$\Pi_t^{1-\xi} = \lambda \Pi_{ss}^{1-\xi} + (1-\lambda) (\Pi^*_t)^{1-\xi}$$

Average inflation of price adjusters

$$(\Pi^*_t)^{1-\xi} = \omega \left(\Pi^*_{t-1} \right)^{1-\xi} + (1-\omega) \Pi_t^{1-\xi} \left(\tilde{P}^f_t \right)^{1-\xi}$$

where

$$\tilde{P}^f_t = \frac{j_{1,t}}{j_{2,t}}$$

$$j_{1,t} = \frac{MC_t}{MC_{ss}} Y_t + \mathbb{E}_t \left\{ \lambda \Lambda^s_{t,t+1} \left(\frac{\Pi_{t+1}}{\Pi_{ss}} \right)^{\xi} j_{1,t+1} \right\}$$

$$j_{2,t} = Y_t + \mathbb{E}_t \left\{ \lambda \Lambda^s_{t,t+1} \left(\frac{\Pi_{t+1}}{\Pi_{ss}} \right)^{\xi-1} j_{2,t+1} \right\}$$

$$MC_t = \frac{W_t}{Z}$$

$$MC_{ss} = \frac{\xi - 1}{\xi}$$

Output

$$Y_t = \frac{ZN_t}{\mathcal{K}_t}$$

Price dispersion

$$\mathcal{K}_t = \left(\frac{\Pi_t}{\Pi_{ss}} \right)^{\xi} \lambda \mathcal{K}_{t-1} + (1-\lambda) \Pi_t^{\xi} \left(\Pi_t^* \right)^{-\xi}$$

Market Clearing

Final goods

$$C_t^b + C_t^s + \delta P_t^h H_t + \frac{\kappa^{div}}{2} (div_t - \bar{div})^2 + \frac{\kappa^B}{2} \left(\frac{B_t}{M_t} - v^B \right)^2 M_t = Y_t \tag{21}$$

Labor

$$N_t^b + N_t^s = N_t$$

Housing

$$H_t = \bar{H}$$

Government bonds

$$A_t = 0$$

B Data Used in Local Projections and Additional Projections

Name	FRED ID	Frequency	Log	Period	Source
Interest rates and spreads					
Info. Robust Instrument for Monetary Shocks		FOMC		1991-2010	Miranda-Agrippino and Ricco (2021b)
1-Year Treasury Constant Maturity Rate	DGS1	day		1987-2013	FRED, link
10-Year Treasury Constant Maturity Rate	WGS10YR	week		1987-2013	FRED, link
U.S. 30 Year Fixed Rate Mortgage		week		1987-2013	Fannie Mac, link
Deposit Rate		quarter		1987-2013	US Call Reports, link
TED Spread	TEDRATE	day		1987-2013	FRED, link
Excess Bond Premium		month		1987-2013	Favara et al. (2016), link
Bank variables					
Non-deposit Liabilities		quarter	✓	1987-2013	US Call Reports, link
Deposits		quarter	✓	1987-2013	US Call Reports, link
Non-financial variables					
Industrial Production Index	INDPRO	month	✓	1987-2013	FRED, link
Unemployment Rate	UNRATE	month		1987-2013	FRED, link
Consumer Price Index for All Urban Consumers	CPIAUCLS	month	✓	1987-2013	FRED, link
CRB Commodity Price Index		month	✓	1987-2013	Miranda-Agrippino and Ricco (2021b)

Table B.1: Data Descriptions and Sources

With the exception of the monetary surprises, all daily and weekly series are transformed into quarterly series using the last observation in each quarter. Similarly, monthly series are transformed into quarterly using the last monthly observation in each quarter. The Miranda-Agrippino and Ricco (2021b) monetary shocks are aggregated to quarterly frequency by summing them over each quarter.

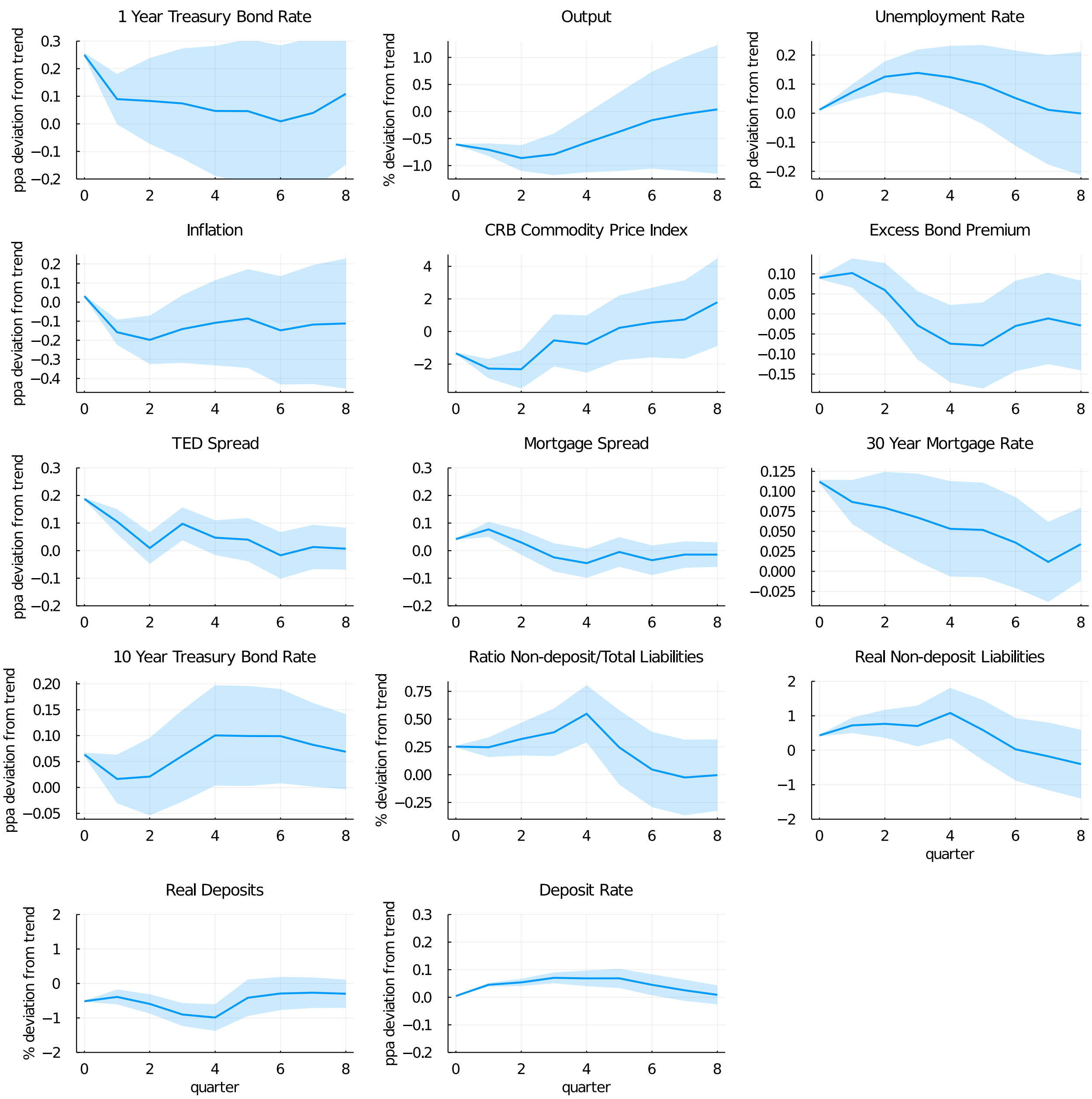


Figure B.1: Local Projections with Monetary Policy Shock

Shaded areas correspond to 90% confidence bands (with HAC standard errors).

C Representation of CES Deposit Demands as Aggregate Choices of Individuals

CES with habits from discrete choice model (Anderson et al., 1987)

Consider N banks offering deposits. Each saver household consists of a continuum of members of mass 1. Each period, each member has to decide 1) what *single* bank to deposit at and 2) how much to deposit. The saver household is willing to forgo Y to hold deposits at banks. Since at the beginning of each period all members are identical, each of them will have the same interest income Y to forgo on deposits.

Suppose that, after stage 1), bank j was determined to be the preferred bank by one of the members - let us call her ι - between periods t and $t+1$. If bank j offers a net deposit rate i_j^d between these periods, the cost to the member of holding deposits at j is the deposit spread $m_j^d = i - i_j^d$. Then the member has to satisfy $Y = d_j(\iota) m_j^d$[42], and accordingly deposit demand will be $d_j(\iota) = Y / m_j^d$.

Let us assume that the indirect utility for a member from deposits at bank j is

$$v_j(d_j) = \log(d_j) + \theta \log(S_j)$$

where S_j is the habit stock of bank j. The habit appears as a preference shifter, increasing the indirect utility from holding deposits at a bank for any household member.

Then, given the deposit demand,

$$v_j(m_j^d) = \log(Y) - \log(m_j^d) + \theta \log(S_j)$$

Going back to stage 1), let us assume the choice of a bank by household member ι follows the stochastic utility approach used in discrete choice theory. Therefore,

$$u_j(\iota) = v_j(m_j^d) + \Xi \epsilon_j(\iota) \text{ for each } j = 1, \ldots, N$$

where $u_j(\iota)$ is the stochastic indirect utility associated with bank j by member ι, $\Xi > 0$ and $\epsilon_j(\iota)$ is a random variable with Gumbel distribution.

Assuming that $\epsilon_j(\iota)$'s are *iid* across household members and banks, by a law of large numbers, the share of household members who choose bank j is

$$p_j = \text{Prob}\left(j = \text{argmax}_{z=1,\ldots,N} u_z(\iota)\right) \text{ for each } j = 1, \ldots, N$$

which, using the definition of $v_j(m_j^d)$, becomes

$$p_j = \frac{(S_j^\theta / m_j^d)^{\frac{1}{\Xi}}}{\sum_{z=1}^{N} (S_z^\theta / m_z^d)^{\frac{1}{\Xi}}} \text{ for each } j = 1, \ldots, N$$

[42]The unique discount factor shared by all members cancels from each side of the equality, since rates are known in advance.

Finally, the demand for deposits at bank j by the household is

$$d_j^* \equiv \int_0^1 d_j(\iota)\,\mathrm{d}\iota = \frac{Y}{m_j^d} p_j = \frac{S_j^{\frac{\theta}{\Xi}} (m_j^d)^{-\frac{1}{\Xi}-1}}{\sum_{z=1}^N (S_z^\theta / m_z^d)^{\frac{1}{\Xi}}} Y \text{ for each } j = 1, \ldots, N \tag{22}$$

Letting $\Xi = \frac{1}{\eta - 1}$ and defining

$$\tilde{m}^d \equiv \left[\sum_{z=1}^N (m_z^d S_z^{-\theta})^{1-\eta} \right]^{\frac{1}{1-\eta}}$$

we have

$$d_j^* = \frac{(m_j^d)^{-\eta} S_j^{\theta(\eta-1)}}{(\tilde{m}^d)^{1-\eta}} Y \text{ for each } j = 1, \ldots, N$$

Since the interest income given up is $Y = \tilde{m}^d D$ (see Appendix D), then

$$d_j^* = \frac{(m_j^d)^{-\eta} S_j^{\theta(\eta-1)}}{(\tilde{m}^d)^{1-\eta}} \tilde{m}^d D = \left(\frac{m_j^d}{\tilde{m}^d} \right)^{-\eta} S_j^{\theta(\eta-1)} D \text{ for each } j = 1, \ldots, N$$

which is the form of deposit demand from the CES function obtained in Appendix D.

CES with habits from characteristics model (Anderson et al., 1989)

Consider N banks offering deposits and M characteristics.[43] As before, each saver household consists of a continuum of members of mass 1. However, now it is assumed that they are distributed over characteristics according to a multinomial logit. Each period, each member has to decide 1) what *single* bank to deposit at and 2) how much to deposit. The saver household is willing to forgo Y to hold deposits at banks. Since the household cannot condition on the characteristics of each member, each of them will have the same interest income Y to forgo on deposits.

Given the interest income that members can forgo, deposit demands are as in the previous model with discrete choice: $d_j = Y / m_j^d$.

The main difference relative to the discrete choice model example is the form of the indirect utility. For a household member whose ideal characteristics are $\underline{z}$, the indirect utility from deposits at bank j is

$$v_j(\underline{z}; d_j) = \log(d_j) - c \sum_{k=1}^M (z^k - z_j^k)^2 + \theta \log(S_j)$$

The interpretation is that the habit reduces the cost of deviating from the ideal variety uniformly across depositors, with scale θ.

Using this indirect utility with habits and following the approach in Anderson et al. (1989), it is possible to derive the demand function in Equation (22) under the discrete choice model, and then derive the CES demand following the same steps.

[43] $M = N - 1$, if it is greater, then the density is non-unique (Anderson et al., 1989).

D Derivation of CES Deposit Demands

Considering two banks i and z, their relative deposit demand is

$$\frac{d^s_{it}}{d^s_{zt}} = \left(\frac{m^d_{it}}{m^d_{zt}}\right)^{-\eta} \left(\frac{S_{i,t-1}}{S_{z,t-1}}\right)^{\theta(\eta-1)}$$

Multiplying by m^d_{it} and integrating with respect to i we have

$$\int_i m^d_{it} d^s_{it} \,\mathrm{d}i = d^s_{zt} \left(m^d_{zt}\right)^{\eta} S^{-\theta(\eta-1)}_{z,t-1} \int_i \left(m^d_{it} S^{-\theta}_{i,t-1}\right)^{1-\eta} \mathrm{d}i$$

which implies that, for a generic bank i,

$$d^s_{it} = \frac{\left(m^d_{it}\right)^{-\eta} S^{\theta(\eta-1)}_{i,t-1}}{\int_i \left(m^d_{it} S^{-\theta}_{i,t-1}\right)^{1-\eta} \mathrm{d}i} \int_i m^d_{it} d^s_{it} \,\mathrm{d}i$$

Let us define the average deposit spread

$$\tilde{m}^d_t \equiv \left[\int_i \left(m^d_{it} S^{-\theta}_{i,t-1}\right)^{1-\eta} \mathrm{d}i\right]^{\frac{1}{1-\eta}}$$

Then

$$d^s_{it} = \left(\frac{m^d_{it}}{\tilde{m}^d_t}\right)^{-\eta} S^{\theta(\eta-1)}_{i,t-1} \frac{\int_i m^d_{it} d^s_{it}}{\tilde{m}^d_t}$$

Finally, plugging into the definition of D^s_t we have

$$\begin{aligned}
D^s_t &= \left[\int_i \left(\frac{\left(m^d_{it}\right)^{-\eta} S^{\theta(\eta-1)}_{i,t-1}}{S^{-\theta}_{i,t-1}}\right)^{1-\frac{1}{\eta}} \mathrm{d}i\right]^{\frac{\eta}{\eta-1}} \frac{\int_i m^d_{it} d^s_{it} \,\mathrm{d}i}{\left(\tilde{m}^d_t\right)^{1-\eta}} \\
&= \left[\int_i \left(m^d_{it} S^{-\theta}_{i,t-1}\right)^{1-\eta} \mathrm{d}i\right]^{\frac{\eta}{\eta-1}} \frac{\int_i m^d_{it} d^s_{it} \,\mathrm{d}i}{\left(\tilde{m}^d_t\right)^{1-\eta}} \\
&= \left(\tilde{m}^d_t\right)^{-\eta} \frac{\int_i m^d_{it} d^s_{it} \,\mathrm{d}i}{\left(\tilde{m}^d_t\right)^{1-\eta}} \\
&= \frac{\int_i m^d_{it} d^s_{it} \,\mathrm{d}i}{\tilde{m}^d_t}
\end{aligned}$$

i.e.

$$\tilde{m}^d_t D^s_t = \int_i m^d_{it} d^s_{it} \,\mathrm{d}i$$

so the demand for deposits at bank i becomes

$$d^s_{it} = \left(\frac{m^d_{it}}{\tilde{m}^d_t}\right)^{-\eta} S^{\theta(\eta-1)}_{i,t-1} D^s_t$$

The budget constraint can be rewritten as

$$
\begin{aligned}
C_t^s + A_t^s + \int_0^1 d_{jt}^s \,\mathrm{d}j + B_t^s + \Theta(B_t^s, M_t) = (1-\tau^y) W_t N_t^s + \frac{1+i_{t-1}}{\Pi_t}\left(\int_0^1 d_{j,t-1}^s \,\mathrm{d}j + A_{t-1}^s\right) + \\
- \int_0^1 \frac{i_{t-1} - i_{j,t-1}^d}{\Pi_t} d_{j,t-1}^s \,\mathrm{d}j + \frac{1+i_{t-1}^B}{\Pi_t} B_{t-1}^s + T_t^s + \Xi_t^s \\
C_t^s + A_t^s + \int_0^1 d_{jt}^s \,\mathrm{d}j + B_t^s + \Theta(B_t^s, M_t) = (1-\tau^y) W_t N_t^s + \frac{1+i_{t-1}}{\Pi_t}\left(\int_0^1 d_{j,t-1}^s \,\mathrm{d}j + A_{t-1}^s\right) + \\
- \frac{\tilde{m}_{t-1}^d}{\Pi_t} D_{t-1}^s + \frac{1+i_{t-1}^B}{\Pi_t} B_{t-1}^s + T_t^s + \Xi_t^s
\end{aligned}
$$

E Bank's No-Arbitrage Condition with Adjustable-Rate Mortgages

With adjustable-rate mortgages, the no-arbitrage condition of the bank is the same,

$$\mathbb{E}_t\left[\frac{\Lambda^s_{t,t+1}}{\Pi_{t+1}}\Omega_{t+1}\right] i^B_t = \mathbb{E}_t\left[\Lambda^s_{t,t+1}(\Omega^X_{t+1}q^*_t + \Omega^M_{t+1})\right]$$

However, the marginal values of mortgage principal and payment to the bank become

$$\Omega^X_t = \frac{\Omega_t}{\Pi_t}$$

$$\Omega^M_t = \underbrace{\mathbb{E}_t\left[\Lambda^s_{t,t+1}\left(\Omega^X_{t+1}q^*_t + \Omega^M_{t+1} - \frac{\Omega_{t+1}}{\Pi_{t+1}}i^B_t\right)\right]}_{=0}\frac{(1-\nu)(1-\mu_t)}{\Pi_t} - \nu\frac{\Omega_t}{\Pi_t}$$

since now the rate on all outstanding mortgage principal is reset each period.

Substituting back into the no-arbitrage condition we get

$$\mathbb{E}_t\left[\frac{\Lambda^s_{t,t+1}}{\Pi_{t+1}}\Omega_{t+1}\right] i^B_t = \mathbb{E}_t\left[\frac{\Lambda^s_{t,t+1}}{\Pi_{t+1}}\Omega_{t+1}\right](q^*_t - \nu)$$

Hence $q^*_t = i^B_t + \nu$ for all t.

F No-Arbitrage Condition and Marginal Value of Profits

Absent the portfolio-adjustment cost, $i_t^B = i_t$ and the no-arbitrage condition of the bank is

$$\mathbb{E}_t\left[\frac{\Lambda^s_{t,t+1}}{\Pi_{t+1}}\Omega_{t+1}\right] i_t = \mathbb{E}_t\left[\Lambda^s_{t,t+1}(\Omega^X_{t+1}q^*_t + \Omega^M_{t+1})\right]$$

which, once expressed in percentage deviations from the deterministic steady-state, becomes

$$-\mathbb{E}_t\hat{\Pi}_{t+1} + \mathbb{E}_t\hat{\Omega}_{t+1} + \hat{i}_t = \frac{\Pi}{i}\left[q^*\Omega^X\left(\mathbb{E}_t\hat{\Omega}^X_{t+1} + \hat{q}^*_t\right) + \Omega^M\mathbb{E}_t\hat{\Omega}^M_{t+1}\right]$$

where hatted variables denote percentage deviations from steady state and variables without time subscript denote steady state values. Notice that I used the result that in steady state the marginal value of profits $\Omega = 1$.

Separating the terms that depend on $\hat{\Omega}_t$'s we have

$$\left(\hat{i}_t - \mathbb{E}_t\hat{\Pi}_{t+1}\right)\frac{i}{\Pi q^*\Omega^X} - \hat{q}^*_t = \mathbb{E}_t\hat{\Omega}^X_{t+1} - \mathbb{E}_t\hat{\Omega}_{t+1}\frac{i}{\Pi q^*\Omega^X} + \frac{\Omega^M}{q^*\Omega^X}\mathbb{E}_t\hat{\Omega}^M_{t+1} \tag{23}$$

Expressing the definitions of marginal value of mortgage payments X_t and principal M_t to the bank

$$\Omega^X_t = \mathbb{E}_t\left[\Lambda^s_{t,t+1}\Omega^X_{t+1}\right]\frac{(1-\nu)(1-\mu_t)}{\Pi_t} + \frac{\Omega_t}{\Pi_t}$$

$$\Omega^M_t = -\mathbb{E}_t\left[\Lambda^s_{t,t+1}\Omega^X_{t+1}\right]\frac{q^*_t(1-\nu)(1-\mu_t)}{\Pi_t} - \nu\frac{\Omega_t}{\Pi_t}$$

in percentage deviations from steady state yields

$$\Omega^X\hat{\Omega}^X_t = \frac{\Lambda^s}{\Pi}\Omega^X(1-\nu)(1-\mu)\left[\mathbb{E}_t\hat{\Lambda}^s_{t,t+1} + \mathbb{E}_t\Omega^X_{t+1} - \frac{\mu}{1-\mu}\hat{\mu}_t - \hat{\Pi}_t\right] + \frac{1}{\Pi}\left(\hat{\Omega}_t - \hat{\Pi}_t\right)$$

$$\Omega^M\hat{\Omega}^M_t = -\frac{\Lambda^s}{\Pi}\Omega^X q^*(1-\nu)(1-\mu)\left[\mathbb{E}_t\hat{\Lambda}^s_{t,t+1} + \mathbb{E}_t\Omega^X_{t+1} + \hat{q}^*_t - \frac{\mu}{1-\mu}\hat{\mu}_t - \hat{\Pi}_t\right] - \frac{\nu}{\Pi}\left(\hat{\Omega}_t - \hat{\Pi}_t\right)$$

Substituting for Ω^X_{t+1} and Ω^M_{t+1} in the *rhs* of Equation (23) we have

$$\left(\hat{i}_t - \mathbb{E}_t\hat{\Pi}_{t+1}\right)\frac{i}{\Pi q^*\Omega^X} - \hat{q}^*_t = -\mathbb{E}_t\hat{\Omega}_{t+1}\frac{i}{\Pi q^*\Omega^X} + \frac{\left(\mathbb{E}_t\hat{\Omega}_{t+1} - \mathbb{E}_t\hat{\Pi}_{t+1}\right)}{\Omega^X\Pi}\left(1 - \frac{\nu}{q^*}\right)$$
$$- \frac{\Lambda^s}{\Pi}(1-\nu)(1-\mu)\mathbb{E}_t q^*_{t+1}$$

Since $\Omega = 1$, we have that

$$q^* = i + \nu$$

thus the term

$$\frac{\mathbb{E}_t\hat{\Omega}_{t+1}}{\Pi q^*\Omega^X}(q^* - i - \nu) = 0\ \forall t$$

and the dynamics of the marginal value of profits Ω_t are irrelevant for this equation to the first order, near the steady state.

The only other equation where the marginal value of profits appears is the intertemporal equation (17) of the deposit spread m_t^d, and it does affect the deposit spread through that equation. In addition to that equation, the other equations where deposits, habit stock or the deposit spread appear are: the saver's Euler equation for deposits (15), the saver's budget constraint (16), the definition of dividends (18), the balance-sheet constraint (19), and the resource constraint (21).[44]

It is easy to show that, by Walras' law, the saver's budget constraint is redundant. Then: i) bonds B_t appear only in the balance-sheet constraint and the definition of dividends; ii) dividends div_t appear only in the resource constraint through the cost $f(div_t)$ and the marginal value Ω_t; iii) the marginal value Ω_t, to the first order, only appears in the Euler equation for the deposit spread (17); iv) the deposit spread/deposit rate only appears in the saver's Euler equation for deposits (15) and dividends.

Hence, except for the dividend adjustment cost, this block of equations is recursive. Since the dividend adjustment cost is quadratic, it only affects decisions through Ω_t to a first order, and the evolution of deposit-related variables is irrelevant for the rest of the economy without the bond-adjustment cost.

[44]The law of motion of the habit stock (20) does not need to be in the list, since it only involves habit stock and deposits, which are already counted in the other equations listed.

G Additional Impulse Response Functions

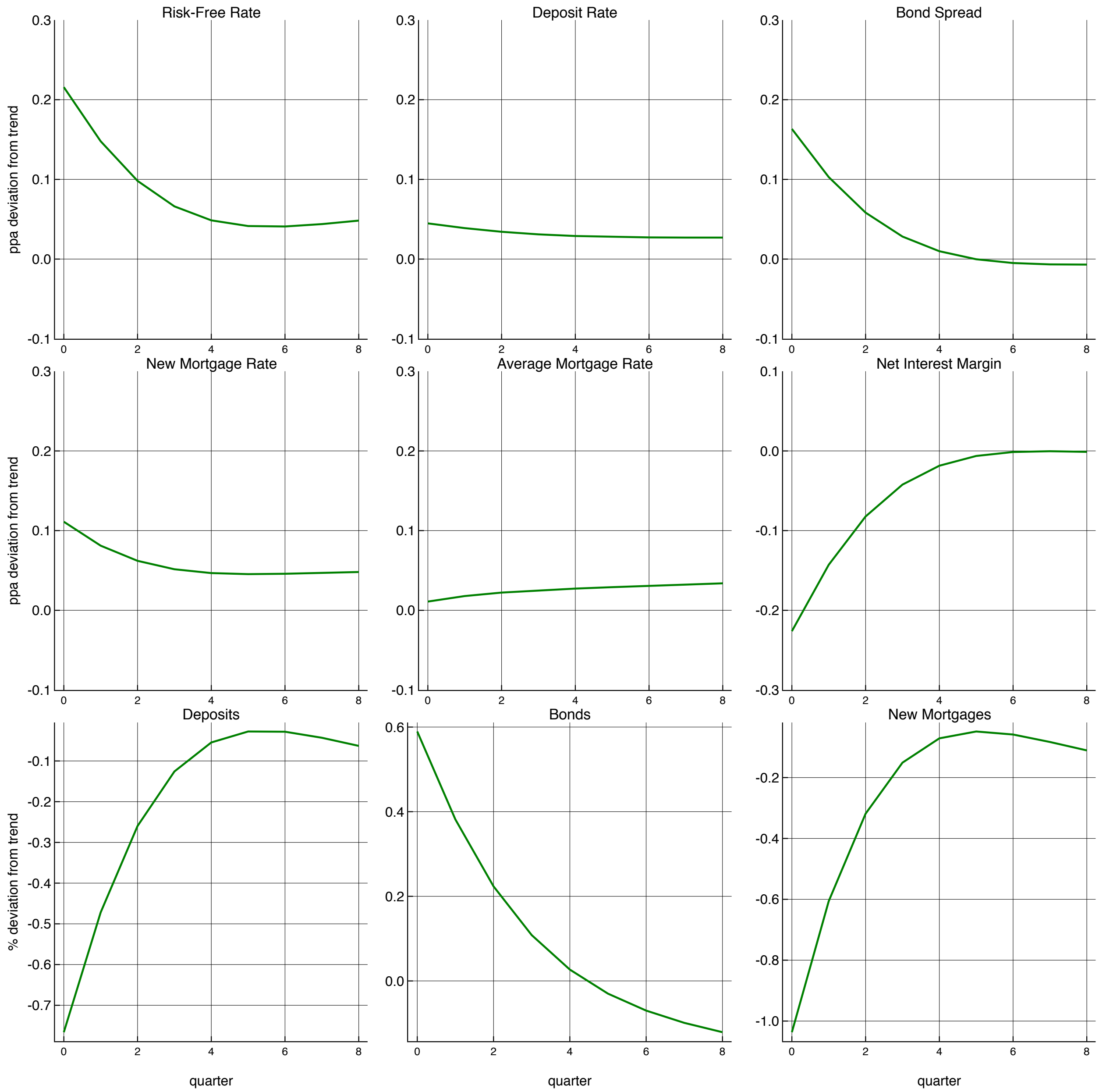


Figure G.1: IRFs to Monetary Policy Shock

Bank's Variables

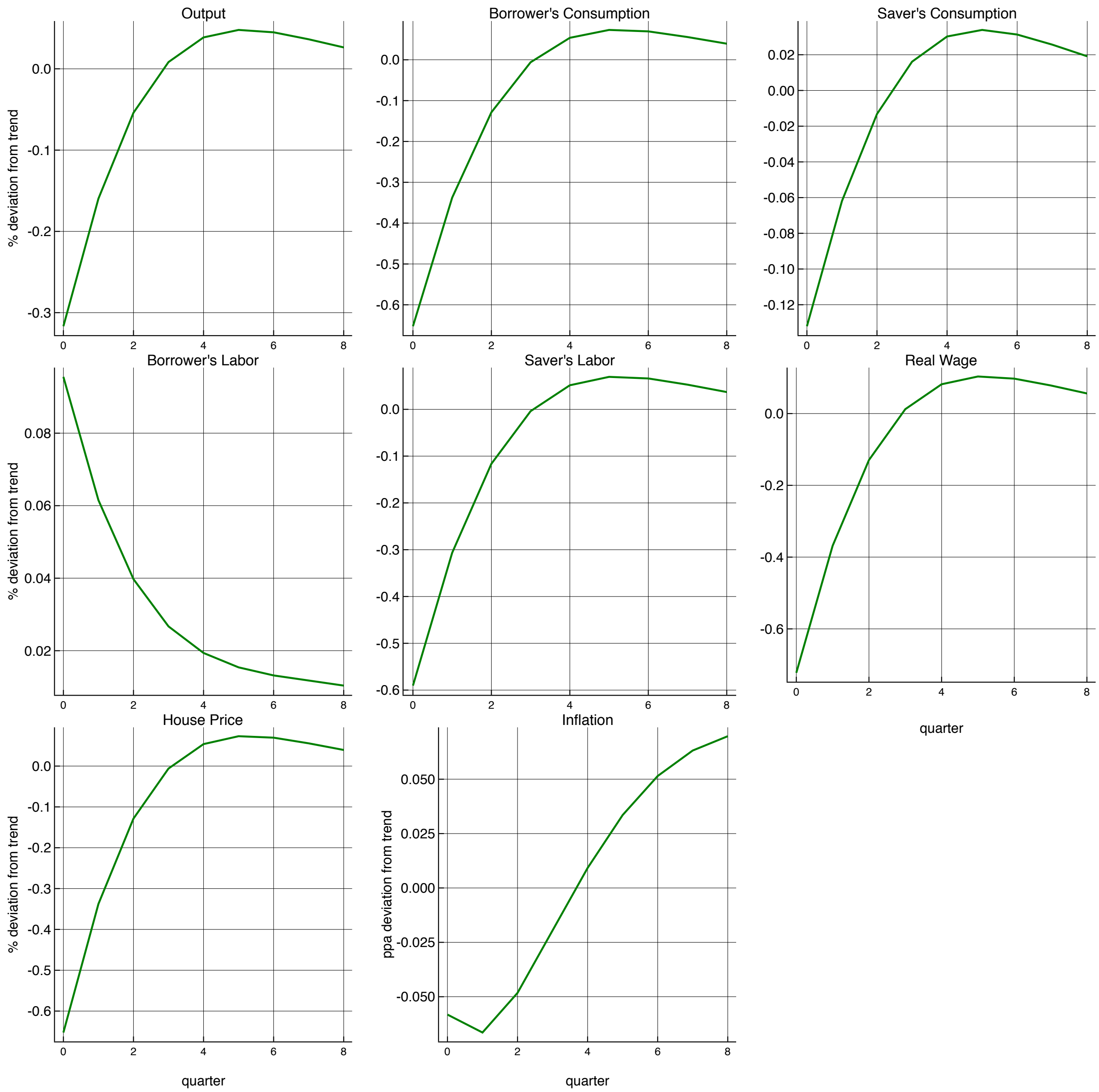


Figure G.2: IRFs to Monetary Policy Shock

Real Variables

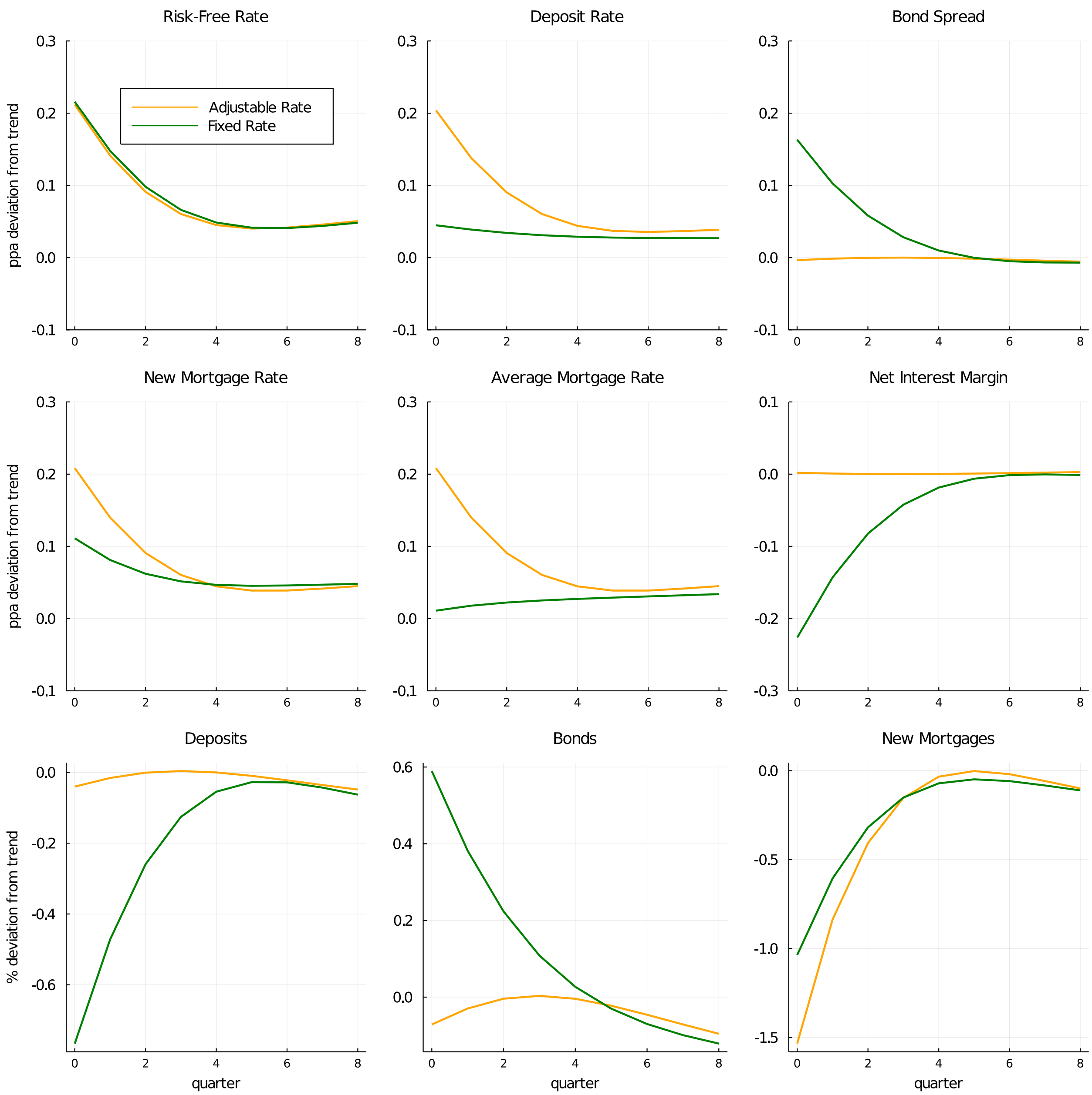


Figure G.3: IRFs to Monetary Policy Shock- Adjustable Rate Mortgages

Bank's Variables

H Evidence in Support of Model Assumptions

An important assumption in the model is that deposit demands faced by banks have a persistent component, captured in reduced form through deep habits for deposits.

Evidence in support of a dynamic component of demand for banks' deposits is provided by limited turnover of banks' customers and depositors. Honka et al. (2017) discuss[45] survey estimates saying that 8.4% of the US population switches primary bank in a year, and 14% opens at least one new account[46] with another bank each year. They also report that "a study conducted by TD Bank in 2013 says that 12% of the study respondents switched primary bank during the last two years" and "a NY Times article published in 2010 mentions that [r]oughly 10 to 15 percent of households move their checking account from one bank to another each year, a figure that hasn't changed substantially in recent years, according to several industry consultants and market researchers". Finally, Gourio and Rudanko (2014) report a customer turnover in online banking accounts of 10 to 20% per year. Overall, these estimates of turnover are similar, if not lower, than for turnover of customers in retail goods markets (Paciello et al., 2019).

There are also branches of the management and statistics literature which focus on customer valuation and prediction of customer attrition specifically at banks. Even if this includes customers who are not just depositors, it further supports the idea that retail customer relationships are important for banks, including those with depositors. For instance, Haenlein et al. (2007) develop a customer valuation model for retail banking and test it using data of a leading German bank. While data confidentiality prevents them from reporting exhaustive statistics about customer turnover, they say that 1 to 10% of customers aged 37/38 terminate their relationship with the bank in a year - and this provides an upper bound also for depositors' turnover. He et al. (2014) develop a machine learning technique to predict customer attrition for commercial banks, and motivate it precisely based on the difficulty in predicting attrition from a very imbalanced sample between churners and non-churners at the bank.

In order to provide further evidence in support of the assumption that the deposit demand faced by banks is persistent, I look at persistence in the portion of banks' market shares in the deposit market which is not explained by deposit rates or other sources of differentiation across banks suggested in the literature that estimates structural demand models of commercial banks' deposits (Dick 2008, Egan et al. 2017a, Egan et al. 2017b among others). The procedure is described in Appendix I. I find that the autocorrelation of residuals is high, ranging from 0.995 at one quarter to 0.97 at five years. While Egan et al. (2017b) call these residuals 'productivity', they reflect various unexplained factors, including limited turnover of banks' depositors.

[45] In the notes to the paper.

[46] While the types of accounts considered in the main survey in the paper include deposits, credit cards, mortgages and investment accounts, the vast majority of shoppers open deposit accounts (85% checking, 58% saving), and the third most common type of account opened is credit cards (26%).

Other assumptions

Banks are represented in the model as holding only mortgages as assets, earning only interest income, and managing a duration-mismatched portfolio. These features are motivated by the empirical evidence on the banking sector.

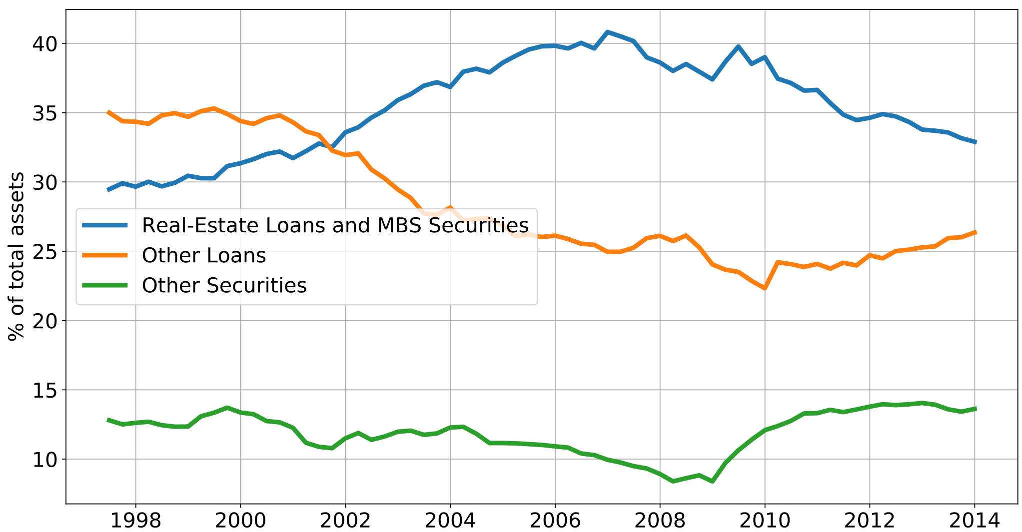


Figure H.1: Shares of Banks' Assets by Asset Class

Figure H.1 shows that real-estate loans and mortgage-backed securities are the largest asset-category for commercial banks using data from the FFIEC Consolidated Reports of Condition and Income (US Call Reports). The average share of total assets accounted for by this class is approximately 35% over the period 1997-2013, while all other loans and all other securities account for 28% and 11% on average over the period, respectively.[47]

I also find that interest income accounts for most of total (interest and non-interest) income of commercial banks. This is shown in Figure H.2 based on US FDIC Historical Statistics on Banking data. While with the decrease in the term premium the share of total income accounted for by interest income has decreased, even in the recent low-interest rate environment the share stands at around 65%-70%.

Regarding duration mismatch, I follow the same procedure described in Section 6.1 but at the level of the aggregate US commercial banking sector in order to estimate an aggregate average duration of banks' assets and liabilities. The resulting time series are reported in Figure H.3. As Drechsler et al. (2020) find, the average duration of the aggregate of banks' assets is approximately 4.3 years during 1997-2013, while for liabilities it stands at 0.4 years. Excluding transaction and

[47]Cash, Federal funds sold and trading assets essentially account for the remaining part of total assets.

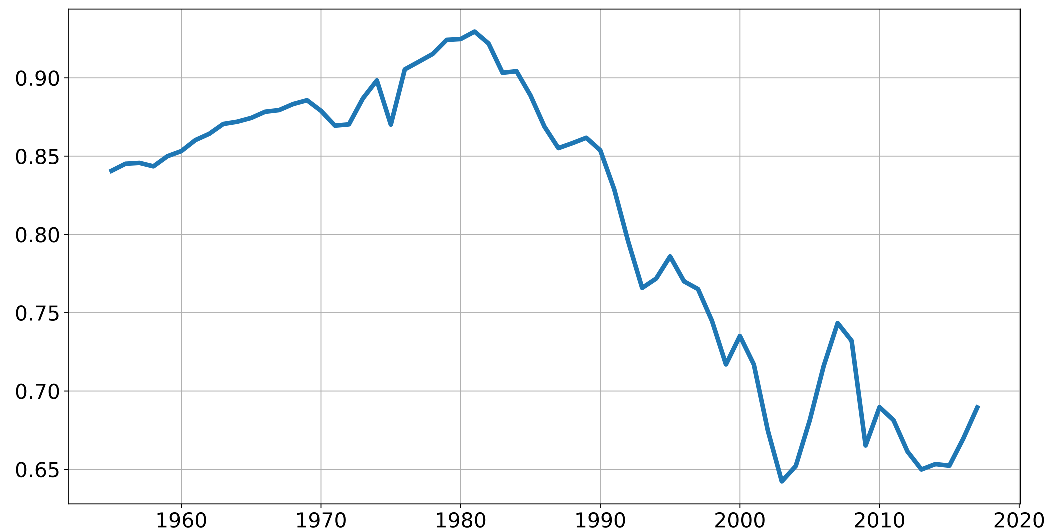


Figure H.2: Banks' Interest Income Share of Total Income

savings deposits for which the duration is assumed to be 0, I find that the average duration of remaining banks' liabilities is approximately 0.9 years - still significantly lower than for assets. Finally, even if commercial banks are sophisticated investors and could hedge the interest-rate risk generated by their duration-mismatched portfolio through derivatives, Begenau et al. (2015) find that only approximately 50% of bank holding companies use interest rate derivatives[48], and most banks use them to take on more interest rate risk. In this sense, the model assumption that banks always manage a duration mismatched portfolio is justified.

[48] Drechsler et al. (2020) instead look at holdings of interest-rate derivatives disaggregated by banks - not at the aggregate bank holding company level - and report that only 8% of banks use such derivatives.

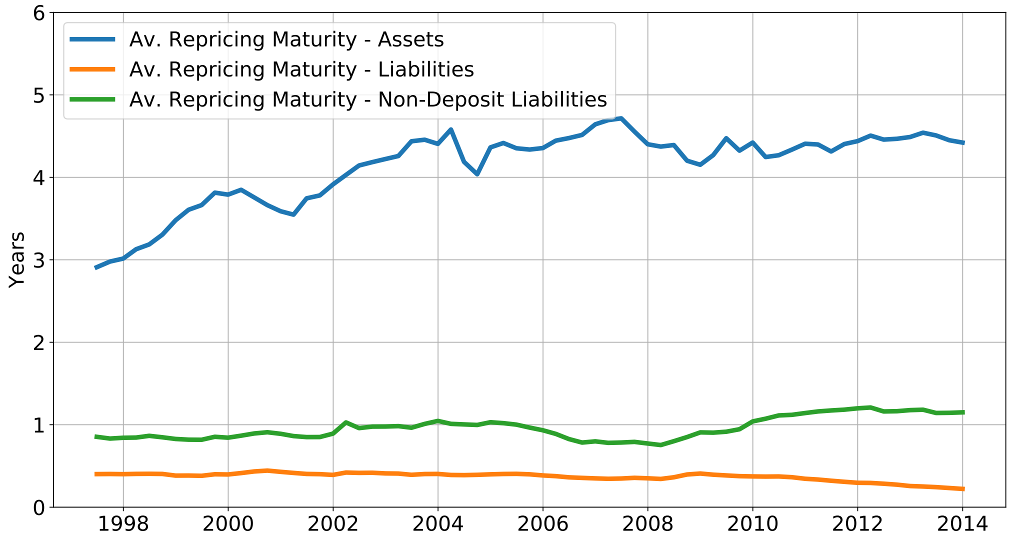


Figure H.3: Repricing Maturity of Banks' Assets and Liabilities

I Estimation of Deposit Market Share Residuals

Using quarterly US Call Report data at the bank holding company level, I estimate the following panel regression

$$\log(s_{it}) = \alpha_i + \beta i^d_{it} + \Gamma X_{it} + \delta_t + \epsilon_{it}$$

where s_{it} is the share of total deposits in the US held by bank i at time t, i^d_{it} is the deposit rate it offers, X_{it} are other observables of the bank, and α_i and δ_t are bank- and time-fixed effects. This equation can be obtained from a discrete choice model of deposit services. As done by Egan et al. (2017b), I use as controls X_{it}: the number of employees of the bank, its non-interest expenditure (which includes salaries and costs related to management of bank branches), and the number of bank branches. Deposits are the sum of transaction and savings deposits and the deposit rate is the ratio of interest expense to the total stock of deposits for these two classes of deposits. In order to account for endogeneity of deposit rates, I use as instrument the average characteristics of other products in the market (Berry et al., 1995). Following Egan et al. (2017b), these are identified with the number of branches, employees, total non-interest expenditures, and service charges on deposits of the competitors of a bank. Information on MSAs where a bank operates through its branches comes from FDIC data. For each bank characteristic, I compute the average value across competitors for each MSA and quarter[49] where the bank operates. Then these averages are aggregated across MSAs by taking the weighted average based on the share of deposits in the MSA held by a bank. The instruments then are the lagged values of these average characteristics. They will be relevant to the extent that a bank is induced to offer a higher deposit rate if its competitors offer better products. The instruments are valid if, in each period, they are orthogonal to bank i-period t demand shocks.[50]

Table I.1 below shows the results of the panel IV estimation. The results are in line with Egan et al. (2017b) and the instruments pass under-identification, weak-identification and over-identification tests. At a market share of 5%, an increase in the deposit rate by 100 bps increases the market share by 1.1 percentage points.

Finally, I compute the residuals

$$\hat{\epsilon}_{it} = \log(s_{it}) - \hat{\alpha}_i - \hat{\beta} i^d_{it} - \hat{\Gamma} X_{it} - \hat{\delta}_t$$

and find that the autocorrelation of residuals is high, ranging from 0.995 at one quarter to 0.97 at five years.

[49] MSAs are another standard level of aggregation in defining deposit markets, see e.g. Dick (2008).

[50] Since competitors' characteristics used in the instruments adjust slowly relative to rates and are lagged, validity is more likely to hold.

	(1)
	Log-deposit market share
Deposit rate	23.173**
	(9.4546)
N. employees (1,000s)	0.011***
	(0.0037)
Non-interest expense (billions)	-0.109
	(0.0684)
N. branches	0.012***
	(0.0021)
Bank FE	Y
Time FE	Y
N	212,254
R2	0.932

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Data is from US Call Reports and FDIC, Q1 1994 - Q4 2013. The dependent variable is the natural logarithm of the share of total US deposits in a quarter accounted for by a bank, where deposits are transaction and saving deposits. The deposit rate is the ratio of interest expense to stock of deposits, and its coefficient reported in the table is the IV estimate using the Berry et al. (1995) instruments - as explained in the main text. Independent variables are winsorized at the 1% level. The instruments are relevand and valid. The null hypothesis of an LM underidentification test (instruments are not correlated with the endogenous regressor) is rejected with a value of the Kleibergen-Paap rk LM statistic of 59.6 (p=0), the null hypothesis of a 'weak' identification test (instruments are only weakly correlated with the endogenous regressor) is rejected with a value of the robust Kleibergen-Paap Wald rk F statistic of 202.7 (p=0), and the null hypothesis of the overidentification test (instruments are uncorrelated with the error term) is not rejected with a value of the Hansen J statistic of 1.1 (p=0.75).

Table I.1: Deposit Demand IV Estimation

J Derivation of Equations with Additional Liquidity Source

Given the CES aggregator of utility from liquidity services of deposits and CBDC, we have

$$\frac{\partial D_t}{\partial \Delta_t} = \alpha \left(1 - \frac{1}{\varrho}\right) (\Delta_t)^{-\frac{1}{\varrho}}$$

$$\frac{\partial D_t}{\partial d_{jt}} = \left(1 - \frac{1}{\varrho}\right) \left(\left[\int_0^1 \left(d_{jt} S^{\theta}_{j,t-1} \right)^{1-\frac{1}{\eta}} \mathrm{d}j \right]^{\frac{\eta}{\eta-1}} \right)^{-\frac{1}{\varrho}} \left[\int_0^1 \left(d_{jt} S^{\theta}_{j,t-1} \right)^{1-\frac{1}{\eta}} \mathrm{d}j \right]^{\frac{\eta}{\eta-1}-1} \left(d_{jt} S^{\theta}_{j,t-1} \right)^{-\frac{1}{\eta}} S^{\theta}_{j,t-1}$$

In a symmetric equilibrium,

$$\frac{\partial D_t}{\partial d_t} = \left(1 - \frac{1}{\varrho}\right) \left(d_t S^{\theta}_{t-1} \right)^{-\frac{1}{\varrho}} S^{\theta}_{t-1}$$

Therefore, in addition to the Euler equation for deposits (Equation 4), we have an Euler equation for CBDC

$$\frac{\mathbb{E}_t \left[\frac{\Lambda_{t,t+1}}{\Pi_{t+1}} \right] (i_t - i^{\Delta}_t)}{\mathbb{E}_t \left[\frac{\Lambda_{t,t+1}}{\Pi_{t+1}} \right] (i_t - i^{d}_t)} = \frac{\frac{U_{D_t} \frac{\partial D_t}{\partial \Delta_t}}{U_{C_t}}}{\frac{U_{D_t} \frac{\partial D_t}{\partial d_t}}{U_{C_t}}}$$

Notice how the CES functional form yields a tractable relationship between the allocation of savings between CBDC and deposits and the opportunity cost of holding the two assets:

$$\frac{\Delta_t}{d_t} = \left(\frac{i_t - i^{\Delta}_t}{i_t - i^{d}_t} \frac{S^{\theta}_{t-1}}{\alpha} \right)^{-\varrho} S^{\theta}_{t-1} \text{ with } \alpha > 0$$

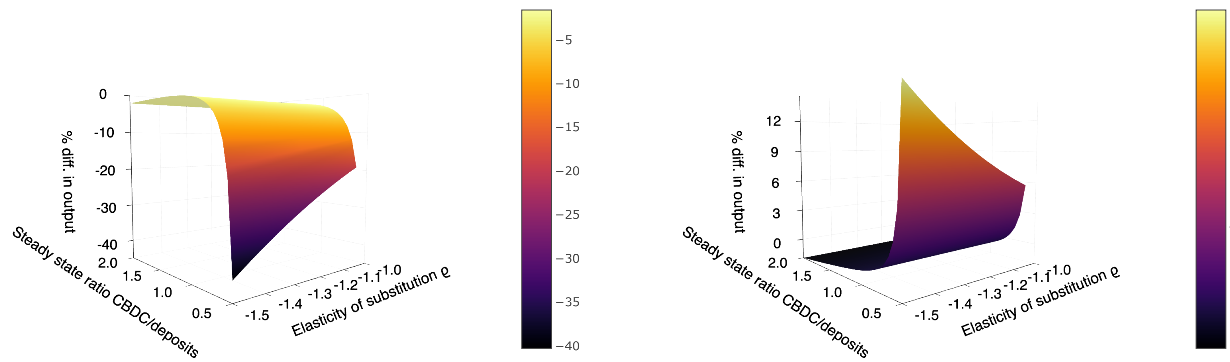
It is straightforward to show that the demand for deposits at bank i becomes

$$d_{it} = \left(\frac{m^d_{it}}{\tilde{m}^d_t} \right)^{-\eta} S^{\theta(\eta-1)}_{i,t-1} \left[\left(D_t - \alpha \left\{ \Delta_t \right\}^{1-\frac{1}{\varrho}} \right)^{\frac{\varrho}{\varrho-1}} \right]$$

and in a symmetric equilibrium

$$d_t = S^{-\theta}_{t-1} \left[\left(D_t - \alpha \left\{ \Delta_t \right\}^{1-\frac{1}{\varrho}} \right)^{\frac{\varrho}{\varrho-1}} \right]$$

K Complementarity between Additional Liquidity Source and Deposits



(a) Full pass-through to CBDC rate

(b) Limited pass-through to CBDC rate

Figure K.1: 1-year cumulative output response to monetary shock (% diff. from baseline)