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Imperfect pass-through to deposit rates and monetary policy transmission

Alberto Polo

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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.

Key words: Monetary policy transmission, deposit rates, banks, market power.

JEL classification: E43, E52, G21.

(1) Bank of England. Email: alberto.polo@bankofengland.co.uk

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Bank of England, Threadneedle Street, London, EC2R 8AH
Email enquiries@bankofengland.co.uk

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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.

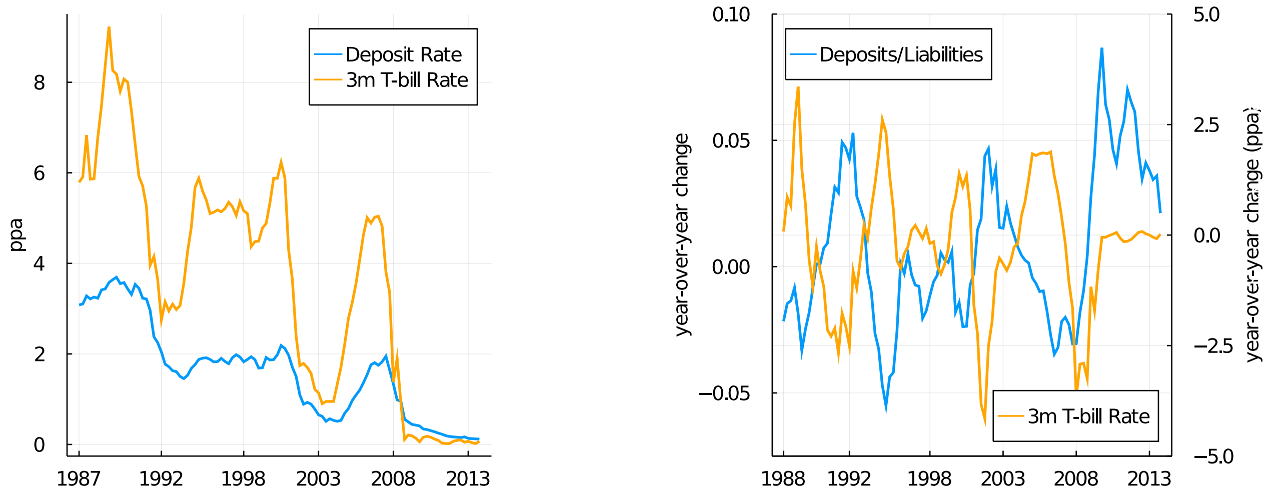
This paper investigates the monetary transmission mechanism by focusing on the effects of monetary policy changes on real activity through the banking sector and the deposit market. Specifically, I study a general equilibrium monetary model which is consistent with three key facts about monetary policy 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 I.



(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. Floyd et al. (2015) argue that banks have a more stable propensity to pay dividends than industrials. The dividend-smoothing motive is captured 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 the model.

Then, I use the model to investigate the implications of this 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 4% larger decrease in output on impact (2% 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 quantifies the effect.

Finally, I provide two main validations of the model. First, I compare 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.

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. In particular, 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 (2018) 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 assesses the model against the empirical evidence and studies the relationship between duration mismatch and pass-through to deposit rates in the model and the data. 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 (2020) 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

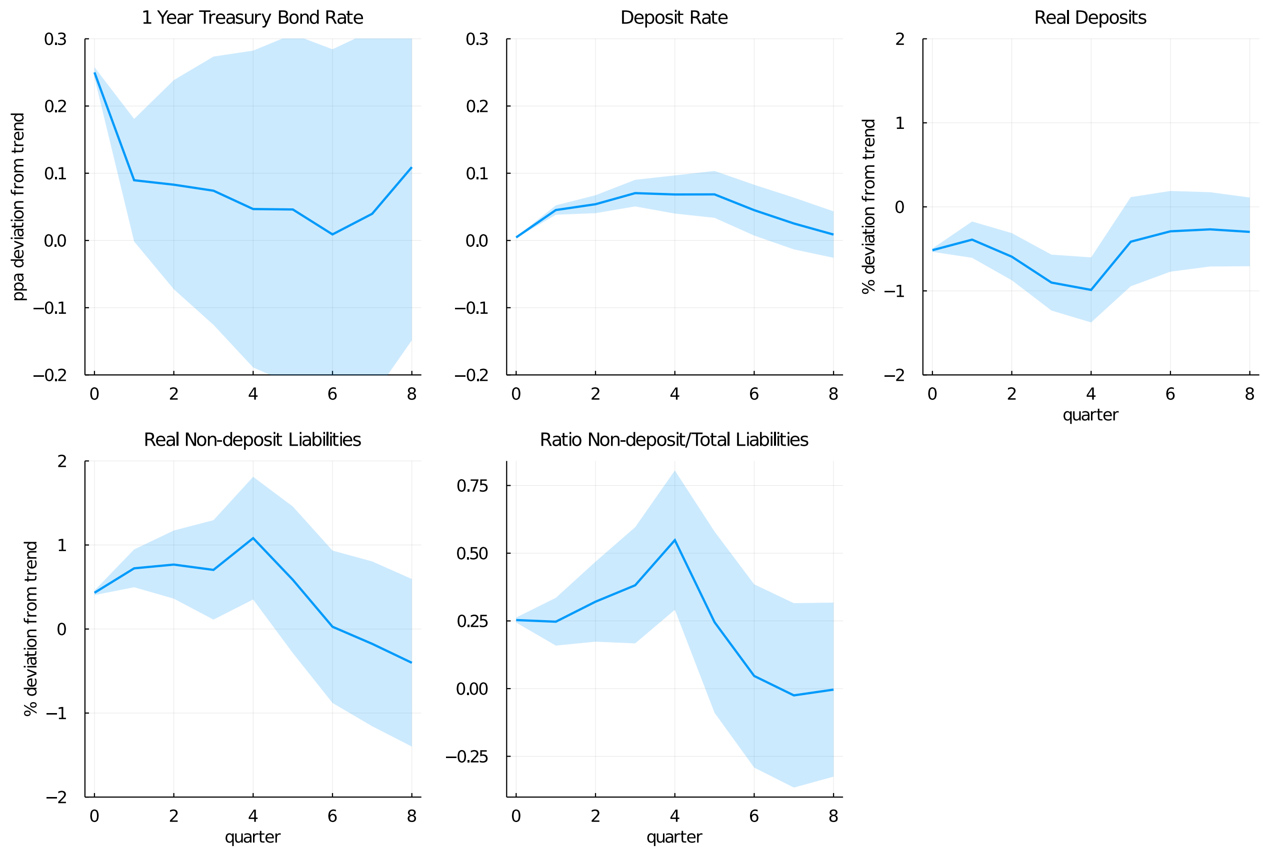
$$y_{t+h} = \alpha_h + \beta_h i_t + \Gamma_h X_{t-1} + u^y_{t+h} \tag{1}$$

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 (2020): four lags of industrial

[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.



Source: US Call Reports, various Federal Reserve releases, Miranda-Agrippino and Ricco (2020) 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

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]

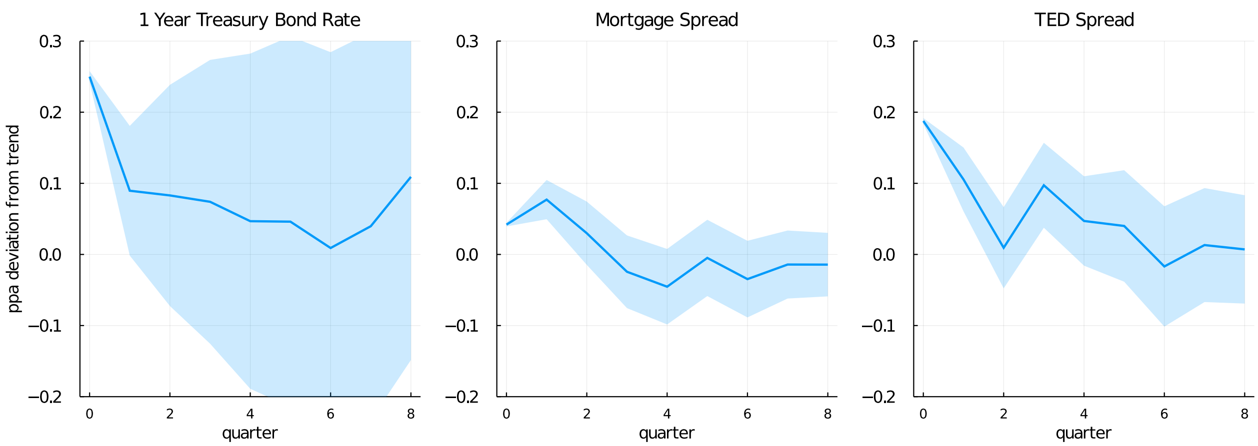
Figure 2 shows the first set of results. The first panel describes the response of the 1-year Treasury bond rate to the monetary shock, normalized to increase by 25 bps on impact. Following the exogenous increase in the policy indicator, deposit rates adjust only partially, deposits decrease and banks'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

[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.

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 (2020) 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.



Source: Federal Reserve H.15 and Interest Rate Spreads releases, Freddie Mac Primary Mortgage Market Survey, Miranda-Agrippino and Ricco (2020) 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

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 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 three aggregate shocks: a total factor productivity (TFP) shock, and 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

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

[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.

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. 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.

[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.

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 $1 + i^d_{jt}$ 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 $1 + i^B_t$ 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^s_t, labor supply N^s_t, holdings of government bonds A^s_t, holdings of banks' bonds B^s_t and deposits d^s_{jt} at each bank $j \in [0,1]$ to maximize the expected present discounted value of utility

$$\mathbb{E}_0 \left[\sum_{t=0}^{\infty} \beta_s^t U^s \left(C^s_t, N^s_t, D^s_t \right) \right], \beta_s \in (0,1)$$

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

$$C^s_t + A^s_t + \int_0^1 d^s_{jt} \mathrm{d}j + B^s_t + \Theta(B^s_t, M_t) \leq (1 - \tau^y) W_t N^s_t + \frac{1 + i_{t-1}}{\Pi_t} A^s_{t-1} + \int_0^1 \frac{1 + i^d_{j,t-1}}{\Pi_t} d^s_{j,t-1} \mathrm{d}j + \frac{1 + i^B_{t-1}}{\Pi_t} B^s_{t-1} + T^s_t + \Xi^s_t$$

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

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

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

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

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

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

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

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_{jt}^s, which writes

$$\mathbb{E}_t\left[\frac{\Lambda_{t,t+1}^s}{\Pi_{t+1}}\right] \underbrace{(i_t - i_{jt}^d)}_{\equiv m_{jt}^d, \text{ bank } j\text{'s deposit spread}} = \frac{U_{D_t^s}^s \frac{\partial D_t^s}{\partial d_{jt}^s}}{U_{C_t^s}^s} \tag{3}$$

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 (3) allows to obtain closed-form solutions for deposit demands. Saver s's deposit demand from bank j has a standard CES form,

$$d^s_{jt} = \left(\frac{m^d_{jt}}{\tilde{m}^d_t}\right)^{-\eta} S^{\theta(\eta-1)}_{j,t-1} D^s_t \tag{4}$$

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

$$M_{jt} = \mu_t M^*_{jt} + (1-\mu_t)(1-\nu)\frac{M_{j,t-1}}{\Pi_t} \quad (5)$$

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,

$$X_{jt} = \mu_t q^*_t M^*_{jt} + (1-\mu_t)(1-\nu)\frac{X_{j,t-1}}{\Pi_t} \quad (6)$$

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},

$$M_{jt} = d_{jt} + B_{jt} \quad (7)$$

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 4). 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,

$$S_{jt} = \rho_s S_{j,t-1} + (1-\rho_s) d_{jt} \quad (8)$$

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

[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.

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.

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

$$div_{j,t+1} = \frac{1}{\Pi_{t+1}}\left[X_{jt}(q^*_t) - \nu M_{jt} - (i^d_{jt}+\kappa)d_{jt} - i^B_t B_{jt}\right] - f(div_{j,t+1}) \tag{9}$$

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

subject to laws of motion (5), (6), (8), deposit demand (4) and balance sheet constraint (7).

The term in brackets in (9) 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^d_{jt} and interest on bonds at rate i^B_t.[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^d_{jt}[17] is in order (Equation 16 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

[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^s_t. 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.

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

$$\mathbb{E}_t\left[\frac{\Lambda_{t,t+1}^s}{\Pi_{t+1}}\Omega_{j,t+1}\right]\left(\frac{\eta}{\eta-1}-\frac{m_{jt}^d}{\kappa}\right)=\theta\mathbb{E}_t\left[\frac{\Lambda_{t,t+2}^s}{\Pi_{t+2}}\Omega_{j,t+2}\frac{m_{j,t+1}^d}{\kappa}\frac{d_{j,t+1}}{d_{jt}}\right] \tag{10}$$

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 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_{jt}^d/κ is the time-varying markup set by the bank on deposits, as the deposit spread m_{jt}^d 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 (10) immediately implies

$$\frac{m_{jt}^d}{\kappa}=\frac{\eta}{\eta-1}$$

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_{jt}^d 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

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

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 (10). 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.

Introducing a positive bank bond spread, Equation (10) becomes

$$\mathbb{E}_t\left[\frac{\Lambda^s_{t,t+1}}{\Pi_{t+1}}\Omega_{j,t+1}\right]\left[\frac{\eta}{\eta-1}\left(1-\frac{i^B_t - i_t}{\kappa}\right)-\frac{m^d_{jt}}{\kappa}\right] = \theta\mathbb{E}_t\left[\frac{\Lambda^s_{t,t+2}}{\Pi_{t+2}}\Omega_{j,t+2}\frac{m^d_{j,t+1}}{\kappa}\frac{d_{j,t+1}}{d_{jt}}\right] \quad (11)$$

The only difference relative to Equation (10) 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 (11) 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

[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).

cost of funds i_t^B 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, which depends on the evolution of future mortgage rates. As shown by Greenwald (2018), endogenous prepayment amplifies the transmission of shocks into output.[20] Despite the *iid* prepayment cost shocks, thanks to the assumption of perfect insurance within the borrower family, the problem of the borrowers aggregates to that of a representative borrower.

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

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

[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.

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,

$$M_t^{b*} \leq \frac{PTIW_tN_t^b}{q_t^*}$$

Finally, the borrower is subject to laws of motion for mortgage principal and payments analogous to equations (5) and (6) for the bank, in addition to a law of motion for housing

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

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

$$Y_t = \left(\int_0^1 Y_t(\iota)^{1-\frac{1}{\xi}}\,\mathrm{d}\iota\right)^{\frac{\xi}{\xi-1}}, \xi > 1 \tag{12}$$

Optimality requires that the producer minimizes total expenditure $\int_0^1 P_t(\iota)Y_t(\iota)\,\mathrm{d}\iota$ subject to (12), yielding CES demands for each intermediate good ι

$$Y_t(\iota) = \left(\frac{P_t(\iota)}{P_t}\right)^{-\xi} Y_t \tag{13}$$

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,

$$Y_t(\iota) = Z_tN_t(\iota)$$

where Z_t is exogenous TFP and $N_t(\iota)$ is labor hired to meet the final good producer's demand (13). 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

[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.

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:

$$P^b_t(\iota) = P^*_{t-1}\Pi_{t-1}$$

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.

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

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

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

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

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^i_t.

Aggregate TFP follows another AR(1) process

$$\log(Z_t) = (1-\rho_Z)\log(\bar{Z}) + \rho_Z\log(Z_{t-1}) + \epsilon^Z_t,\ \epsilon^Z_t \sim N(0,\sigma_Z)$$

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 $(C^s_t, C^b_t, N^s_t, N^b_t)$ 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 $(\Pi_t, W_t, P^h_t, i_t, i^d_t, i^B_t, q^*_t)$ 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

$$C^b_t + C^s_t + \delta P^h_t H_t + f(div_t) + \Theta(B_t, M_t) = Y_t$$

while the labor, housing market, and government bond clearing conditions are $N^b_t + N^s_t = N_t$, $H_t = \bar{H}$, 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. 2017, Gerlach et al. 2018), and they are the largest class of deposits. All parameter values are listed in Table 1.

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 υ^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).

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

[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 for details about how duration is estimated.

Parameter	Value	Description	Moment / Source / Target
		Parameters related to deposits	
ψ	$3 \cdot 10^{-6}$	Weight on deposits in utility	(Transaction + saving deposits) / bank liabilities = **0.43**
γ	0.160	Utility curvature in deposits	Std(real deposits) / std(real GDP) = **3.05**
η	1.464	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	0.800	Degree of habit formation	Gilchrist et al. (2017) (see sensitivity)
		Parameters most relevant for banks	
ν	0.059	Share of mortgage principal repaid	Avg. duration of banks' assets = 4.26 years
κ^{div}	770.0	Scale of dividend adjustment cost	Deposit rate pass-through = **0.39** (Drechsler et al., 2017)
κ^B	0.045	Scale of portfolio adjustment cost	**TED spread IRF** (see text)
κ	36 bp	Marginal cost of supplying deposits	(see text)
υ^B	0.543	Bliss point of portfolio adj. cost	Median daily TED spread = **0.49% pa**
		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	5.744	Saver's labor disutility (weight)	Saver's labor supply = **1/3**
ζ_b	7.600	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)
		Other parameters	
PTI	0.430	Max DTI ratio	Dodd-Frank act
$\bar{H}$	4.400	Fixed housing supply	Normalize house price to **1**
μ_k	1.843	Mean mortgage issuance cost	Average prepayment rate = **15% pa** (Elenev, 2017)
s_k	1.843	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	0.750	Share of backward-looking firms	**Inflation IRF** (see text)
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)
$\sigma_{\bar{\Pi}}$	0.001	Standard deviation of inflation target	Garriga et al. (2016)
σ_i	0.003	St. deviation of *iid* monetary shock	Garriga et al. (2016)
$\bar{Z}$	1.099	Steady state productivity	Normalize steady state output to 1
ρ_Z	0.948	Persistence of productivity	Estimate from adj. TFP non-equipment (Fernald, 2014)
σ_Z	0.007	Standard deviation of productivity	"

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

Table 1: Summary of Parameterization

The degree of habit formation θ is set to a standard value in the literature on deep habits, 0.8 (Ravn et al. 2006, Gilchrist et al. 2017). 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

[26] Interpreting the habit stock as customer base, and the law of motion of the habit stock as a function that

is in the middle of the values reported in the literature surveyed in Appendix I. 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 1.464. Finally, the weight on deposits in the utility function ψ ($3 \cdot 10^{-6}$) 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, $\zeta_b = 7.6$ and $\zeta_s = 5.744$, 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 $1-\chi = 0.399$.[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 $\bar{H} = 4.4$ 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 $\mu_k = 0.226$ and the scale parameter $s_k = 0.071$ 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.

maps demand into customer base, then $1-\rho_s$ would be the rate of attrition of the customer base.

[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.

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 $\rho_{\bar{\Pi}}$ and standard deviation $\sigma_{\bar{\Pi}}$ of the inflation target process are set to 0.99 and 0.001, respectively (Garriga et al., 2016), while trend inflation Π_{ss} is set to 1.005 (2% annual inflation rate). Garriga et al. (2016) provide also an estimate of the standard deviation σ_i of the transitory shock to the Taylor rule, equal to 0.003. Steady state productivity $\bar{Z} = 1.099$ is set to normalize steady-state output to 1, while autocorrelation $\rho_Z = 0.948$ and standard deviation $\sigma_Z = 0.007$ are estimated from Fernald (2014) over 1987 to 2013 using utilization-adjusted TFP of non-equipment output. 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.

Simulated Moments

Four parameters are set internally based on simulations of the model. The curvature parameter of saver's utility with respect to deposits γ, which governs the volatility of deposits; the scale of the dividend adjustment cost κ^{div}, which affects the degree of deposit rate pass-through; the scale of the portfolio-adjustment cost κ^B, which affects the response of the bank bond rate relative to the risk-free rate; and the share of backward-looking price setters ω, which determines the response of inflation to shocks. I set them jointly to match: i) the ratio of the standard deviations of quarterly real deposits to real GDP (3.05)[28]; ii) the average pass-through of the policy rate to deposit rates for the largest 5% of banks estimated by Drechsler et al. (2017), equal to 0.39[29]; iii) the response on impact of the TED spread to the monetary shock identified in Section 2[30]; iv) the trough in the response of inflation to the same monetary shock (shown below in Figure 6). As a result, I set $\gamma = 0.16$, $\kappa^{div} = 770$, $\kappa^B = 0.045$ and $\omega = 0.75$.

[28]Deposits are total transaction and savings deposits in the US Call Reports, smoothed using a 4-lag moving average in order to eliminate seasonality and deflated by the GDP deflator. Both deposits and GDP are then logged and HP-filtered.

[29]For these first two moments, I simulate the model 2000 times for 2108 periods, and burn the first 2000 periods to purge the effect of initial conditions, leaving 108 quarters, as the number of quarters in the corresponding data between 1987 and 2013.

[30]For this IRF matching, I feed the Taylor rule an inflation target shock $\epsilon_0^{\bar{\Pi}}$ and a transitory shock ϵ_0^i so that the 1-year risk-free rate in the model goes up by 25 bps on impact, and hits the average level of the 1-year Treasury bond rate in quarters 7 to 9 in the local projection to the identified monetary shock illustrated in Figures 2 and 3.

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.[31] 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.

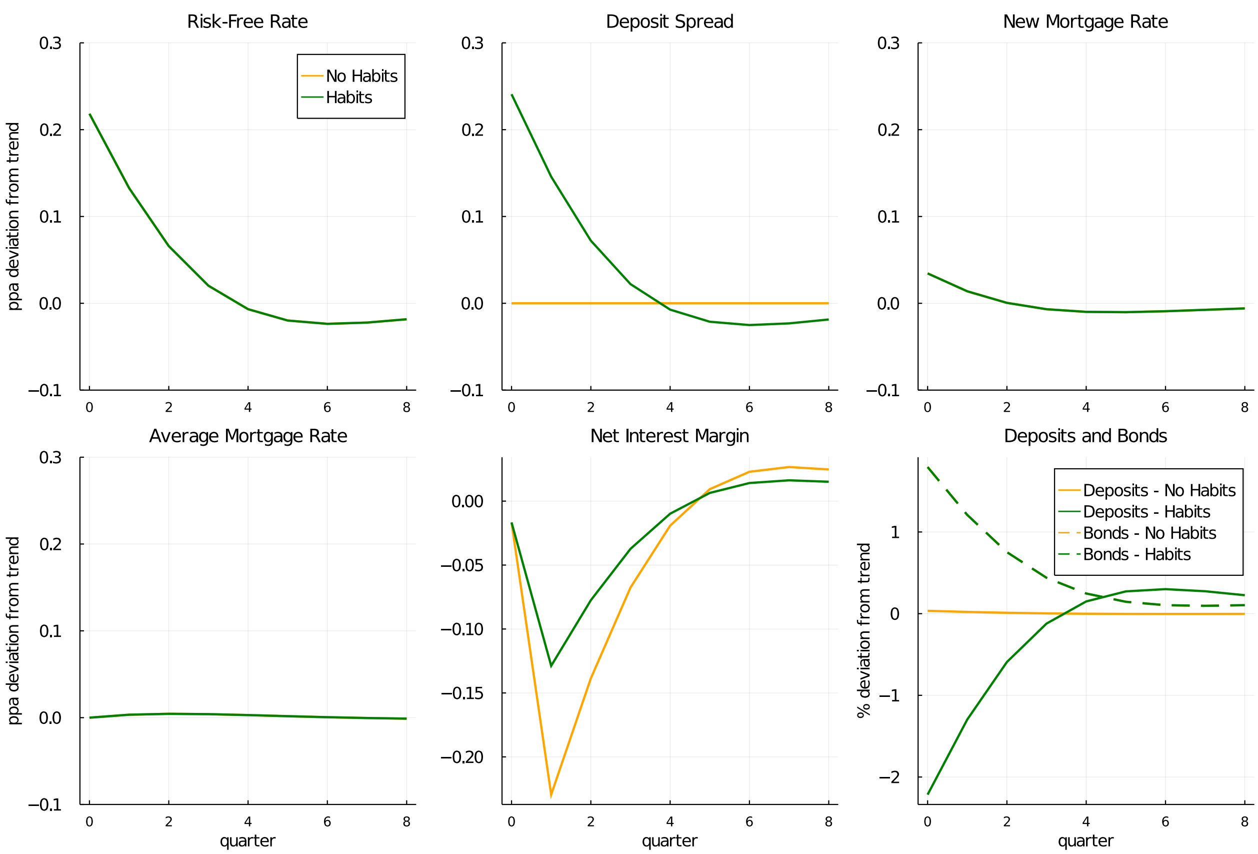


Figure 4: Impulse Response Functions to 25 bp Transitory Monetary Shock ϵ^i

Figure 4 shows impulse response functions of various financial variables to an annualized 25 bp transitory monetary shock ϵ^i.[32] 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

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

[32] Impulse response functions of other financial and real variables to this shock, to the more persistent shock to the 1-year risk-free rate, and the TFP shock are in Appendix G.

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.[33] 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 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 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 4 make clear, absent deposit habits in this simple version of the model, pass-through to deposit rates would be full and the balance-sheet composition of banks would remain unchanged.

Still abstracting from the portfolio-adjustment cost, we can linearize the intertemporal condition for the deposit spread around the steady state[34] to disentangle three forces that affect the response of the deposit spread – or equivalently, the deposit markup. The deviation of the deposit spread from steady state can be decomposed as[35]

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

[33]As showed in the impulse response functions to the shock to the 1-year risk-free rate (Figure G.1 in Appendix G), 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.

[34]Equation (10), but with $\rho_s > 0$.

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

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 5 allows to compare the relative contribution of each force to the response of the deposit spread $i_t - i_t^d$ following the 25 bp shock analyzed in Figure 4. 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.

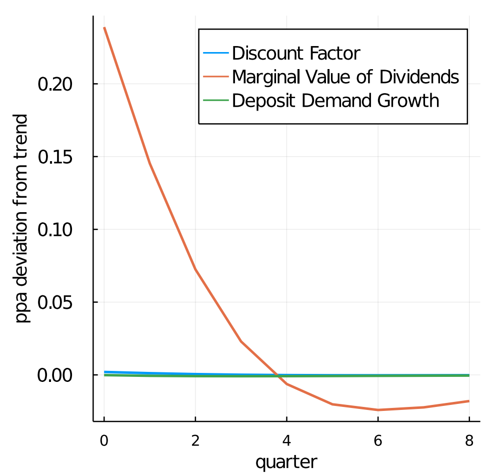


Figure 5: Impulse Response of Deposit Spread Broken Up by Component

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 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.

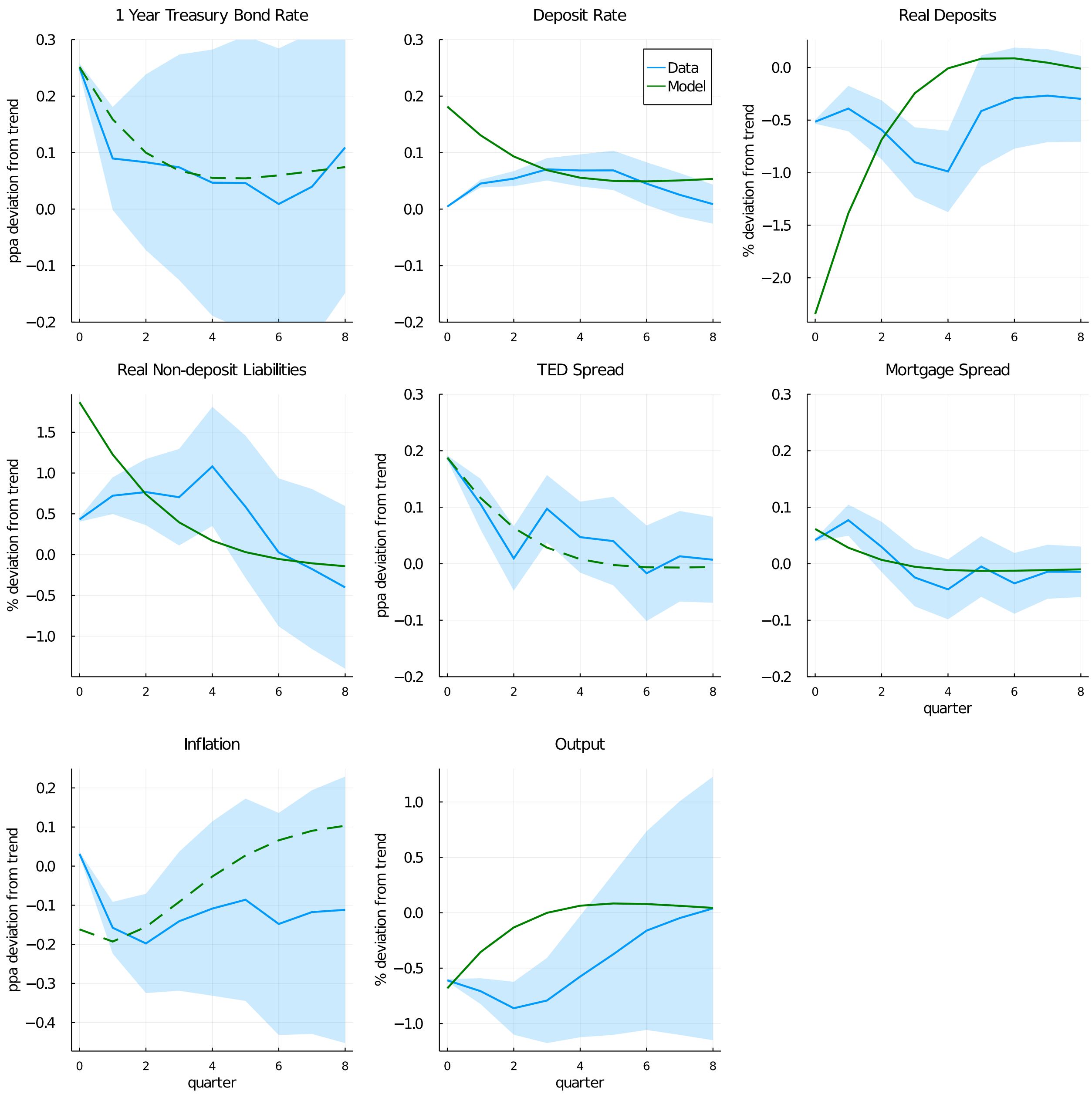
Now I turn to discussing the portfolio-adjustment cost. In Appendix F I show that, absent such cost, the marginal value of profits Ω_t - which appears in the intertemporal condition for the deposit spread (11) - drops instead from the no-arbitrage condition[36] linking the marginal cost of funding an 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. Appendix H describes the effects of breaking assumption ii).

6 Model Assessment

Figure 6 allows to assess the model against the local projections to the monetary shock identified in Section 2. The model responses of the 1-year risk-free rate, bond spread and inflation are shown as dashed lines, as these variables are used in the parameterization to target (a subset of) the moments of the corresponding local projections (see Section 4). The responses of the remaining variables show that the mechanisms and parameter values of the model provide impulse response functions to the monetary shock that are reasonably close to the data, in particular for the mortgage spread and non-deposit liabilities of banks. However, the model does miss some of the persistence, sluggishness and humpedness of the data.

Next, I assess the model by testing one of its key implications. 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 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.7 in Appendix G, which shows impulse response functions to a 25 bp transitory monetary shock ϵ^i when all banks' assets are assumed to be adjustable-rate mortgages (in yellow), and compares them to the base-

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



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

Figure 6: Data vs Model in Response to Monetary Policy Shock

line 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

	(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

a perturbation in its profits and dividends from a duration mismatch.[37] Other reasons for

[37]The small dip in the net interest margin in Figure G.7 stems from the small substitution from deposits to bonds – which require a higher rate. Other than this, variations in the marginal value of profits Ω_t only reflect the fact that the dividend target is defined in real terms, while interest income and expense of the bank are nominal, thus realized inflation perturbs realized real dividends. However, given the low volatility of inflation, this effect on its own is not enough to induce the bank to substantially change its markup and keep the deposit rate from adjusting fully with the short-term rate.

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 (11), 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.

Since in the model the duration of assets[38] 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 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

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

finding in Drechsler et al. (2020) of a negative correlation between the interest expense beta[39] of a bank, averaged over time, and the duration of its assets.

7 Imperfect Pass-through and Monetary Transmission

The impulse response functions in Figure 7 compare the full-fledged model with imperfect pass-through to deposit rates against the version of the model with perfect pass-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 6, which combines an inflation target shock and a transitory shock to the Taylor rule to track the empirical response of the 1-year Treasury bond rate.

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 7. 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 4 bp decrease in output on impact in response to the 25 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 4% on impact, and 2% 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

[39] 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.

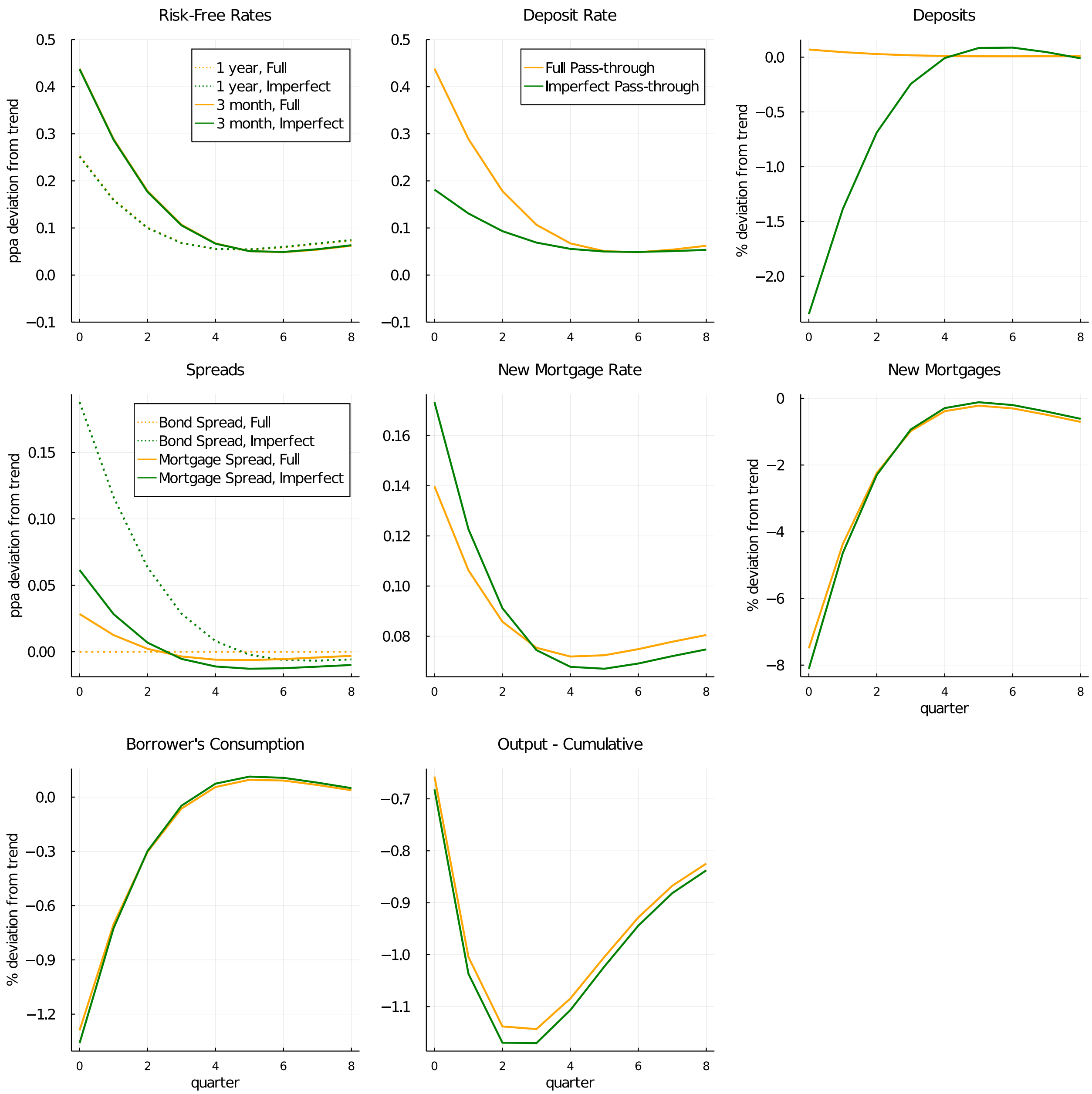


Figure 7: Imperfect vs Full Pass-through with Monetary Policy Shock

this paper allows to quantify the effects of imperfect pass-through to deposit rates for the aggregate economy.

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 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. Accordingly, structural or policy changes that strengthen pass-through of monetary policy to deposit rates would be expected to dampen this channel of monetary policy transmission, other things equal.

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 4% on impact and 2% 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.

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.

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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

$$\mathbb{E}_t \left[\frac{\Lambda^s_{t,t+1}}{\Pi_{t+1}} \right] (i_t - i^d_t) = \frac{U^s_{D^s_t} S^\theta_{t-1}}{U^s_{C^s_t}} \tag{14}$$

Budget constraint (redundant by Walras' law)

$$\begin{aligned} C^s_t + A_t + d_t + B_t + \frac{\kappa^B}{2} \left(\frac{B_t}{M_t} - v^B \right)^2 M_t = (1 - \tau^y) W_t N^s_t + \frac{1 + i_{t-1}}{\Pi_t} (d_{t-1} + A_{t-1}) \\ + \frac{1 + i^B_{t-1}}{\Pi_t} B_{t-1} - \frac{\tilde{m}^d_{t-1}}{\Pi_t} D_{t-1} + T^s_t + \Xi^s_t \end{aligned} \tag{15}$$

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

$$\mathbb{E}_t \left[\frac{\Lambda^s_{t,t+1}}{\Pi_{t+1}} \Omega_{t+1} \right] \left(\frac{\eta}{\eta - 1} \left(1 - \frac{i^B_t - i_t}{\kappa} \right) - \frac{m^d_t}{\kappa} \right) = \tag{16}$$

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

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

$$div_t = \frac{1}{\Pi_t} \left[X_{t-1} - \nu M_{t-1} - (i^d_{t-1} + \kappa) d_{t-1} - i^B_{t-1} B_{t-1} \right] - \frac{\kappa^{div}}{2} (div_t - \bar{div})^2 \tag{17}$$

Balance-sheet constraint

$$M_t = d_t + B_t \tag{18}$$

Law of motion of deposit habit stock

$$S_t = \rho_s S_{t-1} + (1 - \rho_s) d_t \tag{19}$$

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

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

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

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

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

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

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

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

Output

$$Y_t = \frac{Z_t N_t}{\mathcal{K}_t}$$

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

$$C_t^b + C_t^s + \delta P_t^h H_t + \frac{\kappa^{div}}{2} (div_t - \bar{div})^2 + \frac{\kappa^B}{2} \left(\frac{B_t}{M_t} - v^B \right)^2 M_t = Y_t \tag{20}$$

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 (2020)
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 (2020)

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 (2020) monetary shocks are aggregated to quarterly frequency by summing them over each quarter.

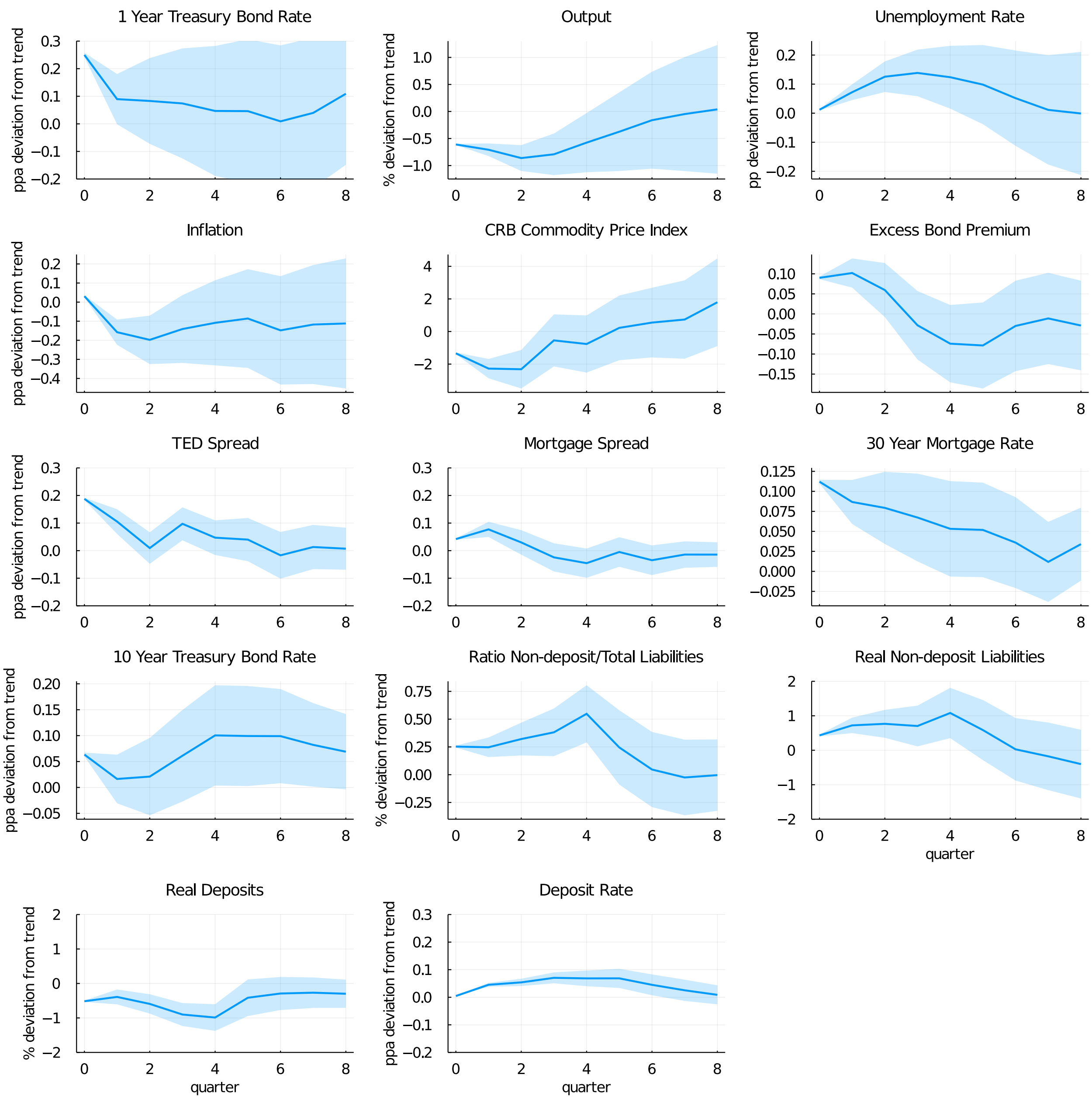

Figure B.1: Local Projections with Monetary Policy Shock

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 $Y = d_j(\iota) m_j^d$[40], 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

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

[40] 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

$$d_j^* \equiv \int_0^1 d_j(\iota)\,\mathrm{d}\iota = \frac{Y}{m_j^d} p_j = \frac{S_j^{\frac{\theta}{\Xi}} (m_j^d)^{-\frac{1}{\Xi}-1}}{\sum_{z=1}^N (S_z^\theta / m_z^d)^{\frac{1}{\Xi}}} Y \text{ for each } j = 1, \ldots, N \tag{21}$$

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.[41] 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 (21) under the discrete choice model, and then derive the CES demand following the same steps.

[41] $M = N - 1$, 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

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

Multiplying by m_{it}^d and integrating with respect to i we have

$$\int_i m_{it}^d d_{it}^s \,\mathrm{d}i = d_{zt}^s \left(m_{zt}^d\right)^{\eta} S_{z,t-1}^{-\theta(\eta-1)} \int_i \left(m_{it}^d S_{i,t-1}^{-\theta}\right)^{1-\eta} \mathrm{d}i$$

which implies that, for a generic bank i,

$$d_{it}^s = \frac{\left(m_{it}^d\right)^{-\eta} S_{i,t-1}^{\theta(\eta-1)}}{\int_i \left(m_{it}^d S_{i,t-1}^{-\theta}\right)^{1-\eta} \mathrm{d}i} \int_i m_{it}^d d_{it}^s \,\mathrm{d}i$$

Let us define the average deposit spread

$$\tilde{m}_t^d \equiv \left[\int_i \left(m_{it}^d S_{i,t-1}^{-\theta}\right)^{1-\eta} \mathrm{d}i\right]^{\frac{1}{1-\eta}}$$

Then

$$d_{it}^s = \left(\frac{m_{it}^d}{\tilde{m}_t^d}\right)^{-\eta} S_{i,t-1}^{\theta(\eta-1)} \frac{\int_i m_{it}^d d_{it}^s}{\tilde{m}_t^d}$$

Finally, plugging into the definition of D_t^s we have

$$\begin{aligned}
D_t^s &= \left[\int_i \left(\frac{\left(m_{it}^d\right)^{-\eta} S_{i,t-1}^{\theta(\eta-1)}}{S_{i,t-1}^{-\theta}}\right)^{1-\frac{1}{\eta}} \mathrm{d}i\right]^{\frac{\eta}{\eta-1}} \frac{\int_i m_{it}^d d_{it}^s \,\mathrm{d}i}{\left(\tilde{m}_t^d\right)^{1-\eta}} \\
&= \left[\int_i \left(m_{it}^d S_{i,t-1}^{-\theta}\right)^{1-\eta} \mathrm{d}i\right]^{\frac{\eta}{\eta-1}} \frac{\int_i m_{it}^d d_{it}^s \,\mathrm{d}i}{\left(\tilde{m}_t^d\right)^{1-\eta}} \\
&= \left(\tilde{m}_t^d\right)^{-\eta} \frac{\int_i m_{it}^d d_{it}^s \,\mathrm{d}i}{\left(\tilde{m}_t^d\right)^{1-\eta}} \\
&= \frac{\int_i m_{it}^d d_{it}^s \,\mathrm{d}i}{\tilde{m}_t^d}
\end{aligned}$$

i.e.

$$\tilde{m}_t^d D_t^s = \int_i m_{it}^d d_{it}^s \,\mathrm{d}i$$

so the demand for deposits at bank i becomes

$$d_{it}^s = \left(\frac{m_{it}^d}{\tilde{m}_t^d}\right)^{-\eta} S_{i,t-1}^{\theta(\eta-1)} D_t^s$$

The budget constraint can be rewritten as

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

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

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

$$\left(\hat{i}_t - \mathbb{E}_t\hat{\Pi}_{t+1}\right)\frac{i}{\Pi q^*\Omega^X} - \hat{q}^*_t = \mathbb{E}_t\hat{\Omega}^X_{t+1} - \mathbb{E}_t\hat{\Omega}_{t+1}\frac{i}{\Pi q^*\Omega^X} + \frac{\Omega^M}{q^*\Omega^X}\mathbb{E}_t\hat{\Omega}^M_{t+1} \tag{22}$$

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 (22) 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 (16) 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 (14), the saver's budget constraint (15), the definition of dividends (17), the balance-sheet constraint (18), and the resource constraint (20).[42]

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 (16); iv) the deposit spread/deposit rate only appears in the saver's Euler equation for deposits (14) 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.

[42]The law of motion of the habit stock (19) 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

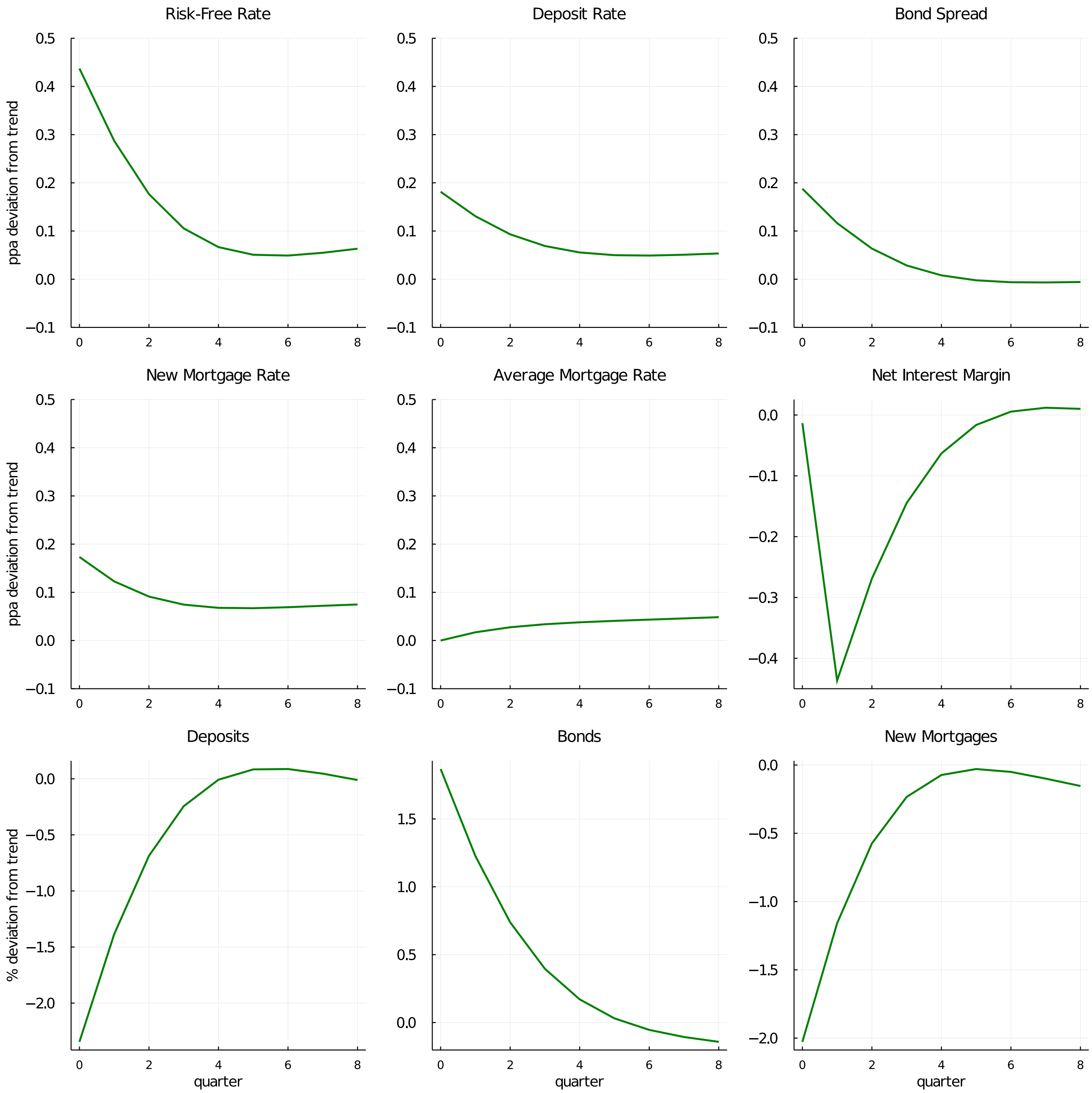

Figure G.1: IRFs to 25 bp Monetary Shock to 1-Year Risk-Free Rate

Bank's Variables

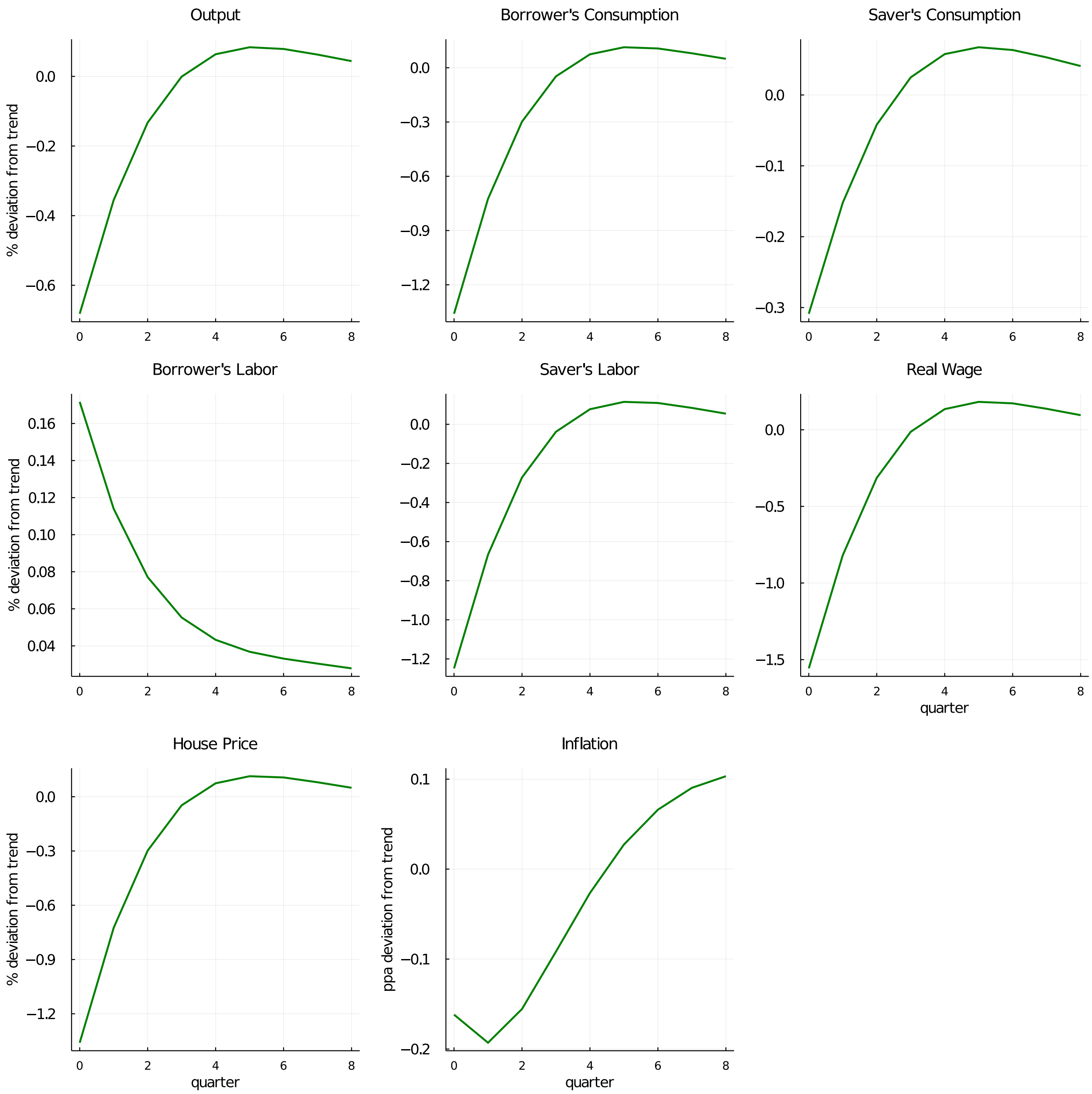

Figure G.2: IRFs to 25 bp Monetary Shock to 1-Year Risk-Free Rate

Real Variables

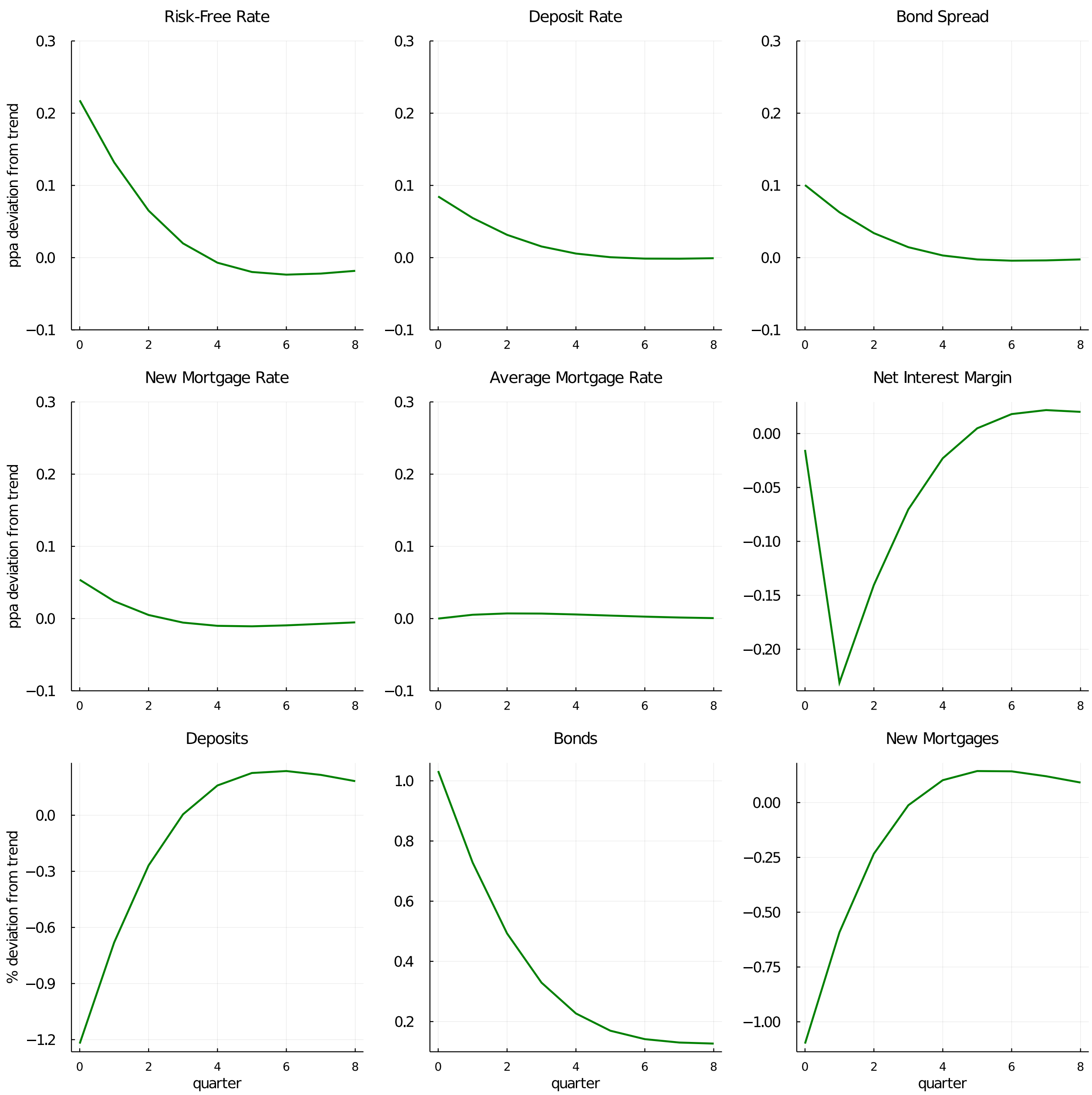

Figure G.3: IRFs to 25 bp Transitory Monetary Shock ϵ^i

Bank's Variables

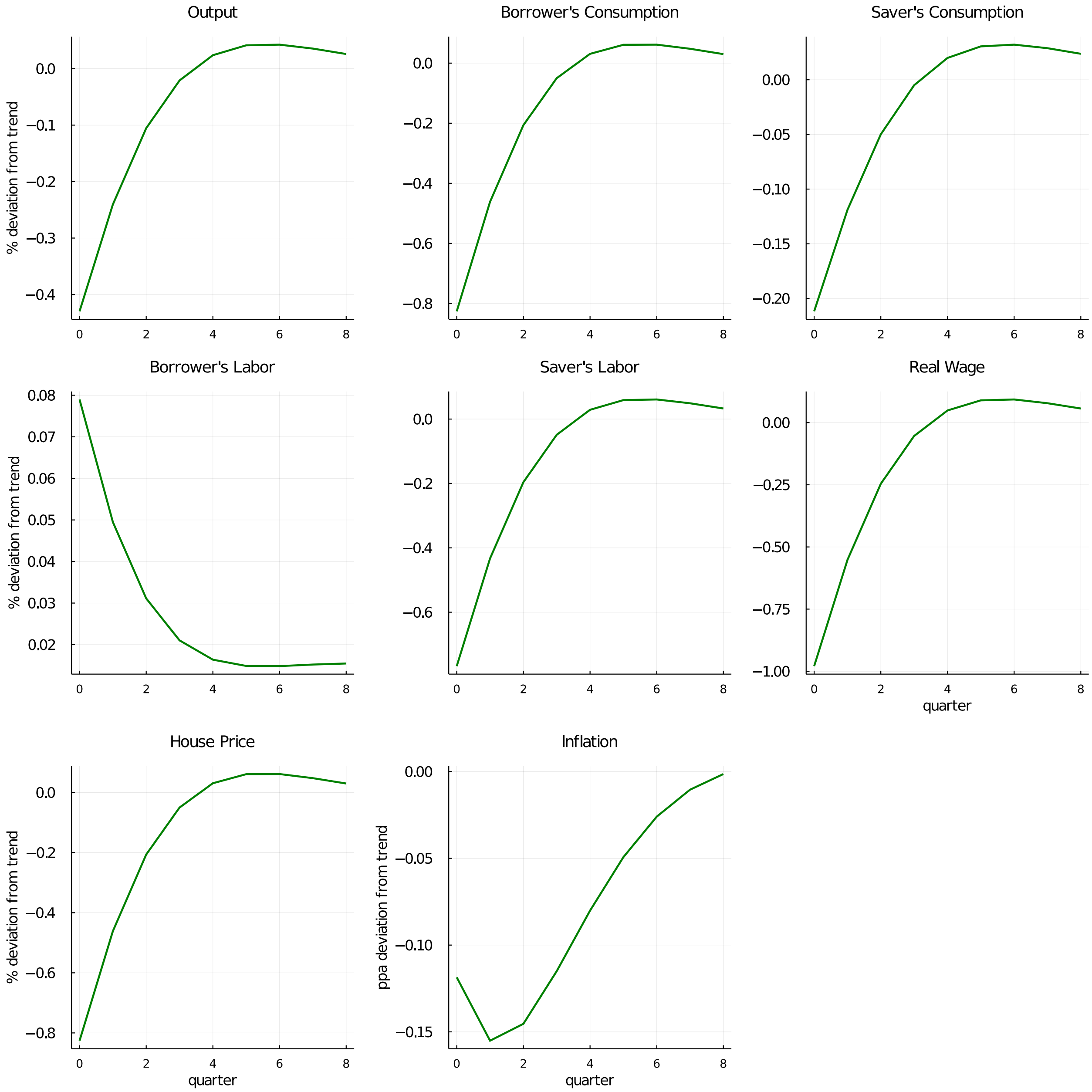

Figure G.4: IRFs to 25 bp Transitory Monetary Shock ϵ^i

Real Variables

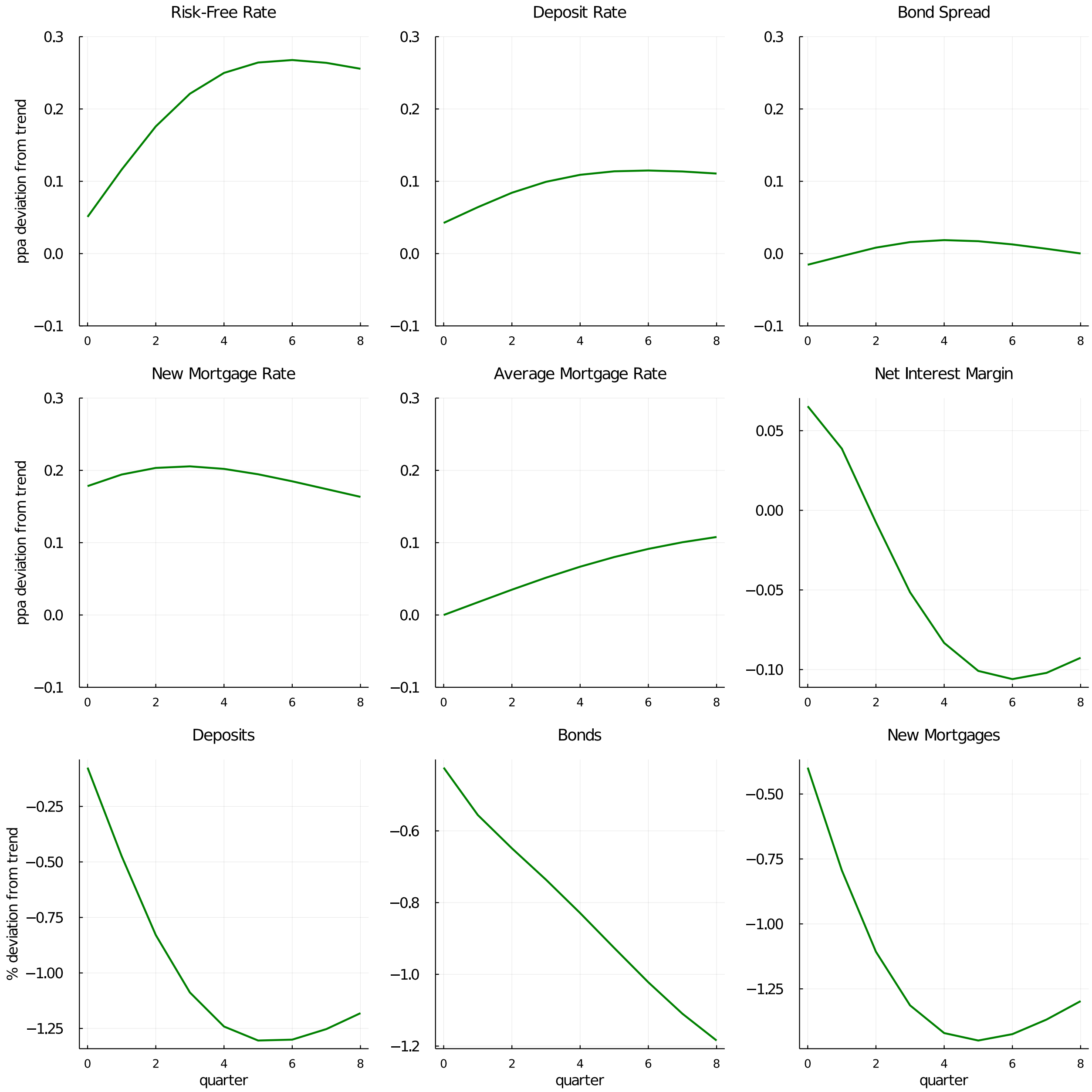

Figure G.5: IRFs to Negative 1% Productivity Shock

Bank's Variables

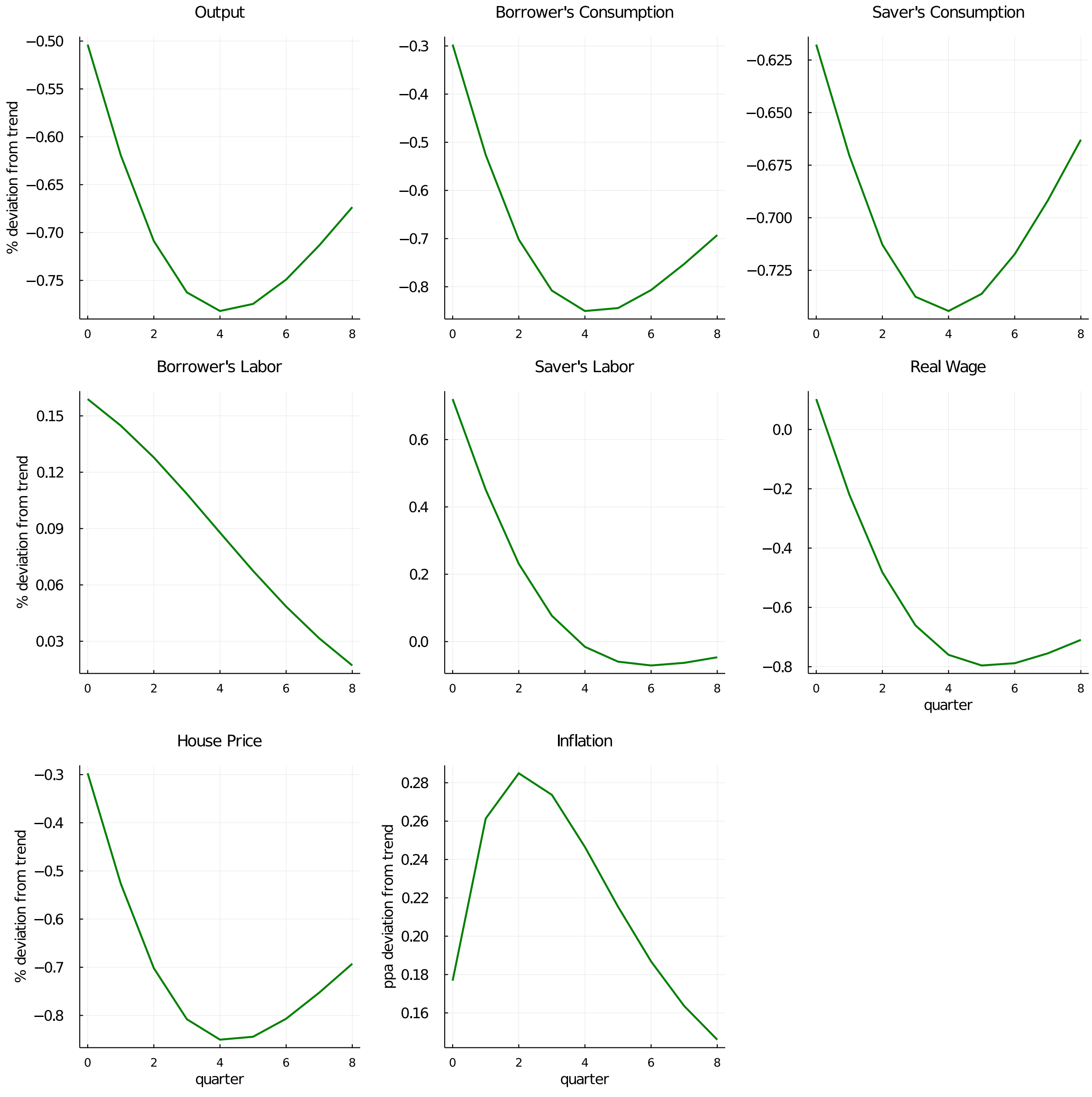

Figure G.6: IRFs to Negative 1% Productivity Shock

Real Variables

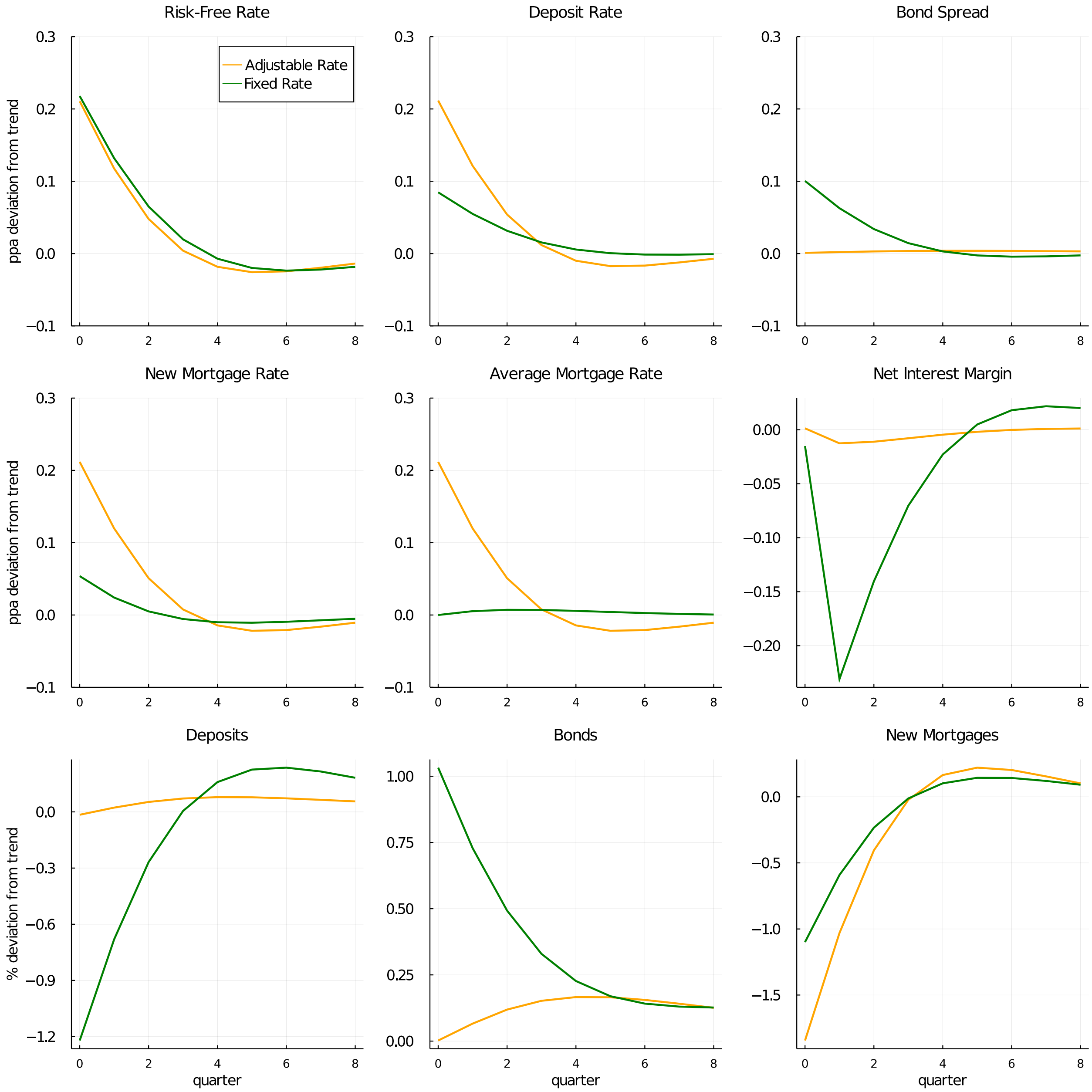

Figure G.7: IRFs to 25 bp Transitory Monetary Shock ϵ^i - Adjustable Rate Mortgages

Bank's Variables

H Complementarity between Consumption and Deposits in Utility

In order to break the assumption that consumption and deposits are separable in the utility function, which may not hold in practice if there is a positive correlation between the level of economic activity and demand for liquidity, I follow Piazzesi et al. (2021) and specify the utility function of the saver as

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

With this different assumption, the marginal utility of consumption of the saver becomes

$$\frac{\partial U^s}{\partial C_t^s} = (1-\psi)\left[(1-\psi)\left(\frac{C_t^s}{\chi^s}\right)^{1-\frac{1}{\gamma}} + \psi\left(\frac{D_t^s}{\chi^s}\right)^{1-\frac{1}{\gamma}}\right]^{\frac{\frac{1}{\gamma}-\frac{1}{\sigma}}{1-\frac{1}{\gamma}}}\left(\frac{C_t^s}{\chi^s}\right)^{-\frac{1}{\gamma}}\frac{1}{\chi^s}$$

thus the quantity of (habit-adjusted) deposits enters the marginal utility of consumption and then the Euler equation for bonds, allowing for real effects of changes in deposit spreads and quantities. If the curvature parameter γ is smaller than the IES σ, then consumption and deposits are complements and an increase in the deposit spread which reduces demand for deposits, will also reduce consumption by savers.

Abstracting from the portfolio-adjustment cost for clarity, Figure H.1 shows impulse response functions to a 25 bp inflation-target shock with complementarity between consumption and deposits[43], and compares it with a version with separable preferences and no habits, i.e. with full pass-through to deposit rates. Figure H.1 shows that real variables behave differently in the model with imperfect pass-through relative to the model with full pass-through. In particular, saver's consumption increases by less, and as a result output increases by less.[44] The increase in the deposit spread leads to a reduction in deposits demanded by the saver relative to the model with full pass-through. Because deposits are complements with consumption in the utility function, the saver increases consumption by less, and as output is partially demand-determined in this New Keynesian setting, output increases by less.

[43]I re-parameterize internally-set parameters to match the targets described in Section 4 with the exception of the TED spread, as the bond spread is constant absent the portfolio-adjustment cost.

[44]The inflation target shock leads to a decrease in the real short-term rate, so consumption of the saver – the Ricardian household – increases.

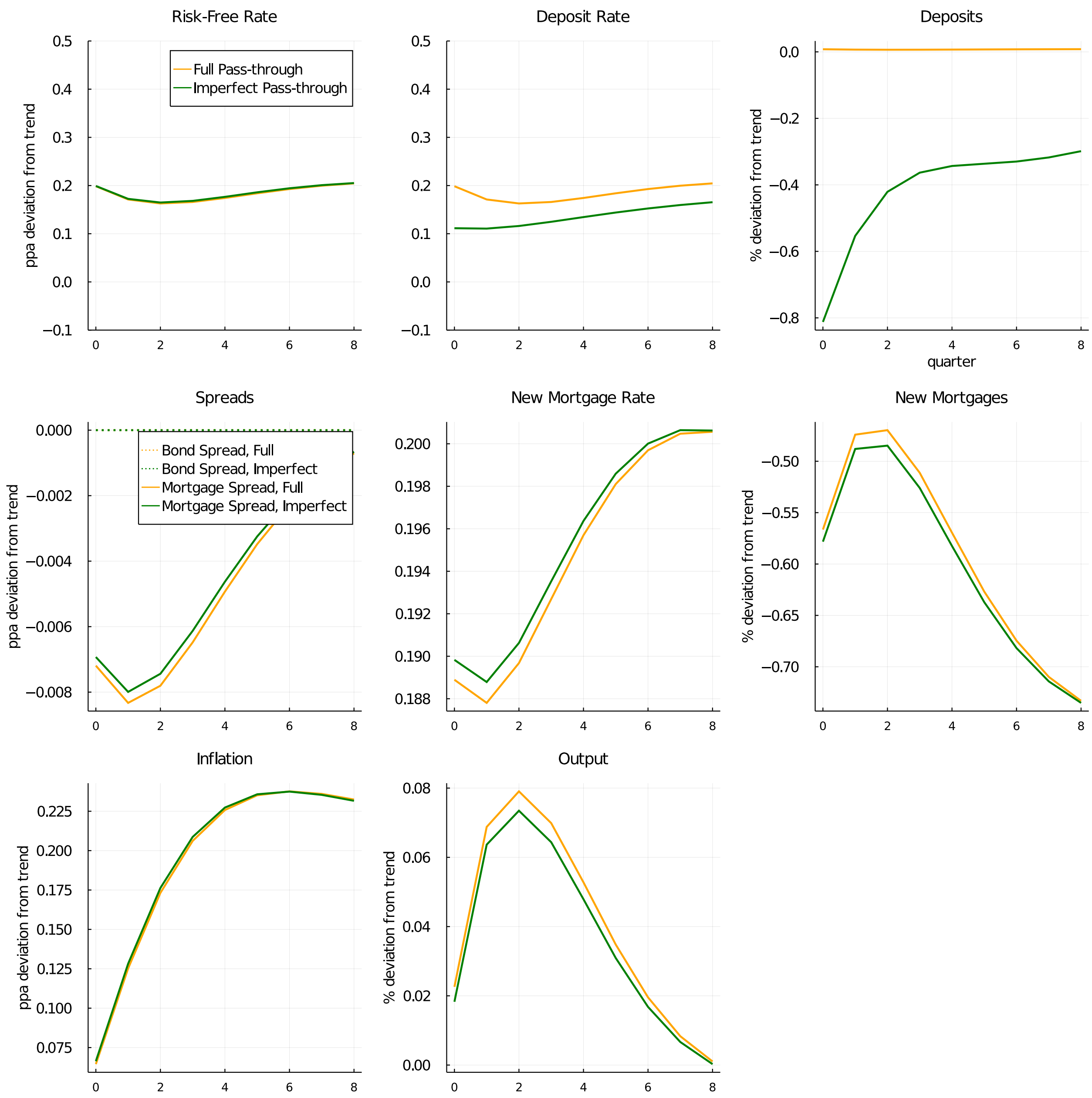

Figure H.1: IRFs to 25 bp Inflation Target Shock - Non-separable Preferences

I 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 J. 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.

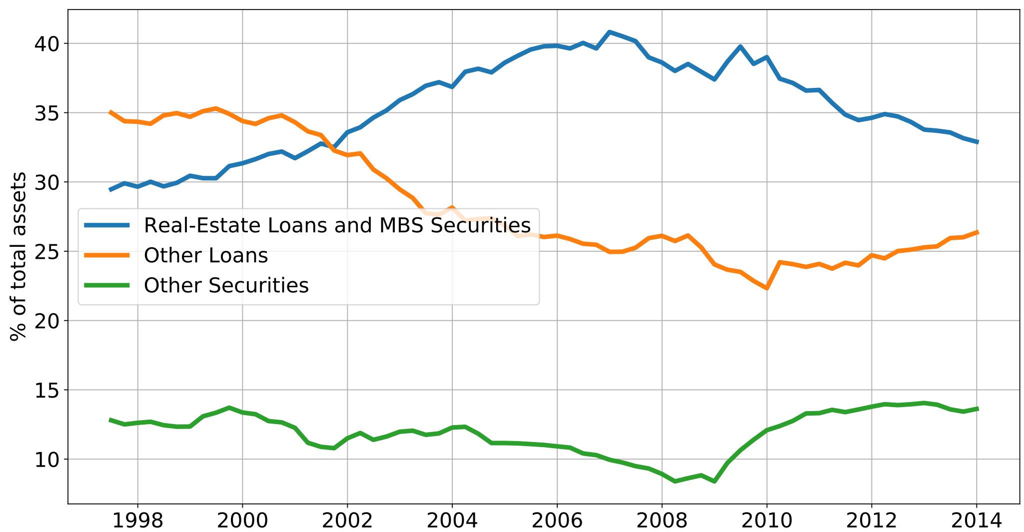

Figure I.1: Shares of Banks' Assets by Asset Class

Figure I.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 I.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 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 I.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 savings

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

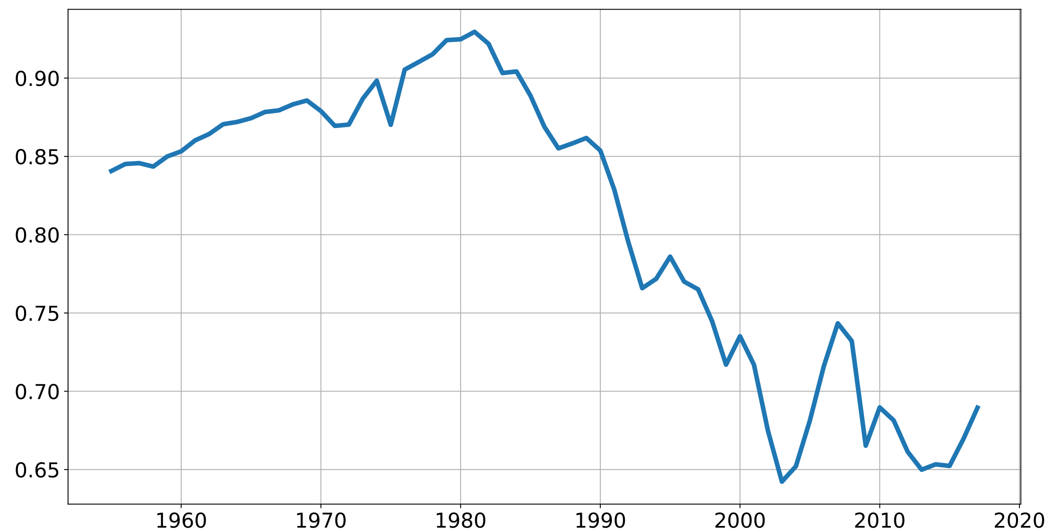

Figure I.2: Banks' Interest Income Share of Total Income

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.

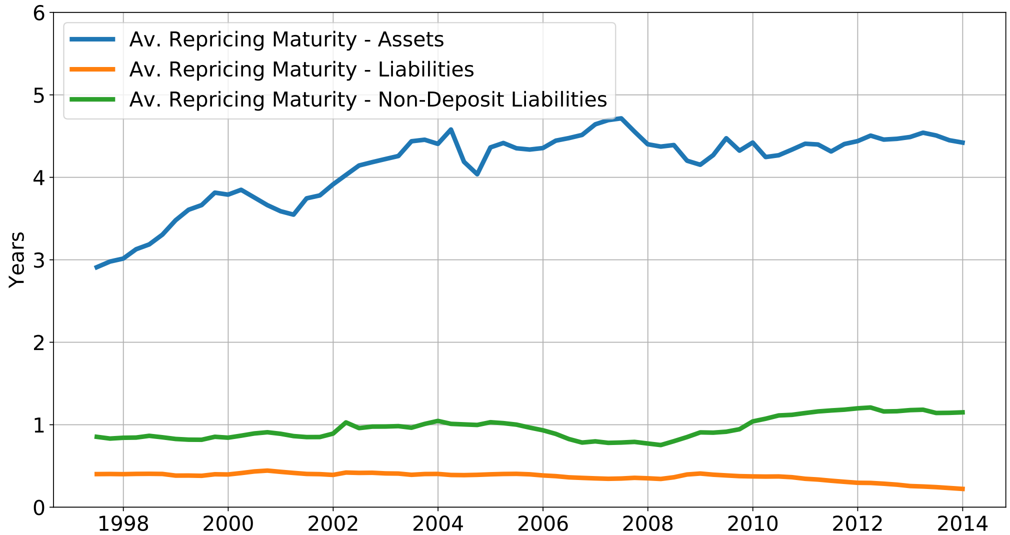

Figure I.3: Repricing Maturity of Banks' Assets and Liabilities

J 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 J.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 J.1: Deposit Demand IV Estimation