The Passthrough of Treasury Supply to Bank Deposit Funding

Wenhao Li, Yiming Ma and Yang Zhao[*]

December 6, 2019

Abstract

We demonstrate the passthrough of Treasury supply to deposit funding through bank market power. We show that an increase in Treasury supply leads to a net deposit outflow. At the same time, reliance on wholesale funding decreases. The effect is heterogeneous in nature - banks in more competitive markets experience larger outflows. The explanatory power of Treasury supply is not driven by monetary policy and bank-specific investment opportunities. Our empirical findings are rationalized with a model of imperfect deposit competition. Consistent with "The Deposits Channel of Monetary Policy" (Drechsler et al., 2017), the model and empirics predict the opposite effect for Fed Fund rate hikes: there is a larger response in less competitive markets. Our results also shed light on the effect of the Reverse Repurchase (RRP) Facility on monetary policy passthrough.

1 Introduction

There has been a growing recent literature exploring the liquidity provision function of banks (Diamond and Dybvig, 1983, Gorton and Pennacchi, 1990). This literature sees banks as transforming illiquid real assets into liquid assets that are valued by the non-financial sector and comprise a stable source of funding for banks. Bank funding capacity, funding structure, and systemic risk are then driven by the liquidity needs of the non-bank sector. Drechsler et al. (2017) have shown how bank market power allows monetary policy to pass through to bank balance sheets through influencing the market price of liquidity. At the same time, government liquid assets, such as Treasury bonds, also satisfy the demand for liquidity and enter the equilibrium determination of the price and quantity of liquidity transformation (Krishnamurthy and Vissing-Jorgensen, 2015, Greenwood et al., 2010).

This paper provides a coherent framework to compare and contrast the impact of government-supplied liquidity on bank liquidity provision with that of monetary policy in the presence of bank market power. While existing work has focused on time series fluctuations (Nagel, 2016, Krishnamurthy and Vissing-Jorgensen, 2015), we explore the cross-section to remove comovements in the aggregate economy. This cross-section variation allows us to identify and quantify how Treasury supply crowds out bank deposit funding but with opposite effects on financial stability and the distribution of bank funding capacity as monetary tightening.

To predict how banks respond to changes in Treasury supply and monetary policy, we develop a simple model in which banks set deposit rates to compete for investors' funding. For investors, Treasuries and deposits are substitutes in providing liquidity so that an increase in Treasury supply leads to a drop in the demand for deposits. The extent to which deposit quantity contracts in equilibrium then depends on the elasticity of the aggregate deposit supply curve. When more banks compete for deposits, the aggregate supply is more elastic, and the same shift in deposit demand shrinks the deposit base by more. The opposite trend emerges when the Fed funds rate rises: deposit funding contracts less when deposit competition is higher. The difference is because the predominant effect of Fed funds rates hikes is in reducing the aggregate supply of deposits. The same shift in deposit supply leads to a smaller decrease in deposit volume when supply elasticity is higher, i.e., deposit competition is more intense. The latter result is in line with Drechsler et al. (2017).

To verify our model predictions in the data, we compare branches of the same bank to remove confounding by macroeconomic conditions that could be co-moving with government-supplied liquidity such as the demand for bank loans. We find that branches in more competitive deposit markets indeed experience larger outflows when government liquid asset

supply increases and smaller outflows when monetary policy rates increase. Therefore, the passthrough of government liquidity supply persists and bears opposite distributional effects when jointly analyzed with changes in monetary policy.

We complement Drechsler et al. (2017), who show that increases in the Fed funds rate reduce bank liquidity provision. Our model also predicts that Fed funds rate hikes reduce bank deposit creation by more in less competitive areas. At the same time, it generates larger deposit outflows in *more* competitive areas when Treasury yields change. These opposite trends arise because banks' asset side returns are predominantly determined by the policy rate and not Treasury yields.[1] Our empirical work thereby confirms Drechsler et al. (2017)'s deposits channel of monetary policy, as well as the different passthrough of Treasury supply to bank funding.

The difference in passthroughs is important for understanding the effect of the Reverse Repo (RRP) Facility, which is an extension of the scope of monetary policy to include non-bank intermediaries, on the banking market equilibrium. Changes in the RRP rate do not have the same impact as changes in the Fed funds rate. We show that the impact of the RRP rate on bank leverage and funding composition is more akin to that of the Treasury yield because non-banks included in the RRP Facility, such as money market mutual funds, invest a significant portion of their assets in Treasury securities. Our model and empirics provide a better guide in this regard.

In addition, the difference in passthroughs is essential for knowing how the level, distribution, and composition of bank leverage changes with government-supplied liquidity and monetary policy and for correctly identifying the types of institutions that lever most in response to changes in liquidity premia. We find that while Fed funds rate hikes spur reliance on wholesale funding and relative growth in wholesale-dependent banks, higher levels of government-supplied liquidity curbs the relative expansion of wholesale funding and wholesale-funding reliant banks. These results also imply that jointly raising the RRP rate with the target Fed funds rate can reduce the buildup of potentially risky wholesale funding associated with traditional monetary tightening using just the Fed funds rate.

The aggregate time series provides preliminary evidence for the crowding out of bank deposits by Treasuries. As Treasury growth increases, total deposit growth falls with wholesale types of funding flowing out by more. Although changes in the monetary policy rate are conditioned on, increases in government-supplied liquidity may not be exogenous so that

---

[1]From 1980 to 2018, US commercial banks on average held less than 4% of total assets in Treasuries and more than 64% in loans (Figure 3). The bank prime loan rate, which is the standard benchmark rate for commercial and residential loans, is determined by the Fed funds rate plus a premium. See Figure 2.

the exact transmission channel is unclear. It could be because deposits and Treasuries are substitutes as we conjectured. But it could also be due to other macroeconomic variables that co-move with Treasury supply and deposit volume. For example, the real interest rate channel maintains that public debt funds public expenditure, which crowds out private investments by firms, shifting banks' supply of deposits through firms' demand for bank loans.

To shed light on the mechanism at play, we develop a simple model of imperfect deposit competition and identify the model predictions using cross-sectional variation. In our model, investors have a demand for liquid assets like deposits and banks supply deposits with imperfect competition. Investors can also invest in a benchmark capital market bond available at the Fed funds rate. The Fed funds - Treasury spread and the Fed-funds - deposit spread can thus be viewed as the opportunity cost of holding Treasuries and deposits, respectively. When Treasury supply increases, the cost of holding Treasuries drops, i.e., the Fed funds - Treasury spread decreases. This shifts the deposit demand inwards because deposits and Treasuries are substitutes in providing liquidity. The equilibrium change in spreads and deposit quantities then depend on the elasticity of the aggregate deposit supply. The elasticity of the aggregate deposit supply increases with deposit competition so that deposits flow out by more in more competitive deposit markets. At the same time, the Fed funds - deposit spread drops by less so that the opportunity cost of holding deposits relative to Treasuries, as captured by the Treasury - deposit spread, increases by more.

In contrast, increases in the Fed funds rate primarily shift the aggregate supply of bank deposits so that higher supply elasticity, i.e., more intense deposit competition, leads to a less pronounced drop in deposit volume and the Fed funds - deposit spread. The shift in deposit supply arises because banks lend to firms at the Fed funds rate plus a margin. When Fed funds rates are higher, banks' profit margin from lending decreases and they reduce their supply of deposits accordingly.[2] This channel is not driving the overall impact of Treasury supply changes because commercial banks invest in many more loans than Treasury securities so that their asset returns are predominantly influenced by changes in the Fed funds rate.[3]

Our model also points to the opposite effect by increases in Treasury supply versus monetary tightening on the banking sector's wholesale funding ratio. Whole-types of investors are more sensitive to deposit rate changes, which leads to a more elastic deposit supply curve for wholesale-types of funding relative to retail deposit categories. Since a more elastic deposit

---

[2]Notice that this effect is not due to a change in firms' demand for loans. Rather, it is through changes in the loans fundable holding constant the firm loan demand.

[3]From 1980 to 2018, US commercial banks on average held less than 4% of total assets in Treasuries and more than 64% in loans (Figure 3). The bank prime loan rate, which is the standard benchmark rate for commercial and residential loans, is determined by the Fed funds rate plus a premium (Figure 2).

supply magnifies the effect of Treasury supply but diminishes that of Fed fund rate hikes, government supplied liquidity curbs the reliance on wholesale funding whereas monetary tightening raises the wholesale funding ratio.

We use within-bank, across-branch variation in deposit volumes and rates to test our model predictions. Looking at branches of the same bank eliminates confounding by time-varying investment opportunities at the bank level, which could co-move with Treasury supply in the time series. The assumption is that funds can be freely transferred within branches of the same banks so that remaining variation observed across branches of the same bank should be due to banks' pricing strategies for the level of local deposit competition. In the baseline specification, we use a standard Herfindahl Index (HHI) as a measure for local deposit competition at the county level. We also control for Fed funds rate changes to clearly distinguish between the effects of monetary policy and Treasury supply.

Our estimation results confirm the model predictions. When Treasury supply increases, banks widen their deposit spreads by more and experience larger outflows at branches located in more competitive areas. Fixing the Fed funds rate, a one standard deviation increase in Treasury growth causes branches in counties at the 25th percentile of HHI to experience a 20.2 bps larger drop in deposit growth compared to branches of the same bank in counties at the 75th percentile of HHI. In aggregate, we find a 64.4 bps drop in deposit growth for a one standard deviation increase in Treasury growth.[4]

The distributional effect of Fed funds rate changes is opposite as that for Treasury growth. A one standard deviation increase in Fed fund rate changes causes branches in counties at the 25th percentile of HHI to experience a 22.4 bps smaller drop in deposit growth compared to branches of the same bank in counties at the 75th percentile of deposit market competition. In comparison, the average time series effect is 151.5 bps for a one standard deviation increase in Fed fund rate changes, implying that for the same one standard deviation increase, the aggregate effect of Treasury growth is about 40% of that for Fed fund rate hikes. Taken together, Treasury supply and monetary policy are both important determinants of the banking market equilibrium but bring about opposite distributional effects for bank deposit funding.

Furthermore, Treasury supply and monetary tightening also affect bank funding structure in opposite ways. When Treasury supply increases, institutional investors' funds flow out more because these investors are more price sensitive. On the other hand, banks increase

---

[4]To obtain the time-series result, we follow Drechsler et al. (2017) to multiply the semi-elasticities of deposits with respect to the deposit spreads by the effect of Treasury supply on deposit spreads.

their reliance on wholesale funding after Fed fund rate hikes. These predictions are confirmed in the data, where a one standard deviation increase in Treasury growth curbs the wholesale funding ratio by 32.8 bps, whereas a one standard deviation increase in Fed funds rate corresponds to a 26.6 bps higher wholesale funding rate.

These differences become especially relevant when considering the effect of the Reverse Repurchase (RRP) Facility, by which the Federal Reserve extended its set of counterparties for conducting monetary policy to include non-bank intermediaries. After September 2013, non-bank intermediaries such as money market mutual funds can directly lend to the Fed via reverse repos at the RRP rate. Given the novelty of the program, an important policy question has been to understand how changes in the RRP rate may affect the banking sector and the economy.

Our model and estimates provide some answers to this question. We show that the effects of the RRP Facility resemble changes in the Treasury yield because a significant portion of non-bank counterparties' balance sheets comprises of government securities. Guided by the model, we apply the pre-RRP crowding-out sensitivities from Treasuries to quantify the impact of this newly introduced monetary policy tool to be a quarter of that of Fed funds rate changes. This implies that raising the RRP rate in tandem with the target Fed funds rate improves passthrough to bank deposit funding growth by about a quarter. The passthrough to bank funding structure is also affected. With the RRP Facility, monetary tightening no longer leads to a buildup of wholesale funding but is accompanied by a higher proportion of stable retail deposit funding in the banking sector. This highlights the financial stability benefits of the RRP Facility in addition to the improvement in the overall passthrough efficiency.

Literature Review

Our paper contributes to a few strands of research. We build on the safe asset literature that has demonstrated an aggregate demand for money-like convenience services by Treasuries (Krishnamurthy and Vissing-Jorgensen, 2012, Greenwood and Vayanos, 2014, Duffee, 1996), and has shown that Treasury supply crowds-out safe and liquid debt issued by the private sector (Krishnamurthy and Vissing-Jorgensen, 2015, Greenwood et al., 2010, 2015, 2016, Carlson et al., 2014, Sunderam, 2014). We provide better identified empirical support for the liquidity provision role of banks. The literature so far has mostly used time-series variation to show a negative correlation between government liquidity and aggregate bank-supplied liquid assets. However, one concern is that macroeconomic shocks, such as recessions, which impact deficits and Treasury supply, may also drive bank funding through

non-liquidity channels, e.g., firms demanding fewer bank loans. We generate predictions for the cross section and verify them using variations across branches of the same bank. This removes the confounding by changing macroeconomic conditions for each bank to identify the passthrough to bank deposits.

Further, while the issuer of private safe debt has so far been thought of as a representative firm or sector, we identify the importance of imperfect competition between providers of safe assets. Specifically, we focus on commercial banks, which hold illiquid long-term assets financed by short-term liquid liabilities. We show that their market power in deposit markets determines the aggregate passthrough of Treasury supply to bank funding. [5] In addition, cross-sectional heterogeneity in local deposit competition also induces significant distributional effects on the cost of deposit funding across regions.

Imperfect deposit competition also informs the discussion on private safe assets and financial stability. Stein (2012) finds that the production of private safe asset can be excessive from a social welfare point of view, while Gorton (2010), Gorton and Metrick (2012), Sunderam (2014), Kacperczyk et al. (2017) illustrate how the demand for safe and liquid assets fueled the expansion of shadow banks. In the wake of the financial stability concerns, (Greenwood et al., 2015, 2016, Carlson et al., 2014) derive optimal responses in the maturity of government debt and the production of safe assets by the Federal Reserve. We show that differences in investor sophistication between deposit categories lead to variation in crowd-out sensitivity. Retail deposits, which are FDIC insured and easily withdrawn, are crowded out less than wholesale types of funding because less attentive retail depositors create more market power for banks.[6] This is an important consideration given the different financial stability implications of wholesale and retail bank deposits.

Our findings imply that in the presence of imperfect deposit competition, Treasury supply is an important factor affecting bank deposit funding in addition to monetary policy, which has been the focus of the existing literature. A number of papers examine frictions in deposit rate adjustments following changes in the policy rate (Berger and Hannan, 1989, Hannan, 1991, Neumark and Sharpe, 1992, Yankov, 2014). More recently, Drechsler et al. (2017) show permanent widening in the Fed funds-deposit spread following Fed fund rate hikes arising

---

[5]Banks have long been thought of as playing an important role in the transformation of illiquid long-term assets into short-term liquid debt demanded by depositors (Diamond and Dybvig, 1983, Gorton and Pennacchi, 1990, Dang et al., 2009). The banking literature has also shown the importance of retail deposits as a stable funding source for banks Kashyap et al. (2002), Hanson et al. (2015).

[6]Among retail deposits, time deposits can only be withdrawn after a set date or with a notice of withdrawal. However, our results also hold for retail savings deposits, which are not subject to the withdrawal constraint.

from imperfect deposit competition. We show, theoretically and empirically, that imperfect deposit competition drives the widening of the Treasury-deposit spread when Treasury yields increase, rendering Treasury supply as an important determinant of bank deposit funding. We build a coherent framework to contrast the passthrough of both Treasury supply and monetary policy and obtain theoretical predictions confirmed by the data and consistent with Drechsler et al. (2017).

Finally, we contribute to the recent and growing literature on the effects of the RRP Facility. While several papers, such as Anbil and Senyuz (2018) and Anderson and Kandrac (2017), have focused on the RRP Facility's effects on financial stability we analyze its impact on monetary policy passthrough, which is the primary goal of its implementation. Our empirical estimation can quantify the add-on effect on passthrough efficiency as mentioned in Duffie and Krishnamurthy (2016) and extends the result to capture distributional effects and funding structure implications.

This paper is organized as followed. Section 2 examines the aggregate time series, while Section 3 develops a model of imperfect deposit competition to rationalize the observed trends and guide the subsequent empirical strategy. Section 4 explains the data sources used in estimating the crowding-out of deposits in Section 5. Section 6 examines the effect of Treasury supply on the ratio of wholesale funding. Section 7 applies the model and empirics to analyze the Reverse Repurchase (RRP) Facility, and Section 8 concludes.

2   Aggregate Trends

We begin by examining the aggregate relationship between Treasury supply and deposit funding. Figure 1a is a binned scatterplot of total deposit growth against Treasury growth from 1964 to 2019.[7] Both variables are residualized against changes in the Fed Funds rate, which is another important determinant of deposit funding Drechsler et al. (2017). The negative relationship depicted in the graph is in line with Treasuries, the public safe asset, crowding out bank deposits funding, a privately issued substitute of the public safe asset. The negative comovement with Treasury growth is even more pronounced for wholesale types of funding. As Figure 1c shows, periods with higher Treasury growth also have lower ratios of wholesale funding in the banking sector.[8]

---

[7]In this paper, we will be using growth rates because variables like Treasury supply and deposit volume display strong persistence over time. To capture the Treasuries available to US private investors, Treasury supply is calculated as the total supply minus foreign holdings and intragovernmental holdings.

[8]Wholesale funding ratio is measured as large time deposits over total deposits. All variables are residualized against changes in the Fed funds rate.

Variations in the spread between Treasuries and deposits shed light on why the negative correlation between Treasury growth and deposit growth is observed. Figure 1b is a binned scatterplot of changes in the spread between Treasury yield and maturity-matched deposit rate with Treasury supply growth, both of which are residualized against the Fed Funds rate. The pattern suggests a larger widening of spreads as Treasury growth picks up, consistent with banks raising deposit rates less than the rise in Treasury yields following increases in Treasury supply. For a given Fed funds rate, the Treasury-deposit spread is an important proxy for the opportunity cost of holding deposits relative to deposits, whereby a larger spread renders deposits more expensive to hold and induces substitution away from deposits into Treasuries. This is consistent with Treasuries crowding out deposits as a substitute good, where the price of Treasuries drops by more than that of deposits, giving rise to a higher opportunity cost of holding deposits.

While the above trends are consistent with the idea of crowding-out between substitutes, there could be other variables co-moving in the time series that bring about similar aggregate observations. For example, standard macroeconomics would suggest that public spending financed by public debt reduces private investment via the real interest rates. That would affect banks' supply of deposits but through the demand for bank loans by firms, which would entail different economic implications.

To shed light on the transmission mechanism, the next section develops a micro-foundation for the crowding-out of deposits by Treasury supply to guide the subsequent empirical identification.

3   Model

We present a simple theory to rationalize the empirical relationship between Treasury supply and bank deposits and derive the effect of bank market power. The model features imperfect deposit competition and investor demand for liquid assets. In Section 7, we further extend the baseline model to understand the effects of the Federal Reserve's new Reverse Repurchase (RRP) Facility.

The model has two types of agents: households demanding deposits and N banks of mass $1/N$ competing to supply deposits.[9] Banks optimize their profits, taking into account the deposit response at different deposit rates. Households optimize over wealth and liquidity

---

[9]We follow Drechsler et al. (2017) to assume that banks are of mass $1/N$. It ensures that the effect of increasing the number of banks does not mechanically operate through the total volume of deposits but the extent of deposit competition.

benefits of holding deposits and Treasurys.

3.1 Demand for Deposits

Households hold deposits from bank $i \in \{1, 2, \cdots, N\}$ at r_i^D and government bonds at r^G to satisfy their demand for liquidity. They also invest in a third benchmark asset, capital market bonds, which do not provide convenience but a return of r set by the central bank monetary policy. The opportunity cost of holding deposits issued by bank i and government bonds can thus be denoted as the Fed-funds - deposit spread, $s_i = r - r_i^D$, and the Fed funds = Treasury spread, $\ell = r - r^G$. Aggregate deposits D and government bonds G are imperfect substitutes in providing liquidity to households with degree of substitutability $\sigma > 1$:

$$L = \left(D^{\frac{\sigma-1}{\sigma}} + \delta G^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}, \tag{1}$$

where δ measures the liquidity of Treasuries relative to deposits. Aggregate deposits D are made up of individual bank deposits[10] that are imperfect substitutes for each other with the elasticity of substitution $\eta > 1$:

$$D = \left(\frac{1}{N} \sum_{i=1}^{N} D_i^{\frac{\eta-1}{\eta}} \right)^{\frac{\eta}{\eta-1}}. \tag{2}$$

Households distribute their deposit holdings across banks to minimize the average cost of of holding deposits, $s = \sum_{i=1}^{N} s_i D_i / N$. Imposing symmetry in equilibrium, we have $s = s_i$, $D = D_i$ and the same demand elasticity[11] for individual banks:

$$-\frac{\partial \log(D_i)}{\partial \log(s_i)} = \frac{N-1}{N}\eta. \tag{3}$$

In aggregate, the representative household maximizes the sum of wealth and liquidity value

$$\max_{x,D,G} \quad W_1 + \log(L) \tag{4}$$

subject to the budget constraint

$$W_1 = W_0(1+r) - D \cdot s - G \cdot \ell + \log(L) \tag{5}$$

---

[10]Formally, D_i and D represent the rate of deposit production. Since the aggregate banking sector has mass 1, the aggregate deposit production rate D is the same as the aggregate deposit quantity.

[11]Refer to Appendix A.1 for derivation details.

Solving the above problem, we get the aggregate demand for deposits and Treasuries:

$$D = \frac{1}{s + \ell^{-(\sigma-1)}(\delta s)^\sigma} \tag{6}$$

$$G = \frac{1}{\ell + s^{-(\sigma-1)}(\ell/\delta)^\sigma} \tag{7}$$

These solutions imply that deposits and Treasuries are substitutes so that a drop in the cost of one reduce the demand of the other. We add one regularity assumption that the effect of changing the own cost of deposits (Treasuries) is greater than that of changing the cost its substitute, i.e, Treasuries (deposits). Mathematically, this is equivalent to $|G_\ell'/G_s'| > 1$ and $|D_s'/D_\ell'| > 1$.[12]

3.2 Supply of Deposits and Bank Market Power

Banks fund with deposits D_i and invest in loans Q_i. On the deposits side, they are subject to individual deposit demand as described in the previous subsection. On the asset side, they face a downward sloping[13] loan demand curve

$$Q(r_i^l) = \bar{Q} - 2\beta r_i^l \tag{8}$$

The bank chooses deposit rates to maximize profits:

$$\max_{r_i^D} \quad (Q^{-1}(D_i) - r_i^D)D_i, \tag{9}$$

where $Q^{-1} = \bar{Q} - D_i/(2\beta)$ is the inverse loan demand curve. Then we express the lending–deposit spread as $Q^{-1}(D_i) - r_i^D = Q^{-1}(D_i) - r + s_i^D$. Solving the individual bank optimization and imposing symmetry, we obtain the aggregate deposit supply function as

$$\hat{D}(s,r) = \frac{\bar{Q}}{2} + \beta \left(\frac{(N-1)\eta - N}{(N-1)\eta} s - r \right). \tag{10}$$

As long as $\eta(N-1)/N > 1$, the aggregate deposit supply increases with the Fed funds–deposit spread s, i.e., the supply curve is upward sloping. Further, the deposit supply contracts when the Fed funds rate r. This is because an increase in r reduces the profit margin of bank lending, which reduces the incentive to raise deposits and lowers the deposit

---

[12]Refer to Appendix A.2 fur further discussions of this regularity assumption.
[13]The use of a downward sloping loan demand curve is in line with the extension model of Drechsler et al. (2017). Our specific formulation was chosen to keep the exposition simple.

supply.

Differentiating $\hat{D}$ with respect to the Fed funds–deposit spread s, we get the slope of the aggregate supply curve as

$$\hat{D}'_s(s, r) = \beta \frac{(N-1)\eta - N}{(N-1)\eta}. \tag{11}$$

We find that $\hat{D}'_s$ increases in both N and η. Therefore, the aggregate deposit supply becomes more elastic when more banks compete or when bank deposits are better substitutes for each other, i.e., when deposit competition becomes more intense. In contrast, when there are fewer competitors or when bank deposits are not close substitutes to each other, banks have more market power and the aggregate supply of deposits is more inelastic. Summarizing deposit market competition with an index $\mathcal{C}$, we can express Equation (11) as

$$\hat{D}'_s(s, r) = \beta \cdot \mathcal{C} \tag{12}$$

where $\mathcal{C}$ is increasing in the number of banks N as well as the degree of substitution between banks η.

3.3 Market Clearing

Having derived the demand and supply of deposits, we can now close the model using market clearing conditions:

$$D(s, \ell) = \hat{D}(s, r), \tag{13}$$

$$G(s, \ell) = G_0, \tag{14}$$

where G_0 is the government's supply of bonds and r is the monetary policy rate determined by the central bank. They determine the equilibrium Fed funds - deposit spread s^*, the Fed funds Treasury spread ℓ^* and the quantity of deposits D^*.

3.4 Impact of Treasury Supply on Deposit Markets

Proposition 1. *The equilibrium deposit quantity decreases with Treasury supply, and the effect becomes more pronounced with deposit competition $\mathcal{C}$, i.e.,*

$$\frac{\partial D^*}{\partial G_0} < 0, \qquad \partial \left(\frac{\partial D^*}{\partial G_0} \right) / \partial \mathcal{C} < 0 \tag{15}$$

The equilibrium Fed funds-deposit spread decreases with Treasury supply, and the effect

11

diminishes with deposit competition $\mathcal{C}$, i.e.,

$$\frac{\partial s^*}{\partial G_0} < 0, \qquad \partial\left(\frac{\partial s^*}{\partial G_0}\right) / \partial\mathcal{C} > 0 \tag{16}$$

The equilibrium Treasury-deposit spread increases with Treasury supply, and the effect becomes more pronounced with deposit competition $\mathcal{C}$, i.e.,

$$\frac{\partial(s^* - \ell^*)}{\partial G_0} > 0, \qquad \partial\left(\frac{\partial(s^* - \ell^*)}{\partial G_0}\right) / \partial\mathcal{C} > 0 \tag{17}$$

For a formal proof, refer to Appendix A.4.

Intuitively, when Treasury supply increases, the cost of holding Treasuries drops, i.e., the Fed funds - Treasury spread decreases. This shifts the deposit demand inwards because deposits and Treasuries are substitutes in providing liquidity. The equilibrium change in spreads and deposit quantities then depends on the elasticity of the aggregate deposit supply. Because the elasticity of the aggregate deposit supply increases with deposit market competition, deposits flow out by more when deposit competition is high, or equivalently, when bank market power is low. At the same time, the Fed funds - deposit spread drops by less so that the opportunity cost of holding deposits relative to Treasuries, as captured by the Treasury - deposit spread, increases by more.

3.5   Impact of Monetary Policy on Deposit Markets

Proposition 2. *The equilibrium deposit quantity decreases with the Federal funds rate, where the effect diminishes with deposit competition $\mathcal{C}$, i.e.,*

$$\frac{\partial D^*}{\partial r} < 0, \qquad \partial\left(\frac{\partial D^*}{\partial r}\right) / \partial\mathcal{C} > 0 \tag{18}$$

The equilibrium Fed funds - deposit spread increases with the Federal funds rate, where the effect diminishes with deposit competition $\mathcal{C}$, i.e.,

$$\frac{\partial s^*}{\partial r} > 0, \qquad \partial\left(\frac{\partial s^*}{\partial r}\right) / \partial\mathcal{C} < 0 \tag{19}$$

The equilibrium Treasury-deposit spread increases with the Federal funds rate, where the

effect diminishes with deposit competition $\mathcal{C}$, i.e.,

$$\frac{\partial(s^* - \ell^*)}{\partial r} > 0, \qquad \partial \left(\frac{\partial(s^* - \ell^*)}{\partial r} \right) / \partial \mathcal{C} < 0 \tag{20}$$

For a formal proof, refer to Appendix A.5.

Notice that the cross-sectional impact of Fed funds rate hikes in Proposition 2 is in the opposite direction as that of Treasury growth in Proposition 1. This is because the primary effect of Fed funds rate arises through an inward shift of the aggregate deposit supply so that higher deposit competition, i.e., a more elastic supply curve, leads to a less pronounced drop in deposit volume. In our model, the inward shift in deposit supply stems from the downward-sloping firm loan demand with respect to loan rates, which is equal to the Fed funds rate plus a premium. When Fed funds rates are higher, the profit margin on loans decreases and banks reduce their supply of deposits accordingly.[14]

This channel is not driving the overall impact of Treasury supply changes in the model, because banks do not invest in Treasuries so that their asset side returns are not affected by changes in the Treasury yield. The assumption that banks do not invest in Treasuries is a reasonable approximation of reality. Typically, loan rates are set at a premium above the prime rate that moves in tandem with monetary policy. Empirically, commercial banks invest in many more loans than Treasury securities so that their asset returns are predominantly influenced by changes in monetary policy.[15] For robustness, we allow banks to hold Treasuries and loans in Appendix A.7 and show that the baseline results are preserved as long as the bank asset-side incentives from Treasury holdings are not dominant.

Our time-series and cross-sectional results for Fed fund rate hikes verify the findings by Drechsler et al. (2017), who also attribute the effects arising from the supply side of deposits. While Drechsler et al. (2017) microfound the effect through a change in the relative price and substitutability of cash with deposits, we do not introduce cash as an additional asset and solely rely on a downward sloping loan demand curve, which is also present in the extension model by Drechsler et al. (2017).

---

[14]Notice that this effect is not due to a change in firms' demand for loans. Instead, it is through changes in loan profit margins holding firm loan demand constant.

[15]From 1980 to 2018, US commercial banks on average held less than 4% of total assets in Treasuries and more than 64% in loans (Figure 3). The bank prime loan rate, which is the standard benchmark rate for commercial and residential loans, is determined by the Fed funds rate plus a premium (Figure 2).

3.6 Wholesales Funding and Investor Sophistication

So far, we have assumed a homogeneous investor base, whereas in reality, investors may differ in their levels of sophistication. For example, retail investors may be sleepy in response to changing deposit rates or have a higher cost of switching from one bank to the other. Effectively, they are less able or willing to substitute between banks and suffer a lower elasticity of substitution across different bank deposits. In contrast, sophisticated wholesale investors are more attentive to changes in deposit rates and more readily substitute between banks, depending on who offers a higher rate.

To incorporate investor heterogeneity into our model, we let the elasticity of substitution of wholesale and retail investors be η_W and η_R respectively, where $\eta_R < \eta_W$. If wholesale deposits comprise fraction α_W of bank balance sheets, then we can show that the elasticity of banks' individual deposit demand is

$$\frac{N-1}{N}\left(\alpha_W \eta_W + (1 - \alpha_W)\eta_R\right), \tag{21}$$

which implies that a larger fraction of wholesales deposits α_W increases the individual deposit demand elasticity as well as deposit market competition $\mathcal{C}$. This gives rise to the following proposition:

Proposition 3. *When the fraction of wholesale funding increases, the equilibrium deposit quantity decreases by more with Treasury supply, i.e.,*

$$\partial\left(\frac{\partial D^*}{\partial G_0}\right)/\partial \alpha_W < 0 \tag{22}$$

When the fraction of wholesale funding increases, the equilibrium deposit quantity decreases by less with the Fed funds rate, i.e.,

$$\partial\left(\frac{\partial D^*}{\partial r}\right)/\partial \alpha_W > 0 \tag{23}$$

For a formal proof, refer to Appendix A.6.

In other words, when deposit contraction is achieved by Treasury supply increases, more wholesale-types of funding flow out more, which decreases the banking sector's reliance on wholesale funding. In contrast, monetary tightening increases the ratio of wholesale funding because wholesale-types of funding flow out by less. This shows that the difference

in passthroughs of Treasury supply and monetary policy also bears important implications for financial stability.

4   Data

Before detailing the estimation strategy, we explain the data sources and the construction of the main variables.

4.1   Data Sources

Bank balance sheet data is from US Call Reports provided by the Federal Reserve Bank of Chicago. Our sample is from January 1994 to December 2016. The data contains quarterly data on the income statements and balance sheets of all US commercial banks. We match bank-level Call Reports to branch-level RateWatch and FDIC data using the FDIC bank identifier.

Data on deposit volumes is from the Federal Deposit Insurance Corporation (FDIC). It covers the universe of US bank branches at an annual frequency from June 1994 to June 2016. Information about branch characteristics such as the parent bank, address, and geographic coordinates are also available.

Data on deposit rates is from RateWatch. RateWatch collects weekly branch-level deposit rates by product from January 1997 to December 2016. Our analysis focuses on the most common deposit categories, including the 2.5K savings accounts, the 25K money market accounts, and 10K CDs with three-month, six-month and one-year maturities.

Fed funds target rates and Treasury yields are from Federal Reserve Economic Data (FRED). We compute the average of the upper and lower Fed funds target rates after 2008. Treasury volumes are from the TreasuryDirect website.

County data. We collect data on county characteristics from the 2000 US Census and County Business Patterns. Relevant demographic variables include median age, median income, and the proportion of college graduates.

4.2   Definition of Key Variables

In the baseline specifications, our proxy for local deposit market competition is the standard Herfindahl index (HHI), which corresponds to the number of banks in our (symmetric) model. Because investor sophistication is another driver of deposit competition, we further explore the effect of demographic characteristics related to investor sophistication in an extension

exercise. We also examine the interaction with wholesale funding in Section 6.

Branch HHI: We assign to each bank branch the HHI of the county in which it is located and refer to it as the branch HHI. County-level HHI is calculated by summing the squared deposit market shares of all banks that operate branches in a given county in a given year and then taking the average of that amount over all years (1994-2016). Figure 4a shows that it stays relatively constant over our sample period.

Bank HHI: Bank HHI is calculated by first taking the weighted average of the bank's branch-level HHI in each year and then collapsing it by bank. Figure 4b shows the distribution of bank HHI, which is centered at around 0.2 and has almost all of its weight below 0.6.

Deposit growth: The log difference of bank or branch deposit volume in a year. We are limited to using annual deposit growth rates at the branch level because FDIC deposit volumes are only reported annually. For Call Report data, the annual deposit growth rate is calculated quarterly.[16]

Deposit spread: Deposit spread is calculated as either the Treasury yield benchmark less the deposit rate or the Fed funds rate less the deposit rate. We choose Treasury yields with maturities corresponding to each deposit category.[17]

Treasury growth: The log difference of Treasury volume outstanding in a year. To capture Treasuries available to the the US private sector, we exclude foreign official holdings, intra-governmental holdings, and Federal Reserve holdings. We treat Treasuries as homogeneous in the baseline specifications but allow for more granular breakdowns as a robustness check.

5   Empirical Estimation

This section tests our model empirically. We first explain our identification strategy, which uses variations in deposit spread and deposit volume across branches of the same bank, and then present the estimation results.

5.1   Estimation Strategy

Because the time series suffer from potential confounding as discussed in section 2, we turn to verify our model predictions in the cross-section.

---

[16]Consistent with Drechsler et al. (2017), we use deposit growth to remove persistence in deposit levels.

[17]Consistent with Drechsler et al. (2017), we use changes in deposit spreads to remove persistence in rates.

We begin by looking at how branches subjected to different levels of deposit competition respond to changes in Treasury supply. Figure 5 plots the average sensitivity of deposit growth towards changes in Treasury growth for branches located in different counties, where counties are divided into 20 bins by their level of deposit competition. The average sensitivity, γ_h, of branches in bin h is obtained from:

$$DepGrowth_{it} = \alpha_i + \gamma_h \mathbf{1}\{bin_h\} * TSYGrowth_t + \theta_t + \epsilon_{it}, \tag{24}$$

where the dependent variable is the deposit growth of branch i at time t.

Consistent with the theory, Figure 5 shows that branches in more competitive areas, i.e., lower HHI percentile, on average experience a larger dip in deposit growth following periods with higher Treasury growth than those in less competitive areas, i.e., higher HHI percentile.

Also in line with the theory, branches in more competitive areas widen deposit spreads by more than branches in less competitive areas as competition intensifies (Figure 6). Sensitivities for time deposit and savings deposit spreads are obtained similarly as before:

$$\Delta DepSpread_{it} = \alpha_i + \gamma_h \mathbf{1}\{bin_h\} * TSYGrowth_t + \theta_t + \epsilon_{it} \tag{25}$$

The above specifications include a time fixed effect to control for changes in deposit rates and volumes due to other reasons, such as banks' investment opportunities and monetary policy. However, these variables may not affect all banks in the same way, which is especially worrying if the impact correlates with the level of deposit competition. To this end, we further focus on within-bank variation by only comparing branches of the same bank.

We illustrate our identification strategy with a simple example. Figure 7 plots the deposit spread of the three-month CD for two different branches of Huntington Bank from October 2004 to April 2005. We observe that as Treasury growth increases by 3.24% from 2004Q4 to 2005Q1, the deposit spread in the more competitive county, Macomb, MI, increases more than that in the less competitive county, Hamilton, OH. We attribute the divergence in deposit spreads across branches to the level of local deposit competition because changes in the macroeconomic environment should affect the investment opportunities of Huntington Bank as a whole. The implicit assumption here is that deposits are fungible across bank branches, i.e., Huntington bank can raise a dollar of deposits at one branch and lend it at another branch until the marginal returns of lending across its branches are equalized. This assumption is empirically supported by Drechsler et al. (2017), who show that a bank's lending in a given county is not related to local deposit-market concentration. It is corroborated

by the banking literature, which shows that banks channel deposits to areas with high loan demand (Gilje et al., 2016).

To implement the estimation, we include bank-time fixed effects, δ_{jt}, and state-time fixed effects, λ_{st}, in the following specifications:

$$DepGrowth_{it} = \alpha_i + \eta_c + \lambda_{st} + \delta_{jt} + \beta_1 TSYGrowth_t * HHI_c + \beta_2 \Delta FFR * HHI_c + \epsilon_{it} \quad (26)$$

$$\Delta DepSpread_{it} = \alpha_i + \eta_c + \lambda_{st} + \delta_{jt} + \beta_1 TSYGrowth_t * HHI_c + \beta_2 \Delta FFR * HHI_c + \epsilon_{it} \quad (27)$$

Bank-time fixed effects control for time-varying loan demand at the bank level while state-time fixed effects further limit the comparison to branches in the same state to rule out confounding by state-specific regulation and geopolitical differences. The remaining branch-level variation should then identify different sensitivities to Treasury supply and monetary policy arising from the level of local deposit competition. These are captured by β_1 and β_2, respectively.

5.2   Baseline Results

We proceed to estimate the differential effect of Treasury supply and monetary policy across branches of the same bank to control for changes in bank-specific lending opportunities that co-move in the time series.

Results for deposit volume from Equation (1) are reported in the first two columns of Table 1. Column 1 demonstrates that when comparing branches of the same bank in the same state, Treasury growth causes the crowding-out of deposit growth to a larger extent in more competitive regions, i.e., counties with a lower HHI index. The statistical and economic significance of this result remains after taking changes in the Fed funds rate into account, as indicated in column 2. In column 2, also notice that the coefficient for changes in the Fed funds rate is positively significant, meaning that in contrast to the effect of Treasury growth, Fed funds rate hikes have the largest impact on deposit growth in the least competitive areas, which agrees with our model predictions and the results in Drechsler et al. (2017).

The magnitude of coefficients reveals a strong distributional effect of Treasury growth and Fed funds rate hikes. For a one standard deviation increase in Treasury growth, a branch located in a county at the 25th percentile of HHI, which is 0.18, experiences a 20.2 bps larger drop in deposit growth relative to a branch of the same bank located in a county at the 75th percentile, which is 0.39. As we will show, this makes up almost a fifth of the average time series crowding-out effect, demonstrating that regions experience significantly different

18

degrees of deposit outflow depending on their level of deposit competition. In contrast, a one standard deviation increase in Fed funds rate changes causes a 22.4 bps smaller drop in deposit growth for branches of the same bank in counties at the 25th percentile of HHI relative to those in counties at the 75th percentile of HHI.

Within-bank estimation controls for time-varying bank-specific investment opportunities but limits the sample to banks with two or more branches, which decreases the sample size by about 10%. Nevertheless, columns (3) and (4) of Table 1 show that the qualitative results in the full sample of bank branches agree with those for the subsample.

Tables 2 and 4 present within-bank estimates for various Treasury-deposit spreads and Fed funds-deposit spreads. As expected from the results on deposit volume, Treasury-deposit spreads widen more in competitive areas as Treasury growth increases; whereas Fed funds-deposit spreads widen more in concentrated areas. These contrasting distributional effects of Treasury supply and monetary policy rate hikes are graphically depicted in Figures 8a and 8b. The upper panel groups counties by their decline in deposit growth for a one standard deviation increase in Treasury growth. while the lower panel shows the corresponding result for Fed funds rate hikes. Counties with darker shades experience more pronounced deposit outflows, which occurs in more competitive deposit markets for Treasury growth and less competitive areas for monetary rate hikes. Extending the analysis to the full sample does not alter the significance of the results as seen in Tables 3 and 5.

For the overall effects of Treasury growth, we follow Drechsler et al. (2017) by first calculating the cross-elasticities and then multiplying them by the average time series effect for Treasury-deposit spreads and Fed funds-deposit spreads. Weighing deposit spreads by the volume of time and savings deposits, we obtain a cross-elasticity of -9.23 with respect to Treasury-deposit spread increases. On average, the Treasury-deposit spread widens by 0.61 bps for a 100 bps increase in Treasury growth, which implies that a one standard deviation increase in Treasury growth corresponds to a 64.36 bps drop in deposit growth. Using the same approach, a one standard deviation increase in Fed funds rate hikes leads to a 151.52 bps drop in deposit growth. Juxtaposing the two channels, the aggregate effect of Treasury growth on bank deposits is substantial at about 40% of that for monetary policy rate hikes.

5.3 Local Clientele and Market Power

So far, we have used the HHI as a measure for imperfect deposit competition. Nevertheless, counties may differ in other ways that influence the market power of banks to determine the impact of Treasury supply. In particular, the level of sophistication among the local clientele

could affect how attentive they are to changes in deposit rates and hence banks' market power. County fixed effects can take care of the time-invariant components, but there may still be an interaction effect with changes in Treasury supply.

We repeat the analysis controlling for characteristics of the local clientele that can proxy for investor sophistication. We use county-level measures from the 2000 US Census and County Business Patterns data, including the proportion of residents above 65 years old, median income level and percentage of the population with a college degree. Table 6 shows that the effect of imperfect competition as measured by HHI remains after including the full set of local clientele interaction effects. The coefficients on the county characteristics are also significant, and provide an additional dimension to understanding the effective market power of banks.

5.4   Maturity Structure of Treasuries

Another concern is that the maturity of Treasuries matters in determining the crowding-out of deposits, whereas we have been treating Treasury supply as homogeneous. Greenwood et al. (2010), for example, only consider short-term private safe debt and public safe debt as substitutes.

To incorporate differences in substitutability, we use haircuts on Treasury collateral in repo transactions to weigh Treasuries of different maturities. Examining haircut data from the New York Fed's website, we find that haircuts remain rather stable over time. Because this time series dataset only goes back to 2010, we follow the estimates in Krishnamurthy and Vissing-Jorgensen (2012) that bills and non-bills have a haircut of 2% and 5%, respectively. This yields a haircut-weighted Treasury supply series, which is used to obtain the results in Table 7. The estimates remain qualitatively unchanged and statistically significant.

5.5   Treasuries as Collateral

Another issue is that changes in Treasury supply not only affect banks through the returns on the Treasury portion of their assets but also via the availability of collateral for repo financing. To alleviate this concern, we purge the sample of banks that rely heavily on repo financing and repeat the analysis. Table 8 shows results excluding banks above the third quartile of repo financing as a fraction of their balance sheet size. The baseline results continue to hold.

6   Effects on Bank Funding Structure

The recent financial crisis has illustrated how reliance on short-term wholesale funding increases banks' funding liquidity risks. A number of new regulations like the Liquidity Coverage Ratio (LCR) and the Net Stable Funding Ratio (NSFR) were introduced to curb the use of runnable funding by financial institutions. We find that government-supplied liquidity influences the type of funding banks are able to raise and thus becomes a determinant of the composition of bank leverage and the concentration of funding risk.

Our model implies that the sensitivity of deposit outflows with respect to Treasury supply depends on the sophistication of the depositor base. Table 9 offers evidence for heterogeneous crowd-out sensitivities. Core deposits, including checking, savings, and small-time deposits, are mainly servicing retail depositors and display the lowest sensitivity towards changes in Treasury growth.[18] Wholesale funding, which is mostly provided by institutional investors, is about four times more responsive to Treasury growth than core deposits. This relationship is graphically reflected in Figure 9a, which shows that the crowding-out effect by Treasuries on wholesale types of funding is stronger than that for core deposits as long as the HHI is below 0.6. This is the case for over 99% of banks, as evident from the distribution of bank-level HHI in Figure 4b.

In contrast, Table 9 and Figure 9b reveal the opposite effect for monetary policy: hikes in the Fed funds rate crowd out core deposits by more than wholesale funding.

The variation in crowd-out sensitivities implies that higher levels of government-supplied liquidity steer the ratio of wholesale funding in the opposite direction of monetary policy rate hikes. Because institutional deposit account types are more affected by Treasury growth, whereas core deposit growth takes the largest hit from monetary policy rate hikes, the ratio of wholesale funding on banks' balance sheets decreases with Treasury growth and increases with larger Fed fund rate hikes. Table 10 illustrates this effect. Quantitatively, changes in the wholesale funding ratio dip by 32.8 bps following a one standard deviation increase in Treasury growth, but increase by 26.6 bps after a one standard deviation increase in Fed funds rate hikes.

Heterogeneous crowd-out sensitivities also bring about distributional effects for banks adopting different funding structures. Higher policy rates would disproportionately cut growth in retail deposit-reliant banks, which are mostly focused on lending to small- and

---

[18]Deposit volumes for different deposit types are only available at the bank level, which is why results in this subsection can only be computed at the bank level. We calculate the effective HHI for a bank as the weighted average of its branch-level HHIs.

medium-sized firms and households, while spurring relative growth in large banks reliant on wholesale funding. Higher Treasury supply, however, would cut growth the most at these wholesale-reliant institutions, but have a smaller effect on banks reliant on core deposits. To see this effect empirically, we divide banks into five groups according to their ratio of wholesale funding and interact the group dummies with Treasury growth and Fed funds rate changes. The coefficients are graphically illustrated in Figures 10a and 10b. The left axis plots the mean wholesale funding ratios while the right axis displays the crowding-out coefficients. As expected, Treasury growth leads to a larger drop in banks' funding growth as their reliance on wholesale funding increases, whereas Fed funds rate hikes have the opposite effect.

The above findings are especially important in light of the view that monetary tightening by central banks to contain credit booms also leads banks to increase their reliance on wholesale funding and concentrate growth in wholesale-reliant banks, which is precisely what post-crisis liquidity regulations intended to curtail. We show that an expansion government-supplied liquidity would achieve tightening in the same sense of an overall deposit outflow while reducing the reliance on wholesale funding and discouraging the growth of wholesale-reliant banks. These factors should be taken into consideration when designing new monetary policy tools, one of which is the Reverse Repurchase Facility.

7   Application to the Reverse Repurchase Facility

This section extends and applies estimates from the baseline model to uncover the effect of the RRP Facility. The RRP Facility was an unprecedented extension of the scope of the monetary policy in the US. It expanded the Federal Reserve's set of counterparties beyond depository institutions and primary dealers also to include money market mutual funds, allowing them to directly lend to the Fed through reverse repo transactions.

The goal of the RRP Facility is to improve monetary policy passthrough but direct analysis of its effectiveness has been limited. One challenge is that the announcement and implementation happened in multiple stages so that individual event studies cannot quantify the effect. Further, there is a limited sample for study since the RRP Facility was only introduced in September 2013 and various other regulatory changes occurred shortly afterwards, e.g., the Liquidity Coverage Ratio (LCR) and the Supplementary Leverage Ratio (SLR) were both implemented in 2014.

Our framework allows for an indirect assessment, which uses the estimated crowding-out coefficient from changes in government-supplied liquidity to proxy for the effect of the RRP

Facility. To guide our analysis, we introduce the RRP Facility in our baseline model of deposit competition. An introduction of the RRP Facility would allow investors to invest at the RRP rate r_{RRP} set by the central bank with no limit on supply through money market mutual funds. Money market mutual funds can hold on to their Treasuries or lend them to the Fed, depending on which offers a higher rate of return.

Denoting the IOER - RRP spread as $\ell_{RRP} = r - r_{RRP}$, the household deposit demand becomes

$$D(s, \min\{\ell, \ell_{RRP}\}), \tag{28}$$

as long as investors are indifferent between the MMMF investing in Treasuries or reverse repos with the Federal Reserve. When the RRP Facility offers a rate below the market-clearing rate for Treasuries without the RRP Facility, there is no demand for the facility, and the original deposit demand function applies. If the RRP offered rate is above the Treasury yield, the market clearing of Treasuries will adjust Treasury yields endogenously so that in equilibrium, $\ell^* = \ell_{RRP} = \ell_0$, where ℓ_0 solves the original equilibrium system in (13) and (14). In this case, the deposit market clearing will be

$$D(s, \ell_{RRP}) = \hat{D}(s, r) \tag{29}$$

which is the same as before implementing the RRP facility. In practice, the RRP rate offered exceeds the one-month Treasury yield most of the time (see Figure 11).[19] In other words, all comparative statics of deposits with respect to Treasuries before the implementation of the RRP can proxy for the impact of changes in the RRP rate on bank deposit funding.

Guided by the model prediction, we can now analyze the effect of the RRP Facility on monetary policy passthrough to bank deposit funding by repeating our empirical specifications with a sample ending in 2013Q3 and with Treasury yield as policy variable instead of Treasury supply. As before, we first obtain cross-elasticities for deposit growth with respect to Treasury-deposit spread and Fed funds-deposit spread increases as in the baseline (Table 11). On average, for a 100 bps increase in the Treasury yield, the Treasury deposit spread rises by 57 bps when the Fed funds rate is held constant. Then, a 100 bps increase in the Treasury yield lowers bank deposit growth by 128 bps. The same calculation yields a 425 bps drop in deposit growth for a 100 bps increase in the Fed funds rate. This implies that for a given monetary policy rate change, having the RRP Facility rate move in tandem with the target Fed funds rate improves the passthrough to bank deposit growth by about a quarter.

---

[19]This is already a conservative measure because the RRP Facility is overnight and the one-month Treasury yield is higher than Treasury yields of shorter maturities because of term premia.

The RRP Facility not only improves the overall passthrough efficiency of monetary policy but also impacts the passthrough to bank funding structure. As Section 6 has shown, standard rate hikes lead to an increased reliance on bank wholesale funding because core deposits are crowded out more. Hikes in the RRP rate, however, resemble increases in Treasury supply and yields so that deploying the RRP Facility can reduce and revert the potentially risky buildup in wholesale funding arising with monetary policy tightening.

8   Conclusion

This paper identified the passthrough of government liquidity provision to bank liquidity provision through imperfect deposit competition. It complements The Deposits Channel of Monetary Policy (Drechsler et al., 2017) to establish Treasury supply and monetary policy as important yet different determinants of the volume and structure of bank funding.

To establish causation, we remove confounding by bank-level investment opportunities by showing that for the same bank, branches in more competitive regions experience more pronounced deposit outflows in response to Treasury growth, while branches in more concentrated regions suffer the largest drop in deposit growth after Fed funds rate hikes. We also demonstrate an impact on the structure of bank liabilities, which matters for financial stability and systemic risk. Institutional investors are more sensitive to changes in Treasury issuance, and the ratio of wholesale funding drops when Treasury supply increases. With monetary tightening, however, the ratio of wholesale funding increases.

We provide a theoretical framework to microfound our empirical analysis in which banks supply deposits with imperfect competition and investors demand liquidity services provided by deposits and Treasuries. The model generates predictions in line with the empirical estimates and rationalizes the contrasting effects of Fed funds rate hikes and Treasury growth as a result of commercial bank balance sheets being primarily invested in loans rather than Treasuries.

We applied our model and empirical estimates to infer the effect of extending the access of monetary policy through the RRP Facility. We showed that the effect of the RRP Facility is akin to changes in the Treasury yield, used the pre-RRP sensitivity estimates to quantify its effect, and found it to be around a quarter of that of conventional monetary policy. This indirect inference approach can avoid direct estimation based on a short sample period with numerous regulatory changes. Nevertheless, the flexibility of a reduced form model is still limited. A more structural approach would allow for more in-depth analysis and a richer set of counterfactuals. This paper has focused on frictions in deposit markets because depositors,

especially retail depositors, have limited sophistication and geographic mobility, rendering imperfect competition a salient feature. Borrowers, e.g., firms, tend to be more efficient at screening loan rates than depositors. However, in some markets, imperfect competition for loans is also nontrivial, e.g., small business lending and residential mortgages. Future work can consider exploring imperfect competition on both the asset and liability side to understand the interplay and its implications for passthrough. Dynamic models could also explore how banks choose their competitive environment and how that choice interacts with fiscal and monetary policy in equilibrium.

References

Sriya Anbil and Zeynep Senyuz. The regulatory and monetary policy nexus in the repo market. *FEDS Working Paper*, 2018.

Alyssa G Anderson and John Kandrac. Monetary policy implementation and financial vulnerability: Evidence from the overnight reverse repurchase facility. *The Review of Financial Studies*, 31(9):3643–3686, 2017.

Allen N Berger and Timothy H Hannan. The price-concentration relationship in banking. *The Review of Economics and Statistics*, pages 291–299, 1989.

Mark A Carlson, Burcu Duygan-Bump, Fabio M Natalucci, William R Nelson, Marcelo Ochoa, Jeremy C Stein, and Skander Van den Heuvel. The demand for short-term, safe assets and financial stability: Some evidence and implications for central bank policies. 2014.

Tri Vi Dang, Gary Gorton, and Bengt Holmstrom. Opacity and the optimality of debt for liquidity provision. *Manuscript Yale University*, 2009.

Douglas W Diamond and Philip H Dybvig. Bank runs, deposit insurance, and liquidity. *Journal of political economy*, 91(3):401–419, 1983.

Itamar Drechsler, Alexi Savov, and Philipp Schnabl. The deposits channel of monetary policy. *The Quarterly Journal of Economics*, 2017.

Gregory R Duffee. Idiosyncratic variation of treasury bill yields. *The Journal of Finance*, 51(2):527–551, 1996.

Darrell Duffie and Arvind Krishnamurthy. Passthrough efficiency in the fed's new monetary policy setting. In *Designing Resilient Monetary Policy Frameworks for the Future. Federal Reserve Bank of Kansas City, Jackson Hole Symposium*, 2016.

Erik P Gilje, Elena Loutskina, and Philip E Strahan. Exporting liquidity: Branch banking and financial integration. *The Journal of Finance*, 71(3):1159–1184, 2016.

Gary Gorton and Andrew Metrick. Securitized banking and the run on repo. *Journal of Financial Economics*, 104(3):425–451, 2012.

Gary Gorton and George Pennacchi. Financial intermediaries and liquidity creation. *The Journal of Finance*, 45(1):49–71, 1990.

Gary B Gorton. *Slapped by the invisible hand: The panic of 2007*. Oxford University Press, 2010.

Robin Greenwood and Dimitri Vayanos. Bond supply and excess bond returns. *The Review of Financial Studies*, 27(3):663–713, 2014.

Robin Greenwood, Samuel Hanson, and Jeremy C Stein. A gap-filling theory of corporate debt maturity choice. *The Journal of Finance*, 65(3):993–1028, 2010.

Robin Greenwood, Samuel G Hanson, and Jeremy C Stein. A comparative-advantage approach to government debt maturity. *The Journal of Finance*, 70(4):1683–1722, 2015.

Robin Greenwood, Samuel G Hanson, and Jeremy C Stein. The federal reserve's balance sheet as a financial-stability tool. In *Designing Resilient Monetary Policy Frameworks for the Future," Jackson Hole Symposium: Federal Reserve Bank of Kansas City*, 2016.

Timothy H Hannan. Bank commercial loan markets and the role of market structure: Evidence from surveys of commercial lending. *Journal of Banking & Finance*, 15(1):133–149, 1991.

Samuel G Hanson, Andrei Shleifer, Jeremy C Stein, and Robert W Vishny. Banks as patient fixed-income investors. *Journal of Financial Economics*, 117(3):449–469, 2015.

Marcin T Kacperczyk, Christophe Perignon, and Guillaume Vuillemey. The private production of safe assets. 2017.

Anil K Kashyap, Raghuram Rajan, and Jeremy C Stein. Banks as liquidity providers: An explanation for the coexistence of lending and deposit-taking. *The Journal of Finance*, 57(1):33–73, 2002.

Arvind Krishnamurthy and Annette Vissing-Jorgensen. The aggregate demand for treasury debt. *Journal of Political Economy*, 120(2):233–267, 2012.

Arvind Krishnamurthy and Annette Vissing-Jorgensen. The impact of treasury supply on financial sector lending and stability. *Journal of Financial Economics*, 118(3):571–600, 2015.

Stefan Nagel. The liquidity premium of near-money assets. *The Quarterly Journal of Economics*, 131(4):1927–1971, 2016.

David Neumark and Steven A Sharpe. Market structure and the nature of price rigidity: evidence from the market for consumer deposits. *The Quarterly Journal of Economics*, 107(2):657–680, 1992.

Jeremy C Stein. Monetary policy as financial stability regulation. *The Quarterly Journal of Economics*, 127(1):57–95, 2012.

Adi Sunderam. Money creation and the shadow banking system. *The Review of Financial Studies*, 28(4):939–977, 2014.

Vladimir Yankov. In search of a risk-free asset. *FEDS Working Paper No. 2014-108*, 2014.

Tables and Figures

Table 1: Deposit Volume and Treasury Supply

This table estimates the effect of Treasury supply on deposit growth. The data is at the branch-year level and covers 1994 to 2016. For columns (1) and (2), the sample consists of all banks with branches in two or more counties. For columns (3) and (4), the full sample of banks is used. TSY Growth is the log change in Treasury supply. Branch HHI measures market concentration in the county where a branch is located. Δ Target FF is the change in the Fed funds target rate. The data is from the FDIC and TreasuryDirect. Fixed effects are denoted at the bottom of the table. Standard errors are clustered by county.

| | Branch-Level Deposit Growth | | | |
| | $\geq$ 2 Counties | | All Counties | |
	(1)	(2)	(3)	(4)
TSY Growth * HHI	0.086**	0.084**	0.265***	0.264***
	(0.039)	(0.039)	(0.031)	(0.031)
Δ Target FF * HHI		-0.007***		-0.015***
		(0.003)		(0.002)
Observations	1,503,852	1,503,852	1,661,292	1,661,292
R-squared	0.338	0.338	0.234	0.234
Bank Year FE	Yes	Yes	No	No
State Year FE	Yes	Yes	Yes	Yes
Branch FE	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
SE Cluster	County	County	County	County

Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Table 2: Deposit Spread and Treasury Supply: ≥ 2 Counties

This table estimates the effect of Treasury supply on the Treasury-deposit spread. The data is at the branch-quarter level and covers January 1997 to December 2016. The sample consists of all banks with branches in two or more counties. Spread changes for savings and money market deposits are equal to the changes in the three-month Treasury yield minus the changes in deposit rates at the branch level. Spread changes for time deposits are equal to the changes in maturity-matched Treasury yield minus the changes in deposit rates at the branch level. TSY Growth is the log change in Treasury supply. Branch HHI measures market concentration in the county where a branch is located. Δ Target FF is the change in the Fed funds target rate. The data is from RateWatch and TreasuryDirect. Fixed effects are denoted at the bottom of each panel. Standard errors are clustered by county.

| | Δ Treasury - Deposit Spread Change (≥ 2 Counties) | | | | |
| | (1) | (2) | (3) | (4) | (5) |
	Saving	MM	3m CD	6m CD	12m CD
TSY Growth * HHI	-2.717***	-1.427***	-0.784***	-0.320*	-0.216
	(0.328)	(0.271)	(0.218)	(0.173)	(0.154)
Δ Target FF * HHI	0.528***	0.484***	0.320***	0.283***	0.216***
	(0.036)	(0.033)	(0.025)	(0.020)	(0.017)
Observations	191,211	206,905	202,856	216,686	216,666
R-squared	0.960	0.884	0.875	0.863	0.844
Bank Time FE	Yes	Yes	Yes	Yes	Yes
State Time FE	Yes	Yes	Yes	Yes	Yes
Branch FE	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes
SE Cluster	County	County	County	County	County

Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Table 3: Deposit Spread and Treasury Supply: All Counties

This table estimates the effect of Treasury supply on deposit spreads. The data is at the branch-quarter level and covers January 1997 to December 2016. The sample consists of all banks. Spread changes for savings and money market deposits are equal to the changes in the three-month Treasury yield minus the changes in deposit rates at the branch level. Spread changes for time deposits are equal to the changes in maturity-matched Treasury yield minus the changes in deposit rates at the branch level. TSY Growth is the log change in Treasury supply. Branch HHI measures market concentration in the county where a branch is located. Δ Target FF is the change in the Fed funds target rate. The data is from RateWatch and TreasuryDirect. Fixed effects are denoted at the bottom of each panel. Standard errors are clustered by county.

| | Δ Treasury - Deposit Spread (All Counties) | | | | |
| | (1) | (2) | (3) | (4) | (5) |
	Saving	MM	3m CD	6m CD	12m CD
TSY Growth * HHI	-2.282***	-1.494***	-1.045***	-0.640***	-0.400***
	(0.187)	(0.165)	(0.115)	(0.099)	(0.091)
Δ Target FF * HHI	0.354***	0.422***	0.228***	0.214***	0.191***
	(0.019)	(0.021)	(0.016)	(0.014)	(0.012)
Observations	480,960	499,507	480,499	522,482	523,215
R-squared	0.934	0.818	0.792	0.769	0.737
Bank Time FE	No	No	No	No	No
State Time FE	Yes	Yes	Yes	Yes	Yes
Branch FE	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes
SE Cluster	County	County	County	County	County

Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Table 4: Deposit Spread and Monetary Policy: $\geq$ 2 Counties

This table estimates the effect of monetary policy on deposit spreads. The data is at the branch-quarter level and covers January 1997 to December 2016. The sample consists of all banks with branches in two or more counties. Spread changes are equal to the changes of the Fed funds target rate minus the changes in deposit rates at the branch level. TSY Growth is the log change in Treasury supply. Branch HHI measures market concentration in the county where a branch is located. Δ Target FF is the change in the Fed funds target rate. The data is from RateWatch and TreasuryDirect. Fixed effects are denoted at the bottom of each panel. Standard errors are clustered by county.

| | Δ Fed funds - Deposit Spread ($\geq$ 2 Counties) | | | | |
| | (1) | (2) | (3) | (4) | (5) |
	Saving	MM	3m CD	6m CD	12m CD
TSY Growth * HHI	-2.648***	-1.313***	-0.716***	-0.212	0.081
	(0.344)	(0.284)	(0.239)	(0.186)	(0.173)
Δ Target FF * HHI	0.577***	0.541***	0.389***	0.340***	0.320***
	(0.039)	(0.035)	(0.027)	(0.022)	(0.021)
Observations	191,211	206,905	202,856	216,686	216,666
R-squared	0.964	0.898	0.898	0.887	0.880
Bank Time FE	Yes	Yes	Yes	Yes	Yes
State Time FE	Yes	Yes	Yes	Yes	Yes
Branch FE	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes
SE Cluster	County	County	County	County	County

Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Table 5: Deposit Spread and Monetary Policy: All Counties

This table estimates the effect of monetary policy on deposit spreads. The data is at the branch-quarter level and covers January 1997 to December 2016. The sample consists of all banks. Spread changes are equal to the changes of the Fed funds target rate minus the changes in deposit rates at the branch level. TSY Growth is the log change in Treasury supply. Branch HHI measures market concentration in the county where a branch is located. Δ Target FF is the change in the Fed funds target rate. The data is from RateWatch and TreasuryDirect. Fixed effects are denoted at the bottom of each panel. Standard errors are clustered by county.

| | Δ Fed Funds - Deposit Spread (All Counties) | | | | |
| | (1) | (2) | (3) | (4) | (5) |
	Saving	MM	3m CD	6m CD	12m CD
TSY Growth * HHI	-2.308***	-1.479***	-1.064***	-0.634***	-0.312***
	(0.197)	(0.173)	(0.126)	(0.107)	(0.101)
Δ Target FF * HHI	0.387***	0.462***	0.273***	0.255***	0.264***
	(0.021)	(0.023)	(0.018)	(0.015)	(0.014)
Observations	480,960	499,507	480,499	522,482	523,215
R-squared	0.941	0.842	0.831	0.813	0.805
Bank Time FE	No	No	No	No	No
State Time FE	Yes	Yes	Yes	Yes	Yes
Branch FE	Yes	Yes	Yes	Yes	Yes
County FE	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes
SE Cluster	County	County	County	County	County

Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Table 6: Deposit Volume and Treasury Supply: Local Clientele ($\geq$ 2 Counties)

This table estimates the effect of local clientele features on deposit growth. The data is at the branch-year level from 1994 to 2016. The sample consists of all banks with branches in two or more counties. Age is the share of the county population that is aged 65 or older. Income is the natural log of county-level median household income. College is the county share of the population with a college degree. TSY Growth is the log change in Treasury supply. Δ Target FF is the change in the Fed funds target rate. Data is from the FDIC, TreasuryDirect and 2000 US Census and County Business Patterns. All regressions include state-year, bank-year, branch, county and year fixed effects. Standard errors are clustered by county.

| | Branch Level Deposit Growth ($\geq$ 2 Counties) | | | |
	(1)	(2)	(3)	(4)
TSY Growth * HHI	0.118***	0.133***	0.166***	0.125***
	(0.033)	(0.035)	(0.036)	(0.035)
TSY Growth * Age	0.008***			0.008***
	(0.001)			(0.001)
TSY Growth * Income		-0.050***		-0.061**
		(0.018)		(0.025)
TSY Growth * College			-0.000	0.002***
			(0.000)	(0.001)
Δ Target FF * HHI				0.002
				(0.002)
Δ Target FF * Age				0.000
				(0.000)
Δ Target FF * Income				-0.001
				(0.001)
Δ Target FF * College				0.000
				(0.000)
Observations	1,421,135	1,421,135	1,421,135	1,421,135
R-squared	0.350	0.350	0.350	0.350

Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Table 7: Deposit Volume and Treasury Supply: Haircut ($\geq$ 2 Counties)

This table estimates the effect of the maturity structure of Treasuries on deposit growth. The data is at the branch-year level and covers the years 1994 to 2016. The sample consists of all banks with branches in two or more counties. Deposit growth is the log change in deposits at the branch level. TSY Growth is the log change in Treasury supply as measured by a weighted haircut volume. We use CRSP treasury master file to divide total treasury volume into categories with remaining maturity of less than one-year and over one-year and then multiply by their respective haircut rates. Branch HHI measures market concentration in the county where a branch is located. Δ Target FF is the change in the Fed funds target rate. The data is from the FDIC, TreasuryDirect, CRSP and Krishnamurthy and Vissing-Jorgensen (2012). Fixed effects are denoted at the bottom of the table. Standard errors are clustered by county.

| | Branch-Level Deposit Growth ($\geq$ 2 Counties) | | |
	(1)	(2)	(3)
TSY Growth * HHI	0.085**		0.084**
	(0.037)		(0.037)
Δ Target FF * HHI		-0.007***	-0.007***
		(0.003)	(0.003)
Observations	1,503,852	1,503,914	1,503,852
R-squared	0.338	0.338	0.338
Bank Year FE	Yes	Yes	Yes
State Year FE	Yes	Yes	Yes
Branch FE	Yes	Yes	Yes
County FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
SE Cluster	County	County	County

Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Table 8: Deposit Volume and Treasury Supply: Repo Funding ($\geq$ 2 Counties)

This table estimates the effect of Treasury supply on deposit growth for banks below the third quartile of repo funding. The data is at the branch-year level. Deposit growth is the log change in deposits at the branch level. TSY Growth is the log change in Treasury supply. Branch HHI measures market concentration in the county where a branch is located. Δ Target FF is the change in the Fed funds target rate. The data is from the FDIC and TreasuryDirect. Fixed effects are denoted at the bottom of the table. Standard errors are clustered by county.

| | Branch-Level Deposit Growth | |
	(1)	(2)
TSY Growth * HHI	0.222***	0.219***
	(0.067)	(0.067)
Δ Target FF * HHI		-0.010**
		(0.005)
Observations	365,810	365,810
R-squared	0.395	0.395
Bank Year FE	Yes	Yes
State Year FE	Yes	Yes
Branch FE	Yes	Yes
County FE	Yes	Yes
Year FE	Yes	Yes
SE Cluster	County	County

Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Table 9: Crowd-Out Sensitivity by Deposit Type

This table estimates the effect of Treasury supply on deposit growth for different types of deposits. The data is at the bank-year level and covers the years 1994 to 2016. Deposit growth is the log change in deposits at the bank level. TSY Growth is the log change in Treasury supply. Bank HHI measures the average market concentration of the bank's branches, where each branch takes the HHI of the county it is located in. Δ Target FF is the change in the Fed funds target rate. Core Deposits are comprised of checking, savings and small time deposits (less than 100K). Time Deposits are the sum of small and large time deposits. Wholesale Funding is comprised of wholesale deposits, Fed funds, repo borrowing, and other borrowed money. The data is from the FDIC, Call Reports, and TreasuryDirect. Bank controls include log total assets, leverage ratio and returns on assets. Fixed effects are denoted at the bottom of the table. Standard errors are clustered by bank.

| | Bank-Level Deposit Growth Rates | | |
	Core Deposits	Time Deposits	Wholesale Funding
TSY Growth	-0.1289***	-0.2017***	-0.4899***
	(0.013)	(0.018)	(0.027)
TSY Growth * HHI	0.3116***	0.3062***	0.7542***
	(0.044)	(0.059)	(0.098)
Δ Target FF	-0.0123***	0.0124***	0.0236***
	(0.001)	(0.001)	(0.002)
Δ Target FF * HHI	0.0119***	-0.0195***	-0.0065
	(0.002)	(0.004)	(0.007)
Observations	965,376	962,237	957,909
R-squared	0.020	0.022	0.015
Bank FE	Yes	Yes	Yes
Bank Controls	Yes	Yes	Yes
SE Cluster	Bank	Bank	Bank

Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Table 10: Treasury Supply and the Wholesale Funding Ratio

This table estimates the effect of Treasury supply on wholesale funding. The data is at the bank-year level and covers the years 1994 to 2016. The Wholesale Funding Ratio is the ratio of wholesale funding over total deposit funding, where wholesale funding is the sum of large time deposits, repo borrowing, Fed funds, and other borrowed money. TSY Growth is the log change in Treasury supply. Bank HHI measures the average market concentration of the bank's branches, where each branch takes the HHI of the county it is located in. Δ Target FF is the change in the Fed funds target rate. The data is from the FDIC, Call Reports and TreasuryDirect. Bank controls include log total assets, leverage ratio and returns on assets. Fixed effects are denoted at the bottom of the table. Standard errors are clustered by bank.

| | Δ Wholesale Funding Ratio | |
	(1)	(2)
TSY Growth	-0.030***	-0.036***
	(0.001)	(0.002)
TSY Growth * Bank HHI		0.029***
		(0.009)
Δ Target FFR	0.002***	0.002***
	(0.000)	(0.000)
Δ Target FFR * Bank HHI		-0.001**
		(0.001)
Observations	1,007,682	966,954
R-squared	0.011	0.010
Bank FE	Yes	Yes
Bank Controls	Yes	Yes
SE Cluster	Bank	Bank

Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Table 11: Effect of the Reverse Repurchase Facility

This table estimates the effect of the Reverse Repurchase Facility. The dependent variable in Column (1) is deposit growth, which is the log change in deposit volume at the branch-year level. The sample covers 1997 to 2013 and consists of all banks with branches in two or more counties. The dependent variable for columns (2) and (3) are changes in the spread between the Treasury yield and deposit rates at the branch-quarter level. The dependent variable for columns (4) and (5) are changes in the spread between the Fed funds rate and deposit rates at the branch-quarter level. The sample covers 1997Q1 to 2013Q3 and consists of all banks with branches in two or more counties. Δ TSY and Δ Target FF are changes in the Treasury yield and the Fed funds target rate respectively. Branch HHI measures market concentration in the county where a branch is located. The data is from Ratewatch, FDIC and TreasuryDirect. All specifications include bank-time, state-time, branch, county and time fixed effects. Standard errors are clustered by county.

	Dep Growth	Δ TSY - Dep Spread		Δ FF - Dep Spread	
	(1)	(2)	(3)	(4)	(5)
	Total	Savings	Time	Savings	Time
Δ TSY * HHI	0.016*	-0.838**	-0.508**	-0.741**	-0.191
	(0.067)	(0.305)	(0.243)	(0.322)	(0.193)
Δ Target FF * HHI	-0.018***	0.469***	0.306***	0.421***	0.305***
	(0.002)	(0.032)	(0.024)	(0.030)	(0.025)
Observations	1,107,828	190,050	185,881	190,016	185,197
R-squared	0.354	0.886	0.877	0.899	0.884

Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Figure 1: Treasury Supply and Bank Deposits in the Aggregate Time Series

Panel (a) is a binned plot of year-over-year growth in the total deposits of commercial banks against Treasury supply growth from 1964 to 2019. Panel (b) is a binned plot of year-over-year changes in the spread between the 3-month Treasury yield and the 3-month CD rates against Treasury supply growth from 1964 to 2019. Panel (c) is a binned plot of year-over-year growth in the ratio of wholesale funding and Treasury supply growth from 1973 to 2019. The wholesale funding ratio is defined as large time deposits over total deposits. All variables are residualized against year-over-year changes in the Fed Funds rate. We use a number of sources to extend the time series for each plot. Treasury supply held by the private sector is available from the Flow of Funds. Total deposit volume is available from the FDIC historical banking data from 1964 onwards. 3-month Treasury yields, the Fed Funds rate and 3-month CD rates are available from FRED, where the 3-month CD rates are available from 1964 onwards. Large time deposits are available from FRED from 1973 onwards.

a Deposit Growth and Treasury Supply

b Deposit Spread and Treasury Supply

c Wholesale Funding Ratio
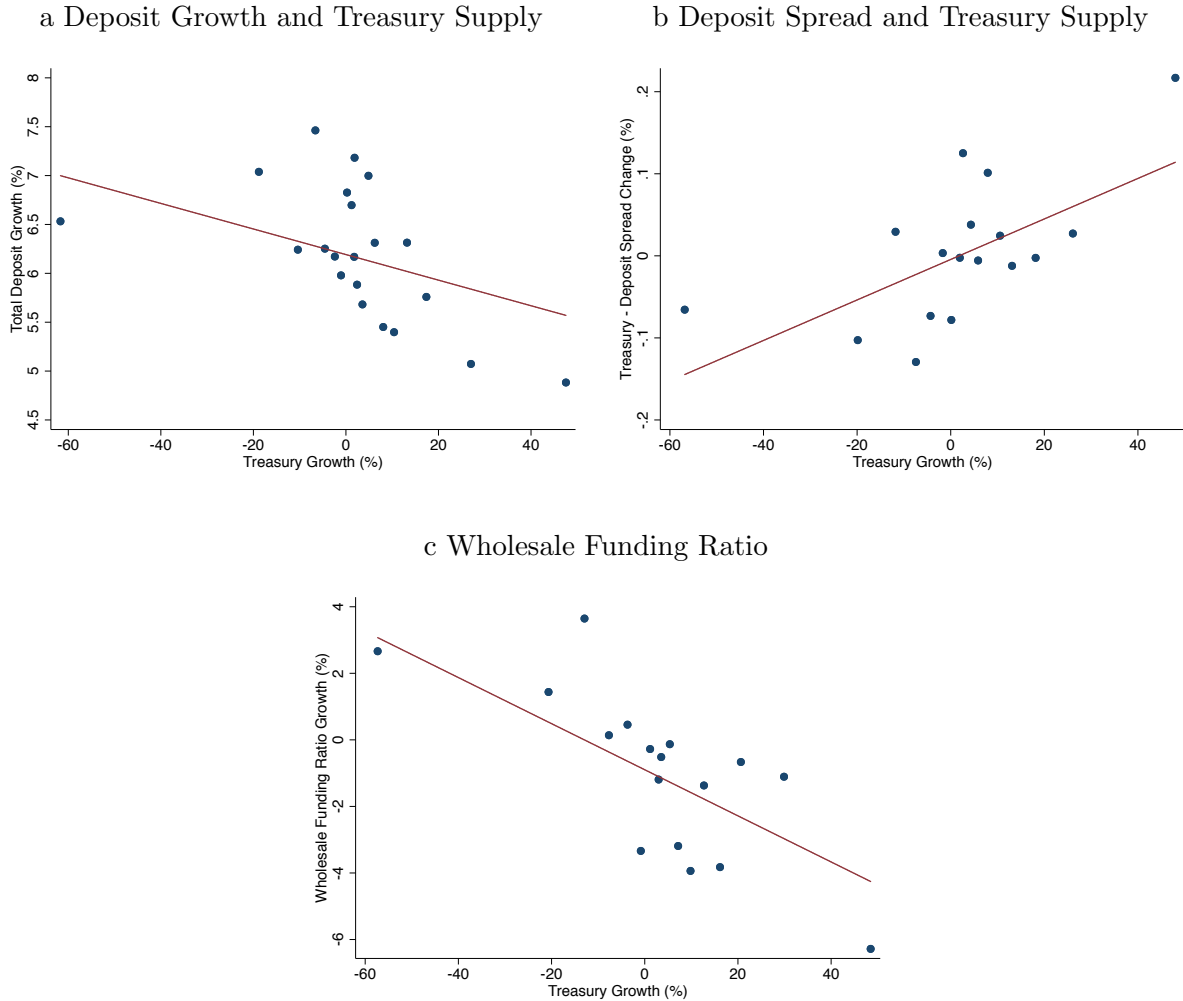
Figure 2: Bank Prime Loan Rate and Fed Funds Rate

This figure plots the average monthly Fed funds rate and bank prime loan rate from 1982 to 2018.
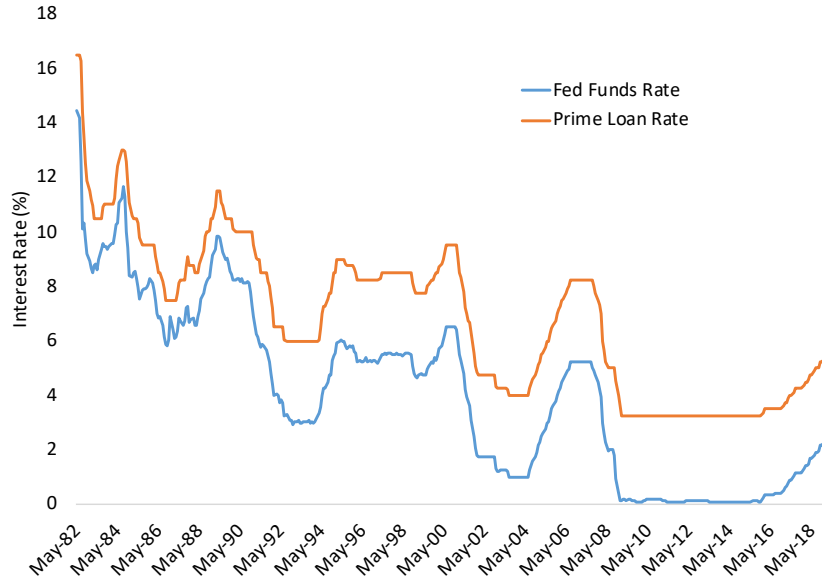
Figure 3: Composition of Bank Asset Holdings

This figure shows the asset composition of the US commercial banking sector from 1980 to 2018. Data is from the Flow of Funds.
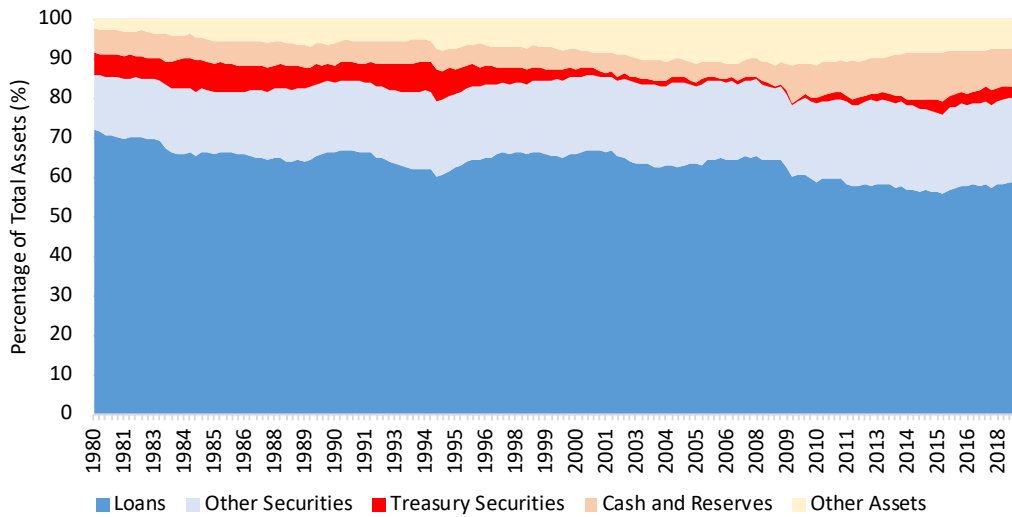
Figure 4: Deposit Competition in the US

This figure presents information on county-level and bank-level deposit competition in the US. Subfigure (a) plots the first, second and third quartile of county-level HHI over time from 1997 to 2016. Subfigure (b) plots the distribution of the bank-level HHI, which is measured as the weighted average of the bank's branch-level HHI. Data is from the FDIC.

a County-level Herfindahl Index from 1997 to 2016
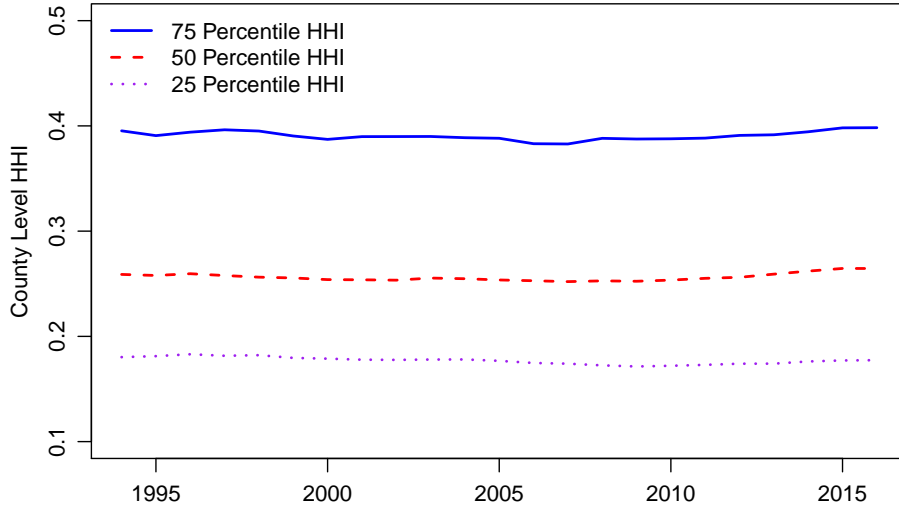
b Bank-level Herfindahl Index Distribution
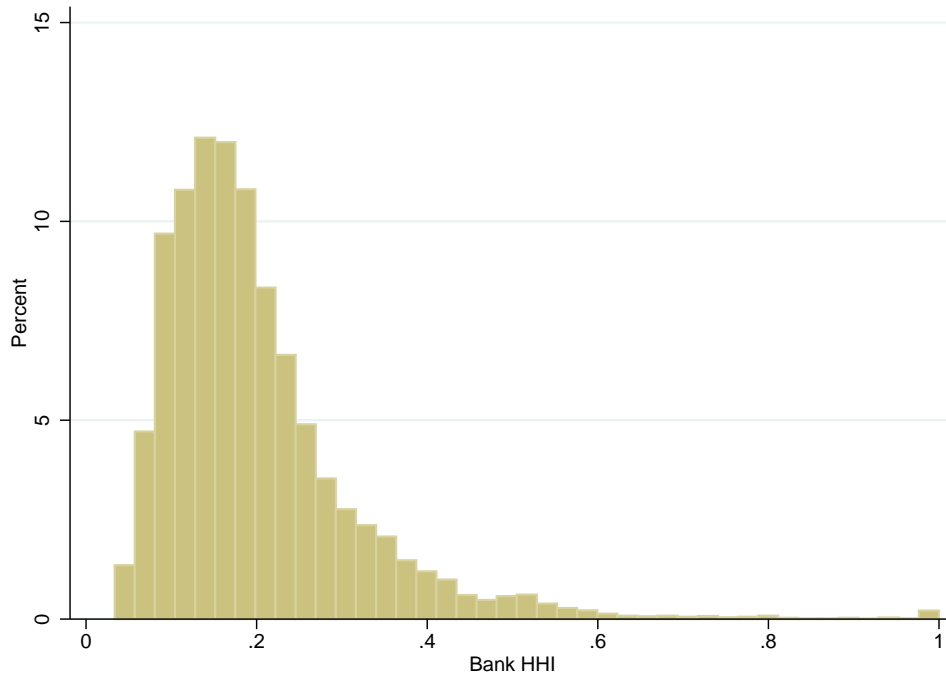
Figure 5: Sensitivity of Deposit Growth by Deposit Competition

This figure plots deposit growth sensitivities towards Treasury growth against county-level HHI. The data is at the branch-year level and covers years 1994 to 2016. Counties are first divided into 20 equal-sized bins according to their HHI Index. Then, branch-level deposit growth is regressed against Treasury growth interacted with indicator variables for each bin and controlling for year and branch fixed effects. The coefficients on the indicator variables correspond to the average sensitivity of deposit growth to Treasury growth among bank branches located in a given region of deposit competition. The last bin is taken as the baseline for comparison. Data is from the FDIC and TreasuryDirect.
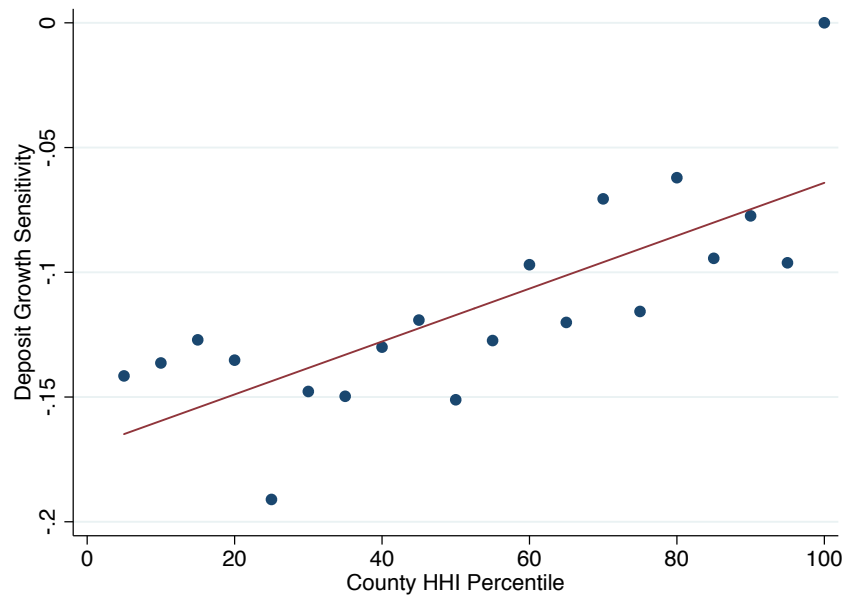
Figure 6: Sensitivity of Deposit Spreads by Deposit Competition

This figure plots deposit spread sensitivities towards Treasury growth against county-level HHI. Panels (a) and (b) show results for time and savings deposits, respectively. The data is at the branch-quarter level and covers years 1997 to 2016. Counties are first divided into 20 equal-sized bins according to their HHI Index. Then, branch-level deposit spread changes are regressed against Treasury growth interacted with indicator variables for each bin and controlling for year and branch fixed effects. The coefficients on the indicator variables correspond to the average sensitivity of deposit spread changes to Treasury growth among bank branches located in a given region of deposit competition. The last bin is taken as the baseline for comparison. Data is from RateWatch, FDIC and TreasuryDirect.

a Sensitivity of Time Deposit Spread

b Sensitivity of Savings Deposit Spread
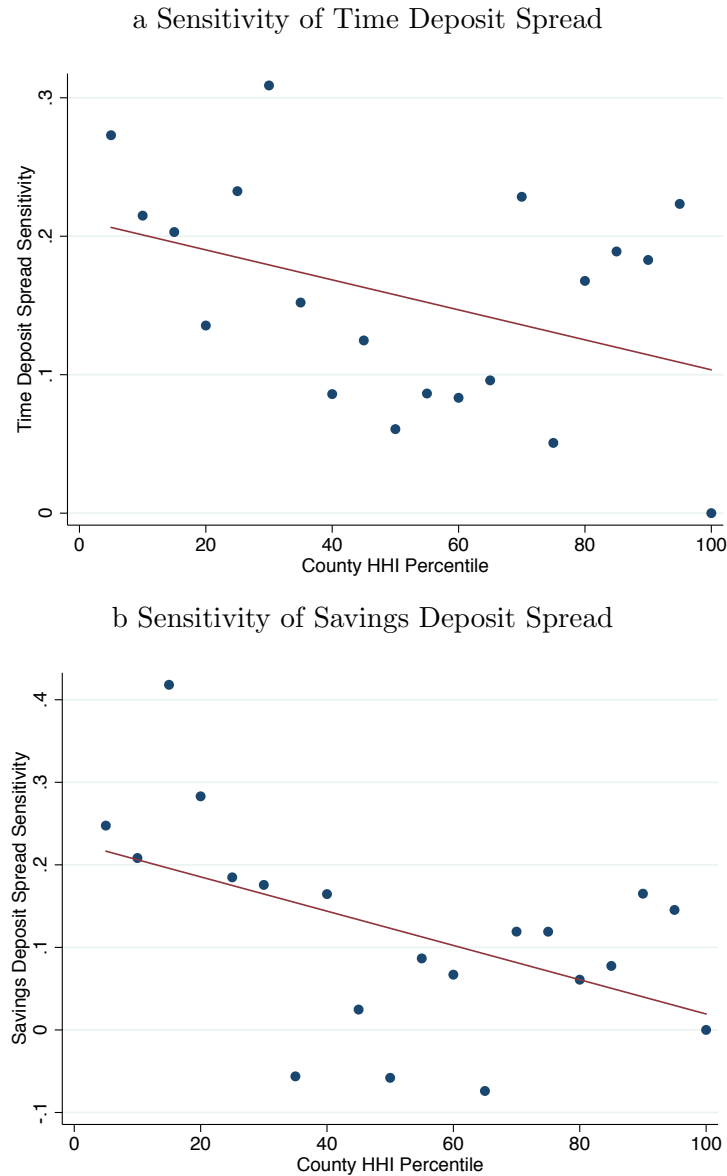
Figure 7: Example of Deposit Spreads for Two Branches of Huntington Bank

This figure plots the 3-month Treasury-3-month CD spread at two branches of Huntington Bank from October 2004 to April 2005. One branch is located in Macomb, MI (red), while the other is in Hamilton, OH (blue). This is a period when Treasury growth increased by 3.24% from 2004Q4 to 2005Q1. Data is from Ratewatch, FDIC and TreasuryDirect.
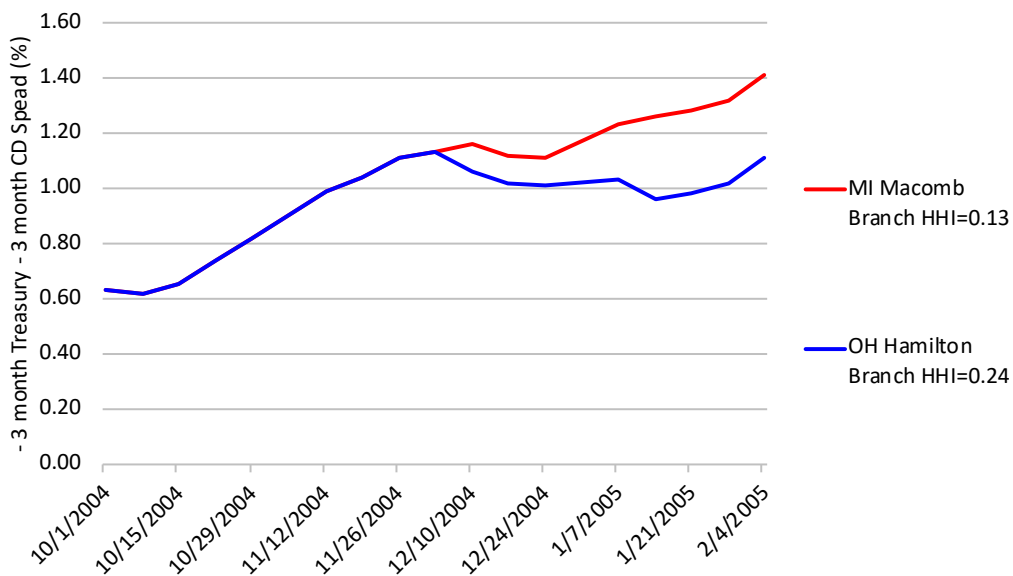
Figure 8: Passthrough of Treasury Supply and Monetary Policy to County-level Deposits

This figure plots county-level deposit volume passthrough sensitivities towards Treasury supply and monetary policy. Panel (a) shows the decrease in deposit growth (bps) due to a one standard deviation increase in Treasury supply growth for each county. Darker shades correspond to a more pronounced effect, which occurs in counties with a lower average HHI, i.e. more competitive counties. Panel (b) shows the decrease in deposit growth (bps) due to a one standard deviation increase in Fed funds rate hikes for each county. Darker shades correspond to a more pronounced effect, which occurs in counties with a higher average HHI, i.e. less competitive counties. Data is from RateWatch, FDIC and TreasuryDirect.

a Passthrough of Treasury Supply
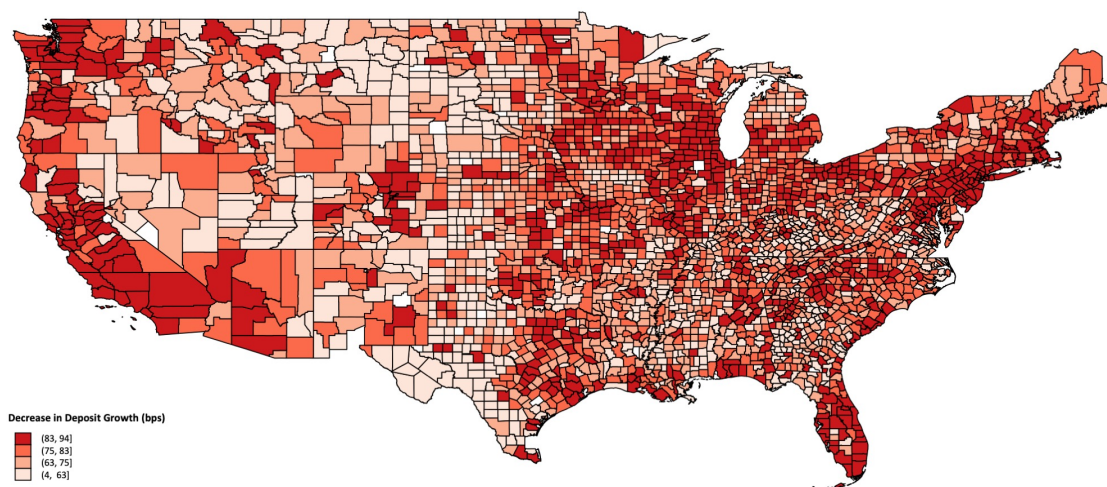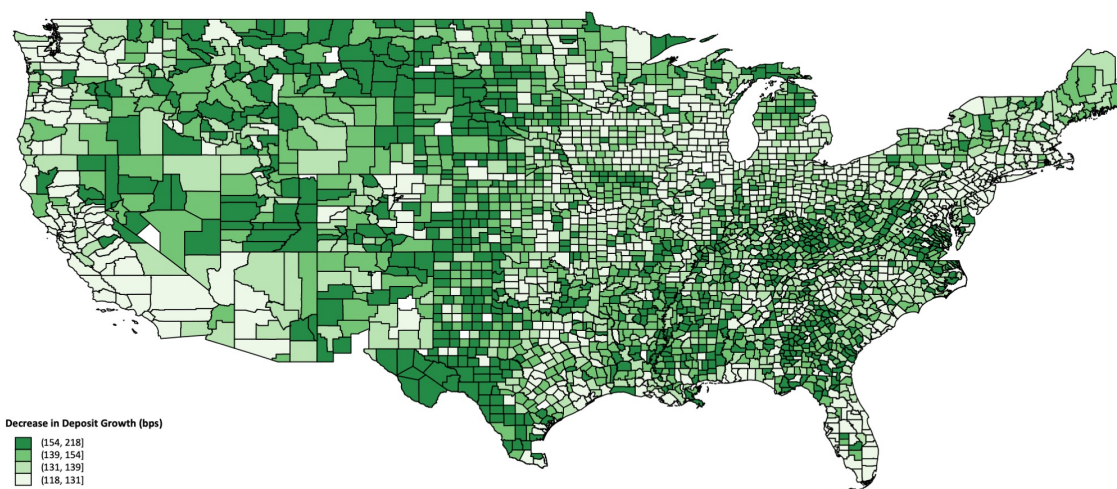

b Passthrough of Monetary Policy

Figure 9: Crowd-Out Sensitivity by Deposit Type

This figure plots the crowd-out sensitivities for different types of deposits against bank HHI. The data covers the years 1994 to 2016. Crowd-out sensitivities are obtained from the bank level regression of deposit growth on Treasury growth and Fed fund rate changes interacted with Bank HHI as detailed in Table 11. Solid lines indicate point estimates while dotted lines show the 95% confidence interval. Bank HHI measures the average market concentration of the bank's branches, where each branch takes the HHI of the county it is located in. Core deposits are comprised of checking, savings and small time deposits (less than 100K). Wholesale funding is comprised of large time deposits, Fed funds, repo borrowing, and other borrowed money. Data is from the FDIC, Call Reports and TreasuryDirect.

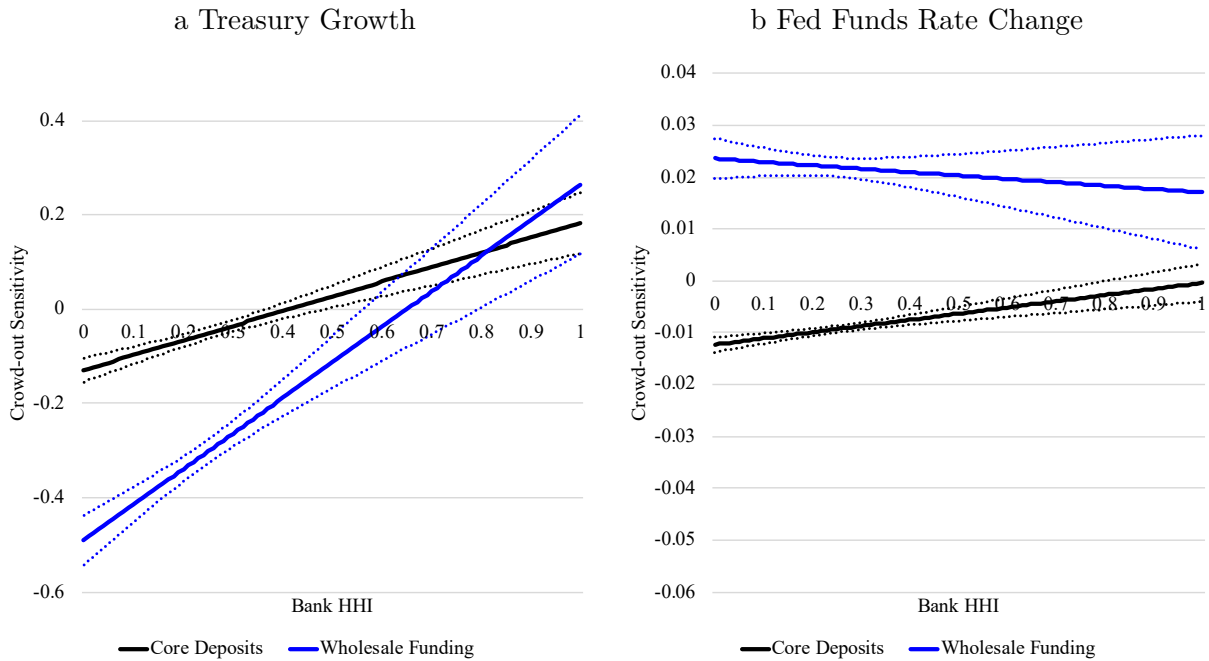a Treasury Growth

b Fed Funds Rate Change

Figure 10: Bank-Level Crowd-Out Sensitivity by Wholesale Funding Ratio

This figure shows how crowd-out sensitivities vary with the level of wholesale funding. The sample is from 1994 to 2016. Banks are first divided into quntiles according to their ratio of wholesale funding. The columns (left axis) indicate the average wholesale funding ratio in each quantile. The blue line (right axis) marks the crowd-out sensitivities for each quintile group. In panel (a), they are calculated by regressing deposit growth on Treasury growth interacted with dummy variables for each quintile group and controlling for changes in the Fed funds rate, log of total assets, leverage ratio, return on assets and bank fixed effects. In panel (b), they are calculated by regressing deposit growth on Fed funds rate changes interacted with dummy variables for each quintile group and controlling for Treasury growth, log of total assets, leverage ratio, return on assets and bank fixed effects. Dotted lines indicate the 95th confidence interval. Data is from the FDIC, Call Reports and TreasuryDirect.

a Treasury Growth
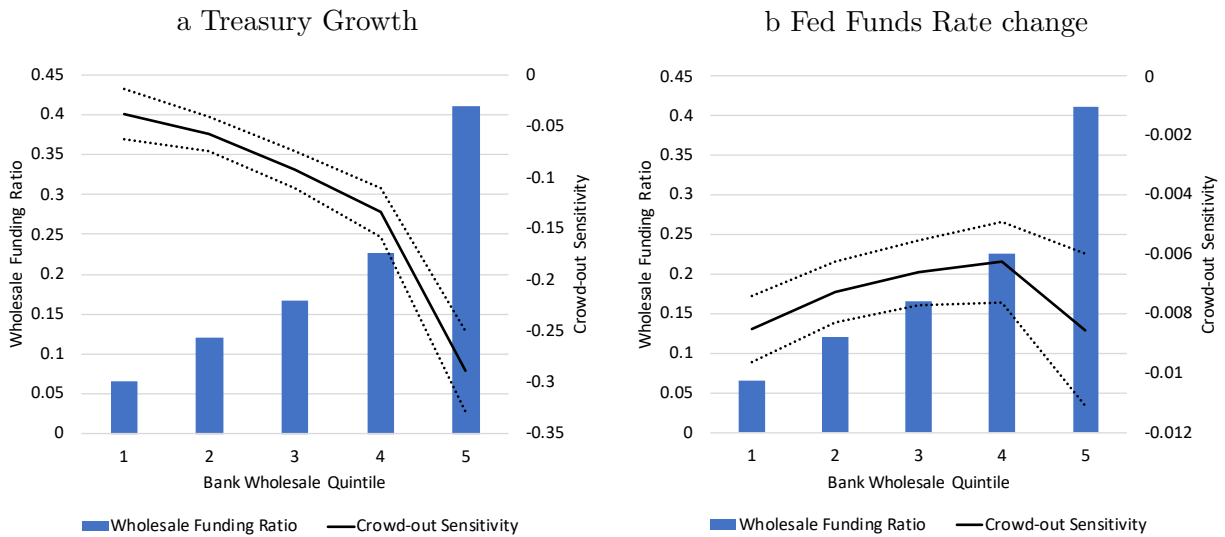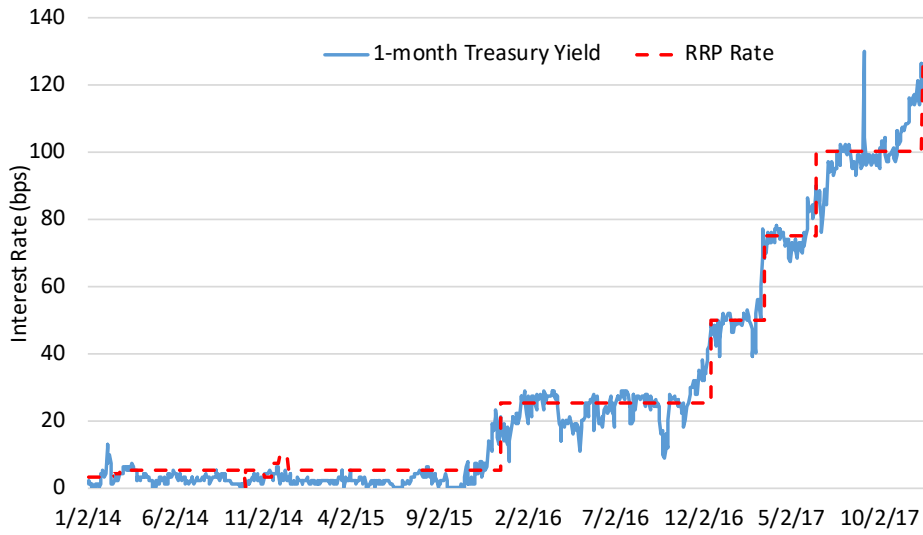
b Fed Funds Rate change

Figure 11: Treasury Yield and the Reverse Repurchase Facility Rate

This figure compares the one-month Treasury yield with the RRP Facility rate. Data is from FRED and the New York Federal Reserve website.

A   Appendix: Model Derivations

In this section, we provide detailed derivations for the model.

A.1   Derivations for Deposit Demand and Supply Curves

Aggregate Deposit Demand

The first order conditions for problem (4) and (5) is

$$\ell = \delta L^{\frac{1}{\sigma}-1} G^{-\frac{1}{\sigma}}$$

$$s = L^{\frac{1}{\sigma}-1} D^{-\frac{1}{\sigma}}$$

which implies

$$(\frac{G}{D})^{-\frac{1}{\sigma}} \delta = \frac{\ell}{s}$$

and

$$L = (1 + \delta^{\sigma} (\frac{s}{\ell})^{(\sigma-1)})^{\frac{\sigma}{\sigma-1}} D$$

Then plug in the expressions of L and G as a function of D into the FOC on D, and we get

$$D = \frac{1}{s + \ell^{-(\sigma-1)}(\delta s)^{\sigma}}$$

$$G = \frac{1}{\ell + s^{-(\sigma-1)}(\ell/\delta)^{\sigma}}$$

Demand for Deposits from Individual Banks

Next, we solve the household optimization over individual bank's deposit. The individual deposit optimization problem is

$$\min_{D_i, i \in \{1,2,\cdots,N\}} \sum_{i=1}^{N} \frac{1}{N} D_i s_i \tag{30}$$

subject to

$$D = \left(\frac{1}{N} \sum_{i=1}^{N} D_i^{\frac{\eta-1}{\eta}} \right)^{\frac{\eta}{\eta-1}}$$

The FOC over D_i is

$$s_i = \mu \cdot D^{\frac{1}{\eta}} D_i^{-\frac{1}{\eta}} \tag{31}$$

where μ is the Lagrangian multiplier over the constraint (2). The above FOC implies

$$(\frac{D_i}{D_j})^{-\frac{1}{\eta}} = \frac{s_i}{s}$$

Since $s_j = s$ for $j \neq i$, we get

$$D_{j_1} = D_{j_2}, \quad j_1 \neq j_2, \quad \text{for all } j_1, j_2 \neq i$$

Then we can solve $D_j, j \neq i$ as

$$D_j = \left(\frac{ND^{\frac{\eta-1}{\eta}} - D_i^{\frac{\eta-1}{\eta}}}{N-1} \right)^{\frac{\eta}{\eta-1}}$$

Then we can express the aggregate deposit D as a function of D_i, and then plug this into the equation (31) to get

$$D_i = D\left(\frac{1}{N} \left(1 + (N-1)\left(\frac{s_i}{s}\right)^{\eta-1} \right) \right)^{-\frac{\eta}{\eta-1}}$$

Taking log, we have

$$\log(D_i) = \log(D) - \frac{\eta}{\eta-1} \left(\log(1 + (N-1)\left(\frac{s_i}{s}\right)^{\eta-1}) - \log(N) \right)$$

Thus the derivative of the optimal D_i over s_i is

$$\frac{\partial \log(D_i)}{\partial \log(s_i)} = -\frac{(N-1)}{1 + (N-1)\left(\frac{s_i}{s}\right)^{\eta-1}} \eta \left(\frac{s_i}{s}\right)^{\eta-1}$$

In the symmetric equilibrium, we have $s = s_i$, which implies

$$\frac{\partial \log(D_i)}{\partial \log(s_i)} = -\frac{N-1}{N}\eta$$

Denote the demand elasticity as e. Then we have

$$e(N, \eta) = \frac{N-1}{N}\eta$$

which is an increasing function in both N and η.

Aggregate Deposit Supply

With the inverse loan demand function (8), problem (9) is expressed as

$$\max_{s_i} \quad (s_i + \frac{\bar{Q}}{2\beta} - r - \frac{\tilde{D}_i}{2\beta})\tilde{D}_i \tag{32}$$

The first order condition implies

$$\frac{s_i}{s_i + \frac{1}{2\beta}\bar{Q} - r - \frac{1}{\beta}\tilde{D}_i} = -\frac{\partial \log(\tilde{D}_i)}{\partial \log(s_i)} \tag{33}$$

which characterizes the optimal bank deposit spread choice given the deposit demand function $\tilde{D}_i$. In the symmetric equilibrium, $\tilde{D}_i = D$, and $s = s_i$. We can invert the relationship in (33) to get the aggregate bank deposit supply function as

$$\hat{D}(s, r) = \frac{\bar{Q}}{2} + \beta\left(\frac{e-1}{e}s - r \right)$$

50

which increases with deposits spread s but decreases with the risk-free rate r. The supply curve slope with respect to deposit spread is

$$\hat{D}'_s(s,r) = \beta \frac{e-1}{e} > 0$$

We define an index as

$$\mathcal{C} = \frac{e-1}{e} \quad \Rightarrow \quad \hat{D}'_s(s,r) = \beta\mathcal{C}$$

The index $\mathcal{C}$ is higher when e is larger. Since $e = e(N, \eta)$ is an increasing function of N and η, i.e., a larger number of banks N and a higher elasticity of substitution across bank deposits both result in a larger $\mathcal{C}$. In other words, if the banking sector competition is higher, then the index $\mathcal{C}$ is larger. For this reason, we are going to call $\mathcal{C}$ as "bank deposit competition". We find that bank deposit competition $\mathcal{C}$ only affects $\hat{D}'_s$, not $\hat{D}'_r$.

We note that $\mathcal{C}$ enters the supply function $\hat{D}$, but not the demand function D. This is because we are considering the **aggregate** deposit demand and supply. Intuitively, when viewing the banking sector as a whole, the household is making a choice of liquid assets between deposits and Treasurys. Such a choice is only affected by the relative attractiveness of deposits and Treasurys, reflected by the average deposit spread s and Treasury convenience yield ℓ. The elasticity of substitution η and the number of banks N will affect banks' sensitivity to household demand due to the induced competition among banks, therefore affecting the deposit supply curve $\hat{D}$.

A.2 Conditions for the Assumptions on Substitutability

For our main results, we need the following regularity assumptions:

$$|\frac{D_s{'}}{D_\ell{'}}| > 1, \quad |\frac{G_\ell{'}}{G_s{'}}| > 1 \tag{34}$$

The economic intuition for (34) is that we need the elasticity of substitution between bank deposits and Treasurys. In what follows, we provide conditions for these assumptions in terms of model primitives.

With the expressions of $G(s, \ell)$ and $D(s, \ell)$ in (6) and (7), we have

$$D_\ell{'} = \frac{(\sigma-1)(\delta s)^\sigma \ell^{-\sigma}}{(s + \ell^{-(\sigma-1)}(\delta s)^\sigma)^2}$$

$$D_s{'} = -\frac{1 + \ell^{-(\sigma-1)}\delta^\sigma s^{\sigma-1}}{(s + \ell^{-(\sigma-1)}(\delta s)^\sigma)^2}$$

$$G_\ell{'} = -\frac{1 + s^{-(\sigma-1)}\delta^{-\sigma}\ell^{\sigma-1}}{(\ell + s^{-(\sigma-1)}(\ell/\delta)^\sigma)^2}$$

$$G_s{'} = \frac{(\sigma-1)(\ell/\delta)^\sigma s^{-\sigma}}{(\ell + s^{-(\sigma-1)}(\ell/\delta)^\sigma)^2}$$

As a result, (34) is equivalent to

$$1 + (\frac{\ell}{s} + 1 - \sigma)(\delta s)^\sigma \ell^{-\sigma} > 0$$

and
$$1 + (\frac{s}{\ell} + 1 - \sigma)(\delta s)^{-\sigma} \ell^{\sigma} > 0$$

There is a variety of conditions that can satisfy the above two inequalities simultaneously. For example, suppose that $\delta s = \ell$, then we need

$$\sigma < 2 + \delta$$

to guarantee the positiveness of both expressions.

Since our current setup is restricted to the log utility in liquidity, the parameter space is quite restricted. In general, the conditions to guarantee Assumption 34 are quite broad. For example, suppose that the household optimization problem is changed into

$$\max W_1 + L^{\beta}$$
$$s.t.$$
$$W_1 = x(1 + r) + D(1 + r^D) + G(1 + r^G)$$
$$x + D + G = W_0$$
$$L = \left(D^{\frac{\sigma-1}{\sigma}} + \delta G^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}$$

where $\beta \in (0, 1)$ to guarantee monotonicity and concavity of the function over the liquidity bundle L. First order conditions are

$$L^{\beta-1} L^{\frac{1}{\sigma}} \delta G^{-\frac{1}{\sigma}} = \ell$$
$$L^{\beta-1} L^{\frac{1}{\sigma}} D^{-\frac{1}{\sigma}} = s$$
$$\Rightarrow \delta(\frac{G}{D})^{-\frac{1}{\sigma}} = \frac{\ell}{s}$$

Therefore,

$$L = \left(1 + \delta(\frac{\delta s}{\ell})^{\sigma-1} \right)^{\frac{\sigma}{\sigma-1}} D$$

Then we can solve D as

$$\left(1 + \delta(\frac{\delta s}{\ell})^{\sigma-1} \right)^{\frac{\sigma}{\sigma-1}(\beta-1+\frac{1}{\sigma})} D^{\beta-1} = s$$

To guarantee that D increases in ℓ, we need

$$\beta < 1 - \frac{1}{\sigma}$$

Then denote

$$\theta = \frac{\sigma}{\sigma-1} \frac{\beta-1+\frac{1}{\sigma}}{\beta-1} = \frac{\sigma}{\sigma-1} + \frac{1}{\sigma-1}\frac{1}{\beta-1} > 0$$

We have

$$D = s^{-\frac{1}{1-\beta}} \left(1 + \delta^{\sigma}(\frac{s}{\ell})^{\sigma-1} \right)^{-\theta}$$

$$= \frac{1}{s^{\frac{1}{1-\beta}} \left(1 + \delta^{\sigma}(\frac{s}{\ell})^{\sigma-1} \right)^{\theta}}$$

Similarly,

$$G = \ell^{-\frac{1}{1-\beta}} \left(\delta^{-\sigma} (\frac{\ell}{s})^{\sigma-1} + 1 \right)^{-\theta} (\delta)^{\sigma(1-\theta)}$$

$$= \frac{\delta^{\sigma(1-\theta)}}{\ell^{\frac{1}{1-\beta}} \left(\delta^{-\sigma} (\frac{\ell}{s})^{\sigma-1} + 1 \right)^{\theta}}$$

As a result,

$$\log(D) = -\frac{1}{1-\beta} \log(s) - \theta \log(1 + \delta^{\sigma} (\frac{s}{\ell})^{\sigma-1})$$

$$\frac{\partial \log(D)}{\partial \log(s)} = -\frac{1}{1-\beta} - \theta \frac{\delta^{\sigma} (\sigma-1)(\frac{s}{\ell})^{\sigma-2}}{1 + \delta^{\sigma} (\frac{s}{\ell})^{\sigma-1}} \frac{s}{\ell}$$

$$\frac{\partial \log(D)}{\partial \log(\ell)} = \theta \frac{\delta^{\sigma} (\sigma-1)(\frac{s}{\ell})^{\sigma-2}}{1 + \delta^{\sigma} (\frac{s}{\ell})^{\sigma-1}} \frac{s}{\ell}$$

Therefore,

$$|\frac{\partial \log(D)}{\partial \log(s)}| > |\frac{\partial \log(D)}{\partial \log(\ell)}|$$

regardless of the parameter σ. When s and ℓ are close, this also directly translates into $|D'_s| > |D'_\ell|$.
Similarly,

$$\frac{\partial \log(G)}{\partial \log(\ell)} = -\frac{1}{1-\beta} - \theta \frac{\delta^{-\sigma} (\sigma-1)(\frac{\ell}{s})^{\sigma-2}}{\delta^{-\sigma} (\frac{\ell}{s})^{\sigma-1} + 1} \frac{\ell}{s}$$

$$\frac{\partial \log(G)}{\partial \log(s)} = \theta \frac{\delta^{-\sigma} (\sigma-1)(\frac{\ell}{s})^{\sigma-2}}{\delta^{-\sigma} (\frac{\ell}{s})^{\sigma-1} + 1} \frac{\ell}{s}$$

which implies

$$|\frac{\partial \log(G)}{\partial \log(\ell)}| > |\frac{\partial \log(G)}{\partial \log(s)}|$$

regardless of the parameter σ. When s and ℓ are close, this inequality results in $|G'_\ell| > |G'_s|$.

A.3   Abstractions and Generality

In the main text, we have set up the model with microfoundations, including how banks compete for deposits at a micro level. Actually, our main results are relying on much simpler assumptions. We can get the results in Proposition 1, Proposition 2, and Proposition 3 directly starting from properties of the supply and demand curves. We only need the following properties for our main results:

1. Deposit and Treasury demand curves are both downward sloping in their own opportunity costs, respectively,

$$\frac{\partial D(s, \ell)}{\partial s} < 0, \quad \frac{\partial G(s, \ell)}{\partial \ell} < 0$$

2. Deposits and Treasurys are substitutable,

$$\frac{\partial G(s, \ell)}{\partial s} > 0, \quad \frac{\partial D(s, \ell)}{\ell} > 0$$

3. Among all the derivatives of supply and demand functions, only $\hat{D}'_s$ is related to $\mathcal{C}$. Furthermore, $\hat{D}'_s$ is positive, and increases with $\mathcal{C}$.

$$\hat{D}'_s(s,r) = \hat{D}'_s(s,r;\mathcal{C}) > 0, \quad \frac{\partial \hat{D}'_s(s,r)}{\partial \mathcal{C}} > 0$$

4. The sensitivity of deposit supply with respect to the risk-free rate is negative,

$$\hat{D}'_r(s,r) < 0$$

A.4 Proof of Proposition 1

Taking derivatives over G on the market clearing conditions (13) and (14), we have

$$D_s{}' s_G{}' + D_\ell{}' \ell_G{}' = \hat{D}_{s'} s_G{}'$$

$$G_s{}' s_G{}' + G_\ell{}' \ell_G{}' = 1$$

Then in equilibrium, the deposit spread and convenience yield response to Treasury supply is

$$s_G{}' = \frac{1}{G_\ell{}'} \frac{1}{\frac{G_s{}'}{G_\ell{}'} - \frac{D_s{}'}{D_\ell{}'} + \frac{\hat{D}'_s}{D_\ell{}'}}$$

$$\ell_G{}' = \frac{1}{G_\ell{}'} \frac{\frac{\hat{D}'_s}{D_\ell{}'} - \frac{D_s{}'}{D_\ell{}'}}{\frac{G_s{}'}{G_\ell{}'} - \frac{D_s{}'}{D_\ell{}'} + \frac{\hat{D}'_s}{D_\ell{}'}}$$

Then we have the quantity sensitivity

$$\frac{\partial D^*}{\partial G_0} = -\frac{1}{-G_\ell{}'} \frac{\hat{D}'_s}{\frac{G_s{}'}{G_\ell{}'} - \frac{D_s{}'}{D_\ell{}'} + \frac{\hat{D}'_s}{D_\ell{}'}}$$

With assumption (34), we have

$$\frac{G_s{}'}{G_\ell{}'} - \frac{D_s{}'}{D_\ell{}'} > 0$$

Furthermore,

$$\frac{\hat{D}'_s}{D_\ell{}'} > 0, \quad -G_\ell{}' > 0, \quad \hat{D}'_s > 0$$

As a result, we have

$$\frac{\partial D^*}{\partial G_0} < 0$$

In addition, it is easy to see that $|\partial D^*/\partial G_0|$ increases in $\hat{D}'_s$, which increases in $\mathcal{C}$. In summary,

$$\partial \left(|\frac{\partial D^*}{\partial G_0}| \right) / \partial \mathcal{C} > 0$$

or equivalently,

$$\partial \left(\frac{\partial D^*}{\partial G_0} \right) / \partial \mathcal{C} < 0$$

Next, the equilibrium Treasury–deposit spread sensitivity is

$$\frac{\partial(s^* - \ell^*)}{\partial G_0} = \frac{1}{-G_\ell'} \frac{\frac{\hat{D}_s'}{D_\ell'} - 1 - \frac{D_s'}{D_\ell'}}{\frac{\hat{D}_s'}{D_\ell'} + \frac{G_s'}{G_\ell'} - \frac{D_s'}{D_\ell'}}$$

Since

$$\frac{G_s'(s,\ell)}{G_\ell'(s,\ell)} - \frac{D_s'(s,\ell)}{D_\ell'(s,\ell)} > -1 - \frac{D_s'(s,\ell)}{D_\ell'(s,\ell)} > 0$$

we have

$$\frac{\partial(s^* - \ell^*)}{\partial G_0} > 0$$

Furthermore, the above derivative increases with $\hat{D}_s'$, or increases with deposit competition. As a result, the deposit spread positively responds to the increase in Treasury supply, and the response is stronger with more fierce deposit supply competition.

Finally, the FFR–deposit spread sensitivity is

$$s_G' = \frac{1}{G_\ell'} \frac{1}{\frac{G_s'}{G_\ell'} - \frac{D_s'}{D_\ell'} + \frac{\hat{D}_s'}{D_\ell'}} < 0$$

and the magnitude decreases with $\hat{D}_s'$, which means that the magnitude decreases with $\mathcal{C}$, i.e.,

$$\frac{\partial s_G'}{\partial \mathcal{C}} < 0$$

A.5   Proof of Proposition 2

Suppose $\ell^* = \ell(G_0, r)$ is fixed. In other words, G_0 is adjusted to make sure a change in r is not affecting ℓ^*. After taking derivatives over r on the equilibrium market clearing condition (13), we have

$$D_s' s_r' = \hat{D}_s' s_r' + \hat{D}_r'$$

$$s_r' = \frac{-\hat{D}_r'}{\hat{D}_s' - D_s'} > 0$$

and the magnitude decreases in $\mathcal{C}$. Furthermore,

$$\frac{\partial D^*}{\partial r} = D_s' \cdot s_r' = D_s' \frac{-\hat{D}_r'}{\hat{D}_s' - D_s'} < 0$$

and the outflow sensitivity decreases in $\mathcal{C}$.

If G_0 is fixed instead, then we need to use both market clearing conditions (13) and (14) to get

$$D_s' s_r' + D_\ell' \ell_r' = \hat{D}_s' s_r' + \hat{D}_r'$$

$$G_s' s_r' + G_\ell' \ell_r' = 0$$

which implies that

$$s'_r = \frac{-\hat{D}'_r}{\hat{D}'_s - D_s{}' + D_\ell{}'\frac{G_s{}'}{G_\ell{}'}}$$

which has an additional term in the denominator. All we need is to guarantee that the denominator is positive, which requires

$$\hat{D}'_s - D_s{}' + D_\ell{}'\frac{G_s{}'}{G_\ell{}'} > 0$$

By (34), we have

$$-D_s{}' + D_\ell{}'\frac{G_s{}'}{G_\ell{}'} > 0$$

Therefore,

$$s'_r > 0$$

Moreover, the functional form implies that a higher $\mathcal{C}$ results in a smaller s'_r.

Next, the Treasury–deposit spread response is

$$\frac{\partial(s^* - \ell^*)}{\partial r} = \frac{1 + \frac{G_s{}'}{G_\ell{}'}}{\hat{D}'_s - D_s{}' + D_\ell{}'\frac{G_s{}'}{G_\ell{}'}}(-\hat{D}'_r) > 0$$

and the sensitivity decreases with $\mathcal{C}$.

The equilibrium quantity response is

$$\frac{\partial D^*}{\partial r} = \hat{D}'_r \frac{-D_s{}' + D_\ell{}'\frac{G_s{}'}{G_\ell{}'}}{\hat{D}'_s - D_s{}' + D_\ell{}'\frac{G_s{}'}{G_\ell{}'}} < 0$$

and the magnitude of this response is stronger when $\mathcal{C}$ is smaller (or $\hat{D}'_s$ is smaller).

A.6 Proof of Proposition 3

The elasticity of bank i's deposit demand is

$$\frac{\partial \log(\tilde{D}_i^W + \tilde{D}_i^R)}{\partial \log(s_i)} = \frac{\tilde{D}_i^W}{\tilde{D}_i^W + \tilde{D}_i^R}\frac{\partial \log(\tilde{D}_i^W)}{\partial \log(s_i)} + \frac{\tilde{D}_i^R}{\tilde{D}_i^W + \tilde{D}_i^R}\frac{\partial \log(\tilde{D}_i^R)}{\partial \log(s_i)} \qquad (35)$$

Denote the deposit market share of wholesales depositors W as α_W. Then we get the demand elasticity as

$$e = \frac{N-1}{N}\left(\alpha_W \eta_W + (1-\alpha_W)\eta_R\right) \qquad (36)$$

which implies that a larger fraction of wholesales deposits α_W will increase the deposit demand elasticity e, and therefore, increases the competition $\mathcal{C}$.

When α_W is larger, since $\eta_W > \eta_R$, we get a higher demand elasticity e, or more fierce bank deposit competition $\mathcal{C}$, which implies a larger $\hat{D}'_s$. Keeping everything else equal, this implies that

the equilibrium deposit response to Treasury supply

$$\frac{\partial D^*}{\partial G_0} = -\frac{1}{-G_\ell{}'}\frac{\hat{D}_s'}{\frac{G_s{}'}{G_\ell{}'} - \frac{D_s{}'}{D_\ell{}'} + \frac{\hat{D}_s'}{D_\ell{}'}}$$

increases with η_W.

The equilibrium response of deposit quantity to federal funds rate is

$$\frac{\partial D^*}{\partial r} = \hat{D}_r'\frac{-D_s{}' + D_\ell{}'\frac{G_s{}'}{G_\ell{}'}}{\hat{D}_s' - D_s{}' + D_\ell{}'\frac{G_s{}'}{G_\ell{}'}}$$

which is negative, and the magnitude of the response decreases with $\hat{D}_s'$, keeping everything else equal. Therefore, with a larger α_W, the demand elasticity for individual deposit e increases, which implies that $\mathcal{C}$ increases, leading to a smaller magnitude of deposit response.

A.7 Banks' Demand for Government Bonds

To think about how banks' demand for government bonds affect our results, we assume that individual bank has a "Govt-bonds-in-the-utility" function $v_G(x^G)$, which is increasing and concave in the quantity of government bond holding x^G. Then the problem of bank i becomes

$$\max_{x^G, s_i} v^G(x^G) + x^G(r^G - r_i^D) + (D_i - x^G)\left(Q^{-1}(D_i - x^G) - r_i^D\right)$$

Denote the inverse function of dv_G/dx^G as $X_G(\cdot)$, which can be interpreted as the bank's demand function for Treasurys. Given the property of $v_G(\cdot)$, we know that $X_G(\cdot)$ is a decreasing function.

Denote the new bank deposit supply function still as $\hat{D}$, which now depends not only on s and r, but also on ℓ. To get similar results as in Proposition 1 or 2, we need additional assumptions as follows.

Assumption 1. *Assume that deposit supply function responds more to deposit spread than Treasury convenience yield,*

$$|\frac{\hat{D}_s'}{\hat{D}_\ell'}| > 1$$

Assumption 2. *Assume that the relative impact of Treasury convenience yield on the deposit demand function is larger than that on the deposit supply function,*

$$|\frac{D_\ell{}'}{D_s{}'}| > |\frac{\hat{D}_\ell'}{\hat{D}_s'}|$$

Assumption 1 can be interpreted as restricting the magnitude of $\hat{D}_\ell'$. In other words, we need to restrict how much the bank deposit supply function is affected by the Treasury convenience yield. This sensitivity is directly related to the slope of banks' liquidity benefit function v^G. If satisfying the liquidity demand of banks is easy, i.e., we have a large $|(v^G)''|$, then the magnitude of $\hat{D}_\ell'$ is small. Assumption 2 restricts the relative importance of Treasury convenience yield on bank deposit supply versus on bank deposit demand.

Next, we have the following proposition.

Proposition 4. *Under assumptions 1 and 2, Proposition 1 still holds. Under assumptions 2, Proposition 2 still holds.*

According to Proposition 4, the conditions required by Proposition 1 to still hold are stronger than the conditions required by Proposition 2. Intuitively, this is because the results about FFR and deposit outflows are about bank asset side responses, and therefore, we only need to impose additional assumptions on bank deposits supply. On the other hand, the results about Treasurys crowding out deposits are relying on the substitution between Treasurys and deposits on the demand side. To generate the same results when banks demand Treasurys themselves, we not only need that the bank demand for Treasurys is not too strong, but also that it is smaller than the substitution effect between Treasurys and deposits.

Proof for Proposition 4

Let's rewrite the optimization problem as

$$v_G(x^G) + x^G(r^G - r_i^D) + (D_i - x^G)\left(\frac{\bar{Q} - (D_i - x^G)}{2\beta} - r_i^D\right)$$

$$\Rightarrow v_G(x^G) + x^G(s_i - \ell) + (D_i - x^G)\left(\frac{-(D_i - x^G)}{2\beta} + g(r) + s_i\right)$$

Then the first order condition over government bond holding x^G is

$$v_G'(x^G) = \ell - s_i \tag{37}$$

The first order condition over s_i is

$$x^G + \frac{\partial D_i}{\partial s_i}\left(\frac{x^G}{\beta} - \frac{D_i}{\beta} + g(r) + s_i\right) + (D_i - x^G) = 0$$

Using the assumption

$$\frac{\partial \log(D_i)}{\partial \log(s_i)} = -\eta$$

We can simplify the FOC into

$$\frac{s_i}{\frac{x^G}{\beta} - \frac{D_i}{\beta} + g(r) + s_i} = -\frac{\partial \log(D_i)}{\partial \log(s_i)} = \eta$$

which implies the aggregate supply curve as

$$\hat{D} = x^G + \beta\left(g(r) + \frac{\eta - 1}{\eta}s\right)$$

Denote the inverse function of $v_G'(\cdot)$ as $X_G(\cdot)$, which is the bank's Treasury demand function solved from (37). By assumption, $X_G(\cdot)$ is a decreasing function. Plugging in the inverse function, we have

$$\hat{D} = X_G(\ell - s) + \beta\left(g(r) + \frac{\eta - 1}{\eta}s\right)$$

Therefore, the aggregate deposit supply now depends on r, s, and ℓ. It is easy to see that

$$\hat{D}'_\ell < 0, \quad \hat{D}'_r < 0, \quad \hat{D}'_s > 0$$

Furthermore, because of banks' demand for Treasurys, we need to rewrite the aggregate Treasury demand function as

$$\widetilde{G}(s, \ell) = G(s, \ell) + X_G(\ell - s)$$

which increases in s and decreases in ℓ. Furthermore, we note that

$$\frac{\tilde{G}'_\ell}{\tilde{G}'_s} = \frac{G_\ell' + (X_G)'}{G_s' - (X_G)'}$$

Given (34),

$$-G_\ell' > G_s' > 0$$

As a result,

$$\left|\frac{\tilde{G}'_\ell}{\tilde{G}'_s}\right| = \left|\frac{G_\ell' + (X_G)'}{G_s' - (X_G)'}\right| = \left|\frac{-G_\ell' - (X_G)'}{G_s' - (X_G)'}\right| > 1$$

Impact of Treasury Supply

First, when we study the impact of G_0, we fix the federal funds rate r. Then the equation system becomes

$$D(s, \ell) = \hat{D}(s, r, \ell)$$

$$\tilde{G}(s, \ell) = G_0$$

The difference is that we have the additional argument ℓ in the deposit supply function. Taking derivative over G_0, we have

$$D_s' s_G' + D_\ell' \ell_G' = \hat{D}'_s s_G' + \hat{D}'_\ell \ell_G'$$

$$\tilde{G}'_s s_G' + \tilde{G}'_\ell \ell_G' = 1$$

which implies

$$s_G' = \frac{1}{\tilde{G}'_\ell} \frac{\hat{D}'_\ell - D_\ell'}{D_s' - \hat{D}'_s + (\hat{D}'_\ell - D_\ell')\frac{\tilde{G}'_s}{\tilde{G}'_\ell}}$$

$$\ell_G' = \frac{1}{\tilde{G}'_\ell} \frac{D_s' - \hat{D}'_s}{D_s' - \hat{D}'_s + (\hat{D}'_\ell - D_\ell')\frac{\tilde{G}'_s}{\tilde{G}'_\ell}}$$

From Assumption 1, we get

$$D_s' - \hat{D}'_s + (\hat{D}'_\ell - D_\ell')\frac{\tilde{G}'_s}{\tilde{G}'_\ell} < 0$$

As a result,

$$s_G' < 0, \quad \ell_G' < 0$$

59

Next, the spread between Treasurys and bank deposits is

$$s_G{}' - \ell_G{}' = \frac{1}{\tilde{G}'_\ell} \frac{\left(\hat{D}'_\ell - D_\ell{}'\right) - \left(D_s{}' - \hat{D}'_s\right)}{D_s{}' - \hat{D}'_s + (\hat{D}'_\ell - D_\ell{}')\frac{\tilde{G}'_s}{\tilde{G}'_\ell}}$$

Assumption 1 implies

$$\left(\hat{D}'_\ell - D_\ell{}'\right) - \left(D_s{}' - \hat{D}'_s\right) > 0$$

Therefore,

$$\ell_G{}' - s_G{}' > 0$$

Rewrite the difference as

$$s_G{}' - \ell_G{}' = \frac{1}{-\tilde{G}'_\ell} \frac{\left(\hat{D}'_s - D_s{}'\right) - \left(D_\ell{}' - \hat{D}'_\ell\right)}{\hat{D}'_s - D_s{}' - (D_\ell{}' - \hat{D}'_\ell)\frac{\tilde{G}'_s}{-\tilde{G}'_\ell}}$$

Since

$$0 < \frac{\tilde{G}'_s}{-\tilde{G}'_\ell} < 1$$

and

$$0 < (D_\ell{}' - \hat{D}'_\ell)\frac{\tilde{G}'_s}{-\tilde{G}'_\ell} < D_\ell{}' - \hat{D}'_\ell$$

we find that $s_G{}' - \ell_G{}'$ increases in $\hat{D}'_s$, which means that it increases with $\mathcal{C}$. Therefore, we recover our results on deposit spreads.

Next, we show that the quantity responses are similar. The total quantity response is

$$\frac{\partial D^*}{\partial G_0} = D_s{}' s_G{}' + D_\ell{}' \ell_G{}'$$

$$= \frac{1}{\tilde{G}'_\ell} \frac{D_s{}' \hat{D}'_\ell - D_\ell{}' \hat{D}'_s}{D_s{}' - \hat{D}'_s + (\hat{D}'_\ell - D_\ell{}')\frac{\tilde{G}'_s}{\tilde{G}'_\ell}}$$

$$= -\frac{1}{\tilde{G}'_\ell} D_\ell{}' \frac{D_s{}'\frac{\hat{D}'_\ell}{D_\ell{}'} - \hat{D}'_s}{\hat{D}'_s - D_s{}' - (D_\ell{}' - \hat{D}'_\ell)\frac{\tilde{G}'_s}{-\tilde{G}'_\ell}}$$

According to Assumption 1, we have

$$D_s{}'\frac{\hat{D}'_\ell}{D_\ell{}'} - \hat{D}'_s > 0$$

As a result,

$$\frac{\partial D^*}{\partial G_0} < 0$$

Furthermore, the magnitude of the decline

$$\frac{1}{\tilde{G}'_\ell} D_\ell{}' \frac{D_s{}' \frac{\hat{D}'_\ell}{D_\ell{}'} - \hat{D}'_s}{\hat{D}'_s - D_s{}' - (D_\ell{}' - \hat{D}'_\ell) \frac{\tilde{G}'_s}{-\tilde{G}'_\ell}}$$

increases in $\hat{D}'_s$, which increases in $\mathcal{C}$.

In summary, even if banks have a demand of holding Treasurys, with Assumption 1, the same results as in Proposition 1 still hold.

Impact of Federal Funds Rate

Next, we study the influence of federal funds rate r. If the assumption is that Treasury supply keeps ℓ the same, then we arrive at the same equation system as the scenario without bank demand for Treasurys. Therefore, all results go through. Now suppose that the Treasury supply G_0 itself is kept as constant. Then we have

$$\tilde{G}'_s s_r{}' + \tilde{G}'_\ell \ell_r{}' = 0$$

$$D_s{}' s_r{}' + D_\ell{}' \ell_r{}' = \hat{D}'_s s_r{}' + \hat{D}'_r + \hat{D}'_\ell \ell_r{}'$$

which implies that

$$s_r{}' = \frac{-\hat{D}'_r}{\hat{D}'_s - D_s{}' + D_\ell{}' \frac{\tilde{G}'_s}{\tilde{G}'_\ell} - \hat{D}'_\ell \frac{\tilde{G}'_s}{\tilde{G}'_\ell}}$$

As long as

$$\hat{D}'_s > |\hat{D}'_\ell| \tag{38}$$

and the version of (34) on $\tilde{G}$ holds, $s'_r > 0$, and the derivative with respect to $\mathcal{C}$ remains the same. The assumption is that the impact of deposit spread on deposit supply is higher than the impact of convenience yield on bank deposit supply.

The quantity response is

$$\frac{\partial D^*}{\partial r} = D_s{}' s_r{}' + D_\ell{}' \ell_r{}'$$

$$= (D_s{}' - \frac{\tilde{G}'_s}{\tilde{G}'_\ell} D_\ell{}') s_r{}'$$

$$= -\frac{-\hat{D}'_r(-D_s{}' + \frac{\tilde{G}'_s}{\tilde{G}'_\ell} D_\ell{}')}{\hat{D}'_s - D_s{}' + D_\ell{}' \frac{\tilde{G}'_s}{\tilde{G}'_\ell} - \hat{D}'_\ell \frac{\tilde{G}'_s}{\tilde{G}'_\ell}}$$

If (38) holds, then we have

$$\frac{\partial D^*}{\partial r} < 0$$

We notice that the absolute value still decreases with $\mathcal{C}$. Thus Proposition 2 holds when banks have a demand for Treasurys.

A.8 Reverse Repo Facility

In this subsection, we formulate the study of reverse repo facility in a more formal way. In reality, the Reverse Repo Facility is only accessible to money market mutual funds. But if money market mutual funds are pass-through of investor preference, effectively we allow for households direct access to the reverse repo facility. Therefore, we do not explicitly model the money market funds, but directly assume that the Reverse Repo Facility is supplying assets with a reverse repo rate r_{RRP}, and the supplying quantity is elastic to achieve the reverse repo rate. Denote the FFR – reverse repo spread as

$$\ell_{RRP} = r - r_{RRP}$$

Then the demand function for deposits from households can be rewritten as

$$D(s, \min\{\ell, \ell_{RRP}\})$$

since Treasurys and reverse repos are perfect substitutes.

Furthermore, we assume that Treasurys and reverse repos are perfectly substitutable from the households perspective. Denote the solution of ℓ from the original equilibrium system (without reverse repo) in (13) and (14) as ℓ_0. Then there are three scenarios:

- $\ell_{RRP} > \ell_0$, in other words, the reverse repo rate is below the Treasury yield. In this case, households do not hold reverse repo at all, and the demand function for deposits becomes $D(s, \ell)$. In equilibrium, the Treasury convenience yield is $\ell^* = \ell_0$.

- $\ell_{RRP} < \ell_0$, in other words, the reverse repo rate is above the Treasury yield. In this case, households do not hold Treasurys at all, which implies that the equilibrium demand for Treasurys is 0, below the Treasury supply G_0. In this scenario, the market clearing of Treasurys will adjust Treasury yields endogenously so that in equilibrium, $\ell^* = \ell_{RRP} = \ell_0$.

- $\ell_{RRP} = \ell_0$. In this case, we have $\ell^* = \ell_{RRP}$.

Consequently, there are only two scenarios: (1) If $\ell_{RRP} > \ell_0$, we are back to the original solution, and reverse repo facility has zero impact on the equilibrium. (2) If $\ell_{RRP} \leq \ell_0$, then $\ell^* = \ell_{RRP}$, and a decrease in ℓ_{RRP} will decrease Treasury convenience yield at the same time.

Suppose that $\ell^* = \ell_{RRP}$. Then we can use the deposits market clearing to solve for the deposit spread,

$$D(s, \ell_{RRP}) = \hat{D}(s, r)$$

We note that this equation is the same for the model without reverse repo facility. Therefore, once we have estimated the impact of Treasury yield on equilibrium deposit quantity D^* in the world without reverse repo, we can use the same sensitivity as the equilibrium deposit response to the reverse repo rate.

Since the reverse repo rate has zero impact if it is below ℓ_0, we have the following proposition.

Proposition 5. *Denote the equilibrium deposit quantity with the reverse repo facility as D^*_{RRP}, and without reverse repo facility as D^*. Then we have*

$$\frac{\partial D^*_{RRP}}{\partial \ell_{RRP}} = \begin{cases} 0 & \text{if } \ell_{RRP} > \ell_0 \\ \dfrac{\partial D^*}{\partial \ell_0} & \text{if } \ell_{RRP} \leq \ell_0 \end{cases}$$