Will Central Bank Digital Currency Disintermediate Banks?

Toni M. Whited, Yufeng Wu, and Kairong Xiao*

August 27, 2022

Abstract

This paper studies how introducing a central bank digital currency (CBDC) can affect the banking system. We show that CBDC needs not reduce bank lending unless frictions and synergies bind deposits and lending together. We then estimate a dynamic banking model to quantify the importance of these frictions and synergies for the impact of a CBDC on the banking system. Our counterfactual analysis shows that a CBDC can replace a significant fraction of bank deposits, especially when it pays interest. However, CBDC has a much smaller impact on bank lending because banks can replace a large fraction of any lost deposits with wholesale funding. Substitution to wholesale funding makes banks' funding costs more sensitive to changes in short-term rates, increasing their exposure to interest rate risk. We also show that a CBDC amplifies the impact of monetary policy shocks on bank lending.

JEL Codes: E51, E52, G21, G28

Keywords: Central bank digital currency, banking competition, maturity mismatch, financial stability.

*Whited is from the University of Michigan and the NBER; twhited@umich.edu. Wu is from the University of Illinois; yufengwu@illinois.edu. Xiao is from Columbia University; kairong.xiao@gsb.columbia.edu. None of the authors have any relevant or material financial interests related to the research described in this paper. We thank Jonathan Berk, Juliane Begenau, Greg Buchak, Sylvain Catherine, Darrell Duffie, Arvind Krishnamurthy, Jiaqi Li, Christine Parlour, Monika Piazzesi, Claudia Robles-Garcia, David Sraer, and Andrew Usher for their helpful comments and discussions. We also thank participants at Stanford GSB, the Brazilian Society of Econometrics Annual Meeting, the Canadian Economic Association Special Session on Digital Currency, ECB, the Intermediation and Bank Liquidity Conference at Richmond Fed, and the UBC summer conference for their helpful comments.

1. Introduction

A central bank digital currency (CBDC) is a country's official currency in digital form. A CBDC differs from existing digital money such as bank deposits because a CBDC is a direct liability of the central bank rather than of a commercial bank. While a CBDC potentially offers safer, faster, and cheaper payments for the general public, it also raises complex policy issues and risks. A prominent concern is that a CBDC might dis-intermediate the existing banking system and reduce the availability of credit. For instance, a report from the Federal Reserve notes that "a widely available CBDC [...] could reduce the aggregate amount of deposits in the banking system, which could in turn increase bank funding expenses, and reduce credit availability or raise credit costs for households and businesses."[1]

An implicit assumption underlying many extant discussions of CBDC is that shocks to bank deposits are necessarily transmitted to bank lending. Greg Baer, the President and CEO of the Bank Policy Institute, writes that "given that the average loan-to-deposit ratio for banks is generally around 1:1, every dollar that migrates from commercial bank deposits to CBDC is one less dollar of lending."[2] This assumption is also present in academic research on CBDC. For example, Keister and Sanches (2021), Andolfatto (2021), and Chiu, Davoodalhosseini, Jiang, and Zhu (2019) study CBDC with models in which bank lending is entirely funded by deposits. While banks are still largely funded by deposits, such may not be the case in a counterfactual world with CBDC. Even in our current banking system, many banks, especially large ones, can fund deposit shortfalls using wholesale funding. Furthermore, the assumption that bank lending has to be funded by deposits rests upon the fundamental question of whether loan origination is bound to deposit creation.

[1] See "Money and Payments: The U.S. Dollar in the Age of Digital Transformation."
[2] See "Confronting the hard truths and easy fictions of a CBDC," *Business Reporter*, 2021.

We advance the extant literature on CBDC on two fronts. We start with a baseline result that in a frictionless world, deposit creation and loan origination can be entirely separable. Shocks to bank deposits, including those from the introduction of a CBDC, should have no impact on bank lending. Intuitively, loans are priced at the market interest rate rather than the deposit rate. Therefore, a profitable loan would remain so even if banks lose cheap deposits.[3] While banks do not operate in a frictionless world, this baseline allows us to isolate the various frictions that do allow a CBDC to affect the banking system.

To this end, we construct an infinite-horizon, quantitative banking model to evaluate the frictions and synergies that connect loans with deposits. The first set of frictions is related to banks' external financing—banks incur a cost to access wholesale funding, and the wholesale funding is not insured and it charges an interest rate that increases with banks' default risk. Thus, as banks become more reliant on wholesale funding, their funding costs rise, which depresses lending (Kashyap and Stein 1995). In addition, such effect can not be largely alleviated by banks' equity issuance, which is also costly due to information frictions and issuance costs, so banks only tap the equity market infrequently.

The second set of frictions is related to banks' regulatory requirements. Banks are required to maintain a minimum level of capital relative to their assets to maintain sufficient "skin in the game". Many banks also hold excess equity capital on their balance sheet as a buffer against any unexpected shocks. Banks accumulate their equity capital mainly through retained earnings, of which profits from the deposits are a crucial source. An increase in deposit competition may reduce bank capital and, consequently, the capacity to lend.

The model also features an important synergy between deposits and loans. By borrowing

[3] A similar argument has been made by Darrel Duffie in his testimony before the U.S. Senate Committee on Banking, Housing, and Urban Affairs in June 2021, where he says, "Banks do not currently offer unprofitable loans using the irrational justification that they can recoup the associated losses by exploiting their below-market deposit rates." See Duffie (2021).

short-term and lending long-term, banks face a substantial maturity mismatch on their balance sheets, which potentially exposes them to interest rate risk (Flannery 1981). If banks were entirely funded by wholesale funding, an unexpected hike in the short-term rate would decimate banks' equity because their funding costs would increase more than their interest income from long-term loans. However, deposits provide a natural hedge against this interest rate risk that stems from maturity transformation because deposits have an effective long duration despite having short maturity (Drechsler, Savov, and Schnabl 2021).

Facing these frictions and synergies, banks optimally choose deposit and lending rates to maximize profits. We model the deposit and lending markets using a characteristic-based demand approach from the industrial organization literature in which a product is described as a bundle of characteristics (Berry, Levinsohn, and Pakes 1995; Nevo 2001). We then introduce CBDC as a new product in a characteristic-based demand system. This demand system is also conducive to studying different policy proposals concerning CBDC because we can easily vary the attributes of the CBDC.

We discipline the model using U.S. bank data following Wang, Whited, Wu, and Xiao (2021). We first use demand estimation techniques to obtain the elasticities of loan and deposit demand to interest rates. We then plug these estimates into our model and use simulated minimum distance to obtain estimates of parameters that quantify financial frictions and operating costs.

In the estimated model, a CBDC is introduced to the deposit market as a direct central bank liability that households can hold, with the interest rate determined by the central bank. The central bank does not participate in the loan market because loan origination requires local soft information and expertise that the central bank does not possess. Instead, the central bank invests the raised funds from CBDC on government securities. Facing

deposit competition from the CBDC, banks can increase deposit rates, replace deposits with wholesale funding, or cut lending. The exact margins that banks use to accommodate the introduction of CBDC depend on the frictions and synergies that link deposit-taking and loan-origination.

To understand the effects of a CBDC on the banking system, we conduct a variety of counterfactual experiments. First, we consider a CBDC that pays no interest and provides the same transaction services as bank checking accounts. We find that CBDC can significantly affect banks' deposit-taking business: a one-dollar increase in CBDC reduces bank deposits by around 70 cents. However, only a third of the impact on deposits is passed through to lending: a one-dollar increase in CBDC reduces bank lending by around 20 cents. The attenuated impact on bank lending happens because banks can replace deposits with wholesale funding.

However, the substitution is not perfect because of the external financing frictions. Banks cannot replace all of the lost deposits with wholesale funding and instead have to partially cut lending. In addition, as banks replace interest-insensitive deposits with wholesale funding, banks' exposure to interest rate risk also rises. We find that the impact of an unexpected increase in the short-term rates on bank capital increases twofold when CBDC is introduced. Finally, introducing CBDC also lowers banks' profits from the deposit market, which reduces bank capital and the lending capacity. A decomposition of different channels indicates that the first quantity-based channel is the most important one, followed by the profit-based channel.

The impact of CBDC is heterogeneous across banks of different sizes. Big banks rely less on deposits and have better access to non-deposit financing. As result, they are better equipped to adapt to a financial system with CBDC than small banks. Indeed, we find the impact of CBDC on bank lending is three times greater for small banks than for big banks

even though CBDC has comparable effects on deposits across the two groups. Because small firms disproportionately rely on small banks for credit, this result suggests that CBDC could affect small firms' credit access more than big firms.

The impact of CBDC also depends on local deposit market concentration. In a highly concentrated market, the impacts of CBDC on the quantities of deposits and loans are less pronounced because high markups can cushion the impacts of CBDC. In comparison, in a highly competitive market, the impacts of CBDC are more pronounced on both deposits and loans. Because depositors benefit less from CBDC in a highly competitive market but borrowers tend to lose more bank lending, the introduction of CBDC could have redistributional implications across regions with different bank competition.

CBDC can also significantly affect monetary policy transmission in the banking system. The introduction of a CBDC intensifies competition in the deposit market. Therefore, banks have to raise deposit rates more aggressively to avoid losing deposits to the CBDC. This effect, in turn, limits banks' ability to insulate borrowers from rate hikes. As a result, a CBDC amplifies the impact of monetary policy shocks on bank lending. CBDC also has implications for financial stability. Because of the competition from CBDC, banks become less profitable. As a result, CBDC can slow down banks' recovery following negative shocks to capital.

We also consider an alternative policy proposal that allows CBDC to pay interest. On the one hand, this proposal might increase households' surplus from holding CBDC, especially for those that lack access to interest-bearing bank deposits. Moreover, competition from CBDC can force banks to pay higher deposit rates, which benefit depositors. On the other hand, interest-bearing CBDC might be too disruptive because it would divert a significant amount of deposits from the banking sector. Indeed, we find that banks would lose around 30% of

their deposits if a CBDC paid the federal funds rate, despite the competitive response from banks to raise deposit rates. An interest-bearing CBDC also generates different substitution patterns from a non-interest-bearing one. Banks would lose more savings deposits because an interest-bearing CBDC becomes a closer substitute to savings deposits.

We consider possible policy responses to alleviate the adverse impacts of CBDC on the banking system. Because CBDC increases the effective maturity mismatch of private banks, a central-bank policy that could undo this effect would be the use of any raised funds from CBDC to make term loans to banks. This policy would allow banks to access more long-duration liabilities, thus reducing their interest-rate risk. The downside of this policy is the transference of interest-rate risk to the central bank, as it incurs losses when the interest rate changes. This result is related to Brunnermeier and Niepelt (2019), who show that the central bank can undo the impact of a CBDC on private banks by lending back to private banks the funds raised from a CBDC. We show that the effectiveness of this policy depends on the maturity of the central bank's loans to banks. If the central bank only offers short-term loans, this policy cannot undo the increased interest risk faced by private banks.

This paper contributes to a fast-growing body of research on CBDC. Recent surveys of the literature can be found in Carapella and Flemming (2020), Ahnert, Assenmacher, Hoffmann, Leonello, Monet, and Porcellacchia (2022), and Duffie, Foucault, Veldkamp, and Vives (2022). We add to this literature in several ways. First, we clarify an important conceptual issue underlying the extant discussion of CBDC by emphasizing an irrelevance result, that is, deposit-taking and loan-origination are entirely separable in a frictionless world. Therefore, to understand the impact of CBDC on bank lending, it is not sufficient to study the impact on deposits. One has to understand the frictions and synergies that connect deposits and loans. A key contribution of this paper is to lay down the conditions under which the impacts

on deposits may or may not pass through to bank lending.

Furthermore, because CBDCs have been mostly in the stage of policy deliberation, the literature has largely been theoretical. While the existing studies are helpful for illustrating a particular mechanism, they often have predictions that are quantitatively ambiguous. Our paper contributes to this literature by providing quantitative estimates disciplined by the data. For example, Keister and Sanches (2021) and Fernández-Villaverde, Sanches, Schilling, and Uhlig (2021) suggest that a CBDC would structurally decrease deposit funding available to banks, while Kumhof and Noone (2018) and Chiu et al. (2019) argue that the existence of a CBDC as an outside option forces imperfectly competitive banks to match the CBDC rate, which crowds in saving and increases deposits. Our paper clarifies this issue by showing that CBDC can only crowd in deposits if CBDC and deposits are perfect substitutes so that the CBDC rate sets a floor for bank deposit rates. However, if CBDC and deposits are differentiated products, banks can in principle pay a rate below the CBDC rate and the crowd-in effect may not arise. Indeed, in the estimated differentiated products demand system, we find the CBDC-induced increase in deposit rates is not sufficient to crowd in deposits in the equilibrium.

This paper also contributes to a strand of literature studying the macroeconomic implications of CBDC. Piazzesi and Schneider (2020) study the welfare implications of CBDC in a macroeconomic model and show that CBDC can potentially decrease social welfare by interfering with the complementarity between credit lines and deposits built into modern payment systems. Schilling, Fernández-Villaverde, and Uhlig (2020) study the implications of CBDC on price and financial stability. Niepelt (2022) studies the optimal monetary architecture with both reserves and CBDC. Williamson (2019) shows that CBDC can raise welfare by freeing up scarce collateral for banks that are subject to limited commitment. Burlon,

Montes-Galdon, Muñoz, and Smets (2022) studies the optimal quantity of CBDC in a DSGE model. Related to these general equilibrium studies, we focus on the industrial equilibrium of the banking sector because much extant debate centers around the concern about disintermediating banks. This more focused approach allows us to map our model to data and thus provide quantitative predictions about the implications of CBDC on the pass-through of policy rates to bank lending.

Finally, this paper contributes to the broader banking literature. A long-lasting issue in the banking literature is the merit of narrow banking, which is the idea that deposit-taking and loan origination can be done separately by different financial intermediaries (Pennacchi 2012). The policy debate on CBDC is reminiscent of this question as CBDC replaces private banks' deposit-taking but not loan-origination. We provide a quantitative model to evaluate how the private banking system would realign itself following such a structural change and how such a realignment is constrained by the frictions and synergies that bind deposits and loans together. This paper also relates to a fast growing strand of literature that studies the competition between traditional banks and various forms of shadow banks and Fintech (Buchak, Matvos, Piskorski, and Seru 2018; Xiao 2020; Begenau and Landvoigt 2022). Although this study focuses on CBDC, this analysis has broader implications for the rise of vertically disintegrated shadow banks and decentralized finance.

2. Simple Model

This section provides a simple static model to clarify a key conceptual issue in the current discussion on CBDC.

2.1. Frictionless benchmark

We start with the frictionless benchmark. Banks take deposits, D, and make loans, L. If banks do not have enough deposits D to fund loans L, they can borrow wholesale funding, $N = L - D$. We assume that banks face no external financing frictions so that they can borrow any amount of wholesale funding at the current federal funds rate, f.[4] We also assume that both deposits and loans have a maturity of one year, thus precluding any maturity mismatch on the balance sheets. Banks choose deposit rate and lending rates, r^d and r^l, to maximize profits, following:

$$\Pi = \max_{\{r^l, r^d\}} r^l L - r^d D - fN, s.t.\ L = D + N \tag{1}$$

The optimal lending and deposit rates in this frictionless benchmark are given by

$$r^l = f + \left(-\frac{L'}{L}\right)^{-1}, \tag{2}$$

$$r^d = f - \left(\frac{D'}{D}\right)^{-1}, \tag{3}$$

where $L' \equiv \frac{\partial L}{\partial r^l}$ and $D' \equiv \frac{\partial D}{\partial r^d}$.

The optimal lending rate and the equilibrium lending quantity do not depend on the deposit market in this frictionless benchmark. In fact, the deposit and the lending decisions are completely separable. Any shock to the deposits, D, including those from the introduction of a CBDC, would have no impact on lending, L. This result also does not depend on the

[4]Conversely, when there are excess deposits, banks can invest any of this surplus, $D - L$, in government securities and earn the federal funds rate, f.

nature of the competition. The demand curves for loans and deposits can be perfectly elastic or perfectly inelastic.

The intuition of this irrelevance result is the following: if banks can substitute deposits with wholesale funding with no friction, then a loan is priced at the market interest rate, f, rather than the deposit rate, r^d. Therefore, a profitable loan would remain so even if banks have fewer deposits, D, or have to pay higher rates on deposits, r^d.

In this frictionless benchmark, introducing CBDC would still negatively affect bank profits as banks lose a cheap source of financing. However, this does not affect bank lending because deposits are not the marginal source of financing. This point is often missed in many discussions on CBDC, as exemplified by the argument that "given that the average loan-to-deposit ratio for banks is generally around 1:1, every dollar that migrates from commercial bank deposits to CBDC is one less dollar of lending."[5] This is a fallacy that confuses the *average* source of financing with the *marginal* source of financing.

2.2. External financing frictions

One possible way to connect the two sides of banks' balance sheets is external financing frictions. We assume that banks now incur a convex cost Φ in addition to the federal funds rate when engaging in wholesale funding. Such a cost can be motivated by the fact that wholesale funding is not insured, so using more wholesale funding would drive up bank default risks. In addition, accessing the wholesale funding market involves building and maintaining relationships with counterparties, which could also be costly. In this case, the

[5]See "Confronting the hard truths and easy fictions of a CBDC," *Business Reporter*, 2021.

banks' optimization problem is:

$$\Pi = \max_{\{r^l, r^d\}} r^l L - r^d D - fN - \Phi(N), s.t.\ L = D + N \tag{4}$$

The optimal lending and deposit rates in this frictionless benchmark are given by

$$r^l = f + \left(-\frac{L'}{L}\right)^{-1} + \Phi'(L - D), \tag{5}$$

$$r^d = f - \left(\frac{D'}{D}\right)^{-1} - \Phi'(L - D). \tag{6}$$

Note that now banks' optimal lending rate and the equilibrium lending quantity become a function of the marginal external financing cost, $\Phi'(L - D)$, which itself depends on the quantity of deposits, D. In this world, if a CBDC reduces bank deposits, it would force banks to raise more wholesale funding, $L - D$, which drives up the marginal external financing cost. As a result, some loans that are profitable before CBDC become unprofitable afterward. As a result, banks cut lending.

2.3. Maturity mismatch

Another way to connect the two sides of banks' balance sheets is to introduce maturity mismatch. We assume that loans mature in η periods. In each period, $\frac{1}{\eta}$ fraction of the loans are repriced. The federal funds rate, f, is uncertain. Banks' profit conditional on a realization of the federal funds rate is given by

$$\Pi(f) = \overline{r}^l L - r^d D - fN, s.t.\ L = D + N \tag{7}$$

where $\overline{r}^l = (1-\frac{1}{\eta})r^l_{-1} + \frac{1}{\eta}r^l$ is the average interest rates on the loan portfolio. r^l_{-1} is the rate of the old loans, which was set in the past and cannot be changed in this period. Banks can only reprice $\frac{1}{\eta}$ fraction of the loans on the asset side, but the entire liability side is repriced at the realized federal funds rate. With maturity mismatch, an unexpected increase in the federal funds rate would drive up the funding costs, but a large fraction of the assets are locked in a low rate, r^l_{-1}. The profits of banks would fall, which reduces bank capital. Assuming banks are risk-averse,[6] they would try to match the interest sensitivity of the assets with that of the liabilities:

$$\text{Asset interest sensitivity} = \underbrace{\frac{1}{\eta}\frac{\partial r^l}{\partial f}}_{<1}, \tag{8}$$

$$\text{Liability interest sensitivity} = \frac{D}{D+N}\underbrace{\frac{\partial r^d}{\partial f}}_{<1} + \frac{N}{D+N}\underbrace{\frac{\partial f}{\partial f}}_{=1}. \tag{9}$$

If banks are funded by wholesale funding, it is difficult to match the interest sensitivities of assets and liabilities because the interest rate sensitivity of wholesale funding, N, is one. However, deposits are special in the sense that deposit rates are sticky—they do not increase one for one with respect to the federal funds rate (Drechsler, Savov, and Schnabl 2017). The stickiness of deposit rates comes from the fact that deposits generate convenience for depositors and from the convenience, banks derive market power (Xiao 2020). Thus, deposits are a natural hedge of the interest-rate risks stemming from maturity transformation.

If CBDC reduces bank deposits and forces banks to rely more on wholesale funding, banks become more exposed to interest-rate risks. The increased risk exposure endogenously

[6]Banks' risk aversion can be generated by costly equity issuance and default.

increases the credit spread facing banks in the wholesale funding market. As a result, it becomes more costly for banks to raise funding on the margin, which reduces bank lending.

2.4. Capital requirements

Finally, banks face capital regulation, which connects banks' assets to liabilities and allows CBDC to affect bank lending. To be specific, suppose banks face capital regulation that requires bank capital to exceed a certain fraction of bank assets. Banks' optimization problem becomes

$$\Pi = \max_{\{r^l, r^d\}} r^l L - r^d D - fN, s.t.\ L = D + N,\ E + \Pi \geq \kappa L, \tag{10}$$

where E is a bank's initial capital, Π is the bank's profit, and κ is the minimum capital requirement. Because we assume no dividends in our static model, the bank's end-of-period capital is given by $E + \Pi$.

Equation (10) shows that in the presence of capital regulation, CBDC can affect banks' lending capacity through bank capital. When CBDC competes away cheap deposits and forces banks to raise deposit rates, banks' profit margins are squeezed, resulting a lower $E + \Pi$. Hence, the introduction of CBDC can reduce banks' lending capacity by lowering deposit market profits. In a dynamic model, banks can adjust dividends to alleviate the impact of reduced profits. However, the dividend adjustment will not fully offset the impact of reduced profits because bank shareholders are impatient. Instead, banks would reduce both dividends and lending in response to lower profitability.

3. Model

After clarifying the conceptual issue underlying the debate on CBDC, we present the full model. Figure 1 illustrates the flow of funds in the model. We consider an infinite-horizon bank industry equilibrium model with four sectors: households, firms, banks, and a central bank. In the model, households and firms solve static discrete-choice problems in which they choose from several saving and financing vehicles. Banks act as intermediaries between households and firms by taking short-term deposits from households and providing long-term loans to firms. Banks can also finance loans with wholesale funding or equity if deposits are insufficient. The central bank offers CBDC to households and invests the funds in Treasuries. The central bank, however, cannot lend to firms due to a lack of local information and expertise.

3.1. Households

At each time t, the economy contains a mass W_t of households, each of which is endowed with one dollar. Because the households' problem is static, we drop the t subscript hereafter for convenience. We assume that each bank offers two types of deposits, transaction and savings deposits.[7] In addition, households can also hold cash, bonds, or CBDC. We further assume that each depositor can choose only one option. This one-dollar, one-option assumption is without loss of generality. For example, we can interpret this setting as if households make multiple discrete choices for each dollar they have. The probability of choosing each option can be interpreted as a portfolio weight.

[7]Modeling transaction and savings deposits separately allows us to study the different substitution patterns generated by different types of CBDCs. The main quantitative results remain robust if we combine the two types of deposits into one type as in Wang et al. (2021).

Each option is characterized by a yield, r_j^d, and a vector of product characteristics, x_j^d, which captures the convenience of each option. For instance, a household might value branches and staffing when choosing a bank. The yield on cash is 0, and the yield on bonds is the federal funds rate, f, where we abstract from differences between short-term Treasury yields and the federal funds rate. All interest rates are quoted in real terms, as we assume inflation expectations are anchored at zero.

The household chooses the best option to maximize its utility:

$$\max_{j \in \mathcal{A}^d} u_{i,j} = \alpha_i^d r_j^d + \beta_i^d x_j^d + \xi_j^d + \epsilon_{i,j}^d, \tag{11}$$

where $\mathcal{A}^d$ is the choice set of households, which includes cash, short-term bond, CBDC, transaction deposits, and savings deposits for each bank. $i \in 1, 2, \ldots, I$ is the type of depositors. The utility for household i from choosing option j is $u_{i,j}$. α_i^d is the sensitivity to the yield r_j^d. β_i^d, are sensitivities to the non-rate product characteristics, x_j^d, which includes a dummy variable that indicates whether the product allows households to make transactions, number of branches, number of employees per branch, time and product fixed effects. We allow the sensitivities to rate and transaction dummy to differ across households. We refer to $q_j^d \equiv \beta^d x_j^d$ as the perceived quality of the product j, where β^d is the vector of average sensitivity to the non-rate characteristics. ξ_j is the unobservable product-level demand shock. $\epsilon_{i,j}^d$ is a relationship-specific shock to the choice of option j by household i. $\epsilon_{i,j}^d$ captures horizontal differentiation across banks. The optimal choice for household i is given by an indicator function:

$$\mathbb{I}_{i,j}^d = \begin{cases} 1, & \text{if } u_{i,j} \geq u_{i,k}, \text{ for } k \in \mathcal{A}^d \\ 0, & \text{otherwise.} \end{cases} \tag{12}$$

We aggregate the optimal choices across all households to compute the deposit market share of each bank j. Adopting the standard assumption that $\epsilon_{i,j}^d$ follows a generalized extreme value distribution with a cumulative distribution function given by $F(\epsilon) = \exp(-\exp(-\epsilon))$, we can derive the standard logit market share, s_j^d, as follows:

$$s_j^d\left(r_j^d|f\right) \equiv \int \mathbb{I}_{i,j}^d dF(\epsilon) = \sum_{i=1}^{I} \mu_i^d \frac{\exp\left(\alpha_i^d r_j^d + \beta_i^d x_j^d + \xi_j^d\right)}{\sum_{m\in\mathcal{A}^d} \exp\left(\alpha_i^d r_m^d + \beta_i^d x_m^d + \xi_m^d\right)}, \tag{13}$$

where μ_i^d is the fraction of total wealth, W, held by households of type i. The numerator represents the utility from option j. The demand function for option j is then given by the market share multiplied by total wealth,

$$D_j\left(r_j^d\right) = s_j^d\left(r_j^d\right) W. \tag{14}$$

3.2. Firms

There is a mass, K, of firms, each of which wants to borrow one dollar, so aggregate borrowing demand is K. Firms can borrow by issuing long-term bonds or taking out long-term bank loans. We assume each bank is a differentiated lender because of the different geographic locations and industry expertise. Letting each option be indexed by j, the firms' choice set is given by $\mathcal{A}^l$, which includes bonds, loans from each bank, and the option not to borrow at all.

We assume that both bonds and bank loans have the following repayment schedule for tractability. The firm has to pay back a fraction, η, of its outstanding principal plus interest in each period. Thus, if the firm borrows one dollar at a fixed interest rate r, the repayment stream, starting in the next period, is $(1-\eta)\times(\eta+r)^t$, $t = 0, \ldots, \infty$. Accordingly, all firm

debt has an average maturity of $1/\eta$ periods.

Each of the firm's financing options is characterized by a rate, r_j^l, and a vector of product characteristics, x_j^l, capturing the convenience of using each of the financing options. If a firm chooses not to borrow, the interest rate is zero. If a firm chooses to issue bonds, the interest rate is given by the long-term bond interest rate, which equals the expected default cost, $\bar{\delta}$, plus the expected weighted average of future federal funds rates, $\bar{f}_t$:

$$\bar{f}_t = \eta f_t + \mathbb{E}_t \left[\sum_{n=1}^{\infty} \eta(1-\eta)^n f_{t+n} \right]. \tag{15}$$

The firm then chooses the best option to maximize its profits:

$$\max_{j \in \mathcal{A}^l} \pi_{i,j} = \alpha_i^l r_j^l + \beta^l x_j^l + \xi_j^l + \epsilon_{i,j}^l, \tag{16}$$

where $\pi_{i,j}$ is the profits of firm i from choosing option j, and α_i^l is the sensitivity to the interest rate r_j^l, which follows a uniform distribution with a mean, α^l, and a standard deviation, σ_α^l. The sensitivities to non-rate characteristics, x_j^l, are given by β^l, and ξ_j^l is the unobservable product-level demand shock. $\epsilon_{i,j}^l$ is an idiosyncratic shock when firm i borrows from bank j. The optimal choice of firm i is given by an indicator function:

$$\mathbb{I}_{i,j}^l = \begin{cases} 1, & \text{if } \pi_{i,j} \geq \pi_{i,k}, \text{ for } k \in \mathcal{A}^l \\ 0, & \text{otherwise.} \end{cases} \tag{17}$$

We aggregate the optimal choices across all the firms to compute the loan market share of each bank j. Assuming that $\epsilon_{i,j}^l$ follows a generalized extreme value distribution with a cumulative distribution function given by $F(\epsilon) = \exp(-\exp(-\epsilon))$, we can derive the

standard logit market share:

$$s_j^l\left(r_j^l|f\right) \equiv \int \mathbb{I}_{i,j}^l dF\left(\epsilon\right) = \sum_{i=1}^{I} \mu_i^l \frac{\exp\left(\alpha_i^l r_j^l + \beta^l x_j^l + \xi_j^l\right)}{\sum_{m\in\mathcal{A}^l} \exp\left(\alpha_i^l r_m^l + \beta^l x_m^l + \xi_m^l\right)}, \tag{18}$$

where μ_i^l is the fraction of type i firms. The numerator represents the utility from borrowing from bank j. The demand function for loans is then given by the market share multiplied by the total loan market size:

$$B_j\left(r_j^l\,|f\right) = s_j^l\left(r_j^l\,|f\right) K. \tag{19}$$

3.3. Banks

To simplify notation, we suppress the subscript j and use the superscripts S and T to denote savings and transaction deposits. Each bank simultaneously sets its deposit rates for savings and transaction deposits, $\{r_t^{d,S}, r_t^{d,T}\}$, and its loan rate, r_t^l, given the federal funds rate, f_t, which we assume is an exogenous state variable. These rate-setting decisions implicitly determine the quantities of deposits to take from households and credit to extend to firms. For example, given banks' choice of deposit rates, households solve the utility maximization problem as described in equation (11), which yields the quantity of deposits supplied to each bank, which is given by equation (14). Banks face a zero lower bound for deposit rates:

$$r_t^{d,T} \geq 0, r_t^{d,S} \geq 0. \tag{20}$$

The zero lower bound can be motivated by the availability of a vast range of zero-return storage technology available to households, such as holding cash or buying durable goods. Similarly, given banks' choice of lending rates, firms solve their profit-maximization problem,

which yields the quantity of loans borrowed from each bank given by equation (19).

Lending involves a maturity transformation between assets and liabilities. On the asset side, let L_t denote the amount of loans the bank holds. As in the case of bonds, in each period, a fraction, η, of a bank's outstanding loans matures. This assumption about long-term loans captures a traditional maturity transformation role for banks, in which they convert one-period deposits into long-term bank loans with a maturity of $1/\eta$. As noted above, banks can also issue new loans at an annualized interest rate of r_t^l. The new loans, once issued, have the same maturity structure as the existing ones, and the interest rate is fixed over the life of the new loans. From the bank's perspective, the present value of interest income is:

$$I_t = \sum_{n=0}^{\infty} \frac{(1-\eta)^n B_t r_t^l}{(1+\gamma)^n}, \tag{21}$$

where γ is the bank's discount factor, and a bank's outstanding loans evolve according to:

$$L_{t+1} = (1-\eta)\left(L_t + B_t\right). \tag{22}$$

We assume that in each period a random fraction of loans, $\delta_t \in [0, \eta]$, becomes delinquent. The bank takes δ as an exogenous state variable in its decision-making problem. Although we assume that the bank writes off delinquent payments, with charge-offs equal to $L_t \times \delta_t$, defaulting on payment in one period does not exonerate the borrower from future payments. Therefore, delinquency does not affect the evolution of loans in equation (22).

In each period, the bank can obtain outside financing via deposits or wholesale funding, N_t. Bank deposits are insured, and depositors receive rate $\left\{r_t^{d,S}, r_t^{d,T}\right\}$ on their transaction and savings deposits as posted by banks. Wholesale funding is uninsured, and the suppliers of such funds (e.g., money market mutual funds and corporations) are competitive. The

interest rate that they charge, r_t^N, is such that it allows them to break even. We discuss the determination of r_t^N in Section 3.5. Banks incur additional costs beyond the interest payment to use wholesale funding, such as the costs to build and maintain relationships with counterparties. We model these costs as a quadratic function of the borrowing amount. The total cost from wholesale borrowing can be expressed as:

$$\Phi^N(N_t) = \left[r_t^N + \frac{\phi^N}{2} \cdot \left(\frac{N_t}{D_t^S + D_t^N} \right)^2 \right] N_t. \tag{23}$$

Banks incur costs for serving depositors, such as hiring employees. We assume that costs are linear in the dollar amount of deposits:

$$\Phi^d(D_t^S, D_t^T) = \phi^d \left(D_t^S + D_t^T \right). \tag{24}$$

Similarly, we assume that lending incurs costs, such as paying loan officers to screen loans or maintain client relationships. Again, we assume a linear functional form:

$$\Phi^l(B_t) = \phi^l B_t. \tag{25}$$

We model fixed operating costs and noninterest income, which we assume to be independent of the deposit and lending rate decisions. Specifically, we let χ represent the difference between fixed operating expenses and noninterest income per unit of steady-state equity capital, denoted by $\bar{E}$. Therefore, the net fixed operating cost is $\chi \bar{E}$.

The rest of the asset side of each bank's balance sheet consists of reserves, R_t, and holdings of government securities, G_t, which the bank can accumulate if the supply of funds exceeds demand from the lending market. These securities earn the federal funds rate, f_t. The bank's

holdings of loans, government securities, deposits, reserves, and wholesale borrowing must satisfy the standard condition that assets equal liabilities plus equity:

$$L_t + B_t + R_t + G_t = D_t^S + D_t^T + N_t + E_t, \tag{26}$$

where E_t is the bank's beginning-of-period book equity. E_t itself evolves according to:

$$E_{t+1} = E_t + \Pi_t(1-\tau) - C_{t+1}, \tag{27}$$

where Π_t represents the bank's total operating profits from its deposit-taking, security investments, and lending decisions:

$$\Pi_t = I_t - (L_t + B_t)\delta_t + G_t f_t - r_t^{d,S} D_t^S - r_t^{d,T} D_t^T - \Phi^d - \Phi^l - \Phi^N - \chi\bar{E}. \tag{28}$$

τ in equation (27) denotes the linear tax rate on banks' profits, and C_{t+1} is the cash dividends distributed to the shareholders, s.t.

$$C_{t+1} \geq 0. \tag{29}$$

This constraint implies that a bank can increase its inside equity only via retained earnings but cannot raise equity capital to replace deposits or wholesale borrowing. In Online Appendix, we replace this assumption with costly equity issuance, finding only a limited impact on our results, as banks' equity issuances are both tiny and rare, both in the extended model and the data.

3.4. Federal funds rate

We model the federal funds rate as an AR(1) process correlated with loan charge-offs. The joint law of motion is given by:

$$\begin{bmatrix} \ln \delta_{t+1} - \mathbb{E}(\ln \delta) \\ \ln f_{t+1} - \mathbb{E}(\ln f) \end{bmatrix} = \begin{bmatrix} \rho_\delta & \rho_{\delta f} \\ 0 & \rho_f \end{bmatrix} \cdot \begin{bmatrix} \ln \delta_t - \mathbb{E}(\ln \delta) \\ \ln f_t - \mathbb{E}(\ln f) \end{bmatrix} + \begin{bmatrix} \sigma_\delta & 0 \\ 0 & \sigma_f \end{bmatrix} \varepsilon_{t+1}, \tag{30}$$

where ε_{t+1} has a standard bivariate normal distribution.

3.5. Bank default and wholesale funding cost

Let Γ_t denote the cross-sectional distribution of bank states, and P^Γ denote the probability law governing the evolution of Γ_t, we can express the evolution of Γ_t as:

$$\Gamma_{t+1} = P^\Gamma(\Gamma_t). \tag{31}$$

In every period, after observing the federal funds rate, f_t, and the random fraction of defaulted loans, δ_t, an incumbent bank first chooses whether to default or not, we denote $\omega = 1$ if the bank chooses to default and $\omega = 0$ if otherwise:

$$V(f_t, \delta_t, L_t, E_t \big| \Gamma_t) = \max_{\omega \in \{0,1\}} (1-\omega) \times V^c(f_t, \delta_t, L_t, E_t \big| \Gamma_t), \tag{32}$$

where $V^c(\cdot)$ denotes the value if a bank continues its business without default. If an incumbent bank chooses to continue, it then decides the optimal balance sheet variables to maximize

the expected discounted cash dividends to shareholders:

$$V^c(f_t, \delta_t, L_t, E_t|\Gamma_t) = \max_{\{r_t^l, r_t^{d,S}, r_t^{d,T}, R_t, E_{t+1}\}} \frac{1}{1+\gamma}\left\{C_{t+1} + \mathbb{E}V(f_{t+1}, \delta_{t+1}, L_{t+1}, E_{t+1}|\Gamma_{t+1})\right\} \quad (33)$$

$$\text{s.t. } r_t^d \geq 0, \quad (34)$$

$$E_{t+1} \geq \kappa \times (L_t + B_t), \quad (35)$$

$$R_t \geq \theta \times D_t. \quad (36)$$

Equation (20) suggests that because households can hold cash, which has a zero nominal return, a bank faces a zero lower bound for deposit rates; equations (35) and (36) are the capital and reserve regulations.

A bank chooses to default when its continuation value, $V^c(\cdot)$, falls below zero. When that happens, the bank incurs a bankruptcy cost of ξ on its assets. The FDIC will auction the failed bank and use the proceeds to pay the insured depositors first. Any cash flow that remains after paying the insured depositors will go to the wholesale lenders. If the auction proceeds fall short of the bank's liabilities, then the FDIC will use the funds from Deposit Insurance Funds to fully repay the insured depositors but will not cover the wholesale lenders. Let Ω_t denote the probability of a bank default conditional on the current state, which can be expressed as:

$$\Omega(f_t, \delta_t, L_t, E_t|\Gamma_t) = \mathbb{E}\left\{V^c(f_{t+1}, \delta_{t+1}, L_{t+1}, E_{t+1}|\Gamma_{t+1}) \leq 0\right\}. \quad (37)$$

Given banks' default decision, the break-even interest rate changed by wholesale lenders,

r_t^N, should satisfy the following condition:

$$\begin{aligned} N_t \times f_t = N_t r_t^N \times \Omega_t \\ + (1-\Omega_t) \times \left\{ \left[\eta(1-\delta_t) + (1-\eta)(1-\xi) \right] (L_t + B_t) + G_t + R_t - D_t^S - D_t^T \right\}^+, \end{aligned} \tag{38}$$

where the last term in equation (38) divided by the dollar amount of wholesale borrowing, N_t, captures the lenders' expected recovery rate in the event of a bank default.

The FDIC auctions the failed bank to a pool of H potential investors via a second-price auction. Investors are indexed by their private costs to participate in the auction, i.e., $\varsigma_{1,t} < \varsigma_{2,t} < \varsigma_{3,t} < ... < \varsigma_{H,t}$. The winner of the auction recapitalized banks at a required equity capital, $\underline{E}$. The recapitalized bank has the same expected default rate conditional on the current interest rate environment, $\tilde{\delta}_t = \mathbb{E}(\delta_t | f_t)$. Thus, the price submitted by the second highest bidder is equal to:

$$V^c(f_t, \tilde{\delta}_t, 0, E \big| \Gamma_t) - \varsigma_{2,t}. \tag{39}$$

The investor with the lowest cost, $\varsigma_{1,t}$, will pay this price and take over the failed bank.

3.6. Central bank digital currency

We conceptualize CBDC as a new product provided by the central bank in the deposit market where it competes with bank deposits. Like other products in the deposit market, CBDC is characterized by a vector of characteristics: the interest rate of CBDC, the transaction dummy, and the perceived quality. This characteristics-based demand approach allows us to flexibly consider different policy proposals of CBDC, such as whether CBDC is interest-bearing or not.

We calibrate the vector of characteristics of CBDC in the following way. First, the rate-setting decision of CBDC is different from private banks, which set the rates to maximize profits. Instead, we assume the interest rate of CBDC is determined by an exogenous policy decision because the central bank is not a for-profit institution. Second, we set the transaction dummy to one because the CBDC will likely allow payment processing. Third, there is large uncertainty to calibrate the quality of the CBDC because it depends on how CBDC is implemented and how the general public would perceive this new product, which is difficult to predict. There is some work, such as Li (2021), that attempts to predict the market shares of CBDC using surveys. However, such surveys are not available in the U.S. so far. Therefore, instead of trying to find the "correct" value of this parameter, we vary this parameter to estimate the elasticities of bank outcomes to a marginal dollar increase in CBDC induced by changes in the quality. For the counterfactuals that we need to take a stance on the value of this parameter, we use the quality estimate of cash as an intuitive starting point for the perceived quality of CBDC because the government issues both instruments. We then adjust the quality of cash by a digital premium of 20% based on the existing evidence of the quality improvement of private banks when they introduce digital banking.[8]

We assume the central bank does not make loans directly to firms because it requires local information and expertise unavailable to the central bank. Instead, the central bank invests the funds raised by CBDC in government securities. This assumption is consistent with the institutional reality and the existing policy proposals on CBDC. Therefore, the introduction of CBDC will likely lead to a realignment between deposit creation and loan origination in the banking system—a significant fraction of bank deposits could be replaced by CBDC,

[8]There is no direct estimate of the quality adjustment for central bank currency due to digitization. The closest is Koont (2022), which collects release dates of mobile banking apps by U.S. commercial banks and finds that deposit demand increases by around 20% after the digital app release.

while loan origination would largely remain in private banks.

3.7. Equilibrium

We define equilibrium in this economy as follows.

Definition 1 *A stationary equilibrium occurs when:*

1. *All banks solve the problem given by equation* (33)*, taking as given the other banks' choices of loan and deposit rates.*
2. *When a bank fails, the FDIC will auction the failed bank following equation* (39)*, taking as given other solvent banks' choices of loan and deposit rates.*
3. *Suppliers of wholesale funding price their loans according to equation* (38) *so that they break even.*
4. *Households and firms maximize their utilities given the list of rates put forth by banks.*
5. *In each period, the deposit and loan markets clear.*
6. *The probability law governing the evolution of the industry, P^{Γ}, is consistent with the market participants' optimal choices.*

One of the state variables for the banks' problem (Γ_t) is an object whose dimension depends on the number of banks in the economy. We use a low-dimensional approximation of Γ_t, as proposed by Wang et al. (2021).

4. Estimation

This section describes our estimation methods, presents results, and conducts counterfactuals to assess the relative importance of various frictions for bank risk-taking.

We estimate the model in two stages. First, we estimate the loan and deposit demand functions. Second, we plug these estimates into the model and use simulated minimum

distance (SMD) to estimate the remaining parameters that describe banks' balance sheet frictions.

While the technical details regarding the estimation procedure can be found in Wang et al. (2021) a few points specific to our model deserve discussion. First, we allow each bank to offer transaction and savings deposits separately in our setting. Therefore, we use bank-level data on both the rate and quantity of these two types of deposits for the estimation. Second, depositors in our setting have heterogeneous sensitivities to yields and the transaction dummy.

Next, we use two moments to identify the net fixed operating cost, χ. The first is average net noninterest expenses, scaled by assets. This moment measures banks' costs outside their routine deposit-intaking and loan-servicing business. The second moment is banks' average leverage ratio, which indirectly reflects fixed operating costs, as higher fixed costs induce banks to operate with lower leverage. Next, we estimate the quadratic equity issuance cost, ψ, by matching the average percentage of new equity issuance among banks—larger ψ makes equity issuance more costly and lowers the quantity of issuance. We use banks' average dividend yield to identify the discount rate, γ. Intuitively, a high discount rate makes banks impatient, so they pay out more of their profits to shareholders instead of retaining the funds to finance future business.

To identify the relative size of the deposit market, W/K, as well as the value of firms' outside option of not borrowing, q_n^l, we include banks' average deposit-to-asset ratio and the sensitivity of total borrowing to the federal funds rate, which we estimate using a vector autoregression (VAR). These two moments suit this purpose because holding banks' market shares constant, when W/K increases, the value of deposits rises relative to loan value, leading to a higher deposit-to-asset ratio. Next, when the outside option becomes less valuable, its

market share remains low, regardless of the federal funds rate. Thus, the sensitivity of aggregate corporate borrowing to the federal funds rate falls as q_n^l falls. In addition, the high loan-to-deposit ratio is inversely related to q_n^l because loan demand is weaker when firms value the option not to borrow. Finally, we include banks' average market-to-book ratio to ensure that our model predicts the right valuation for banks. We set the firesale discount, ξ, to 30%, which implies that banks in our model pay, on average, a 21 bps risk premium. With a recovery rate of 70%, banks' default probability is around 64 bps. The magnitude is closely aligned with the evidence from bank credit default swaps documented in Berndt, Duffie, and Zhu (2019). Our parameter estimates are reported in Table 2.

5. Counterfactuals

5.1. The impacts of CBDC on deposits and lending

This section examines how introducing a non-interest-bearing CBDC would influence banks' competitiveness in the deposit market, their cost of funding, and stability. To this end, we perform a sequence of counterfactuals, with the results in Table 4. The first column of Table 4 corresponds to the case when CBDC is absent from the deposit market; column (5) shows the results for a case when CBDC is fully adopted. In columns (2)–(4), we examine cases where the market is phasing in the new CBDC, and the households are not fully adjusted to it yet, in which case, CBDC can suffer a "quality discount".

The results in Table 4 suggest that when CBDC is introduced, it competes with banks and results in lower market shares for both transaction and savings deposits. Banks endogenously raise deposit rates to reduce the deposit outflows, resulting in low deposit spreads.

The introduction of CBDC also significantly influences banks' funding structure. With

households switching from bank deposits to holding CBDC, banks need to substitute their lost deposits with more expensive wholesale funding. This effect on the extensive margin and the previously described effect on the intensive margin (banks need to pay higher rates on deposits) lead to higher funding costs for banks. As a result, banks need to cut their dividends and their values also decline. The decreases in bank profit and value also make default more likely, and therefore, banks face a higher credit spread on their wholesale funding. The increased financing cost also generates a feedback effect that amplifies the declines in bank profit and valuation.

In the last column of Table 4, we report the sensitivities of bank characteristics to changes in the market share of CBDC. One dollar increase in CBDC will crowd out transaction deposits by 64 cents and savings deposits by 10 cents. However, a one-dollar increase in CBDC only decreases bank lending by 19 cents. In other words, the impact of CBDC on bank lending is only a quarter of the impact on the total deposits. This result suggests that the claim that "every dollar that migrates from commercial bank deposits to CBDC is one less dollar of lending" is not well founded because banks can substitute deposits with wholesale funding.

5.2. Decomposition of channels

The next step of our analysis is to decompose the channels through which CBDC affects bank lending. Table 5 shows the results. We start with the baseline case in which one dollar of CBDC reduces bank lending by 19 cents. Row (2) examines the first channel where CBDC introduction reduces the quantity of deposits for banks. As deposits fall, banks need to replace the lost deposits using costly wholesale funding, which decreases bank lending. To isolate this channel, we set banks' interest rate risk exposure and profits to the same values

as the baseline case in the absence of the CBDC so that the effect on lending only reflects the deposits quantity channel. We find that one dollar of CBDC reduces bank lending by 15.8 cents through this channel. Row (3) examines a separate channel where CBDC introduction influences banks' interest rate risk exposure: as banks are increasingly financed with rate-sensitive wholesale funding, banks become more exposed to interest rate risks, which leads them to reduce lending. We find that one dollar of CBDC reduces bank lending by 8.4 cents through this channel. Finally, row (4) examines the profit channel: introducing CBDC reduces banks' competitiveness in the deposit market and squeezes their profit margin. The effect impedes banks' accumulation of capital buffer and makes their capital constraint more binding. We find that one dollar of CBDC reduces bank lending by 11.4 cents through this channel. Comparing the three channels, the most important channel is the reduction of the deposit quantity. It is worth noting that the sum of the effects of individual channels does not necessarily equal the combined effect of all three channels because banks' optimization problem is highly non-linear.

5.3. The impacts of an interest-bearing CBDC

The impacts of CBDC can be further amplified if the Fed starts to pay interest on their digital currency. To examine the impact of an interest-bearing CBDC, we perform a sequence of counterfactuals in Table 6 with respect to the interest rates on CBDC. The first column of Table 6 corresponds to the case when CBDC pays no interest; column (5) shows the results for a case when CBDC pays the federal funds rate. Finally, in columns (2)–(4), we examine cases where CBDC pays a fraction of the federal funds rate. The quality parameter is set at the baseline value in all the counterfactuals.

Recall from Table 4, a non-interest-bearing CBDC captures around 7.6% of the deposit

market. As shown in row (1) of Table 6, if the Fed pays an interest rate that equals the federal funds rate, the interest-bearing CBDC will be able to capture an additional 23.7% of the deposit market. Consequently, the impact on bank lending also increases from -1.4% in the non-interest-bearing case to -7.9% in the interest-bearing case, relative to the economy without CBDC.

The last of Table 6 presents the sensitivities of bank characteristics to changes in the market share of CBDC. An interest-bearing CBDC also generates different substitution patterns across different types of deposits from a non-interest-bearing one. Banks would lose more savings deposits when the CBDC pays interests because an interest-bearing CBDC is a closer substitute to savings deposits. The marginal impact on deposit spreads is also greater because an interest-bearing CBDC forces banks to pay higher deposit rates. The marginal impact of CBDC on bank lending also increases because banks lose a fraction of the cheap deposits and need to pay higher rates on the remaining ones.

The results suggest a trade-off between different policy objectives. On the one hand, policymakers are wary of possible disruptions of CBDC on the existing banking system. Paying interests on CBDC will likely increase its impact on private banks significantly. On the other hand, one motivation for introducing CBDC is improving financial inclusion. Not paying interests on CBDC appears to be at odds with this goal because CBDC will not be an effective savings vehicle for people with limited access to the private banking system.

Our counterfactual exercise shows that an increase in the CBDC interest rate reduces bank deposits and lending. In comparison, in Chiu et al. (2019)'s model, an increase in the CBDC interest rate could "crowd in" deposits and lending. The different results originate from the assumption of the degree of product differentiation in the retail deposit market. Chiu et al. (2019) implicitly assumes that CBDC and retail deposits are perfect substitutes

so that the interest rate on CBDC sets a floor for bank deposit rates, much like how the interest rate on central bank reserves sets a floor on wholesale funding rate. In comparison, we allow banks to optimally choose deposit rates in an empirically estimated deposit demand system. We find that the optimal deposit rates could be lower than the interest rate on CBDC because depositors care not only about the interests paid on deposits r_j^d but also the none-rate characteristics x_j^d, such as the number of branches and staff per branch. Furthermore, the estimated retail depositors' preferences have a large idiosyncratic component $\epsilon_{i,j}^d$ so that a dominated product—one with a lower rate and poorer services—will still get some market share in the equilibrium. As a result, some retail depositors would still stay in private banks even if the deposit rate is lower than the CBDC rate. Bank deposit rates would increase in response to CBDC introduction but would not increase to the level that can lead to a crowd-in effect.

Although the CBDC rate does not naturally emerge as a deposit rate floor in the estimated deposit demand system, in certain scenarios, it may make sense to impose it as an exogenous constraint in the model. For instance, bank regulators could impose a deposit rate floor that equals the CBDC rate.[9] Another possibility is that if the CBDC pays a constant interest rate salient to many depositors, then the CBDC rate could become a psychological reference point for depositors so that banks become reluctant to pay deposit rates below it. Nevertheless, it is important to note that even if such an exogenous deposit rate floor is imposed, the crowd-in effect on deposits may not necessarily lead to more lending because CBDC can still depress bank profits and capital, thus constraining banks' capacity to lend.

[9]The Federal Reserve has neither imposed any deposit rate floor before nor indicated the plan to do so in the future. The closest regulation is the deposit rate ceiling in Regulation Q, adopted in 1933.

5.4. The heterogeneous impact of CBDC

In the previous sections, we show that CBDC affects bank lending mainly through reducing deposits and increasing the reliance on costly wholesale funding. Although the aggregate effect on bank lending is only moderate, the degree of disintermediation could be quite different in the cross-section of banks because of the large heterogeneity in banks' costs of accessing the wholesale funding market.

We examine this mechanism in Figure 2, where we calculate how many dollars of deposits and loans would be crowded out by a one-dollar increase in CBDC (the deposits-CBDC and loan-CBDC sensitivities) under varying levels of wholesale funding cost, $r^N - f$. The results suggest that when banks face a small external financing cost from borrowing wholesale funding, the introduction of CBDC only slightly reduces bank loan provision. The impact mainly comes from the decreased profit from the deposit market, which leads to more binding capital regulation. CBDC also competes away deposits, but the effect is neutralized when banks face a negligible cost to replace the deposits with wholesale funding. However, when banks' external financing cost increases, banks find it increasingly difficult to replace the lost deposits. As a result, the decline in deposit quantity leads banks to cut their loan provisions further.

Interestingly, the impacts on deposits follow the opposite pattern. The reduction in deposits is smaller when the wholesale funding cost is higher because banks are more reluctant to tap into wholesale funding. Instead, they raise deposit rates to keep the deposits from flowing to the CBDC. This result is another piece of evidence that deposits and lending do not necessarily move in tandem, in contrast to the common assumptions in the prior literature on CBDC.

The results above are particularly relevant when considering the heterogeneous impacts

of introducing CBDC across bank size distribution. As shown by Kashyap and Stein (1995), small banks face particularly high frictions in accessing the wholesale funding market, so their supply of loans could be impacted more severely when their retail deposits are competed away by CBDC. To test this hypothesis, we perform a subsample estimation by splitting banks based on their size. We refer to banks in the top one percentile of the asset size distribution as big banks and the rest as small banks.[10]

We re-estimate five key parameters related to bank operations that are likely to vary across banks of different sizes, including their cost function to access wholesale funding, size of depositor base, costs to intake deposits and service loans, and their fixed cost of operation.[11] We target eight moments in our subsample estimation, which correspond to those reported in Table 3, except that we omit the dividend and market-to-book ratio, which we cannot calculate in the small bank subsample because most of them are private.

The estimation results reported in Table 7 suggest that big and small banks differ significantly in a few dimensions, especially regarding their external financing costs and fixed operating costs. These parameters imply that for a bank with a deposits-to-assets ratio of 0.8, the cost of accessing wholesale funding is 52 basis points for the small banks, which is significantly higher than that among big banks, which is 33 basis points. Next, we introduce CBDC into the model and examine how it impacts banks' loan provision decisions. We find that the introduction of CBDC will lead to similar deposit outflows: a one-dollar increase in CBDC decreases deposits by 60.2 cents and 67.5 cents for small and big banks, respectively. However, despite the similar impacts on deposits, the impacts on lending are quite different.

[10] As of 2019, there are around 50 big banks, and their total market share of assets is around 80%, and the cutoff is around 40 billion.

[11] We hold constant households' and firms' preferences because they are not bank specific. We also fix banks' discount rates, equity issuance costs, and dividend adjustment costs at the baseline levels because most small banks are private banks with insufficient data to construct the corresponding identifying moments.

A one-dollar increase in CBDC decreases the lending of big banks by only 14.6 cents but decreases the lending of small banks by 40.7 cents. The intuition behind this result is that big banks can rely on their wholesale funding access to replace the lost deposits in a less costly way. Indeed, we find that the impact of CBDC on the funding costs is much larger for small banks than for big banks.

The introduction of CBDC may also have heterogeneous impacts across deposit markets with different degrees of competitiveness (Chiu et al. 2019). Figure 3 examines how the impacts of CBDC vary across markets with different degrees of concentration, as measured by the number of competing banks in the deposit market.[12] We calculate how many dollars of deposits and loans would be crowded out by a one-dollar increase in CBDC (the deposits-CBDC and loan-CBDC sensitivities) under varying numbers of competing banks, $\hat{J}$. Our result suggests when the market is more concentrated, banks have a greater buffer to absorb the impact of the CBDC. Therefore, the influence on banks' loan provision is more muted. On the other hand, when the market becomes less concentrated, banks compete fiercely among themselves, and any further increase in deposit competition from CBDC has a greater impact on bank lending. Regarding the economic magnitude, a one-dollar increase in CBDC will crowd out bank lending by only 5 cents when the number of competing banks is 4 (corresponding to the 50th percentile of the county-level market concentration as of 2019). In comparison, a one-dollar increase in CBDC holdings will crowd out bank lending by 42 cents when the number of competing banks is 8 (corresponding to the 10th percentile of the county-level market concentration as of 2019).

The heterogeneous impacts of CBDC introduction across banks and regions have important policy implications. Because small firms disproportionately rely on small banks for

[12] We hold the loan market concentration fixed and only vary banks' deposit market power, so the result only reflects the impact of deposit market concentration.

credit, CBDC introduction could affect the credit access of small firms more than big firms. Furthermore, in regions with more competitive deposit markets, depositors benefit less from the additional competition from CBDC, while borrowers lose more from reduced bank lending. Therefore, the introduction of CBDC could have redistributional implications across regions with different degrees of bank competition.

5.5. The impact of CBDC on monetary policy transmission

One of the key motivations for central banks to introduce CBDCs is to maintain the role of public money as a monetary anchor against the background of an increasingly cashless world (Ahnert et al. 2022). This section considers the impact of CBDC on the transmission of monetary policy, with a particular focus on the role of banks due to their central role in money creation and credit supply. In Figure 4, we compare banks' deposit spread (Panel A) and deposit market profit (Panel B) when CBDC is absent with when it has been introduced for different levels of the federal funds rate. In the absence of CBDC, banks' deposit spread and profit from the deposit market increase strongly with the policy rate. The effect has been documented in prior works such as Drechsler et al. (2017, 2021)—a higher federal funds rate increases banks' effective market power on the deposit market because it raises the opportunity cost for households to hold cash. Banks exercise their increased market power by charging higher prices for their depository services, which generates higher profitability from the deposit market. Moreover, introducing CBDC limits how much banks can raise their deposit spread when the fed tightens monetary policy. This result is driven by an endogenous change in the yield sensitivity among banks' depositor bases. CBDC mainly competes away households who prefer transaction convenience, leaving banks with more yield-sensitive clientele. When the policy rate increases, these rate-sensitive households are

more likely to switch to treasury securities instead of holding bank deposits. To keep these depositors, banks cannot raise their deposit spreads as much as they can without competition from the CBDC.

A key channel through which monetary policy affects bank lending is bank capital (Van den Heuvel 2002). Because banks fund themselves with short-term liabilities but lend in the long-term, an increase in the short-term interest rate would reduce bank capital and tighten the bank capital constraint (Flannery 1981). Banks' deposit market power partially offsets the impact of monetary policy on bank capital because deposit rates are stickier than other short-term liabilities, thus function as a hedge for the interest rate risk that stems from maturity transformation (Drechsler et al. 2021). If CBDC competes away deposits or lowers banks' effective market power in pricing deposits, monetary policy shocks may have a greater impact on bank capital. Our model confirms this intuition. When the CBDC is absent, our model predicts that a one percentage point monetary policy shock will cause a 2% decline in bank stock prices, which matches closely with the empirical evidence (Wang et al. 2021). However, when CBDC is introduced, the magnitude of model-predicted stock return to monetary policy shocks increases twofold—a one percentage point monetary policy shock leads banks' stock prices to decline by, on average, 4.6%. The reason behind the increased impact on bank capital is shown in Figure 5, where we plot the average and marginal funding costs for different levels of the federal funds rate. After introducing CBDC, variations in the interest rate indeed transmit more strongly onto banks' average and marginal funding costs because CBDC competes away depositors and lowers their effective market power. As a result, banks' funding cost becomes more sensitive to interest rate, which limits banks' ability to insulate borrowers from rate hikes.

5.6. CBDC, bank capital cushion, and resilience

There is also a concern among policymakers on the implications of CBDC for financial stability. The existing literature primarily focuses on the question of whether CBDC can increase run incentives relative to an economy where cash holdings are the only alternative to bank deposits (Williamson 2021; Skeie 2020; Ahnert, Hoffmann, Leonello, and Porcellacchia 2020). We instead focus on the question of CBDC can reduce bank resilience by compressing banks' profit margins and slows down bank recapitalization.

To study this question, we consider a situation where banks experience large and unexpected loan default shocks. To make our exercise more empirically relevant, we calibrate the severity and length of the default shock to match the 2007-09 Global Financial Crisis (GFC). Using our estimated model, we examine the degree to which bank lending will be affected by the default shocks and the speed at which they recover from such shocks. We compare our model predictions when CBDC is introduced into the deposit market with zero interest rates and when it is absent, with the results reported in Figure 6.

Panel B of Figure 6 shows that a GFC-equivalent loan default shock leads to around 21% reduction in bank capital. The magnitude increases by around 6% when CBDC is introduced—this is because, facing the competition of CBDC, banks become less profitable and thus have thinner capital. Due to the decrease in bank capital, banks have to deleverage by reducing their loans.

Panel C shows that the decreased bank capital also gives rise to significantly higher credit spread of wholesale funding, which increases by over four-fold during the crisis without CBDC, and the increase will be six-fold when CBDC is present. Moreover, the higher credit spread induces banks to refrain from wholesale borrowing, leading to additional declines in bank lending.

As shown in Panel D, the introduction of CBDC will lead to a 4 percent further decline in bank lending and slower recovery from default shocks due to the joint effects from the two channels mentioned above. Banks have a more sluggish recovery because they are slower to accumulate returned earnings to replenish their capital with fewer profits from the deposit market.

5.7. Policy implications

The counterfactual exercises show that CBDC can potentially greatly impact bank deposits, especially when it is interest-bearing. Although banks can substitute a large fraction of the lost deposits with wholesale funding, the impact of CBDC on the lending of small banks could be disproportionally larger because of the external financing frictions facing these institutions. Moreover, because small firms usually borrow from small banks, they could suffer more when a CBDC is introduced. To address this concern, the central bank can lend the funds raised by CBDC back to banks, as suggested by Brunnermeier and Niepelt (2019). Nevertheless, passing the funds back to banks is subject to the same frictions that limit the central bank's involvement in the private lending market because the central bank may not have enough information to evaluate the credit worthiness of each bank.

The second policy issue is bank stability. Even if banks can replace a large fraction of lost deposits with wholesale funding, they come with different terms. Deposits offer a natural hedge for interest-rate risks, but wholesale funding does not. In a financial system with CBDC, banks may become more exposed to interest-rate risks because they have greater maturity mismatch on their balance sheets. To address this issue, we need to modify the Brunnermeier and Niepelt (2019) proposal by allowing the central bank to make term funding to banks. It is worth noting that this policy effectively transfers interest-rate risks to the

central bank.

The final issue is bank profitability. Although the competition from CBDC can raise the depositor surplus, bank profitability may go down and banks could become less resilient. One potential way to alleviate the impact of CBDC on bank profitability is to use an "intermediated account-based" CBDC. Under this approach, private banks would offer accounts or digital wallets to facilitate the management of CBDC holdings and earn a fee. This approach also has the advantage of addressing money laundering concerns for an anonymous "token-based" CBDC because banks have the infrastructure to verify the account holders' identities. Banks earn a fee from providing these valuable services, which reduces the impact of CBDC on bank profitability.

6. Conclusion

This paper studies the implications of CBDC on the banking system. We first clarify an important conceptual issue underlying many extant debates on CBDC, that is, CBDC needs not to reduce bank lending unless frictions and synergies bind deposits and lending together. Therefore, evaluating the potential impact of CBDC on bank lending would effectively be an evaluation of the frictions and synergies that bind deposits and loans. We then estimate a dynamic banking model to quantify how important these frictions and synergies are in the U.S. banking system. Our counterfactual analysis shows that CBDC can replace a significant fraction of bank deposits, especially when it pays interests. However, CBDC would have a much smaller impact on bank lending because banks could replace a large fraction of the lost deposits with wholesale funding. Substitution to wholesale funding could make banks' funding costs more sensitive to changes in short-term rates, increasing their exposure to interest rate risks. We discuss the policy implications of these results for the implementation

of CBDC.

References

Ahnert, Toni, Katrin Assenmacher, Peter Hoffmann, Agnese Leonello, Cyril Monet, and Davide Porcellacchia, 2022, The economics of central bank digital currency, *ECB Working Paper* .

Ahnert, Toni, Peter Hoffmann, Agnese Leonello, and Davide Porcellacchia, 2020, Central bank digital currency and financial fragility.

Andolfatto, David, 2021, Assessing the impact of central bank digital currency on private banks, *The Economic Journal* 131, 525–540.

Begenau, Juliane, and Tim Landvoigt, 2022, Financial regulation in a quantitative model of the modern banking system, *The Review of Economic Studies* .

Berndt, Antje, Darrell Duffie, and Yichao Zhu, 2019, The decline of too big to fail, Available at SSRN 3497897.

Berry, Steven, James Levinsohn, and Ariel Pakes, 1995, Automobile prices in market equilibrium, *Econometrica* 63, 841–90.

Brunnermeier, Markus K., and Dirk Niepelt, 2019, On the equivalence of private and public money, *Journal of Monetary Economics* 106, 27–41.

Buchak, Greg, Gregor Matvos, Tomasz Piskorski, and Amit Seru, 2018, Fintech, regulatory arbitrage, and the rise of shadow banks, *Journal of Financial Economics* 130, 453–483.

Burlon, Lorenzo, Carlos Montes-Galdon, Manuel Muñoz, and Frank Smets, 2022, The optimal quantity of cbdc in a bank-based economy .

Carapella, Francesca, and Jean Flemming, 2020, Central bank digital currency: A literature review .

Chiu, Jonathan, Mohammad Davoodalhosseini, Janet Jiang, and Yu Zhu, 2019, Bank market power and central bank digital currency: Theory and quantitative assessment, Manuscript, Bank of Canada.

Drechsler, Itamar, Alexi Savov, and Philipp Schnabl, 2017, The deposits channel of monetary policy, *Quarterly Journal of Economics* 132, 1819–1876.

Drechsler, Itamar, Alexi Savov, and Philipp Schnabl, 2021, Banking on deposits: Maturity transformation without interest rate risk, *Journal of Finance* 76, 1091–1143.

Duffie, Darrell, 2021, Building a stronger financial system: Opportunities for a digital dollar, *Central Bank Digital Currency Considerations, Projects, Outlook* .

Duffie, Darrell, Thierry Foucault, Laura Veldkamp, and Xavier Vives, 2022, Technology and finance .

Fernández-Villaverde, Jesús, Daniel Sanches, Linda Schilling, and Harald Uhlig, 2021, Central bank digital currency: Central banking for all?, *Review of Economic Dynamics* 41, 225–242.

Flannery, Mark J., 1981, Market interest rates and commercial bank profitability: An empirical investigation, *Journal of Finance* 36, 1085–1101.

Kashyap, Anil K., and Jeremy C. Stein, 1995, The impact of monetary policy on bank balance sheets, *Carnegie-Rochester Conference Series on Public Policy* 42, 151–195.

Keister, Todd, and Daniel R. Sanches, 2021, Should central banks issue digital currency?, Working Paper, Federal Reserve Bank of Philadelphia.

Koont, Naz, 2022, Digital banking, Working Paper, Bank of England.

Kumhof, Michael, and Clare Noone, 2018, Central bank digital currencies-design principles and balance sheet implications, Working Paper, Bank of England.

Li, Jiaqi, 2021, Predicting the demand for central bank digital currency: A structural analysis with survey data, Manuscript, Bank of Canada.

Nevo, Aviv, 2001, Measuring market power in the ready-to-eat cereal industry, *Econometrica* 69, 307–342.

Niepelt, Dirk, 2022, Monetary policy with reserves and CBDC, Manuscript, Swiss National Bank.

Pennacchi, George, 2012, Narrow banking, *Annual Review of Financial Economics* 4, 141–159.

Piazzesi, Monika, and Martin Schneider, 2020, Credit lines, bank deposits or CBDC? competition and efficiency in modern payment systems, Working Paper, Stanford University.

Schilling, Linda, Jesús Fernández-Villaverde, and Harald Uhlig, 2020, Central bank digital currency: When price and bank stability collide, Manuscript, University of Chicago.

Skeie, David R, 2020, Digital currency runs, WBS Finance Group Research Paper.

Van den Heuvel, Skander J., 2002, The bank capital channel of monetary policy, Manuscript, University of Pennsylvania.

Wang, Yifei, Toni M. Whited, Yufeng Wu, and Kairong Xiao, 2021, Bank market power and monetary policy transmission: Evidence from a structural estimation, *Journal of Finance* forthcoming.

Williamson, Stephen, 2019, Central bank digital currency: Welfare and policy implications.

Williamson, Stephen D, 2021, Central bank digital currency and flight to safety, *Journal of Economic Dynamics and Control* 104146.

Xiao, Kairong, 2020, Monetary transmission through shadow banks, *Review of Financial Studies* 33, 2379–2420.

Table 1: Summary Statistics

In this table, we report summary statistics for our sample. The sample period is 1994–2019. Deposits, wholesale borrowing, loans, and expenses related to fixed assets and salaries are scaled by the total assets. Deposit and loan rates are calculated using interest expense and income. Deposit and loan rates are reported in percentages. Asset maturity is reported in years. The data sources are the Call Reports and the FDIC Summary of Deposits.

	mean	sd	p10	p25	p50	p75	p90
Transaction deposits	0.112	0.087	0.023	0.053	0.091	0.142	0.236
Savings deposits	0.678	0.185	0.494	0.586	0.668	0.746	0.932
Wholesale borrowing	0.126	0.103	0.001	0.039	0.104	0.202	0.289
Loans	0.565	0.172	0.330	0.461	0.591	0.683	0.761
Transaction deposit rates	0.299	0.432	0.018	0.051	0.128	0.353	0.820
Savings deposit rates	1.435	1.304	0.087	0.227	1.026	2.475	3.249
Loan rates	6.439	2.146	3.732	4.534	6.208	7.835	9.176
Charge-off rate	0.783	1.077	0.008	0.154	0.393	0.985	2.079
Noninterest income	0.019	0.017	0.006	0.010	0.017	0.023	0.031
Noninterest expenses	0.031	0.015	0.020	0.024	0.028	0.035	0.043
No. of branches	1.387	2.005	0.003	0.016	0.313	1.847	5.413
No. of employees per branch	66.385	80.890	12.600	18.000	29.663	54.019	246.500
Expenses of fixed assets	0.032	0.011	0.010	0.037	0.037	0.037	0.037
Salaries	0.125	0.040	0.044	0.141	0.141	0.141	0.141
Loan-to-deposit ratio	0.735	0.264	0.404	0.518	0.740	0.909	1.066
Borrowing-to-deposit ratio	0.190	0.186	0.001	0.045	0.130	0.285	0.467
Book leverage	11.395	3.154	7.564	9.239	11.238	13.446	15.543
Asset maturity	4.745	2.434	1.884	3.034	4.330	6.338	8.077

Table 2: Parameter Values

In this table, we report the model parameter estimates. Panel A presents calibrated parameters. Panel B presents values for parameters that can be calculated as simple averages or by simple regression methods. Panel C presents results for parameters estimated via BLP. Panel D presents results for parameters estimated via SMD. Standard errors for the estimated parameters are clustered at the bank level and reported in brackets.

Panel A. Statutory Parameters		
τ_c	Corporate tax rate	0.35
θ	The reserve ratio	0.02
κ	The capital ratio	0.06
Panel B. Parameters Estimated Separately		
μ	Average loan maturity	3.425
ξ	Firesale discount	0.3
$\hat{J}$	Number of representative banks	6
$\beta^d_{digital}$	Digital premium	0.2
$\bar{f}$	Log federal funds rate mean	-4.342
σ_f	std of innovation to Log federal funds rate	0.761
ρ_f	Log federal funds rate persistence	0.901
$\bar{\delta}$	Log loan chargeoffs mean	-5.678
σ_δ	Log loan chargeoffs std	1.434
$\rho_{\delta f}$	Correlation between federal funds rate and chargeoffs	-0.102
Panel C.Parameters Estimated via BLP		
α^d	Depositor sensitivity to deposit rates	1.469
σ_{α^d}	Dispersion of sensitivity to deposit rates	0.842
σ_{β^d}	Dispersion of sensitivity to transaction dummy	0.214
α^l	Borrower sensitivity to loan rates	-1.847
$q^{d,T}$	Convenience of transaction deposits	5.389
$q^{d,S}$	Convenience of non-transaction deposits	4.556
q^d_c	Convenience of holding cash	3.706
q^l_l	Convenience of borrowing through loans	1.784
Panel D. Parameters Estimated via SMM		
γ	Banks' discount rate	0.009
W_0	Relative size of the deposit market	0.325
q^l_n	Value of firms' outside option	-11.63
ϕ^d	Bank's cost of taking deposits	0.003
ϕ^l	Bank's cost of servicing loans	0.011
ϕ^N	External financing cost	0.010
χ	Net operating cost	0.007

Table 3: Moment Conditions

This table presents the empirical and simulated moments that we target in our SMM estimation, along with the standard errors for testing the pair-wise difference between the empirical and simulated moments.

	Actual Moment	Simulated Moment	Standard error
Dividend yield	0.034	0.026	0.006
Borrowing-to-deposits ratio	0.190	-0.197	0.022
Borrowing-to-deposits ratio dispersion	0.096	0.094	0.027
Deposit spreads	0.013	0.012	0.001
Loan spreads	0.020	0.022	0.002
Deposits-to-assets ratio	0.771	0.761	0.037
Net non-interest expenses	0.012	0.008	0.001
Leverage	11.395	10.901	0.504
Market-to-book ratio	2.059	1.909	0.253
Total credit-FFR sensitivity	-1.062	-0.926	0.299

Table 4: Counterfactual: varying CBDC quality

In this table, we examine how banks' deposits, cost of funding, and other balance sheet variables respond to the introduction of CBDC. Column (1) corresponds to our baseline model when CBDC is absent from the deposit market; column (5) shows the results when CBDC is fully incorporated following our conceptualization in Section 3.6. In columns (2)–(4), we examine cases where CBDC is introduced but suffers a "quality discount"—we set the quality of CBDC ($q^d_{j=CBDC}$) to 25%, 50%, and 75% of the value we use in column (5), respectively. In colume (5), we calculate the sensitivity of each variable of interest to changes in the market share of CBDC. Transaction deposits, savings deposits, and loans are all normalized by the size of the deposit market.

		$\times q_{CBDC}$				
	No CBDC	25%	50%	75%	100%	Sensitivity
CBDC Share	0.000	0.005	0.012	0.030	0.076	1.000
Transaction deposits	0.537	0.541	0.530	0.516	0.489	-0.638
Savings deposits	0.263	0.273	0.268	0.264	0.255	-0.103
Loan	1.021	1.016	1.015	1.015	1.007	-0.189
Deposit spread (%)	1.125	1.117	1.117	1.113	1.092	-0.432
Loan spread (%)	2.177	2.182	2.183	2.182	2.189	0.147
Bank CDS spread (%)	0.100	0.349	0.309	0.339	0.349	3.274
Funding cost (%)	1.291	1.305	1.321	1.335	1.357	0.874
Net Profit (%)	0.708	0.698	0.692	0.697	0.674	-0.440
M/B	1.846	1.843	1.835	1.833	1.821	-0.338

Table 5: Decompose the impact of CBDC

This table presents the results of a series of counterfactual experiments in which we explore the channels through which the introduction of CBDC affects bank lending. We consider a CBDC that pays zero rates. Row (1) presents the total effect on bank lending; row (2) examines the channel where CBDC introduction only influences the quantity of deposits; row (3) explores the channel where CBDC only changes banks' interest rate risk exposure and widens the credit spreads on wholesale funding; row (4) corresponds to the channel where CBDC only influences bank profit by making them less profitable on the deposit market.

		Loan-CBDC sensitivity
(1)	With CBDC	-0.189
(2)	Influencing deposit quantity	-0.158
(3)	Influencing interest rate exposure	-0.084
(4)	Influencing profit	-0.114

Table 6: Counterfactual: varying CBDC rate

In this table, we examine how banks' deposits, cost of funding, and other balance sheet variables respond to the introduction of CBDC. Column (1) corresponds to our baseline model when CBDC is absent from the deposit market; column (5) shows the results when CBDC pays the federal funds rate. In columns (2)–(4), we examine cases where the rate of CBDC ($r^d_{j=CBDC}$) to 25%, 50%, and 75% of the federal funds rate. In column (5), we calculate the sensitivity of each variable of interest to changes in the market share of CBDC. Transaction deposits, savings deposits, and loans are all normalized by the size of the deposit market.

		×FFR				
	Zero rate	25%	50%	75%	Pays FFR	Sensitivity
CBDC Share	0.076	0.099	0.139	0.209	0.313	1.000
Transaction deposits	0.513	0.498	0.474	0.433	0.374	-0.585
Savings deposits	0.255	0.250	0.239	0.216	0.189	-0.278
Loan	1.007	1.003	1.001	0.975	0.942	-0.271
Deposit spread (%)	1.092	1.078	1.060	1.014	0.965	-0.536
Loan spread (%)	2.189	2.185	2.186	2.202	2.203	0.061
Bank CDS spread (%)	0.581	0.656	0.763	0.340	0.672	0.387
Funding cost (%)	1.357	1.396	1.470	1.635	2.104	3.147
Net Profit (%)	0.674	0.690	0.668	0.622	0.695	0.087
M/B	1.821	1.795	1.724	1.511	1.184	-2.682

Table 7: The heterogeneous impacts of CBDC

In Panel A, we present subsample estimation results by splitting banks based on their size. "Big" consists of banks whose sizes are in the top one percentile, and "Small" consists of all the other banks. In Panel B, we examine how banks' deposits, cost of funding, and lending decisions respond to the introduction of CBDC. Deposit-CBDC sensitivity measures the responsiveness in banks' deposit base to each dollar increase in households' CBDC holdings; Loan-/funding cost- CBDC sensitivity is defined analogously. CBDC has quality of q^{CBDC} as described in Section 3.6 and it bears zero interest rate.

		Small Banks	Big Banks
Panel A: Subsample Parameter Estimates			
ϕ^N	External financing cost	0.040	0.011
W_0	Relative size of the deposit base	0.390	0.328
ϕ^d	Bank's cost of taking deposits	0.012	0.011
ϕ^l	Bank's cost of servicing loans	0.006	0.006
χ	Net operating cost	0.196	0.108
Panel B: Impact of Introducing CBDC			
Deposit-CBDC sensitivity		-0.602	-0.675
Loan-CBDC sensitivity		-0.407	-0.146
Funding cost-CBDC sensitivity		1.533	0.852

Figure 1: Flows of Funds in the Banking System

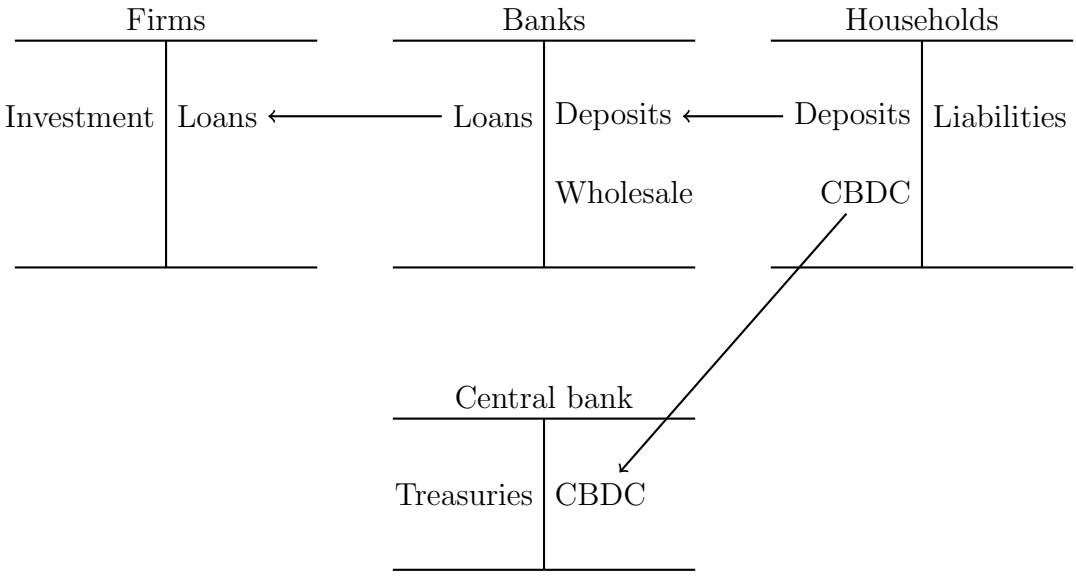
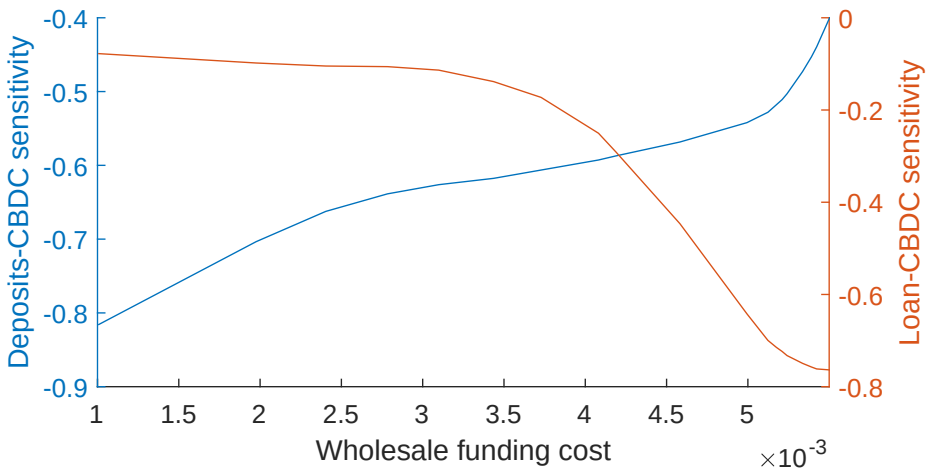
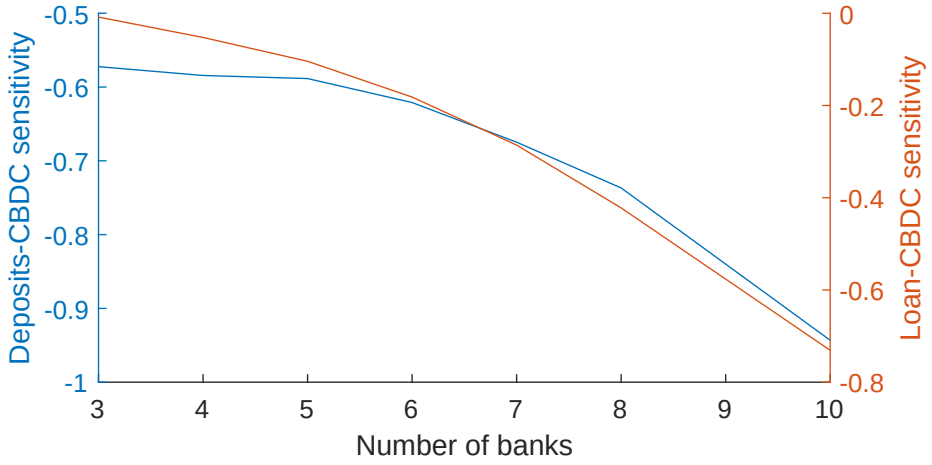


Figure 2: The Role of Wholesale Funding Costs



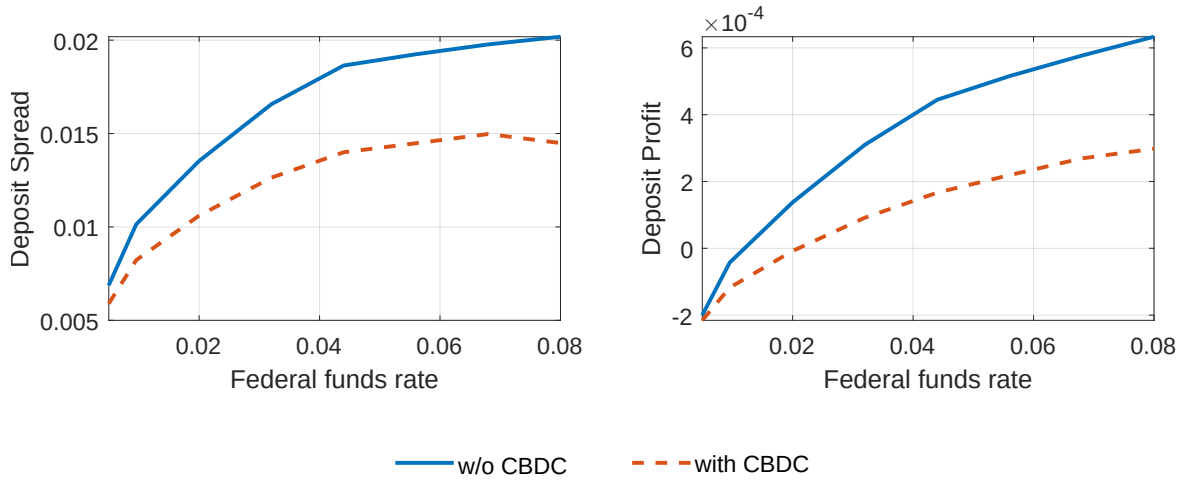
This figure shows the sensitivity of bank deposit intake and loan provision when the CBDC is introduced with quality equals q^{CBDC} and zero interest rate. The change is calculated under varying levels of wholesale funding cost, which is defined as $r^N - f$, with r^N being the wholesale funding lenders' breakeven rate defined in equation (38)

Figure 3: The Role of Deposit Concentration



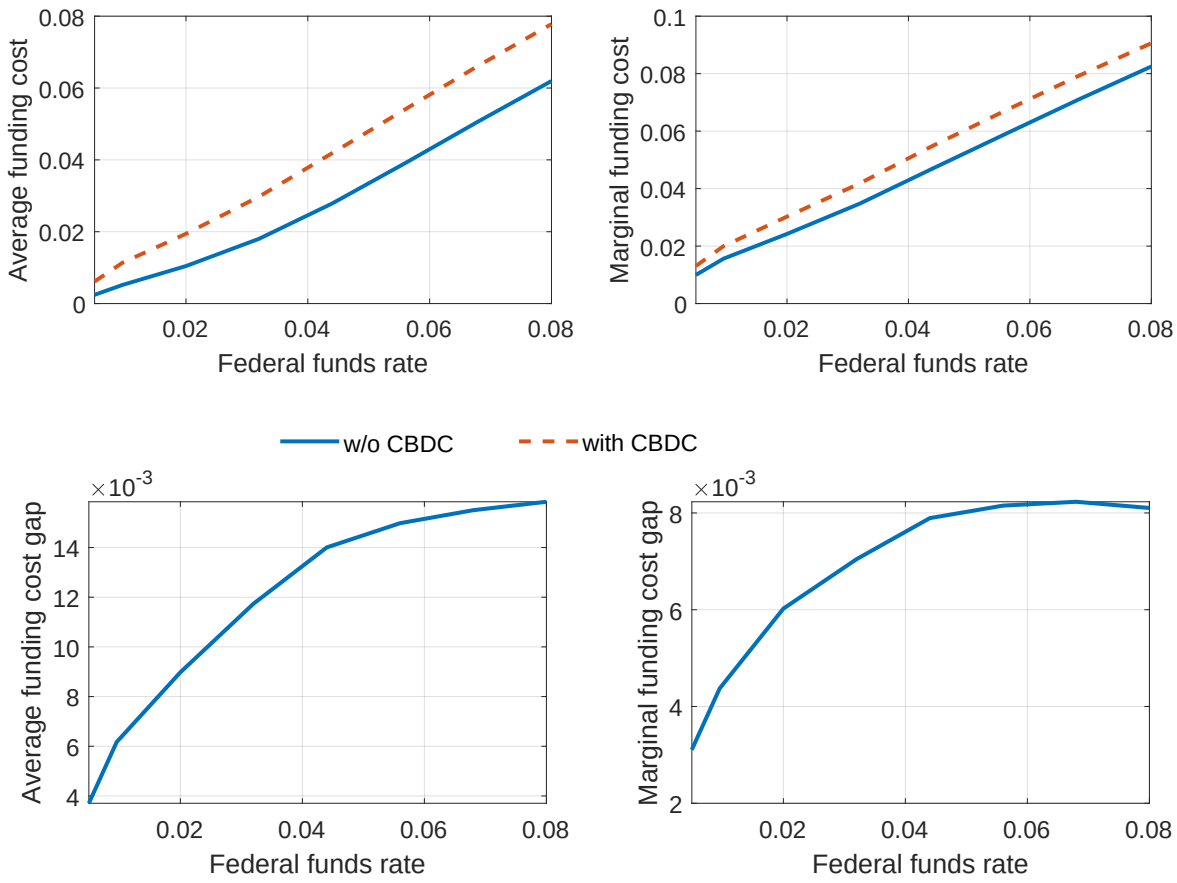
This figure shows the sensitivity of bank deposit intake and loan provision when the CBDC is introduced with quality equals q^{CBDC} and zero interest rate. The change is calculated under varying concentration levels, which is measured by the number of competing banks, J, on the deposit market. High J corresponds to less concentrated markets.

Figure 4: Deposit Spread, Profit, and Interest Rate Cycles



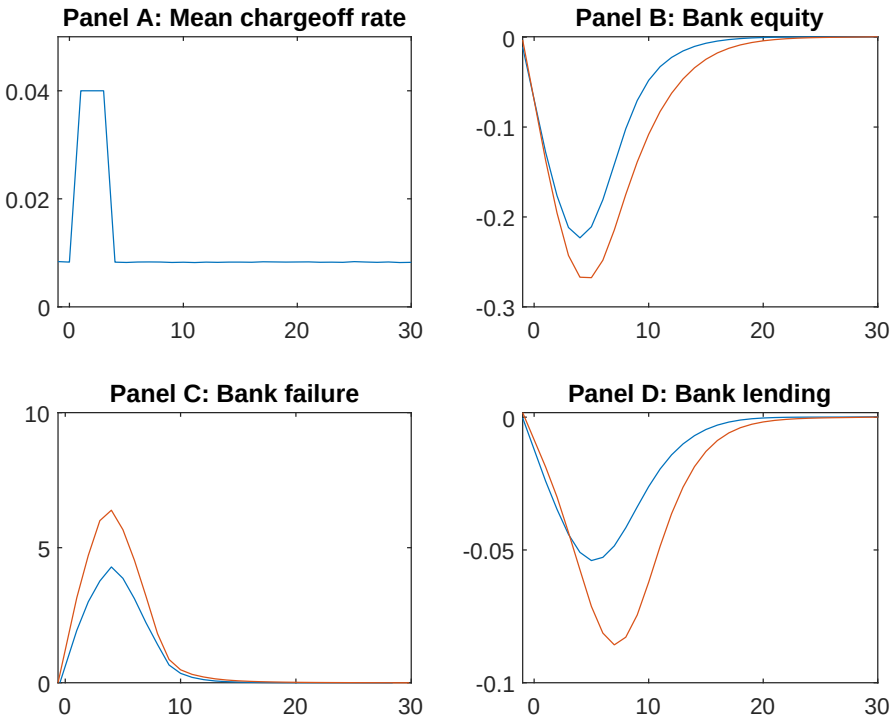
These figures show how banks' deposit spread and deposit market profit change across interest rate cycles with and without the introduction of CBDC.

Figure 5: CBDC, Bank Funding Cost, and Interest Rate Cycles



These figures show how banks' average and marginal funding costs change across interest rate cycles with and without the introduction of CBDC. The average/marginal funding cost difference measures the gap in funding costs in a scenario when CBDC is introduced and when it is absent.

Figure 6: CBDC and Bank Recovery following a Negative Shock



These figures simulate how banks recover from unexpected large default shocks in the baseline model without CBDC and in a counterfactual case when CBDC is introduced. Panel A presents the chargeoff shock process, which is calibrated to match the severity and duration of the 2007-09 Global Financial Crisis; Panel B reports the change in bank equity, scaled by the respective pre-crisis levels in the two simulations; Panel C corresponds to changes in the probability of bank failure, scaled by the probability of bank failure in the baseline model without CBDC and the counterfactual model when CBDC is introduced; Panel D reports the change in outstanding bank loans, scaled by the respective pre-crisis levels in the two simulations. The fed funds rate is fixed at 2% in all years.