Will Central Bank Digital Currency Disintermediate Banks?

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November 27, 2023

Abstract

We estimate a dynamic banking model to quantify the impact of a central bank digital currency (CBDC) on banks. Our counterfactuals show that a one-dollar introduction of CBDC replaces bank deposits by 80 cents on the margin. Lending falls by 25% of the drop in deposits because banks partially replace lost deposits with wholesale funding. This substitution raises banks' interest-rate risk exposure, lowering their resilience to negative equity shocks. If CBDC bears interest or is intermediated through banks, it captures a greater deposit market share, amplifying the impact on lending. CBDC especially affects small banks, which face expensive wholesale funding.

JEL Codes: E51, E52, G21, G28

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

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1. Introduction

A CBDC is a country's official currency in digital form. It 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. It also differs from existing depository accounts at the central bank, such as bank reserves, because the public can hold a CBDC directly.

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 compete with bank deposits, thus disintermediating the existing banking system and reducing credit availability. For example, 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] A related concern with CBDC is that shocks to bank deposits could affect bank lending. For example, 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]

We enter this debate by assessing the quantitative impact of a central bank digital currency (CBDC) on the banking system. To capture the advantages and drawbacks of CBDC and to quantify the effect of CBDC on bank lending, we construct and estimate a dynamic model of the banking industry. We then counterfactually add a CBDC as a product available to depositors and examine the implications for optimal bank actions. Briefly, we find that while bank customers substitute heavily out of deposits and into CBDC, the effect on bank lending is only one-fourth of the effect on deposits, as banks

[1]See "Money and Payments: The U.S. Dollar in the Age of Digital Transformation," January 2022. https://www.federalreserve.gov/publications/files/money-and-payments-20220120.pdf

[2]See "Confronting the hard truths and easy fictions of a CBDC," *Business Reporter*, September 23, 2021. https://www.business-reporter.co.uk/finance/confronting-the-hard-truths-and-easy-fictions-of-a-cbdc

optimally replace deposits with wholesale funding. We also find that the effects of CBDC are amplified for small banks and when the CBDC is intermediated through banks instead of being supplied directly by the central bank.

To flesh out the intuition behind these central results, we describe our model in more detail. It is a banking industry equilibrium model in which imperfectly competitive banks interact with depositors and borrowers. Infinite-horizon banks maximize profits, taking the actions of their competitors as given. They choose deposit and lending rates, as well as the quantities of other assets and liabilities on their balance sheets.

While banks optimize in a dynamic environment, borrowers and depositors make static, discrete choices between the products that banks offer, as well as other outside options. Optimal choices imply demand functions for deposits and loans that depend on interest rates and product and bank characteristics (Berry, Levinsohn, and Pakes 1995; Nevo 2001). We estimate the demand elasticities to interest rates and these characteristics.

In this framework, we start with a baseline observation that deposit creation and loan origination are separable absent informational or institutional frictions. In this case, banks choose optimal deposit rates by equating the marginal benefit of deposits with the federal funds rate. Equivalently, banks choose optimal lending rates by equating the marginal cost of loans with the federal funds rate. Therefore, banks choose their optimal deposit rates without considering their lending opportunities, and they choose their optimal lending policy without considering the source of their liabilities. Therefore, shocks to bank deposits, including those from introducing a CBDC, have no impact on bank lending.

While banks do not operate in a frictionless world, this baseline implies that any impact of CBDC on bank lending operates through the frictions and regulations that bind deposits and loans together, so this baseline enables us to isolate frictions that allow a CBDC to affect bank lending. As such, the banks in our model face realistic frictions such as deadweight default costs, external financing frictions, and capital regulations.

In this setting, we introduce a CBDC counterfactually as a direct central bank liability that depositors can hold, and we characterize CBDC as a new bundle of the characteristics of the savings products offered to depositors. We input the CBDC into the model by using the estimated sensitivities of demand to these characteristics to derive the demand curve for CBDC. Banks then reoptimize, given the existence of this new product. 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 regulation and the estimates of the financial frictions that link deposit-taking and loan origination.

Three frictions are central to banks' response to a CBDC. First, external financing through wholesale funding is costly (Kashyap and Stein 1995). In the model, wholesale funding incurs a small flotation cost and is uninsured, so its interest rate rises with banks' default risk. As a result, shocks to banks' deposit base, including the introduction of a CBDC, can raise the cost of funds and thus potentially affect banks' lending decisions.

Second, banks are imperfectly competitive. Therefore, as in Drechsler, Savov, and Schnabl (2021), deposit rates are sticky, so deposits act as if they have long duration. This behavior implies that even short-term deposits provide a natural hedge against the interest rate risk that stems from the origination of long-term loans. In this setting, when CBDC crowds out deposits, banks use short-duration wholesale funding, and the effectiveness of this natural hedge falls, so they are exposed to more interest rate risk.

Third, banks face regulations such as capital requirements. Imperfect bank competition in the deposit market implies that a CBDC reduces bank capital because banks accumulate equity capital largely through retained profits. Competition from a CBDC can constrain lending by forcing a capital requirement to bind. Similarly, lower profits can slow banks' recovery from shocks to their capital base.

We discipline the model using U.S. bank data following Wang, Whited, Wu, and Xiao (2022). As noted above, we first use demand estimation techniques to obtain the elasticities of loan and deposit demand to interest rates, as well as deposit and loan attributes.

We then input these estimates into our model and use simulated minimum distance to estimate the parameters that quantify financial frictions and operating costs.

Our approach to modeling CBDC is conducive to policy analysis because we can flexibly vary the attributes of CBDC under different policy proposals concerning CBDC implementation. We conduct a variety of counterfactual experiments. First, we consider a CBDC that pays no interest and provides the same transactions services as bank checking accounts. We find that CBDC sharply deteriorates banks' deposit-taking business: a one-dollar increase in CBDC reduces bank deposits by 81 cents. Yet, we find that less than a fourth of the impact on deposits is passed through to lending, with a one-dollar increase in CBDC reducing bank lending by 20 cents. The attenuated impact on bank lending happens because banks can replace deposits with wholesale funding *at the margin*. This result stands in sharp contrast to the policy discussions noted above that emphasize that shocks to bank deposits are likely to be completely or largely transmitted to bank lending.

The substitution into wholesale funding is not perfect for three reasons. First, external financing frictions naturally imply that banks optimally choose not to replace all lost deposits with wholesale funding, as its cost exceeds the federal funds rate. Second, introducing CBDC also lowers banks' profits from the deposit market. Lower profits, in turn, reduce bank capital and lending capacity. Finally, as banks replace interest-insensitive deposits with wholesale funding, banks' exposure to interest rate risk also rises. A further decomposition of different channels indicates that the first quantity-based channel is the most important one, followed by the profit-based channel.

CBDC affects large and small banks differently. Although CBDC affects deposits similarly across the two groups, small bank lending falls by three times the drop in large bank lending, as we estimate that large banks have cheaper access to non-deposit financing.

The impact of CBDC also depends on local deposit market concentration. In a highly concentrated market, the impact of CBDC on the quantities of deposits and loans is less pronounced because high markups cushion the extra competition CBDC poses for deposits. In contrast, in a less concentrated market, the impact on both deposits and loans is more pronounced. These results on size and market power have important distributional implications across banks of different sizes and regions with different bank competition.

We consider two alternative CBDC designs. First, we allow it to pay interest. In this case, banks raise their deposit rates to stay competitive, thus benefiting depositors. However, if a CBDC pays the federal funds rate, its market share rises to 31%, and banks lose 30% of their deposits, despite their higher deposit rates. Also, an interest-bearing CBDC generates substitution patterns that differ from those of a non-interest-bearing CBDC. The crowding out effect becomes stronger for bank deposits and is attenuated for cash, as an interest-bearing CBDC represents a closer substitute for deposits than for cash.

Second, we let CBDC be intermediated through banks, which offer CBDC accounts and earn a fee from the central bank for this service. We model intermediation by ascribing to the CBDC our estimates of bank branch convenience, which induces strong substitution out of deposits and into CBDC. Banks respond by raising deposit rates and using expensive wholesale funding. Although banks earn fees for intermediating CBDC, the net effect on lending is nearly always negative, depending on the fees and convenience.

Our paper contributes to a fast-growing body of research on CBDC, which we classify into three groups.[3] First, several studies examine the effects of CBDC on bank stability. Schilling, Fernández-Villaverde, and Uhlig (2020) study the implications of CBDC for price and financial stability. Relatedly, Ahnert, Hoffmann, Leonello, and Porcellacchia (2020), Skeie (2020), and Williamson (2021) examine the effect of CBDC on bank run risk. Our paper addresses bank instability that stems from interest-rate risk. We show that introducing CBDC can increase banks' interest-rate risk by reducing deposits and capital.

A second strand of CBDC literature studies the macroeconomic implications of CBDC. Piazzesi and Schneider (2020) study the welfare implications of CBDC in a macroeconomic model and show that CBDC can lower social welfare by interfering with the com-

[3]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).

plementarity between credit lines and deposits built into modern payment systems. Niepelt (2022) studies optimal monetary architecture with both reserves and CBDC. Williamson (2022) shows that CBDC can raise welfare by freeing up scarce collateral if banks are subject to limited commitment. Burlon, Montes-Galdon, Muñoz, and Smets (2022) studies the optimal quantity of CBDC in a DSGE model. In contrast, we model the industry equilibrium of the banking sector, which allows us to focus on banks' optimization problems in the face of various frictions. Our results also shed light on how aggregate credit provision can be reshaped by the introduction of CBDC.

Our paper is most closely related to a third strand of the literature that explores the effects of CBDC on disintermediation and bank lending. Previous work has considered single monopolist banks (Andolfatto 2021), as well as numerous perfectly competitive banks (Keister and Sanches 2023). In contrast, our framework nests the entire range of bank concentration. Chiu, Davoodalhosseini, Jiang, and Zhu (2023) develops a general equilibrium banking model to understand whether CBDC would crowd in or crowd out bank deposits. Our model differs from theirs by allowing CBDC and bank deposits to be imperfect rather than perfect substitutes. This feature, combined with heterogeneous depositor preferences over transaction convenience and rates, is important for quantifying the effect of the introduction of CBDC on deposits and lending. Finally, Garratt and Zhu (2021) assess the differential effects of CBDC on large versus small banks, which differ in their convenience. We also explore the heterogeneous effects of CBDC across bank sizes but place greater emphasis on differences in external financing frictions.

Although our model has unique features that differentiate it from other models in the literature, our paper's primary contribution is empirical. As the implementation of CBDCs is limited, data are scarce, so the literature is mainly theoretical. While existing studies offer sharp qualitative intuition, their predictions are often quantitatively ambiguous. Our paper enriches this literature with data-disciplined quantitative estimates.

Our work also contributes to the broader literature on narrow banking, which is the notion that deposit-taking and lending can be done separately by different financial intermediaries (Pennacchi 2012). The policy debate about CBDC is reminiscent of this question, as CBDC replaces private banks' deposits but not loan origination. We provide a quantitative model to evaluate how the private banking system realigns itself following a change to one side of the balance sheet, as well as how the frictions and regulations that bind deposits and loans constrain such a realignment.

Finally, we contribute to the literature on fintech and shadow banking (Buchak, Matvos, Piskorski, and Seru 2018; Xiao 2020; Begenau and Landvoigt 2022). A key question in this literature is the extent to which institutions that do not take deposits can replace traditional banks in the lending market. We quantify the synergies between deposits and loans, thus shedding light on the capabilities and limitations of non-depository institutions in assuming the roles traditionally performed by banks.

2. Simple Model

We start with a static model to clarify the intuition in the dynamic model in Section 3.

2.1. Frictionless Benchmark

We first consider a frictionless benchmark. Banks take deposits, $D(r^d)$, and make loans, $L(r^l)$, which are functions of the deposit and lending rates, r^d and r^l. The dependence of L and D on their respective rates reflects market power in the loan and deposit markets. If loans exceed deposits, banks can borrow via wholesale funding, $N = L - D$. We assume that banks face no external financing frictions, so they can obtain any amount of wholesale funding at their opportunity cost of funds, which is the federal funds rate, f. Conversely, when deposits exceed loans, banks can invest this surplus, $D - L$, in government securities and earn f. We also assume that both deposits and loans have a maturity of one year, thus precluding any maturity mismatch on the balance sheet.

Banks choose deposit rates and lending rates, r^d and r^l, to maximize profits, following:

$$\Pi = \max_{\{r^l, r^d\}} \left[r^l L(r^l) - r^d D(r^d) - fN \right], \quad \text{s.t. } L(r^l) = D(r^d) + N. \tag{1}$$

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 $L' \equiv \partial L / \partial r^l$ and $D' \equiv \partial D / \partial r^d$.

Equations (2) and (3) imply that the optimal lending rate and quantity of lending are independent of the deposit market. Thus, optimal quantities of deposits and loans are entirely separable, and any shock to deposit demand, D, such as the introduction of a CBDC, has no impact on lending, L. This result does not depend on demand elasticities and, consequently, the intensity of competition.

In this simple framework, if the introduction of CBDC shifts deposit demand, banks' profits fall, as they lose a cheap source of financing. Nonetheless, bank lending remains unaffected, as deposits are not the marginal source of financing. Moreover, because the wholesale funding rate is lower than the rate banks charge on loans, loan provision remains profitable when banks use both deposits and wholesale borrowing to fund loans. This point is absent in some discussions of CBDC, as evidenced 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.[4]"

2.2. External financing frictions

Next, we consider external financing frictions, which connect the two sides of banks' balance sheets. We assume that the cost of wholesale funding is $f + \Phi(N)$, in which

[4]See "Confronting the hard truths and easy fictions of a CBDC," *Business Reporter*, September 23, 2021.

$\Phi(N)$ is convex. We motivate this cost by the providers of uninsured wholesale funding requiring banks to pay credit spreads for default risk compensation. Moreover, accessing the wholesale funding market involves building and maintaining relationships with counterparties, which is costly. In this case, the banks' optimization problem is:

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

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

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

Note that banks' optimal lending rate and the equilibrium lending quantity are now 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 reduced bank deposits, it would force banks to raise more wholesale funding, $L-D$, which would drive up the marginal cost of external financing. As a result, some loans that were profitable before the introduction of the CBDC would become unprofitable afterward, and banks would cut lending.

2.3. Capital requirements

Lastly, capital regulation links banks' assets and liabilities, creating another channel for CBDC to affect bank lending. If a bank faces regulation requiring capital to exceed a given fraction of risky assets, it solves the problem in (1) with the added constraint:

$$E + \Pi \geq \kappa L, \tag{6}$$

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

We use $\lambda \geq 0$ to denote the Lagrange multiplier associated with the capital requirement in equation (6). The bank's optimal lending decision can be characterized as:

$$r^l \;=\; f + \left(-\frac{L'}{L}\right)^{-1} + \lambda\kappa \tag{7}$$

In this case, if the introduction of CBDC shifted deposit demand down, banks would optimally raise deposit rates, thus squeezing their profits. The ensuing drop in $E + \Pi$ would increase the tightness of the constraint in equation (6), so λ would rise. From equation (7), banks would raise their optimal loan rates, so optimal lending would fall.

2.4. Maturity mismatch

Another way to connect the two sides of banks' balance sheets is to introduce a maturity mismatch. While this simple static framework is unsuitable for understanding a dynamic concept such as maturity transformation, the intuition is transparent. For example, suppose bank loans mature in η periods, so a fraction $1/\eta$ of the loans is repriced each period, with the interest rates for the rest of the portfolio remaining unchanged. This long repricing maturity implies that when the federal funds rate changes, the transmission to the average interest rate on the bank's loan portfolio falls far below one.

While banks can only reprice a fraction of their loans each period, their liabilities are short-term and might be repriced entirely when the federal funds rate changes. The amount of interest rate risk induced by this maturity mismatch depends on the interest rate sensitivity of banks' liabilities. While the cost of wholesale funding tends to move in lockstep with the federal funds rate, the cost of retail deposits behaves differently. Because banks have substantial deposit market power, deposit rates are sticky and do not move one-for-one with the federal funds rate. Thus, deposits serve as a natural hedge for the interest rate risk stemming from maturity transformation (Drechsler et al. 2021).

CBDC crowds out bank deposits and raises banks' reliance on wholesale funding, which is more sensitive to federal funds rate changes. This sensitivity exposes banks to greater interest rate risk. Because financial frictions can induce banks to behave as though they are risk averse, they reduce their interest rate exposure by lending less.

3. Model

While the simple framework in Section 2 offers intuition, it is ill-suited for quantitative predictions. Therefore, we estimate an infinite-horizon bank industry equilibrium model with four sectors: depositors, borrowers, banks, and a central bank. While the model builds upon the one in Wang et al. (2022), it adds several features, highlighted below, that let us evaluate the impact of CBDC.

3.1. Depositors

The economy contains a mass W_t of depositors, each of which is endowed with one dollar. Because the depositors' problem is static, we drop the t subscript hereafter for convenience. There are $\hat{J}$ banks in the economy, each of which offers two types of deposits: transactions and savings deposits. Modeling transactions and savings deposits separately departs from the single deposit type in Wang et al. (2022). This model feature is important because it allows us to measure depositors' heterogeneous preferences regarding rates versus transactions services. These preferences play a key role in shaping the substitution patterns between CBDC, once introduced, and the different deposit market products with varying rates and services. In addition, depositors can also hold cash and Treasury bills. In our counterfactual analysis below, we extend this set of assets to include CBDC. We make an additional assumption that every depositor can select only a single option, which is without loss of generality, as one can view this assumption as depositors making multiple discrete choices for each dollar available to them, with the probability of selecting each option being interpreted as a portfolio weight.

Each option is characterized by a yield, r_j^d, and a vector of product attributes, x_j^d, which capture the non-rate characteristics of each option. For example, a depositor might value branches and staffing when choosing a bank. The yield on cash is 0, and the yield on

Treasury bills is the federal funds rate, f. While we abstract from differences between short-term Treasury yields and the federal funds rate, we drop this assumption in Section 7.1 below. All interest rates are quoted in real terms, as we assume inflation expectations are anchored at zero.

Each depositor chooses the best option to maximize its utility:

$$\max_{j \in \mathcal{A}^d} u_{i,j} = \alpha_i^d r_j^d + \beta_i^d x_j^d + \xi_j^d + \epsilon_{i,j}^d, \tag{8}$$

where $i \in 1, 2, \ldots, I$ indicates the type of depositor, and $\mathcal{A}^d$ is the depositors' choice set, described above. The utility for depositor i from choosing option j is $u_{i,j}$. The sensitivity to the yield, r_j^d, is α_i^d, and β_i^d is a vector of sensitivities to the non-rate product characteristics, x_j^d. In our estimation below, x_j^d includes a dummy variable that indicates whether the product allows depositors to make transactions, the number of branches, the number of employees per branch, and time and product fixed effects. We allow the sensitivities to the rate and the transactions dummies to differ across depositors, the latter of which is a departure from Wang et al. (2022), in which characteristic sensitivities are depositor invariant. 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 sensitivities to the non-rate characteristics. Finally, ξ_j is an unobservable product-level demand shock, and $\epsilon_{i,j}^d$ is a relationship-specific shock to the choice of option j by depositor i. $\epsilon_{i,j}^d$ captures horizontal differentiation across banks and induces imperfect product substitution.

The optimal choice for depositor i is given by an indicator function:

$$\mathbb{I}_{i,j}^d = \begin{cases} 1, & \text{if } u_{i,j} \geq u_{i,k}, \text{ for } k \in \mathcal{A}^d \\ 0, & \text{otherwise.} \end{cases} \tag{9}$$

We aggregate the optimal choices across all depositors 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:

$$s_j^d\left(r_j^d\right) \equiv \sum_{i=1}^{I} \mu_i^d \int \mathbb{I}_{i,j}^d dF\left(\epsilon_{i,j}^d\right) = \sum_{i=1}^{I} \mu_i^d \frac{\exp\left(\alpha_i^d r_j^d + \beta_i^d x_j^d + \xi_j^d\right)}{\sum_{m\in\mathcal{A}^d} \exp\left(\alpha_i^d r_m^d + \beta_i^d x_m^d + \xi_m^d\right)}, \tag{10}$$

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

$$D_j\left(r_j^d\right) = s_j^d\left(r_j^d\right) W. \tag{11}$$

3.2. Borrowers

There is a mass, K, of borrowers. Each borrower wants to borrow one dollar, resulting in aggregate borrowing demand of K. They can borrow by issuing long-term bonds or taking out long-term bank loans. We assume each bank is a differentiated lender, motivated by differences in geographic location, industry expertise, and prior lending relationships with borrowers. Letting each option be indexed by j, the borrowers' choice set is given by $\mathcal{A}^l$, which includes bonds, bank loans, and an outside option of not borrowing.

To simplify our analysis, we assume that both bonds and bank loans follow the same repayment schedule, where the borrower must repay a proportion, η, of the unpaid principal and interest each period. Thus, if the borrower borrows one dollar at a fixed interest rate r, the repayment stream, starting in the next period, is $(1-\eta)^t \times (\eta + r)$, $t = 0, \ldots, \infty$. Accordingly, all borrower debt has an average maturity of $1/\eta$ periods.

Each borrower's financing options are characterized by a rate, r_j^l, and a vector of non-rate characteristics, x_j^l, that capture the convenience of using each financing option. If a borrower chooses not to borrow, the interest rate is zero. If a borrower chooses to issue bonds, the interest rate is given by the long-term bond interest rate, which equals an expected default cost, $\bar{\delta}$, plus the expected weighted average of future federal funds rates, $\bar{f}_t = \mathbb{E}_t\left[\sum_{n=0}^{\infty} \eta(1-\eta)^n f_{t+n}\right]$.

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

$$\max_{j \in \mathcal{A}^l} \pi_{i,j} = \alpha^l r_j^l + \beta^l x_j^l + \xi_j^l + \epsilon_{i,j}^l, \tag{12}$$

where $\pi_{i,j}$ is the profits of borrower i from choosing option j, and $\alpha^l < 0$ is the sensitivity of profit to the interest rate, r_j^l, and β^l represent the sensitivities to non-rate characteristics. Borrowers in the loan market have homogeneous sensitivities to rates and characteristics. ξ_j^l is an unobservable product-level demand shock; and $\epsilon_{i,j}^l$ is an idiosyncratic shock when borrower i borrows from bank j.

The optimal choice of borrower i is given by an indicator function:

$$\mathbb{I}_{i,j}^l = \begin{cases} 1, & \text{if } \pi_{i,j} \geq \pi_{i,k}, \text{ for } k \in \mathcal{A}^l \\ 0, & \text{otherwise.} \end{cases} \tag{13}$$

To compute the loan market share of each bank j, we aggregate the optimal choices made by all borrowers. Similar to the deposit market, we assume that $\epsilon_{i,j}^l$ follows a generalized extreme value distribution, with which we can derive the standard logit market share:

$$s_j^l \left(r_j^l \right) \equiv \int \mathbb{I}_{i,j}^l dF \left(\epsilon_{i,j}^l \right) = \frac{\exp \left(\alpha^l r_j^l + \beta^l x_j^l + \xi_j^l \right)}{\sum_{m \in \mathcal{A}^l} \exp \left(\alpha^l r_m^l + \beta^l x_m^l + \xi_m^l \right)}, \tag{14}$$

The numerator represents the utility from borrowing from bank j. The demand function for loans is then given by the market share times the total loan market size:

$$B_j \left(r_j^l \right) = s_j^l \left(r_j^l \right) K. \tag{15}$$

3.3. Banks

To simplify notation, we suppress the subscript j. In the deposit market, we use the superscripts S and T to denote savings and transactions deposits, respectively. Each bank sets rates for savings and transactions deposits, $r_t^{d,S}$, $r_t^{d,T}$, and the loan rate, r_t^l, simultaneously based on the federal funds rate, f_t, which is treated as an exogenous state variable. These rate-setting decisions implicitly determine the quantities of deposits accepted from depositors and credit extended to borrowers. For example, given banks' optimal deposit rates, depositors solve the utility maximization problem in equation (8). The solution provides the quantity of deposits supplied to each bank, given by equation (11).

Banks are subject to a zero lower bound on deposit rates:

$$r_t^{d,T} \geq 0, r_t^{d,S} \geq 0. \tag{16}$$

The zero lower bound can be motivated by the availability of zero-return storage technologies available to depositors, such as holding cash or buying durable goods. Similarly, given banks' choice of lending rates, borrowers solve their profit-maximization problem, which yields the quantity of loans borrowed from each bank from equation (15).

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. By assuming that loans are long-term, we capture the conventional role of banks in carrying out maturity transformation, whereby they transform short-term deposits into long-term bank loans that have a maturity of $1/\eta$.

As noted above, banks can also issue new loans at an annualized interest rate of r_t^l. Once issued, the new loans have the same maturity structure as the existing loans with a fixed interest rate. From the bank's perspective, the present value of interest income is:

$$I_t = \sum_{n=0}^{\infty} \frac{(1-\eta)^n B_n r_n^l}{\prod_{s=1}^{n}(1+\gamma_s)}, \tag{17}$$

where γ_s is the bank's discount rate in period s, and a bank's outstanding loans evolve according to:

$$L_{t+1} = (1-\eta)\left(L_t + B_t\right). \tag{18}$$

We assume that in each period, a random fraction of loans, $\delta_t \in [0, \eta]$, becomes delinquent. We assume that borrowers declare delinquency only when their loans mature and the payment is due. The bank takes δ_t as an exogenous state variable in its optimization problem. We assume that the bank writes off delinquent payments, with charge-offs equal to $L_t \times \delta_t$. However, payment default in one period does not exonerate the borrower from future payments, so delinquency does not affect the evolution of loans in equation (18).

In each period, the bank can fund its lending activity via deposits or wholesale funding, N_t. Bank deposits are insured, and depositors receive a rate $\left\{r_t^{d,S}, r_t^{d,T}\right\}$ on their transactions and savings deposits from the bank. Wholesale funding is uninsured, and the suppliers of these funds (e.g., money market mutual funds and corporations) are competitive. The interest rate suppliers charge, r_t^N, is set so that they break even. We discuss the determination of r_t^N in Section 3.5 below. Beyond interest payments, banks' use of wholesale funding incurs additional costs, such as the costs to build and maintain relationships with their counterparties. We model these costs as a quadratic function of the amount borrowed. Thus, the total cost of wholesale borrowing can be expressed as:

$$\Phi^N(N_t) = N_t r_t^N + \left[\frac{\phi^N}{2} \cdot \left(\frac{N_t}{D_t^S + D_t^N}\right)^2\right] \left(D_t^S + D_t^N\right). \tag{19}$$

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

$$\Phi^d(D_t^S, D_t^T) = \phi^d \cdot \left(D_t^S + D_t^T\right). \tag{20}$$

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:

$$\Phi^l(B_t + L_t) = \phi^l \cdot (B_t + L_t) \tag{21}$$

We also model fixed operating costs net of non-interest income, both of which we assume to be independent of deposits and lending. We let χ represent the difference between fixed operating expenses and non-interest 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 required 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 assets earn the federal funds rate, f_t. The bank's holdings of loans, government securities, deposits, reserves, and wholesale borrowing satisfy the standard condition that assets equal liabilities plus equity:

$$L_t + B_t + R_t + G_t = D_t^S + D_t^T + N_t + E_t, \tag{22}$$

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

$$E_{t+1} = E_t + \Pi_t(1-\tau) - C_{t+1}, \tag{23}$$

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

$$\Pi_t = I_t - (L_t + B_t)\delta_t + G_t f_t - r_t^{d,S} D_t^S - r_t^{d,T} D_t^T - \Phi^d - \Phi^l - \Phi^N - \chi\bar{E}. \tag{24}$$

In equation (23), τ denotes the linear tax rate on banks' profits, and C_{t+1} is the cash dividends distributed to the shareholders, with

$$C_{t+1} \geq 0. \tag{25}$$

This constraint implies that a bank can increase its inside equity only via retained earnings and cannot replace deposits or wholesale borrowing with external equity capital. We relax this assumption in Section 7.3 below.

3.4. Federal funds rate

We model the federal funds rate as an AR(1) process, with its law of motion given by:

$$\ln f_{t+1} - \mathbb{E}(\ln f) = \rho_f \left[\ln f_t - \mathbb{E}(\ln f)\right] + \sigma_f \varepsilon_{t+1}^f. \tag{26}$$

We model the bank-level idiosyncratic loan charge-off as the sum of a component that is correlated with the current federal funds rate and an *i.i.d.* shock component:

$$\ln \delta_{t+1} - \mathbb{E}(\ln \delta) = \rho_{\delta f} \left[\ln f_{t+1} - \mathbb{E}(\ln f)\right] + \sigma_\delta \varepsilon_{t+1}^\delta. \tag{27}$$

3.5. Bank default and the 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:

$$\Gamma_{t+1} = P^{\Gamma}(\Gamma_t). \tag{28}$$

In every period, after observing the federal funds rate, f_t, and the random fraction of delinquent loans, δ_t, an incumbent bank first chooses whether to default. This feature of the model is a departure from Wang et al. (2022), in which banks never default. We define a variable $\omega_t = 1$ if the bank chooses to default and $\omega_t = 0$ otherwise:

$$V(f_t, \delta_t, L_t, E_t \big| \Gamma_t) = \max_{\omega_t \in \{0,1\}} (1 - \omega_t) \times V^c(f_t, \delta_t, L_t, E_t \big| \Gamma_t), \tag{29}$$

where $V^c(\cdot)$ denotes the value if a bank continues without default. If an incumbent bank continues, it chooses the optimal interest rates on deposits and loans, as well as balance sheet variables, to maximize the expected discounted cash dividends to shareholders:

$$\begin{aligned}
V^c(f_t, \delta_t, L_t, E_t \big| \Gamma_t) &= \max_{\{r_t^{d,S}, r_t^{d,T}, r_t^l, R_t, G_t, N_t, C_{t+1}, E_{t+1}\}} \frac{1}{1+\gamma_t} \left\{ C_{t+1} + \mathbb{E} V(f_{t+1}, \delta_{t+1}, L_{t+1}, E_{t+1} \big| \Gamma_{t+1}) \right\}, \\
&\text{s.t.} \quad \text{equations (11), (15), (16), (18), (22), (23), (24), (25), (26), (27)} \qquad (30) \\
E_{t+1} &\geq \kappa \times (L_t + B_t), \qquad (31) \\
R_t &\geq \theta \times D_t, \qquad (32)
\end{aligned}$$

where $\gamma_t = f_t + \gamma$ is the bank's discount rate in period t. It consists of the current federal funds rate plus a wedge, γ, that captures shareholder impatience. Equations (31) and (32) reflect the capital and reserve regulations, respectively.

A bank chooses to default when its continuation value, $V^c(\cdot)$, falls below zero, in which case, the bank liquidates its outstanding loans prematurely, incurring a proportional cost of ξ. We assume a government insurer auctions the failed bank, using proceeds to pay insured depositors first. If any cash flow remains, it goes to the wholesale lenders.

If the auction proceeds fall short of the bank's liabilities, then the insurer uses its own resources to repay the insured depositors fully but does not cover the wholesale lenders.

To calculate the interest rate on risky wholesale funding, we let Ω_t denote the probability of a bank default conditional on the current state, which can be expressed as:

$$\Omega(f_t, \delta_t, L_t, E_t \big| \Gamma_t) \quad = \quad \mathbb{E}\left\{V^c(f_{t+1}, \delta_{t+1}, L_{t+1}, E_{t+1} \big| \Gamma_{t+1}) \leq 0\right\}. \tag{33}$$

Given banks' default decisions, the break-even interest rate charged by wholesale lenders, r_t^N, satisfies the following zero-profit condition:

$$\begin{aligned} N_t \times (1 + f_t) \quad = \quad & (1 - \Omega_t) \times N_t(1 + r_t^N) + \Omega_t \times \\ & \left\{[\eta(1-\delta_t) + (1-\eta)(1-\xi)]\,(L_t + B_t) + G_t + R_t - D_t^S - D_t^T\right\}^+, \end{aligned} \tag{34}$$

where the last term in equation (34) captures the wholesale lenders' expected recovery in the event of a bank default. The insurer auctions the failed bank to a pool of H potential investors via a second-price auction. Investors are indexed by their private costs of participating in the auction, that is, $\varsigma_{1,t} < \varsigma_{2,t} < \varsigma_{3,t} < \ldots < \varsigma_{H,t}$. The winner of the auction recapitalizes the bank at a required level of equity capital, $\underline{E}$. The recapitalized bank has an expected default rate, $\tilde{\delta}_t = \mathbb{E}(\delta_t \mid f_t)$, conditional on the current interest rate environment. Thus, the price submitted by the second highest bidder is equal to:

$$V^c(f_t, \tilde{\delta}_t, 0, \underline{E} \big| \Gamma_t) - \varsigma_{2,t}. \tag{35}$$

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

This characterization of bank failure captures the auction process used by the Federal Deposit Insurance Corporation. This modeling also allows us to have a constant number of representative banks in the model. Finally, it implies that the parameters, H and ς, are irrelevant for a bank's optimal decision once it is active. These parameters only determine the rent split between the government insurer and the entrant bank.

3.6. Equilibrium

We define equilibrium in this economy as follows.

Definition 1 *A Markov Perfect Industry Equilibrium occurs when:*

1. *All banks solve the problem given by equation* (30)*, taking as given the other banks' choices of loan and deposit rates.*
2. *When a bank fails, the government insurer auctions the failed bank following equation* (35)*, taking as given other solvent banks' choices of loan and deposit rates.*
3. *Suppliers of wholesale funding price their loans according to equation* (34)*.*
4. *Depositors and borrowers maximize their utilities in equations* (8) *and* (12)*, 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 in Wang et al. (2022). The strategy follows from an algorithm in the spirit of Krusell and Smith (1998) proposed by Weintraub, Benkard, and Van Roy (2008, 2010), and Ifrach and Weintraub (2017).

4. Data

Most of our data are from the Consolidated Reports of Condition and Income (Call Reports), which contain quarterly bank-level balance sheet information for commercial banks in the United States, including deposit and loan amounts, interest income and expense, loan maturities, salary expenses, and fixed-asset-related expenses. We merge the Call Report data with the FDIC Summary of Deposits, which contains the number of bank branches. Our sample period is from 1994 to 2019.

We use additional data sources. Publicly listed bank returns are from CRSP, and the Federal Reserve Economic Data (FRED) database provides us with the effective federal funds rate, one-year Treasury yields, the aggregate amount of corporate bonds issued by U.S. firms, and the aggregate amounts of cash, Treasury bonds, and money-market mutual funds held by households. Table 1 outlines how we construct our variables, and Table 2 contains summary statistics.

5. Estimation

We estimate the model in two steps. First, we use the methods in Berry et al. (1995) to estimate deposit and loan demand functions. Our set of bank characteristics includes the number of branches and employees per branch, bank and time fixed effects, and a transactions dummy. We define the market as the U.S. national market, with each year constituting a separate market. To identify these demand elasticities, we use a set of supply shifters as instrumental variables, specifically, salaries and non-interest expenses related to fixed assets (Dick 2007; Ho and Ishii 2011). Our identifying assumption is that customers do not care about these costs, holding product characteristics constant.

Two features of our estimation differentiate it from that in Wang et al. (2022). First, we allow each bank to offer transactions and savings deposits separately in our setting. Therefore, we use bank-level data on the rate and quantity of these two types of deposits to estimate depositors' preferences towards these services. Second, depositors in our setting have heterogeneous sensitivities not only to the yields of the products but also to the transactions convenience they provide.

Our second stage involves plugging in the estimates of depositors' and borrowers' demand into the model and using simulated minimum distance (SMD) to estimate the remaining seven parameters, $(\gamma, W/K, q_n^l, \phi^d, \phi^l, \phi^N, \chi)$, which govern banks' operating and financing costs. We use SMD instead of demand estimation to estimate q_n^l, the quality associated with not borrowing, as the associated outcomes are unobservable.

Our identification strategy follows Wang et al. (2022). We use the average deposit and loan spreads to identify banks' marginal costs of generating deposits, ϕ^d, and servicing loans, ϕ^l, as both spreads monotonically increase in these costs. We use banks' average net noninterest expenses and leverage ratios to identify the fixed operating cost, χ. The former is positively associated with χ, and the latter is negatively associated. Banks' average dividend yield enables the identification of the discount rate, γ, as a higher rate signifies increased impatience, leading banks to distribute more profits to shareholders instead of retaining funds for future business.

To identify the relative deposit market size, W/K, and borrowers' value of not borrowing, q_n^l, we include banks' average deposits-to-assets ratio, as well as the sensitivity of total borrowing to the federal funds rate, which we estimate with a vector autoregression (VAR). These two moments are appropriate because holding banks' market shares constant, a high W/K implies a larger deposit market, resulting in a higher deposits-to-assets ratio at the bank level. As borrowers' outside option becomes less valuable, the market share of this option remains low regardless of the federal funds rate, causing the sensitivity of aggregate corporate borrowing to the federal funds rate to decrease as q_n^l declines. Moreover, a high loan-to-deposits ratio is inversely related to q_n^l because loan demand is weaker when borrowers value the option not to borrow. Next, we identify the exogenous financing cost parameter, ϕ^N, by matching the mean and variance of the ratio of banks' wholesale funding to deposits. Finally, we target the average bank market-to-book ratio to ensure that our model predicts the right valuation for banks.

We set the fire sale discount, ζ, to 30%, which implies that banks in our model pay, on average, a credit spread of 10 basis points. With a recovery rate of 70%, a bank's default probability is approximately 0.64%. The magnitude is closely aligned with the evidence from bank credit spreads documented in Berndt, Duffie, and Zhu (2020).

Table 3 presents the point estimates for the model parameters, the values of which are largely in line with those in Wang et al. (2022). In Table 4, we compare the empirical and model-implied moments. The model closely matches all of our targeted moments in economic terms, with only mean net non-interest expense differing significantly in the simulated and actual data.

6. Counterfactuals

In this section, we counterfactually introduce a CBDC into the economy and examine the impact on banks' competitiveness in the deposit market, their optimal lending decisions, and their risk exposure. We assume that the central bank issues CBDC directly to depositors but does not make loans directly to borrowers.

We conceptualize CBDC as a new product provided by the central bank that competes with cash and bank deposits. We construct this synthetic CBDC by ascribing to it a set of characteristics that we use in our demand regressions. First, and in contrast to the profit-maximizing decisions made by banks, we assume the interest rate on CBDC is determined by an exogenous policy decision. Second, we set the transactions dummy to one to allow CBDC to process payments. Third, we assign to the CBDC the estimate of the cash fixed effect because the government issues both instruments.

As a final step in constructing this demand curve, we use external estimates to capture the digital nature of a CBDC. Koont (2022) collects the release dates of mobile banking apps by U.S. commercial banks and finds that deposit demand increases by approximately 20% after the digital app release. This finding reflects the value that depositors attach to holding a digital version of a deposit market product under the utility system in equation (8). Therefore, we adjust the quality of CBDC upwards by 20%.

Next, using our estimated sensitivities of market shares to these attributes, we construct a demand curve for CBDC. Specifically, CBDC quality is given by $q^d_{i,CBDC} = \beta^d_i x^d_{CBDC}$, where x^d_{CBDC} includes the digital adjustment and the transactions and cash dummies, and β^d_i is the corresponding vector of estimated coefficients.

Depositors chooses the investment options that maximize their utility as described in equation (8), but now they have one additional option, the CBDC, in their choice set. As before, we can derive the market share for CBDC:

$$s^d_{CBDC} = \sum_{i=1}^{I} \mu^d_i \frac{\exp\left(\alpha^d_i r^d_{CBDC} + q^d_{i,CBDC}\right)}{\sum_{m\in\{\mathcal{A}^d,CBDC\}} \exp\left(\alpha^d_i r^d_m + q^d_{i,m}\right)}, \tag{36}$$

where r^d_{CBDC} is the interest rate on CBDC, which we set to zero in our main counterfactual.

To evaluate the effect of CBDC on bank decisions and outcomes, we then plug this demand curve into the dynamic model and allow the banks to reoptimize. This characteristics-based demand approach allows us to consider different policy proposals for CBDC, with varying levels of interest payments and quality.

6.1. The impact of CBDC on deposits and lending

We first examine how the introduction of a CBDC influences the market share of different deposit market products, as well as banks' credit provision. To this end, we perform a sequence of counterfactuals by comparing banks' behavior when a CBDC is absent with cases when it has been introduced into the banking industry.

The quality parameter for the CBDC is the sum of estimated coefficients associated with the transactions and cash dummies, plus the digital adjustment. Assessing CBDC quality is challenging, as it depends on multiple factors, including implementation and public perception. While Li (2023) attempts to predict CBDC's market share and quality using Canadian survey data, similar surveys are not available in the United States. As a result, instead of taking a definitive stance on the "correct" value of this parameter, we opt to vary CBDC's quality to understand better the influence of quality on bank behavior.

We start by considering a CBDC that does not pay interest, with the results of these counterfactuals in Table 5. Column (1) corresponds to the case in which CBDC is absent from the deposit market; column (5) shows the results for a case in which CBDC is fully adopted. In columns (2)–(4), we examine cases in which we let the quality of CBDC vary from zero to the full value. This quality discount can be interpreted as a phase-in period for a new CBDC, in which depositors have not fully accepted it.

In the first three rows of Table 5, we report the market shares of deposit market products, including CBDC, bank deposits, and cash. In rows (4)-(9), we report bank characteristics, including the amount of loans they issue, the deposit and loan spreads they charge, their credit spread, average funding cost, and bank value scaled by assets. We normalize the quantity of bank loans by the size of the deposit market, so that the numbers in row (4) share the same denominator as those in rows (1)-(3).

In the absence of CBDC, we find that bank deposits and cash are 87.6% and 7.0% of the deposit market, respectively, and the bank loan market is 1.021 times the size of the deposit market. Once CBDC is fully introduced, it accounts for 7.6% of the deposit market, while the market share of bank deposits falls to 81.4% and that of cash falls to 6.2%. We find that the amount of bank loans in the economy falls from 1.021 times the size of the deposit market to 1.007 times.

In sum, Table 5 shows that introducing CBDC lowers market shares for cash and bank deposits. On the extensive margin, banks partially replace lost deposits with more expensive wholesale funding. On the intensive margin, banks also endogenously raise deposit rates to reduce deposit outflows, resulting in lower deposit spreads. The combined effects from the extensive and intensive margins lead to higher bank funding costs, so banks cut dividends, and their value falls. The fall in bank value also makes default more likely, so banks face a higher credit spread on their wholesale funding. This higher cost of financing also generates a feedback effect that amplifies the fall in bank profits and value.

In the last column of Table 5, we report the sensitivities of the outcomes we study to changes in the market share of CBDC, which we calculate as the change in the outcome in question, divided by the market share of CBDC. A one-dollar increase in CBDC crowds out deposits by 81.5 cents. However, a one-dollar increase in CBDC only decreases bank lending by 18.9 cents, so only a quarter of the impact on deposits is passed through to bank lending. 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]

Finally, a one-dollar increase in CBDC crowds out cash by 10.7 cents. Although cash and CBDC have similar attributes, the crowding-out effect is not complete because of the idiosyncratic component of depositor utility. In addition, because cash has a small initial market share, CBDC crowds out more cash than deposits in percentage terms.

6.2. Decomposition of channels

Next, we decompose the channels through which CBDC affects bank lending. We consider the three channels discussed in Section 2. First, banks use more wholesale funding when CBDC crowds out deposits. Second, bank profits fall, erode equity capital, and make the capital constraint bind. Third, banks' increased reliance on wholesale funding raises their effective maturity mismatch. Interest rate risk exposure rises, thus inducing banks to reduce lending. To construct these counterfactuals, we solve the model with no CBDC, harvesting the level of deposits and deposit market profits, as well as the spread between the rate on wholesale funding and the federal funds rate. Next, we add CBDC to the model, holding a subset of these three quantities fixed to isolate the relevant channel.

Table 6 shows the results. In row (1), we present the baseline case from column (6) of Table 5, in which one dollar of CBDC reduces bank lending by 18.9 cents. Row (2) examines the first channel, which we isolate by setting the wholesale funding rate and profits to their baseline levels, so the documented effect on lending only operates through the deposit-quantity channel. We find that a one-dollar increase in CBDC reduces bank lending by 15.8 cents through this channel. Row (3) examines the second channel, which we isolate by setting the wholesale funding rate and the level of deposits equal to their

[5] Anderson, Du, and Schlusche (2023) find much smaller effects of a shock to wholesale funding on bank lending. However, our study focuses on a shock to deposit funding, which is conceptually separate. Competitive pricing and elastic supply imply that wholesale funding sources are easily substitutable. In contrast, retail deposits command significant markups and have a highly inelastic supply. This distinction helps reconcile the near-zero effects of the funding shock in Anderson et al. (2023) with our modest effects on bank lending.

baseline levels. We find that a one-dollar increase in CBDC reduces bank lending by 11.4 cents through this profit channel. We isolate the third channel by holding constant deposits and profits. As seen in row (4), this channel results in an 8.4 cent drop in bank lending. Note that the sum of the effects of the individual channels does not necessarily equal the combined effect of all three channels because the banks' optimization problem is highly non-linear. Comparing the three channels, the most important channel is the first that operates through lower deposits. This conclusion is strengthened if banks can costlessly use interest rate swaps to hedge interest rate risk or access long-term funding markets to match duration. In this case, the interest rate channel is muted.

6.3. The heterogeneous impact of CBDC

Because CBDC affects bank lending mainly by reducing deposits and raising banks' reliance on costly wholesale funding, we now examine heterogeneity in banks' costs of this alternative funding source. First, in Figure 1, we calculate the deposit and loan sensitivities to a one-dollar increase in CBDC for different levels of the wholesale funding cost, $r^N - f$. We find that when banks face a small wholesale funding cost, introducing a CBDC reduces bank lending only slightly. CBDC competes away deposits, but the effect on lending is largely neutralized, as banks replace deposits with wholesale funding. However, when banks' external financing costs rise, banks find it increasingly difficult to replace lost deposits. As a result, the decline in deposits leads banks to cut their lending.

The impact on deposits follows the opposite pattern. Deposits fall by less when the wholesale funding cost is high because banks avoid this expensive funding source. Instead, they raise deposit rates to keep depositors from moving to the CBDC. This result is another piece of evidence that deposits and lending do not necessarily move in tandem.

The results in Figure 1 raise the possibility of heterogeneity in the impact of introducing CBDC across the bank size distribution, as small banks face particularly high frictions in accessing the wholesale funding market (Kashyap and Stein 1995). 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. As of 2019, with a cutoff of 40 billion in assets, we identify 50 big banks, which comprise approximately 80% of total bank assets.

We re-estimate five key parameters related to bank operations that are likely to vary by bank size: the cost of accessing wholesale funding, the size of the depositor base, the costs of taking deposits and servicing loans, and the fixed cost of operation. We hold constant depositor and borrower preferences because they are not bank-specific. We also fix banks' discount rates because most small banks are private banks with insufficient data to construct the corresponding identifying moment. We target eight moments in our subsample estimation: all of those reported in Table 4, except the dividend yield and market-to-book ratio, as we cannot calculate these statistics for the small private banks.

The results reported in Table 7 show that big and small banks differ significantly 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 58 basis points for the small banks and 20 basis points for the big banks. In addition, net operating costs for small banks are over twice those for large banks.

When we introduce CBDC into the model, we find that a one-dollar increase in CBDC lowers deposits by 74 cents and 80 cents for small and big banks, respectively. Although these deposit responses are similar, the loan responses are not. A 10% increase in the CBDC market share raises large banks' funding costs by eight basis points and small banks by 15 basis points.

Next, we consider heterogeneity in the degree of bank competition. Panel B of Figure 1 examines how the impact of CBDC varies with market concentration, as measured by the number of competing banks in the deposit market. In this experiment, we hold loan market concentration fixed and only vary banks' deposit market power, so the results only reflect the impact of deposit market concentration. We calculate the sensitivities of deposits and loans to a one-dollar increase in CBDC for different numbers of competing banks, $\hat{J}$, which is six in our baseline estimation. We find that a one-dollar increase in CBDC crowds out bank lending by five cents with four banks, which corresponds to the fiftieth percentile of the county-level market concentration in 2019. This figure rises to 42 cents when the number of competing banks is eight, which corresponds to the tenth percentile of the county-level market concentration in 2019. The impact of CBDC on bank lending is more muted in concentrated markets because banks have more room to raise deposit rates. They also are more profitable, so they have a higher capital buffer.

6.4. Alternative implementation of CBDC

In this section, we consider two alternative implementations of CBDC: an interest-bearing CBDC, and a CBDC that is intermediated through banks.

6.4.1. Interest-bearing CBDC

First, we show that the impact of CBDC can be further amplified when CBDC pays interest. We perform a sequence of counterfactuals in Table 8 with respect to the interest rate on CBDC. The first column of Table 8 corresponds to the case in which CBDC pays no interest; column (5) shows the results for a case in which CBDC pays the federal funds rate. In columns (2)–(4), we examine cases in which CBDC pays a fraction of the federal funds rate. Column (6) shows the sensitivity of various outcomes to a one-percent increase in CBDC market share, with a baseline of non-interest bearing CBDC. The quality parameter is set to the same baseline value as in column (5) of Table 5.

As shown in the top row of Table 8, a non-interest-bearing CBDC captures 7.6% of the deposit market, while one with interest equal to the federal funds rate captures 31.3%. Consequently, compared to a CBDC-free equilibrium, lending falls by 1.4% in the non-interest-bearing case and 7.9%, in the interest-bearing case.

An interest-bearing CBDC also generates distinct substitution patterns across various deposit market products. As shown in column (6) of Table 8, the crowding-out effect of CBDC on bank deposits increases modestly from 81.5 to 82.9 cents, while the impact on cash falls notably from 10.7 to 6.2 cents. This pattern arises because an interest-bearing CBDC attracts yield-sensitive depositors, thus competing more intensively with bank deposits and Treasury bonds. In contrast, cash appeals to a different group of yield-insensitive clients, so the marginal effect of introducing an interest-bearing CBDC on the cash market share is attenuated. The marginal impact on deposit spreads is greater because an interest-bearing CBDC forces banks to pay higher deposit rates to stay competitive. The sharper increase in the deposit spread contributes to a greater sensitivity of bank lending to CBDC holdings. In addition, when CBDC pays interest, each additional percentage increase in the market share of CBDC also leads to a larger fall in bank value.

Our counterfactual exercise shows that an increase in the CBDC interest rate crowds out bank deposits and lending. In comparison, in the model in Chiu et al. (2023), an increase in the CBDC interest rate can "crowd in" deposits and lending. Our result differs from theirs because of different assumptions about the degree of product differentiation between CBDC and retail deposits. Chiu et al. (2023) assumes that CBDC and retail deposits are perfect substitutes so that the interest rate on CBDC sets a floor for bank deposit rates. Thus, an increase in the CBDC rate can significantly drive up deposit rates and crowd in savings. In comparison, we estimate the substitutability between CBDC and retail deposits using a demand system in which depositors care about not only the interest rate, r_j^d, but also the non-rate characteristics x_j^d. Furthermore, the estimated retail depositors' preferences have an idiosyncratic component $\epsilon_{i,j}^d$, so that a product with a lower rate and poorer services still gets some market share in equilibrium. As a result, in our model, banks can pay a rate lower than the CBDC rate without losing all of their deposits. Although introducing CBDC raises deposit rates, given our model estimates from U.S. banking data, rates do not rise to a level that leads to a crowding-in effect.

6.4.2. Intermediated account-based CBDC

So far, we have considered a CBDC offered directly by the central bank, which interacts with depositors and handles transactions and account balances. This direct model would lead to an expansion in the role of the central bank beyond its current scope, as operational tasks and user-facing activities would shift from private banks to the central bank. Furthermore, this direct model would also limit the services that depositors could obtain from CBDC, as it would be impractical for the central bank to open physical branches and offer customer services in the same way as private banks.

These concerns motivate an intermediated arrangement for CBDCs, in which the central bank uses the existing banks' branch networks and labor force to offer CBDC accounts managed by private banks. The central bank then reimburses private banks for managing the CBDC, thus alleviating the impact of the CBDC on the profitability of private banks. As a result, the intermediated model has been viewed as a more balanced approach to introducing CBDC as it would "reduce the prospects for destabilizing disruptions to the well-functioning U.S. financial system."[6]

However, while an intermediated account-based CBDC provides banks with reimbursement income, it is potentially costly for the banking system because it is more attractive than one directly supplied by the central bank, thus leading to greater migration of deposits from private banks to the central bank. Although individuals interact with private banks to manage CBDC holdings and payments, the CBDC itself remains a liability of the central bank, and the disintermediation of bank lending is still present.

To quantify these costs and benefits of an intermediated CBDC, we assume that this type of CBDC offers additional convenience to depositors via the local branch network and services. We allow CBDC convenience to vary from 25% to 100% of the value depositors attach to an average bank's branch services, which we calculate using equation (8). Also, we assume that the central bank reimburses a fee ranging from 25% to 100% of the

[6]See "Money and Payments: The U.S. Dollar in the Age of Digital Transformation," January 2022, p. 14.

federal funds rate per dollar of CBDC. We explore how CBDC market share, bank valuation, and loan provision change for each combination of branch convenience and fee.

In Panel A of Table 9, we find that holding the fee constant, a greater degree of bank intermediation raises CBDC attractiveness and market share. At the same time, the intermediate model triggers two opposing effects on banks' valuation. On the one hand, better utilization of existing bank infrastructure leads to a higher CBDC market share. Because banks are compensated based on the volume of CBDC they intermediate, the higher CBDC market share leads to greater compensation from the central bank, boosting banks' value. On the other hand, the intermediated CBDC competes away bank deposits more strongly, inducing banks to raise their deposit rates further and rely more on wholesale funding to finance lending. This second effect leads to higher funding costs and lower bank value. The results in Panel B show that the effect of deposit outflows is likely to dominate in most regions. As also illustrated in Panel C, this effect leads to a greater reduction in bank credit provision. Nevertheless, the salutary effect of intermediation fees becomes more influential when the central bank starts to offer generous compensation, giving rise to the hump-shape in bank value in column (5) of Panel B.

Next, holding branch convenience constant, a higher intermediation fee from the central bank facilitates lending by reducing the probability of bank default and lowering the wholesale financing cost. A higher fee also leads to faster bank capital accumulation, which eases the capital constraint and further amplifies the effect on lending. Quantitatively, the impact of a higher intermediation fee depends on the degree of CBDC convenience. When it is low, the effect is limited, but when CBDC convenience increases, paying a higher fee can significantly reduce the disintermediation effect. For example, raising the intermediation fee from 50% to 100% can reduce disintermediation by 12 $((0.890 - 0.842)/0.404)$ cents per dollar of CBDC, as shown in row (5) of Panel C.

Finally, we compare the results in Table 5 for a direct CBDC with those in Table 9 for an intermediated account-based CBDC. We find that an intermediated model does not necessarily result in less disruption. With branch convenience and intermediation fees both at 50%, one dollar of intermediated CBDC displaces bank lending by 13 $((1.021 - 0.994)/0.215)$ cents, which is slightly lower than in a direct CBDC model. However, with branch convenience and fees set at 100%, we find that one dollar of intermediated CBDC displaces lending by 32 $((1.021 - 0.890)/0.404)$ cents, a significantly larger effect than in a direct model.

6.5. CBDC and bank stability

In addition to possible disintermediation, financial stability is another policy concern about CBDC. As much work has already examined how CBDC increases bank-run incentives (Williamson 2021; Skeie 2020; Ahnert et al. 2020), in this section, we examine how CBDC affects banks' interest rate exposure during normal times and hinders their recovery from large negative shocks.

In Panel A of Figure 2, we plot banks' deposit spread for different levels of the federal funds rate. The solid line corresponds to the case without CBDC, and the dashed line corresponds to the case with CBDC. Without CBDC, banks' deposit spreads rise strongly with the policy rate. This effect has also been documented in Drechsler, Savov, and Schnabl (2017, 2021). Intuitively, a higher federal funds rate raises banks' effective market power in the deposit market because depositors' opportunity cost of holding cash rises. Banks exercise their increased market power by charging higher prices for their deposit services, thus generating higher deposit market profits.

The dashed lines show that the introduction of CBDC flattens the relation between the federal funds rate and the deposit spread. Intuitively, CBDC limits the degree to which banks can raise their deposit spreads in response to monetary tightening. This result arises via an endogenous change in the average yield sensitivity of banks' depositor bases. CBDC mainly competes away depositors who prefer transactions convenience, leaving banks with a more yield-sensitive clientele. When the policy rate rises, these rate-sensitive depositors are likelier to switch from bank deposits to Treasury securities. Banks optimally raise deposit rates, leading to a flatter relationship between deposit spreads and the federal funds rate.

In addition to an increase in the deposit rate, the introduction of CBDC also changes banks' funding structure at the extensive margin, thereby making banks rely more on wholesale borrowing, as illustrated in Tables 5 and 8. In Panel B of Figure 2, we compare the overall change in banks' funding cost under different levels of the federal funds rate with and without the presence of CBDC. After the introduction of CBDC, banks' funding costs are higher, and they rise more steeply with the federal funds rate. This change in slope reflects the same forces that flatten the relation between deposit spreads and the federal funds rate in the presence of CBDC.

Next, we consider the response of bank stock prices to a one percentage point shock to the federal funds rate. When CBDC is absent, this shock causes a 2% decline in bank stock prices, which closely matches the empirical evidence (Wang et al. 2022). However, when CBDC is present, the response to the shock is over twice as large, with stock prices falling by, on average, 4.6%.

Relatedly, we consider a situation where banks experience large, unexpected loan default shocks. We calibrate the severity and length of the default shock by adjusting the level of the charge-off rate, δ_t to match the 2007–2009 Global Financial Crisis (GFC), as seen in Panel A of Figure 3. We then use our model to examine the degree to which default shocks affect bank lending and the speed at which banks recover from these shocks. We compare our model predictions with and without a zero-interest CBDC.

Panel B of Figure 3 shows that a GFC-equivalent loan default shock leads to a 21% fall in bank capital. This drop steepens by six percentage points after CBDC. Banks become less profitable when facing competition from CBDC, so they have a thinner capital cushion. Thus, the same shock translates into a larger percentage change in bank capital.

Panel C shows that this lower bank capital also gives rise to higher credit spreads for wholesale funding. The average spread rises by over fourfold after the shock without CBDC and sixfold when CBDC is present. Moreover, the higher credit spread induces banks to refrain from wholesale borrowing, which can further constrain lending. As shown in Panel D, the introduction of CBDC leads to a 4% further decline in bank lending and slower recovery from default shocks. Banks have a more sluggish recovery because they accumulate retained earnings and replenish their capital more slowly with fewer profits from the deposit market.

7. Robustness and Discussion

In this section, we assess the robustness of our results by including elements we have left out of the baseline model. We also compare our quantitative model predictions with existing reduced-form estimates of the pass-through of deposits to lending.

7.1. Incorporating a Treasury premium

In the baseline model, we assume that the Treasury market clears at the prevailing federal funds rate. However, in practice, Treasuries have a liquidity premium. Furthermore, the Treasury premium potentially rises if the central bank invests funds raised from CBDC into Treasuries. Addressing this second point is important because the behavior of the central bank is outside of our model.

We introduce a Treasury premium as a function of central-bank demand for Treasuries by considering a simple constant semi-elasticity demand function for Treasuries:

$$p = a - b \ln(Q - F), \tag{37}$$

where p is the Treasury premium, Q is the total quantity issued by the Treasury, F is the quantity held by the central bank, and b is the demand semi-elasticity. Intuitively, if the quantity issued, Q, is lower, or if F rises as the central bank buys more Treasuries from the market, then Treasuries become scarcer, and the premium rises. To calibrate (37), we express Q and F as a ratio relative to the size of the deposit market. In our sample period, the net supply of Treasury securities, $Q - F$, relative to deposits is approximately one. We set the value of the semi-elasticity of demand, b, to $1/58$, based on the estimates in (Jiang, Richmond, and Zhang 2022, page 24). To calibrate the intercept of the demand function, a, we use the estimate of the average Treasury premium from Nagel (2016), which is approximately 24 basis points. We then plug the average Treasury premium into equation (37) and solve for a.

We first confirm the intuition that introducing CBDC drives up the Treasury premium if the central bank invests the funds raised by CBDC into Treasuries. We find that the average Treasury premium rises from 24 basis points in the baseline economy without CBDC to 38 or 84 basis points in economies with non-interest-bearing and interest-bearing CBDSs, respectively. However, introducing a Treasury premium does not significantly change our baseline results. Table 10 shows that a one-dollar increase in a non-interest-bearing CBDC crowds out 89 cents of deposits and 14.4 cents of loans. These figures are similar to the baseline results in Table 5. Furthermore, Table 10 shows that a one-dollar increase in an interest-bearing CBDC crowds out 77 cents of deposits and 27.7 cents of loans. These findings mirror those in Table 8. Intuitively, demand for Treasuries is highly elastic, so increased demand from the central bank has a modest impact on the Treasury premium. Furthermore, demand in the deposit market is inelastic, so a small increase in the Treasury premium does not significantly change depositors' behavior.

To close this section, we note a related concern. If the central bank uses proceeds from the CBDC to buy Treasuries, the sellers of the Treasuries would receive funds that could eventually be recirculated back to banks in the form of cheaper wholesale borrowing. While this channel would lower the impact of CBDC on bank lending, to the extent that frictions exist in any part of the pathway from the central bank to the banks, CBDC would still have an effect on lending.

7.2. Wholesale borrowing costs

Our results on the limited pass-through from deposits to loans hinge on our estimates of banks' costs of accessing the wholesale market, relative to the costs of expanding deposits or reducing loans. In the baseline model, we represent the cost of wholesale funding by a quadratic function that depends on a bank's ratio of wholesale to retail deposits.

Therefore, we examine two extensions to this cost structure. First, instead of modeling the cost of wholesale funding as a function of banks' own characteristics, we allow this cost to depend on aggregate firm investment in the economy. Denoted as $\tilde{K}_t$, this quantity equals firms' aggregate investment demand, K, minus the fraction of firms that pick their outside option of not investing, as described in Section 3.2. Intuitively, when borrowers invest more, their revenue rises, thus boosting the supply of funds to the wholesale funding market. A low ratio of bank borrowing to funding, $N_t/\tilde{K}_t$ indicates abundant supply of wholesale funding relative to bank demand. Hence, the marginal cost of borrowing an additional dollar is modest. As this ratio rises, wholesale funding becomes scarcer, so banks external funding costs rise. One potential source of the availability of wholesale funding is the introduction of CBDC, which makes banks more reliant on wholesale funding and reduces their lending, shrinking credit availability to firms. Second, we impose no prior on the curvature of banks' marginal cost of borrowing, which can be increasing or decreasing. This specification nests the possibility that as a bank takes a larger share in the wholesale funding market, it can gain negotiation power, which can lower the rate.

To capture these two extensions, we model a bank's cost of accessing the wholesale funding market as follows:

$$\Phi^N = r_t^N \times N_t + \frac{\phi^N}{2} N_t \times \left(\frac{N_t}{\tilde{K}_t}\right)^{\nu}, \tag{38}$$

where r_t^N is the endogenously determined credit spread that banks pays so that the lenders can break even, just as in our baseline model. As a departure from this baseline, the second term in (38) is linear in N_t but multiplied by the fraction $N_t/\tilde{K}_t$, with an exponent

ν that captures the curvature of the bank's wholesale borrowing cost function. We estimate the two new parameters, $\{\phi^N, \nu\}$, using the mean and variance of banks' wholesale funding ratio. The estimate of ν is 0.846 with a standard error of 0.141, suggesting that banks' wholesale borrowing cost is almost quadratic. The result is not surprising, as Table 4 shows that in the baseline model, we can closely match the variance of the ratio of wholesale funding to deposits (0.0952 in the model versus 0.0960 in the data). Our estimate of ϕ^N is 0.037 with a standard error of 0.007. These estimates imply that a one-dollar increase in CBDC crowds out deposits by 81.0 cents and loans by 24.3 cents. These magnitudes are close to our baseline results in Table 5.

7.3. Costly equity issuance

Next, we relax the assumption that banks cannot issue equity. Instead of requiring dividends to be positive as specified in equation (25), we allow them to be negative, subject to a linear equity issuance cost, ϕ^e. We reestimate our model, with the parameter ϕ^e being identified by an additional moment: the ratio of bank equity issuance to total assets. In the data, this moment is 2%. We find that matching this moment yields an equity issuance cost of 7%, which is comparable to the estimates for industrial firms in Hennessy and Whited (2007). All other parameter values stay close to the baseline estimates. With this extended model, we redo the counterfactual analysis in Table 5. We find that a one-dollar increase in CBDC holding reduces bank deposits by 76 cents and bank loans by 16 cents. Thus, the main takeaway that only a modest fraction of the deposit market effect will pass through onto banks' lending decisions remains robust. This result is intuitive, as banks' equity issuances are both tiny and rare, both in the extended model and the data.

7.4. When CBDC hurts lending

Our findings indicate that a CBDC's introduction is unlikely to cause significant bank disintermediation, as banks can replace lost deposits with wholesale funding, with every dollar decrease in bank deposits accompanied by less than a one-third dollar decrease in bank loans. In this section, we explore scenarios where the substitution becomes more costly, thus identifying situations where a CBDC might trigger more substantial disintermediation. In the following experiments, we investigate the changes needed in our model to double the deposit-loan pass-through rate, thus exceeding two-thirds.

First, banks' cost of performing this substitution depends on their reliance on wholesale funding. In Table 8, we show that even when the CBDC captures 30% of the deposit market, this substitution remains effective. However, what happens if the CBDC's market share continues to rise? To answer this question, we examine scenarios in which the CBDC pays the market interest rate, and its quality rises beyond that reported in column (5) of Table 8. We find that the CBDC's deposit market share can reach 62% when its quality doubles. As the CBDC takes a much larger market share, banks shift significantly toward wholesale funding, incurring increasing marginal costs to finance the lost deposits.

Second, in panel A of Figure 1, we find that banks' ability to substitute can be severely limited if the cost of wholesale funding is high. Specifically, the disintermediation effect of CBDC would double if the quadratic financing cost, ϕ^N, increases by fivefold.

Lastly, for banks that use uninsured wholesale funding, their credit spreads can also affect their cost of substitution. Our model features a baseline credit spread of 10 basis points. We calculate that the disintermediation effect would double if this spread rises by 43 basis points. This magnitude resembles levels observed during the Great Financial Crisis. As is also shown in Figure 3, this result suggests that the introduction of CBDC can lead to more extensive disintermediation and a slower recovery during crisis periods.

7.5. Deposit-lending pass-through estimates in prior studies

A key purpose of the model is to assess how much of the impact on bank deposits can be transmitted to bank lending. Depending on the design of the CBDC, our model implies a deposit-lending pass-through that ranges from 23.2 cents for a non-interest-bearing CBDC and 32.8 for an interest-bearing CBDC, where we calculate pass-through as the marginal effect on loans divided by the marginal effect on deposits. We also find the pass-through of deposits to lending varies across bank sizes, with 10 cents per dollar for big banks and 57 for small banks. We compare our model predictions with the reduced-form evidence in Khwaja and Mian (2008) and Gilje, Loutskina, and Strahan (2016). Khwaja and Mian (2008) exploit a natural experiment in Pakistan in which unanticipated nuclear tests in 1998 prompted large deposit outflows from Pakistani banks. Khwaja and Mian (2008) find a one-dollar deposit outflow leads to a 60-cent decline in lending. Gilje et al. (2016) study the response of bank lending to exogenous liquidity windfalls from natural gas shale discoveries in the United States. They find that a one dollar deposit inflow leads to a 51 cent increase in mortgage lending.[7]

Care should be taken in comparing our results with these studies. First, Khwaja and Mian (2008) and Gilje et al. (2016) use cross-bank variation to identify the impact on lending, while our estimate is an aggregate impact. These two types of estimates can differ because of spillover or substitution effects. Second, the sample banks are different. Khwaja and Mian (2008) study Pakistani banks, which likely face greater external financing frictions, and Gilje et al. (2016) use an equally weighted regression in a sample of 1,700, mostly small banks. Nonetheless, we find that for small banks, the deposits-lending pass-through predicted by our model is comparable to these estimates.

8. Conclusion

We study the implications of CBDC for the banking system. We clarify the simple point that CBDC need not reduce bank lending unless frictions and regulations bind deposits

[7] Gilje et al. (2016) find that a 1% increase in the share of branches in boom counties increases deposit growth by 5.67% (Table II, column (1)) and mortgage growth by 6.84% (Table III, column (3)). Because the mortgage to deposit ratio is 0.323/0.827 (Table I, column (3)), we can calculate that a one dollar increase in deposits is associated with an increase in mortgage lending of 51 cents.

and lending. Therefore, evaluating the potential impact of CBDC on bank lending is effectively a quantification of these frictions and synergies. To this end, we estimate a dynamic banking model using data from the U.S. banking system. The most important frictions we consider are imperfect competition, costly external finance, and bank capital regulation. Next, because we have no data on CBDC to discipline the model, we create a synthetic CBDC by attributing to it several characteristics of other financial instruments. We then estimate the sensitivity of demand to these characteristics and insert this demand into our dynamic model to evaluate the impact of CBDC on optimal bank behavior.

Our counterfactual analysis shows that a CBDC replaces a significant fraction of bank deposits, especially when it pays interest. However, CBDC has a much smaller impact on bank lending because banks replace a large fraction of the lost deposits with wholesale funding. We also find that a CBDC intermediated through banks captures a large market share and can depress bank lending more than a CBDC issued directly by the central bank. We also find that substitution to wholesale funding makes banks' funding costs more sensitive to changes in short-term rates, increasing their exposure to interest rate risk. Finally, we find that CBDC has a stronger effect on small banks than on large banks. This result has an important policy implication. Because small firms disproportionately rely on small banks for credit, the introduction of CBDC could affect credit access for small firms more than large firms.

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Table 1: Variable Definitions

Variable	Details of construction
Deposit market share	A bank's deposits divided by the sum of deposits, cash, and Treasury bills in the U.S. economy.
Loan market share	A bank's loans divided by the sum of U.S. corporate and household debt.
Deposit rates	Deposit interest expense divided by deposits.
Loan rates	Loan interest income divided by loans outstanding.
Number of branches	Number of local branches.
Employees per branch	Number of employees divided by number of branches.
Expenses related to fixed assets	Non-interest expenses related to the use of fixed assets divided by total assets.
Salary	Total salary expense divided by total assets.
Average asset maturity	Estimated maturity of each type of asset, weighted by the portfolio weight. Non-mortgage loan maturity is the repricing maturity and average prepayment adjusted mortgage duration is from Elenev, Landvoigt, and Van Nieuwerburgh (2016).
Borrowing-to-deposits ratio	Non-reservable borrowing divided by total deposits.
Deposit spread	Federal funds rate minus a deposit rate.
Loan spread	A loan rate minus the corresponding five-year Treasury yield.
Deposit-to-asset ratio	Deposits divided by total assets.
Net noninterest expense	Noninterest expense minus noninterest income, divided by total assets.
Leverage	Total assets divided by the book value of equity.
Market-to-book ratio	The market value of equity divided by the book value of equity.
Total credit-FFR sensitivity	Three-year impulse response coefficient of total credit to the federal funds rate estimated from a VAR.

Table 2: 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. The data sources are the Call Reports and the FDIC Summary of Deposits.

	mean	sd	p10	p25	p50	p75	p90
Deposits	0.771	0.136	0.617	0.707	0.793	0.859	0.933
Wholesale borrowing	0.126	0.103	0.001	0.039	0.104	0.202	0.289
Deposit rates	1.651	1.300	0.145	0.386	1.461	2.648	3.453
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
Borrowing-to-deposits 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

Table 3: 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 Berry et al. (1995) (BLP). Panel D presents results for parameters estimated via Simulated Minimum Distance (SMD). Standard errors for the estimated parameters are clustered at the bank level and reported in brackets.

Panel A. Statutory and Fixed Parameters			
τ_c	Corporate tax rate	0.35	
θ	The reserve ratio	0.02	
κ	The capital ratio	0.06	
ξ	Fire sale discount	0.3	
$\beta^d_{digital}$	Digital adjustment	0.2	
Panel B. Parameters Estimated Separately			
μ	Average loan maturity	3.425	
$\hat{J}$	Number of representative banks	6	
$\bar{f}$	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 charge-offs mean	-5.678	
σ_δ	Log loan charge-offs std	1.434	
$\rho_{\delta f}$	Correlation between federal funds rate and charge-offs	-0.102	
Panel C.Parameters Estimated via BLP			
α^d	Depositor sensitivity to deposit rates	1.469	(0.486)
σ_{α^d}	Dispersion of sensitivity to deposit rates	0.842	(1.262)
σ_{β^d}	Dispersion of sensitivity to transaction dummy	0.214	(5.528)
α^l	Borrower sensitivity to loan rates	-1.847	(0.514)
$q^{d,T}$	Quality of transactions deposits	5.389	(3.523)
$q^{d,S}$	Quality of savings deposits	4.556	(3.523)
q^d_c	Quality of holding cash	3.706	(3.716)
q^l_l	Quality of borrowing through loans	1.784	(3.402)
Panel D. Parameters Estimated via SMD			
γ	Banks' discount rate premium	0.012	(0.001)
W/K	Relative size of the deposit market	0.325	(0.022)
q^l_n	Value of firms' outside option	-11.631	(0.151)
ϕ^d	Bank's cost of taking deposits	0.011	(0.003)
ϕ^l	Bank's cost of servicing loans	0.007	(0.002)
ϕ^N	External financing cost	0.010	(0.005)
χ	Net operating cost	0.015	(0.003)

Table 4: Moment Conditions

This table presents the empirical and simulated moments we target in our SMD estimation, along with the standard errors for testing the pair-wise differences 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
Sensitivity of total credit to the federal funds rate	-1.062	-0.926	0.299

Table 5: 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 in which CBDC is absent from the deposit market; column (5) shows the results when a CBDC is fully incorporated following our conceptualization in Section 6. In columns (2)–(4), we examine cases in which CBDC is introduced but suffers a "quality discount"—we set the quality of CBDC (q^d_{CBDC}) to 25%, 50%, and 75% of the value we use in column (5), respectively. In column (6), we calculate the sensitivity of each variable of interest to changes in the market share of CBDC. Deposits, cash, and loans are all normalized by the size of the deposit market. Bank value is normalized by the steady-state value of book equity in the baseline model.

	(1) No CBDC	$\times q_{CBDC}$				(6) Sensitivity
		(2) 25%	(3) 50%	(4) 75%	(5) 100%	
(1) CBDC Share	0.000	0.005	0.012	0.030	0.076	1.000
(2) Deposits	0.876	0.872	0.868	0.851	0.814	-0.815
(3) Cash	0.070	0.069	0.068	0.066	0.062	-0.107
(4) Loan	1.021	1.016	1.015	1.016	1.007	-0.189
(5) Deposit spread (%)	1.125	1.117	1.117	1.113	1.092	-0.432
(6) Loan spread (%)	2.177	2.182	2.183	2.182	2.189	0.147
(7) Bank credit spread (%)	0.100	0.112	0.112	0.112	0.132	0.414
(8) Funding cost (%)	1.291	1.305	1.321	1.335	1.357	0.874
(9) Bank value	1.846	1.843	1.835	1.833	1.821	-0.338

Table 6: Decomposing 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 interest. Row (1) presents the total effect on bank lending; row (2) examines the channel through which CBDC introduction only influences the quantity of deposits; row (3) corresponds to the channel through which CBDC only influences bank profit by making them less competitive on the deposit market; row (4) explores the channel through which CBDC only changes banks' interest rate risk exposure and widens the credit spreads on wholesale funding.

		Loan-CBDC sensitivity
(1)	With CBDC	-0.189
(2)	CBDC only affects deposit quantity	-0.158
(3)	CBDC only affects bank profit	-0.114
(4)	CBDC only affects wholesale funding cost	-0.084

Table 7: The Heterogeneous Impact of CBDC

In Panel A, we present subsample estimation results by splitting banks based on their size. "Big" comprises banks whose sizes are in the top one percentile, and "Small" comprises all the other banks. In Panel B, we examine how banks' deposits, funding costs, and lending decisions respond to the introduction of CBDC. Deposit- and loan-CBDC sensitivities measure the responsiveness of banks' deposit or loan base to a one-dollar increase in depositors' CBDC holdings. Funding cost-CBDC sensitivity measures the change in banks' funding cost to each percentage point increase in CBDC's market share. CBDC has quality of q^d_{CBDC} as described in Section 6, and it bears a zero interest rate.

		Small Banks	Big Banks
Panel A: Subsample Parameter Estimates			
ϕ^N	External financing cost	0.033	0.009
		(0.002)	(0.001)
W/K	Relative size of the deposit base	0.280	0.374
		(0.012)	(0.014)
ϕ^d	Bank's cost of taking deposits	0.010	0.012
		(0.001)	(0.001)
ϕ^l	Bank's cost of servicing loans	0.008	0.006
		(0.001)	(0.001)
χ	Net operating cost	0.025	0.009
		(0.001)	(0.003)
Panel B: Impact of Introducing CBDC			
Deposit-CBDC sensitivity		-0.744	-0.801
Loan-CBDC sensitivity		-0.389	-0.126
Funding cost-CBDC sensitivity		1.533	0.852

Table 8: Counterfactual: Varying the CBDC Rate

In this table, we examine how banks' deposits, cost of funding, and other balance sheet variables respond to the introduction of a interest-bearing CBDC. Column (1) corresponds to a case where the CBDC pays zero rate; column (5) shows the results when CBDC pays the federal funds rate. In columns (2)–(4), we examine cases in which the rate on CBDC (r^d_{CBDC}) is set to 25%, 50%, and 75% of the federal funds rate. In column (6), we calculate the sensitivity of each variable of interest to changes in the market share of CBDC. Deposits, cash, and loans are all normalized by the size of the deposit market. Bank value is normalized by the steady-state value of book equity in the baseline model.

	(1) Zero rate	$\times$FFR				(6) Sensitivity
		(2) 25%	(3) 50%	(4) 75%	(5) Pays FFR	
(1) CBDC Share	0.076	0.099	0.138	0.209	0.313	1.000
(2) Deposits	0.814	0.796	0.765	0.712	0.617	-0.829
(3) Cash	0.062	0.060	0.057	0.053	0.047	-0.062
(4) Loan	1.007	1.007	1.000	0.975	0.942	-0.272
(5) Deposit spread (%)	1.092	1.087	1.064	1.014	0.965	-0.536
(6) Loan spread (%)	2.189	2.190	2.193	2.210	2.215	0.108
(7) Bank credit spread (%)	0.132	0.135	0.168	0.398	0.842	1.301
(8) Funding cost (%)	1.357	1.418	1.481	1.635	2.104	3.149
(9) Bank Value	1.821	1.791	1.731	1.511	1.184	-2.684

Table 9: Intermediated Account-based CBDC

In this table, we examine how banks' value and credit provision change when CBDC is intermediated through banks. In each panel, each row corresponds a version of CBDC that is assigned a given percent of our estimate of bank branch convenience, which ranges from 25% to 100%. Each column corresponds to a different level of central bank reimbursement to private banks, given by a fraction of the federal funds rate multiplied by the amount of CBDC held by depositors, with the percent ranging from 25% to 100%. The quantity of bank lending is expressed relative to the size of the deposit market. Bank value is normalized by the steady-state level of book equity in the baseline model when CBDC is absent.

Panel A: CBDC Market Share

		Intermediation fees to banks				
		(1) 0%	(2) 25%	(3) 50%	(4) 75%	(5) 100%
	(1) 0%	0.076	0.075	0.076	0.076	0.076
	(2) 25%	0.130	0.132	0.131	0.133	0.134
Branch convenience	(3) 50%	0.215	0.215	0.215	0.217	0.219
	(4) 75%	0.309	0.310	0.311	0.316	0.320
	(5) 100%	0.369	0.381	0.390	0.401	0.404

Panel B: Bank Value

		Intermediation fees to banks				
		(1) 0%	(2) 25%	(3) 50%	(4) 75%	(5) 100%
	(1) 0%	1.821	1.855	1.867	1.889	1.922
	(2) 25%	1.816	1.838	1.857	1.906	1.970
Branch convenience	(3) 50%	1.772	1.774	1.805	1.896	2.012
	(4) 75%	1.522	1.541	1.621	1.793	1.906
	(5) 100%	1.023	1.077	1.163	1.400	1.616

Panel C: Bank Lending

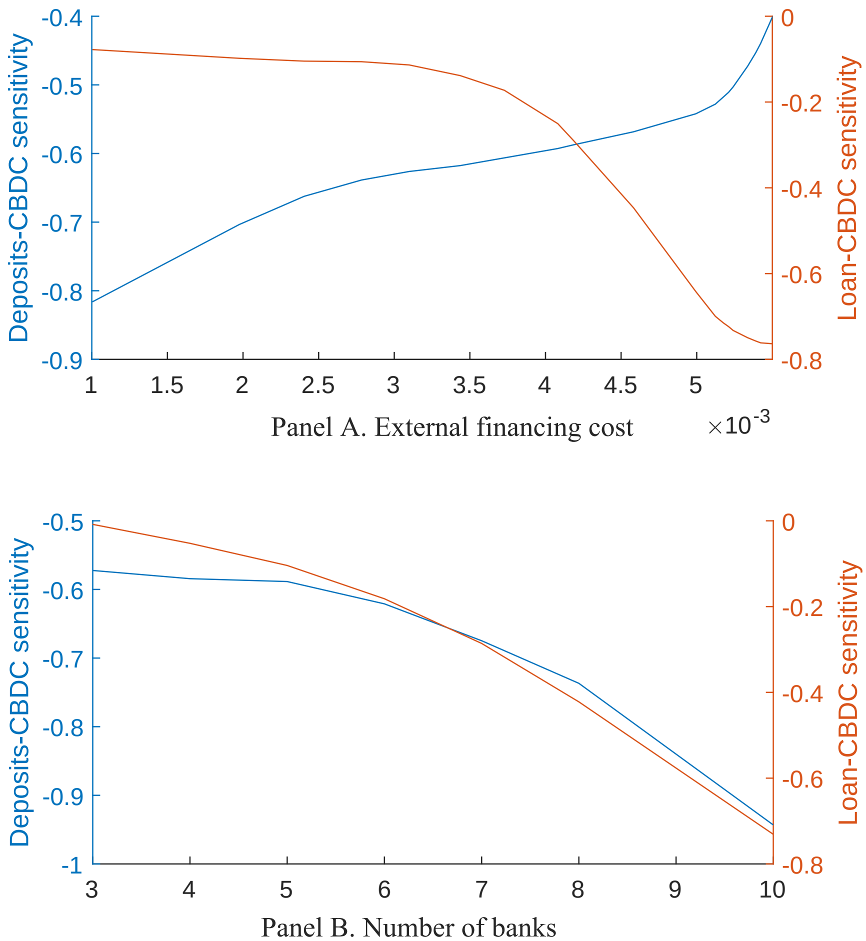
		Intermediation fees to banks				
		(1) 0%	(2) 25%	(3) 50%	(4) 75%	(5) 100%
	(1) 0%	1.007	1.008	1.010	1.011	1.012
	(2) 25%	1.000	1.002	1.002	1.005	1.009
Branch convenience	(3) 50%	0.993	0.993	0.994	0.995	1.008
	(4) 75%	0.947	0.951	0.965	0.976	0.979
	(5) 100%	0.784	0.814	0.842	0.872	0.890

Table 10: Counterfactual: with Treasury Premium

In this table, we examine how banks' deposits, cost of funding, and other balance sheet variables respond to the introduction of CBDC, when the central bank invests the funds raised from CBDC into Treasuries, thus influencing their liquidity premium. Column (1) corresponds to our baseline model in which CBDC is absent from the deposit market; columns (2)–(3) show the results in which a non-interest-bearing CBDC is introduced; columns (4)–(5) show the results in which an interest-bearing CBDC is introduced. Deposits, cash, and loans are all normalized by the size of the deposit market.

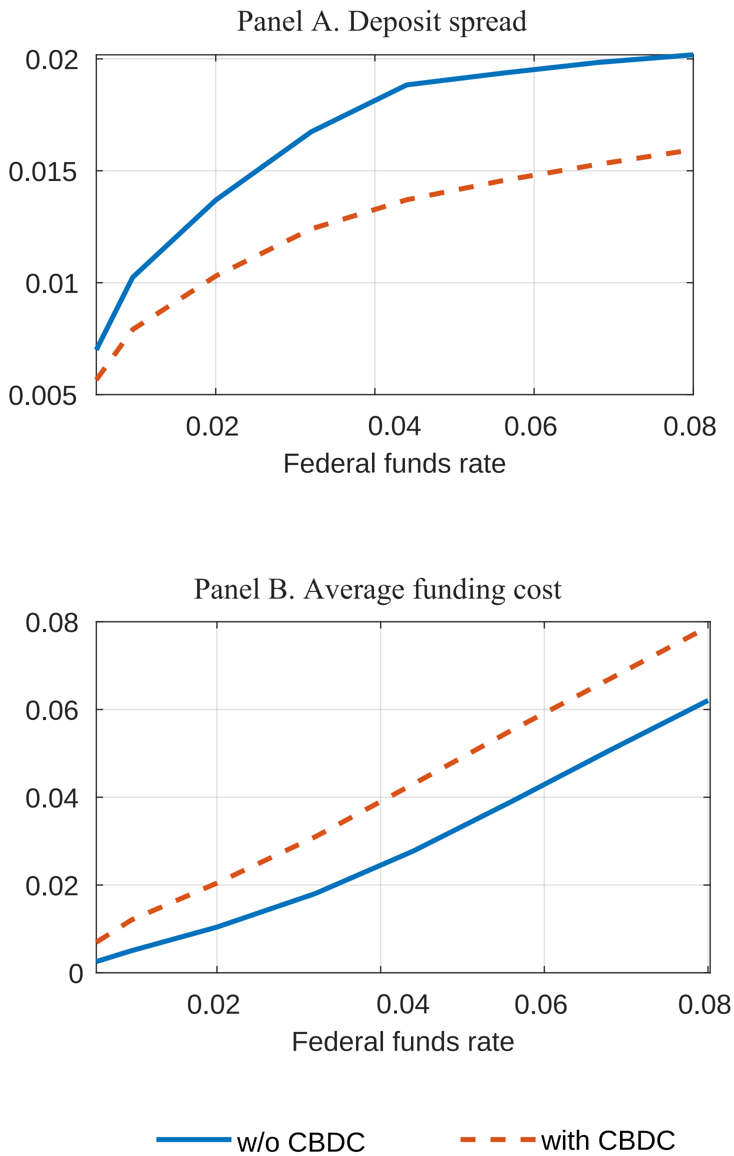
	(1)No CBDC	Non Interest-bearing CBDC		Interest-bearing CBDC	
		(2) Level	(3) Sensitivity	(4) Level	(5) Sensitivity
(1) CBDC Share	0.000	0.076	1.000	0.300	1.000
(2) Deposits	0.870	0.802	-0.894	0.638	-0.773
(3) Cash	0.069	0.062	-0.097	0.047	-0.075
(4) Loan	1.018	1.007	-0.144	0.935	-0.277
(5) Deposit spread (%)	1.120	1.087	-0.445	0.919	-0.669
(6) Loan spread (%)	2.181	2.183	0.036	2.207	0.088
(7) Bank CDS spread (%)	0.063	0.081	0.237	0.692	2.094
(8) Funding cost (%)	1.341	1.406	0.868	2.087	2.485
(9) Bank value	1.827	1.813	-0.182	1.351	-1.588

Figure 1: Heterogeneous Effects of CBDC



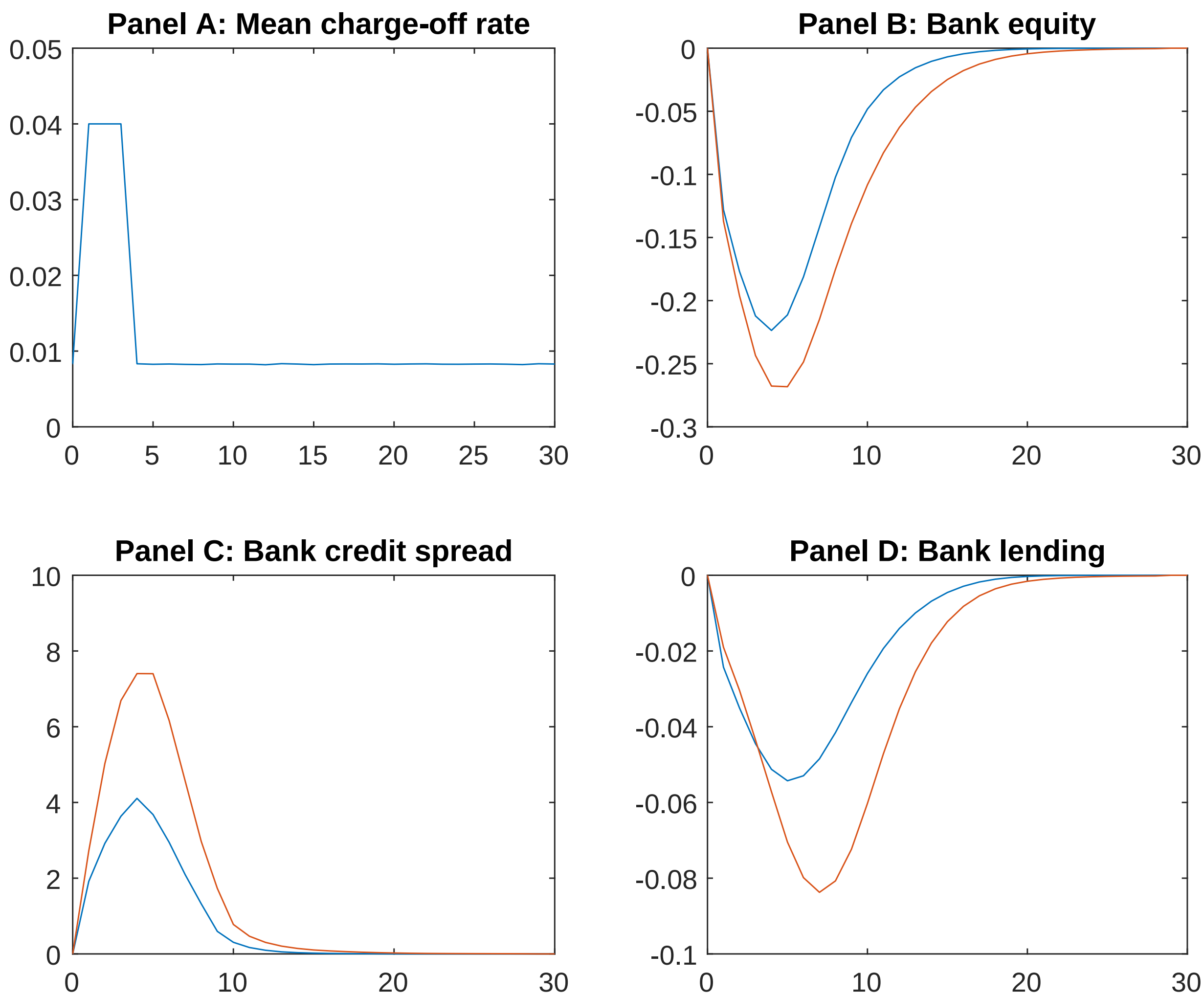
This figure shows the sensitivities of bank deposit intake and loan provision when the CBDC is introduced with quality equal to q^d_{CBDC} and a zero interest rate. In Panel A, the sensitivities are calculated under varying levels of the wholesale funding cost, which is defined as $r^N - f$, with r^N being the wholesale funding lenders' break-even rate defined in equation (34). In Panel B, the sensitivities are calculated under varying concentration levels, which are measured by the number of competing banks, $\hat{J}$, in the deposit market. High $\hat{J}$ corresponds to less-concentrated markets.

Figure 2: Deposit Spread and Funding Cost



This figure shows how banks' deposit spread and average funding cost vary with the level of the federal funds rate, with and without the introduction of CBDC.

Figure 3: CBDC and Bank Recovery Following a Negative Shock



This figure presents simulation results from an experiment in which banks recover from a large shock to loan defaults in the baseline model without CBDC and in a counterfactual case with CBDC. Panel A presents the charge-off 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 the change in the credit spread; Panel D reports the change in outstanding bank loans, scaled by the respective pre-crisis levels in the two simulations. The federal funds rate is fixed at 2% in all years.