# Central Bank Digital Currency and Banking Choices

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**Abstract**

To what extent does a central bank digital currency (CBDC) compete with deposit-taking financial institutions? To answer this question, we develop and estimate a structural model where each household chooses a financial institution to deposit their digital money. Households value the interest paid on digital money, the possibility of obtaining complementary financial products, and access to in-branch services. Introducing a counterfactual CBDC that is non-interest-bearing and does not provide complementary financial products can substantially crowd out bank deposits only if it provides a better service network. Imposing a large limit on CBDC holding would effectively limit this crowding out.

JEL Classification: E50, E58

Keywords: Central Bank Digital Currency; CBDC Designs; Micro-level Deposit Demand Estimation; Banking Competition

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# 1 Introduction

Many central banks are considering issuing a retail central bank digital currency (CBDC), a digital form of central bank money that is available to the general public and can be used for retail transactions. According to the 2021 Bank for International Settlements (BIS) survey, 90% of the central banks are engaging in CBDC work and 62% are conducting experiments or proofs-of-concept.[1] Despite the widespread interest, there are concerns that a CBDC could substantially crowd out bank deposits, which may undermine financial stability by raising the funding cost and reducing the profitability of the banking sector. However, little is known about the potential magnitude of the CBDC adoption and its crowding out effect on bank deposits.

The key to address this question is to understand how a CBDC would differ from bank deposits. This paper quantifies the impact of a CBDC on banks in the deposit market, taking into account two key features that can differ between a CBDC and bank deposits: (i) banks provide a variety of financial products which are complementary to deposits, such as mortgage loans and credit cards, while a CBDC would likely not come with these complementary financial products; (ii) many banks have extensive branch networks for in-person services, while for a CBDC, it depends on the design of the service location network.

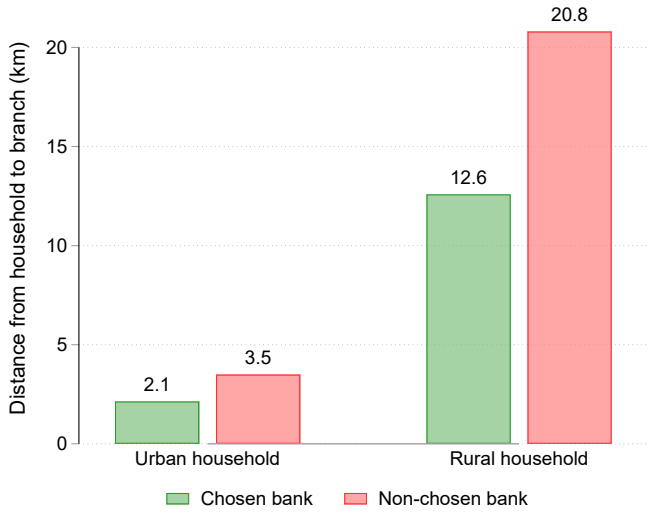
From Canadian household survey data 2010–2017, we find households have strong preferences for bundling additional financial products with deposit banks as well as for obtaining customer service from branches. More specifically, 56% of mortgage borrowers and 45% of credit card holders choose their deposit banks for the respective product. Since the central bank is unlikely to provide a wide range of financial products, the CBDC can be less attractive than bank deposits, limiting its impact on banks.

Additionally, both urban and rural households prefer banks that have branches close to their residences, as illustrated in Figure 1. The same survey data show that 60% of depositors visited their branches at least once in the past month and they value branches for certain types of services. In particular, depositors prefer to use bank branches for non-transaction related services, such as obtaining customer service and support, making complaints, and applying for new products, compared to other banking methods such as online and mobile banking. Therefore, the design of location network that provides these services for CBDC is likely to affect its attractiveness and its impact on banks.

To incorporate these two features, we develop a structural model where households obtain

[1]The survey respondents include 81 central banks that represent close to 76% of the world's population and 94% of global economic output (Kosse and Mattei, 2022). The Bahamas, Eastern Caribbean Central Bank, Jamaica, and Nigeria have already launched retail CBDCs. There are 21 countries that already started their pilots, including China, India, Singapore, South Korea, and Sweden.

Figure 1: Distance to the Nearest Branch of Chosen Bank and Non-chosen Banks




Data sources: CFM 2017, FCAC 2017
Note: The first (second) green bar shows the great-circle distance from an urban (a rural) household to the nearest branch of their chosen deposit banks, which is an average across all urban (rural) households. The first (second) red bar shows the mean distance from an urban (a rural) household to the nearest branch of each of the non-chosen banks in their choice set, which is then averaged across all urban (rural) households. The choice set of an urban (a rural) household includes all the banks with branches that are within 15km (50km) from the household's location.

utility from holding their endowed liquid assets in physical cash and digital money. In the absence of a CBDC, the household first needs to choose one of the private banks to hold the liquid digital money, taking into account that banks offer different deposit rates, complementary financial products, and service locations (bank branches). Each bank faces a deposit demand that is an aggregate of individual household's expected deposit demand and engages in Bertrand competition with differentiated deposits.

A key challenge in estimating this model is to identify households' preferences for obtaining complementary financial products from their deposit banks and for service locations. To achieve identification, we combine a dataset on Canadian bank branch locations with a unique Canadian dataset that contains detailed information on households' bank choices for each different financial product and their residence locations.

After obtaining estimates of the model primitives, we then introduce a CBDC into the model and study its impact on banks in counterfactual analyses. The CBDC is viewed as a new product for households to deposit their digital money, where the attributes of the CBDC are exogenous design choices made by the central bank. We assume the CBDC does not offer complementary financial products and depending on the design, it may have no service location or have a network of service locations that is identical to the network of

Canada Post offices or bank branches. The main findings are as follows.

First, a non-interest-bearing CBDC would require better service locations to be attractive. If the CBDC does not pay interest and has no service location, it would have a negligible impact, capturing only 0.7% of the market and reducing bank deposits by only 0.8%.[2] If it uses Canada Post offices as service locations, the market share grows to about 6.5%. This is close to the current market share of cash (4.5%). Adding bank branches can drive the CBDC market share to about 11.6%.

Second, households greatly value the complementarity between deposits and other financial products, which would limit the impact of the CBDC that does not provide complementary financial products. Even when the CBDC has an extensive network of service locations that includes all bank branches and Canada Post offices, it would obtain only around 11.6% market share and reduce deposits by about 12.3%. In contrast, neglecting the complementarity can lead to a significant overestimation of the impact of the CBDC (around 38% market share and 39% reduction in deposits under the extensive service location network), highlighting the importance of accounting for the complementarity among financial products.

Third, we use the model to study the effect of introducing a limit on CBDC holdings, which is frequently discussed by policymakers as a potential tool to reduce the crowding-out effects of the CBDC. We find that even a large holding limit of 25,000 Canadian dollars, which is much higher than the limit of 3,000 Euros mentioned by the ECB, would reduce the share of liquid assets held in CBDC by half regardless of the service location network. Although this high limit is binding only for slightly more than 10% of households, these households are the ones that tend to hold a large amount of liquid digital balances. Therefore, the holding limit can be very effective in limiting the impact of a CBDC and a large holding limit is likely to be sufficient to avoid disrupting the financial system without damaging the usefulness of the CBDC as a payment instrument.

Lastly, we examine the heterogeneous impacts of a CBDC on both banks and households. We find that banks with higher market shares tend to respond more to the introduction of a CBDC, raising deposit rates by more and losing fewer deposits. Households in rural areas would benefit more from a CBDC than urban households even if the CBDC does not have service locations, because of the lack of competition in rural areas. The difference is larger when the service locations of CBDC include the Canada Post offices, which are more evenly distributed across rural and urban areas compared to bank branches. Therefore, from a financial inclusion point of view, it may be desirable to choose locations as broad as Canada Post offices as service locations for the CBDC.

[2]The market share is out of the total liquid assets held by households, where liquid assets are defined as the sum of cash and demand deposits in this paper.

This paper contributes to the growing literature that studies the effects of a CBDC on banking. One stream of the literature is theoretical, which includes Chiu et al. (2022), Garratt, Yu and Zhu (2022), Keister and Sanches (2022), and Andolfatto (2021).[3] This literature typically assumes that the CBDC is a perfect substitute to bank deposits.[4] Most papers in this stream also do not consider complementarity between deposits and financial products from consumers' point of view and have limited discussions on the designs of CBDC, focusing mainly on the interest rate of a CBDC. By contrast, we use rich micro-level data to estimate households' preferences over product characteristics such as branch networks and complementarity with other financial products, and use these preferences to predict the substitution patterns between deposits and CBDC with different designs.[5]

The other stream of the literature is empirical studies, which is scarce at this point due to the lack of data. A few papers use structural models to estimate the households' holdings of CBDC (Li, 2023) and consumer adoption and usage of CBDC as a payment instrument (Huynh et al., 2020). More recently, Whited, Wu and Xiao (2022) build a structural model to quantify the impact of a CBDC on bank lending using US bank-level data. Our paper contributes to this stream by highlighting the importance of complementarities between deposits and other financial products and service locations.[6]

The rest of the paper is organized as follows. Section 2 lays out the model. Section 3 discusses identification and estimation of the model. Section 4 presents our data sources and estimation results. Section 5 shows how a CBDC would enter the model and the counterfac-

[3]Existing theoretical literature also studies the impact of CBDC on financial stability (e.g., Fernández-Villaverde et al., 2021; Williamson, 2021; Schilling, Fernández-Villaverde and Uhlig, 2020; Brunnermeier and Niepelt, 2019; Skeie, 2019), monetary policy (e.g., Davoodalhosseini, 2021; Jiang and Zhu, 2021; Bordo and Levin, 2017), macroeconomic volatility (e.g., Assenmacher, Bitter and Ristiniemi, 2023; George, Xie and Alba, 2022; Minesso, Mehl and Stracca, 2022; Barrdear and Kumhof, 2021), and welfare (e.g., Williamson, 2022; Assenmacher et al., 2021; Piazzesi and Schneider, 2020). For policy discussions on the macro implications of CBDC issuance, see Gross and Letizia (2023), Davoodalhosseini, Rivadeneyra and Zhu (2020), García et al. (2020), Berentsen and Schar (2018), Mancini-Griffoli et al. (2018), Meaning et al. (2018), Engert and Fung (2017), etc.

[4]Garratt, Yu and Zhu (2022) consider a large bank and a small bank that differ in both deposit rates and convenience values in their theoretical analysis, but they still maintain the perfect substitution assumption in the sense that CBDC demand would be zero if its interest rate and convenience value combined is lower.

[5]While there are a few papers studying the non-price design features of CBDC, such as anonymity (Cheng and Izumi, 2023; Agur, Ari and Dell'Ariccia, 2022; Ahnert, Hoffmann and Monnet, 2022) and expiry date on offline CBDC balances (Kahn, van Oordt and Zhu, 2021), we are the first paper to quantify the impact of CBDC designs in terms of the network of service locations and the complementarity.

[6]This paper also adds to the literature on deposit market competition using structural estimation (e.g., Wang et al., 2020; Xiao, 2020; Abrams, 2019; Aguirregabiria, Clark and Wang, 2019; Egan, Hortaçsu and Matvos, 2017; Ho and Ishii, 2011; Dick, 2008), which often use aggregate bank-level data and do not consider the effects of bundling financial products. We show how household-level data can be useful in this line of research. Carbo-Valverde, Perez Saiz and Xiao (2023) use household-level data to study household credit choice and pricing.

tual analyses for differing CBDC designs including the network of service locations as well as a hard limit on CBDC balances. Section 6 concludes.

# 2 Model

The model consists of two types of agents, households and banks. Each bank $j$ provides a differentiated deposit product and a set of differentiated financial products $\mathcal{K}$, where $k \in \mathcal{K}$ denotes a financial product such as a mortgage and a credit card. These financial products tend to be complementary to the deposit product through the ease of bill payments from the deposit account or convenience of managing the different accounts in one place for instance. Each household chooses one deposit product and allocates its liquid assets between digital money and physical cash, taking into account that it also values other complementary financial products. Aggregating the solution of each household's problem leads to the deposit demand for each bank. The banks take the deposit demand functions as given and set the deposit rates in differentiated Bertrand competition. We now discuss the household's problem and the bank's problem in detail.

## 2.1 Household's Problem

Each household $i$ is endowed with $w_i$ wealth, which it allocates between physical and digital liquid assets. Cash is the only physical liquid asset and bank deposits are the only digital liquid asset before CBDC issuance. To hold deposits, the household needs to open an account at a bank chosen from its choice set $\mathcal{J}_i$. After the deposit bank is chosen, the household may need to purchase each financial product $k \in \mathcal{K}$ with an exogenous probability $\omega^k$. If the household needs to purchase $k \in \mathcal{K}$, it chooses a bank from $\mathcal{J}_i^k$. To capture the complementarity between deposits and financial products, we allow the household to have a home preference for each of the financial product. That is, it enjoys extra utility if it obtains the financial product from its deposit bank. Due to this home preference, the household takes into account the potential needs for financial products when choosing the deposit bank.

The utility from opening a deposit account at bank $j$ is:

$$V_{i,j}^f = \theta \ln L_{i,j}^b + \phi \sum_{k \in \mathcal{K}} \omega^k E[V_{i,j}^k] + \boldsymbol{X}_{i,j} \boldsymbol{\beta}^f + \eta_j^f + \varepsilon_{i,j}^f. \tag{1}$$

Here $L_{i,j}^b$ is the aggregation of physical and digital liquid asset holdings, which we will discuss in detail below. We assume the household has log utility over the aggregate liquid assets. The term $\omega^k E[V_{i,j}^k]$ is the expected utility from obtaining financial product $k$, which is the

product of the probability of obtaining the financial product, $\omega^k$, and the expected value from the financial product, $V_{i,j}^k$. The household does not know its bank specific value for the financial product at the time of choosing the deposit bank, therefore it takes the future expected value $E[V_{i,j}^k]$ into account. The parameters, $\theta$ and $\phi$, capture the importance of the value from liquidity holding and from other financial products, respectively. The vector $\boldsymbol{X}_{i,j}$ contains the branch network of bank $j$ that is specific to household $i$'s local area and $\boldsymbol{\beta}^f$ consists of the preference parameters for each branch network measure. $\eta_j^f$ denotes the bank fixed effect and $\varepsilon_{i,j}^f$ is the idiosyncratic taste for bank $j$.

Household $i$ chooses a bank from their choice set $\mathcal{J}_i$ to maximize $V_{i,j}^f$. Assuming $\varepsilon_{i,j}^f$ follows the type-I extreme value distribution and is independent across banks, the choice probability is:

$$P(j_i^* = j | r_j, \boldsymbol{r}_{-j}) = \frac{\exp\left(\theta \ln L_{i,j}^b + \phi \sum_{k \in \mathcal{K}} \omega^k E[V_{i,j}^k] + \boldsymbol{X}_{i,j}\boldsymbol{\beta}^f + \eta_j^f\right)}{\sum_{m \in \mathcal{J}_i} \exp\left(\theta \ln L_{i,m}^b + \phi \sum_{k \in \mathcal{K}} \omega^k E[V_{i,j}^k] + \boldsymbol{X}_{i,m}\boldsymbol{\beta}^f + \eta_m^f\right)}, \tag{2}$$

where $j_i^*$ denotes the optimal choice, $r_j$ is the deposit rate of bank $j$ and $\boldsymbol{r}_{-j}$ is the vector of deposit rates set by banks other than $j$. We next discuss $L_{i,j}^b$ and $V_{i,j}^k$ in detail.

**Aggregate Liquid Assets.** Household $i$ obtains utility from holding cash $c_{i,j}$ and deposits $d_{i,j}$ in bank $j$, through a CES aggregator:

$$\left[c_{i,j}^\sigma + \left(u_{i,j}^b d_{i,j}\right)^\sigma\right]^{1/\sigma}, \tag{3}$$

where $\sigma \in (0,1)$ controls the substitution pattern between physical and digital liquid assets. We allow the CES aggregator to be bank specific through the per dollar value of holding digital balances $u_{i,j}^b$, which depends on bank $j$'s deposit rate $r_j$, bank-household specific characteristics $\boldsymbol{X}_{i,j}$ that include the branch network measures, household characteristics $\boldsymbol{Z}_i$, the bank fixed effect $\eta_j^b$, a deposit-specific constant $\zeta^b$, and a household's idiosyncratic taste for deposits $\varepsilon_i^b$:

$$u_{i,j}^b = \exp\left(\alpha^b r_{i,j} + \boldsymbol{X}_{i,j}\boldsymbol{\beta}^b + \boldsymbol{Z}_i\boldsymbol{\gamma}^b + \eta_j^b + \zeta^b + \varepsilon_i^b\right), \tag{4}$$

where $r_{i,j} = r_j(1 - \tau_i)$ is the return from deposits after deducting the household-specific marginal income tax rate $\tau_i$. The parameters $\alpha^b$ and $\boldsymbol{\beta}^b$ measure how much these households value their respective characteristics and translate into $u_{i,j}^b$. The household chooses $c_{i,j}$ and $d_{i,j}$ to maximize its utility from aggregate liquid asset holdings:

$$L_{i,j}^b = \max_{c_{i,j}, d_{i,j}} \left[c_{i,j}^\sigma + \left(u_{i,j}^b d_{i,j}\right)^\sigma\right]^{1/\sigma} \quad \text{st} \quad c_{i,j} + d_{i,j} = w_i, \tag{5}$$

taking first order conditions and substituting implies:

$$L_{i,j}^b = \left[1 + \left(u_{i,j}^b\right)^{\frac{\sigma}{1-\sigma}}\right]^{\frac{1-\sigma}{\sigma}} w_i. \tag{6}$$

Moreover, household $i$'s optimal deposit holding if bank $j$ is chosen can be written as:

$$d_{i,j}(r_j) = \frac{(u_{i,j}^b)^{\sigma/(1-\sigma)}}{1 + (u_{i,j}^b)^{\sigma/(1-\sigma)}} w_i. \tag{7}$$

**Value from Financial Products.** If household $i$ needs a financial product $k \in \mathcal{K}$, it will obtain the product from a bank in its choice set $\mathcal{J}_i^k$. If its deposit bank is $j$, the utility of obtaining the product from bank $n$ is:

$$U_{i,n}^k(j) = \kappa^k \mathbb{1}(n = j) + \boldsymbol{X}_{i,n}\boldsymbol{\beta}^k + \eta_n^k + \varepsilon_{i,n}^k, \tag{8}$$

where $\kappa$ is the extra utility household $i$ gets from obtaining the financial product from its deposit bank, $\boldsymbol{X}_{i,n}$ captures the bank branch network, $\eta_n^k$ is the bank fixed effect, and $\varepsilon_{i,n}^k$ is an idiosyncratic taste that follows Type I extreme value distribution. Notice that the home bank preference parameter, $\kappa^k$, captures the complementarity between deposits and the financial product $k$. That is, all else equal, a household prefers to obtain the product $k$ from its deposit bank if $\kappa^k > 0$. The parameters $\boldsymbol{\beta}^k$ reflect the importance of the branch network measures in the bank choice for this product $k$. Let $E[V_{i,j}^k]$ denote the expected indirect utility from borrowing if the home bank is $j$:

$$E[V_{i,j}^k] = E[\max_{n \in \mathcal{J}_i^k} U_{i,n}^k(j)], \tag{9}$$

where the expectation is taken with respect to the logit error $\varepsilon_{i,n}^k$. It can be shown that $E[V_{i,j}^k]$ has a closed-form expression:

$$E[V_{i,j}^k] = \ln\left(\sum_{n \in \mathcal{J}_i^k} \exp\left(\kappa^k \mathbb{1}(n = j) + \boldsymbol{X}_{i,n}\boldsymbol{\beta}^k + \eta_n^k\right)\right). \tag{10}$$

As shown in (10), in the absence of home bank preference when $\kappa^k = 0$ for all $k \in \mathcal{K}$, the expected utility from financial products is identical across potential deposit banks $j$ and thus would not affect the choice of deposit bank.

## 2.2 Banks' Problem

Bank $j$ faces a demand curve for its deposits at the national level, which depends on its deposit rate $r_j$ as well as its competitors' deposit rates $\boldsymbol{r}_{-j}$. This deposit demand is obtained by summing across each household's expected demand:

$$D_j(r_j, \boldsymbol{r}_{-j}) = \sum_i P(j_i^* = j | r_j, \boldsymbol{r}_{-j}) d_{i,j}(r_j), \tag{11}$$

where $d_{i,j}$ is the amount of deposits household $i$ will hold conditional on choosing to deposit at bank $j$ and $P(j_i^* = j | r_j, \boldsymbol{r}_{-j})$ is the probability that they choose bank $j$.

Banks set their deposit rates to compete for deposit funding. They invest all deposits in loans and earn an exogenous return $r_j^l$.[7] Let $mc_j$ denote bank $j$'s marginal cost of managing assets. Bank $j$ takes the deposit rates of other banks $\boldsymbol{r}_{-j}$ as given and chooses a deposit rate $r_j$ to maximize its profit:

$$\pi_j(r_j, \boldsymbol{r}_{-j}) = (r_j^l - r_j - mc_j) D_j(r_j, \boldsymbol{r}_{-j}). \tag{12}$$

Let $\boldsymbol{r^*} = (r_1^*, r_2^*, \cdots, r_J^*)$ denote the equilibrium deposit rates. They satisfy the set of first-order conditions of banks:

$$r_j^l - r_j^* - mc_j = \left[ \frac{\partial D_j(r_j^*, \boldsymbol{r^*}_{-j})}{\partial r_j^*} \frac{1}{D_j(r_j^*, \boldsymbol{r^*}_{-j})} \right]^{-1}, \ \forall j, \tag{13}$$

where the left-hand side is the markup and the right-hand side is the inverse semi-elasticity of deposit demand. The semi-elasticity of deposit demand depends on the parameter $\theta$ capturing the importance of indirect utility from liquidity holding in the deposit bank choice, the preference parameter $\alpha^b$ for the rate of return, the substitution parameter $\sigma$ between cash and deposits, the choice probabilities $P_{i,j} \equiv P(j_i^* = j | r_j, \boldsymbol{r}_{-j})$, and the deposit shares $\frac{d_{i,j}}{w_i}$ across households:

$$\begin{aligned} \frac{\partial D_j(r_j, \boldsymbol{r}_{-j})}{\partial r_j} \frac{1}{D_j(r_j, \boldsymbol{r}_{-j})} = & \sum_i \frac{P_{i,j} d_{i,j}(r_j)}{D_j(r_j, \boldsymbol{r}_{-j})} \left[ \theta \alpha^b (1 - \tau_i) \frac{d_{i,j}(r_j)}{w_i} \right] (1 - P_{i,j}) \\ & + \sum_i \frac{P_{i,j} d_{i,j}(r_j)}{D_j(r_j, \boldsymbol{r}_{-j})} \left[ \frac{\alpha^b (1 - \tau_i) \sigma}{1 - \sigma} \left( 1 - \frac{d_{i,j}(r_j)}{w_i} \right) \right], \end{aligned} \tag{14}$$

where $P_{i,j} d_{i,j}(r_j) / D_j(r_j, \boldsymbol{r}_{-j})$ can be viewed as the weight on household $i$.

[7] We focus on the deposit market and do not explicitly model the loan market since CBDC most directly impacts the deposit market.

# 3 Identification and Estimation

The demand side of the model has four sets of unknown parameters: parameters in the CES aggregator of liquidity, $(\alpha^b, \boldsymbol{\beta}^b, \gamma^b, \eta_j^b, \zeta^b, \sigma)$, preference parameters on financial products, $(\kappa^k, \boldsymbol{\beta}^k, \eta_n^k)$, the probability of needing financial products $\omega^k$, and the weights on different components in the utility for the deposit bank, $(\theta, \phi, \boldsymbol{\beta}^f, \eta_j^f)$. The supply side has a set of unknown parameters $mc_j$. We now discuss how to identify the parameters if we observe deposit rates, demographics, geographic information, as well as bank choices for deposit and other financial products. We focus our discussion on the demand side of the model. Once we obtain the demand-side parameters, we can identify $D_j(r_j, \boldsymbol{r}_{-j})$. We then use banks' first-order conditions (13) to identify their marginal costs, $mc_j$.

Identification of the demand side parameters involves three steps. First, we use households' portfolio allocations to identify the parameters in the CES liquidity aggregator. Second, we use households' bank choices for different financial products to identify the preference parameters in choosing the banks for financial products. Lastly, we combine these two sets of parameters with households' deposit bank choices to identify the parameters in the utility of deposit banks.

### Parameters in the CES Aggregator

The optimal deposit balance choice for household $i$ at bank $j$, (7), and the budget constraint $c_{i,j} + d_{i,j} = w_i$ imply that for all $i$ and $j$

$$\ln \frac{d_{i,j}}{c_{i,j}} = \frac{\sigma}{1-\sigma} \left( \alpha^b r_{i,j} + \boldsymbol{X}_{i,j} \boldsymbol{\beta}^b + \boldsymbol{Z}_i \boldsymbol{\gamma}^b + \eta_j^b + \zeta^b + \varepsilon_i^b \right). \tag{15}$$

This is a linear regression model and it is well-known that the coefficients and residuals are identified if explanatory variables have enough variation, technically if the design matrix is invertible. However, there are two caveats. First, we observe portfolio allocations of household $i$ only at their chosen bank $j_i^*$ from data. Since $\eta_j^b$ is bank-specific, we have information on it only if the bank is chosen by some households. As will be discussed in Section 4.1, we observe a variety of bank choices, including the biggest banks, smaller banks, online banks, and big credit unions, which allows us to identify $\eta_j^b$. Second, we cannot separately identify $\sigma$ and the other parameters because they enter into the linear regression model in a multiplicative way. If we increase $\sigma/(1-\sigma)$ and decrease all the other parameters by the same factor, the predicted portfolio allocation will stay unchanged. Therefore, we can only identify $\tilde{\upsilon} = \frac{\sigma \upsilon}{1-\sigma}$, where $\upsilon \in \{\alpha^b, \boldsymbol{\beta}^b, \boldsymbol{\gamma}^b, \eta_j^b, \zeta^b, \varepsilon_i^b\}$. However, as will be shown later in this section, this is sufficient for our counterfactual analysis.

### Preference Parameters in Choice of Bank for Other Financial Product

If a household needs a financial product $k$ (i.e., mortgage loan, credit card, guaranteed investment certificate), it selects a bank $n$ from its choice set to maximize its utility given its deposit bank choice, i.e., they solve $\max_{n\in\mathcal{J}_i^k} U_{i,n}^k(j_i^*)$. Since the idiosyncratic taste $\varepsilon_{i,n}^k$ is i.i.d. and follows the Type-I extreme value distribution,[8] the household's probability of choosing a bank $n \in \mathcal{J}_i^k$ is:

$$P_i^k(n_i^* = n) = \frac{\exp\left(\kappa^k \mathbb{1}(n = j_i^*) + \boldsymbol{X}_{i,n}\boldsymbol{\beta}^k + \eta_n^k\right)}{\sum_{m\in\mathcal{J}_i^k}\exp\left(\kappa^k \mathbb{1}(m = j_i^*) + \boldsymbol{X}_{i,m}\boldsymbol{\beta}^k + \eta_m^k\right)}. \tag{16}$$

We identify the parameters $(\kappa^k, \alpha^k, \boldsymbol{\beta}^k, \eta_n^k)$ using the conditional choice probabilities of banks for each product, which are directly observed from the data. We use these parameters to construct the weighted index $\sum_{k\in\mathcal{K}}\omega^k E[V_{i,j}^k]$, where $\omega^k$ is measured by the fraction of households that have obtained the financial product $k$.

### Preference Parameters in Deposit Bank Choice

Identification of $(\theta, \phi, \boldsymbol{\beta}^f, \eta_j^f)$ relies on the conditional choice probability of each deposit bank, which is given by (2). Once we know $\ln L_{i,j}^b$ and $E[V_{i,j}^k]$, we can recover the unknown parameters by matching conditional choice probabilities predicted by (2) with those in the data. We can calculate the expected utility from getting a financial product $E[V_{i,j}^k]$ using (10) because all the unknown parameters are identified in the step above. However, we can calculate $\ln L_{i,j}^b$ only up to a scaling factor. To see this, take the log of (6) and obtain:

$$\ln L_{i,j}^b = \frac{1-\sigma}{\sigma}\ln[1 + (u_{i,j}^b)^{\sigma/(1-\sigma)}] + \frac{1-\sigma}{\sigma}\ln w_i. \tag{17}$$

Notice that $(u_{i,j}^b)^{\sigma/(1-\sigma)}$ is equal to the exponent of the right-hand side of (15). Since $\tilde{\upsilon} = \frac{\sigma\upsilon}{1-\sigma}$ is identified in the first step for every $\upsilon \in \{\alpha^b, \boldsymbol{\beta}^b, \boldsymbol{\gamma}^b, \eta_j^b, \zeta^b, \varepsilon_i^b\}$, we can identify $(u_{i,j}^b)^{\sigma/(1-\sigma)}$ for all banks that are chosen by some households. As discussed before, $\sigma$ is not identified, so we can obtain $\ln L_{i,j}^b$ up to the scaling factor $(1-\sigma)/\sigma$. The term $(1-\sigma)\ln w_i/\sigma$ is the same for all banks and thus does not affect the conditional choice probabilities of deposit banks.

To proceed, define $\ln \tilde{L}_{i,j}^b = \ln[1 + (u_{i,j}^b)^{\sigma/(1-\sigma)}]$ and $\tilde{\theta} = (1-\sigma)\theta/\sigma$. We can then rewrite

[8] More explicitly we assume $\varepsilon_{i,n}^k$ are independent of the idiosyncratic taste for the deposit bank. This allows us to consider the other financial product choice conditional on deposit bank choice.

the choice probability (2) as:

$$P(j_i^* = j|r_j, \boldsymbol{r}_{-j}) = \frac{\exp\left(\tilde{\theta}\ln \tilde{L}^b_{i,j} + \phi \sum_{k\in\mathcal{K}} \omega^k E[V^k_{i,j}] + \boldsymbol{X}_{i,j}\boldsymbol{\beta}^f + \eta^f_j\right)}{\sum_{m\in\mathcal{J}_i} \exp\left(\tilde{\theta}\ln \tilde{L}^b_{i,m} + \phi \sum_{k\in\mathcal{K}} \omega^k E[V^k_{i,m}] + \boldsymbol{X}_{i,m}\boldsymbol{\beta}^f + \eta^f_m\right)}. \tag{18}$$

We cannot separate $\sigma$ from $\theta$ because they affect the conditional choice probabilities only through $\tilde{\theta}$. However, knowing $\tilde{\theta}$ is sufficient for our counterfactual analysis. We identify the parameters $(\tilde{\theta}, \phi, \boldsymbol{\beta}^f, \eta^f_j)$ from the conditional choice probabilities of deposit banks in the data.

The estimation strategy follows closely the identification strategy. The estimation of the demand side involves three steps. First, we apply ordinary least squares to (15) to estimate $\tilde{\upsilon} = \frac{\sigma\upsilon}{1-\sigma}$ for $\upsilon \in \{\alpha^b, \boldsymbol{\beta}^b, \boldsymbol{\gamma}^b, \eta^b_j, \zeta^b, \varepsilon^b_i\}$. Second, we apply the MLE to (16) to estimate $(\kappa^k, \alpha^k, \boldsymbol{\beta}^k, \eta^k_n)$. In the third step, we calculate $\ln \tilde{L}^b_{i,j}$ and $E[V^k_{i,n}]$ using the estimates from the first two steps and then apply the MLE to (18) to estimate $(\tilde{\theta}, \phi, \boldsymbol{\beta}^f, \eta^f_j)$. With the estimates of all the demand side parameters, we can estimate $D_j(r_j, \boldsymbol{r}_{-j})$. Then estimates of banks' marginal costs $mc_j$ are obtained from (13) once we replace $D_j(r_j, \boldsymbol{r}_{-j})$ by their estimates.

# 4 Data and Estimation Results

We start with discussing our data in Section 4.1. Then we show the estimation results for the households' banking choices and banks' marginal costs in Section 4.2.

## 4.1 Data

Estimating the model requires two sets of information: (1) information on households including their bank choices for different financial products, allocations of liquid assets, residential locations, and other demographic characteristics, and (2) information on banks such as their interest rates and branch locations. We obtain this information by combining three main data sources, i.e., the Canadian Financial Monitor (CFM) household survey, the Financial Consumer Agency of Canada (FCAC) data on branch location, and CANNEX data on interest rates.

The CFM household survey is a syndicated survey run by Ipsos. A unique feature of the data is that we observe a household's deposit bank and its bank choices for other financial products if it obtained these products, including mortgage loans, credit cards, and guaranteed investment certificates (GICs). These are the financial products we consider in

the estimation, that is $\mathcal{K} = \{\text{credit card}, \text{mortgage}, \text{GIC}\}$. We observe a diversity of bank choices, ranging from the big five banks to some smaller banks, big credit unions, and online banks. The data also contain information on a household's allocation of liquid assets. We define liquid assets as the sum of cash and demand deposits. Cash includes cash in the wallet and other precautionary holdings of cash. Demand deposits are measured as the sum of chequing, chequing/saving, and saving account balances. Moreover, the data record each household's residential location by 6-digit postal code. We use the sample period of 2010–2017 because the survey questions on cash are consistent throughout this period.

The FCAC data contain addresses of all existing branches of banks and credit unions in 2019. They also record all branch closures each year from 2005 to 2020. We combine the two sets of information to construct bank branch locations in years other than 2019. Together with households' locations, we can calculate the (great-circle) distance of a household to each branch location, allowing us to construct the branch network a household has access to. Based on this distance measure, we construct the choice set of each household by assuming that a household considers all available banks that have a branch within a certain distance from its residence. Since the travel cost is different between urban and rural areas, we assume that an urban household considers all banks with a branch within 15 kilometers from his residence and a rural household considers banks with a branch within 50 kilometers.[9] Table 1 shows the summary statistics on the numbers of branches and banks available to each household based the constructed choice set. As can be seen, there is a large difference in the accessibility of banks and branches across provinces and regions.

CANNEX provides bank-level interest rates of demand deposits and mortgage loans.[10] We observe the rates on demand deposits for the big six banks and Laurentian Bank from 2010 to 2017. We assume the deposit rates of the other banks take the average values of the rates at the big six banks.[11] Since households care about the after-tax interest income, we calculate the after-tax interest rates by combining the bank-level deposit rates with household income information from CFM and federal and provincial income tax rates from the Government of Canada website. For the mortgage rate, we consider the 5-year closed mortgages, which are the most popular product in Canada. The mortgage rates are available for the big six banks and the average mortgage rate of the big six is used for mortgage loans

[9]For online banks (Tangerine, PC Financial, and Simplii Financial in the sample) that do not have branches, we assume they are present in each household's choice set. For the estimation in Section 4, we assume the distance to an online bank is 15km (50km) for an urban (a rural) household.

[10]Cross-bank variation in these rates are shown in Figure 11 in Appendix A.2. These rates are at the national level, we believe in Canada that the convention is national pricing. Even in the United States, as Granja and Paixao (2021) show, branch level pricing is not the norm.

[11]Since Laurentian Bank is a small bank that mostly operates in Quebec, we exclude its rates in calculating the average deposit rates.

Table 1: Number of Branches and Banks in the Choice Sets of Urban and Rural Households

**(a) Number of Branches**

| | Urban 15 km | | | | | Rural 50 km | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Min | Median | Max | Mean | Obs | Min | Median | Max | Mean | Obs |
| Alberta | 3 | 260 | 297 | 212 | 1077 | 3 | 92 | 361 | 143 | 183 |
| British Columbia | 4 | 280 | 592 | 310 | 1528 | 1 | 48 | 717 | 181 | 157 |
| Manitoba | 3 | 128 | 132 | 112 | 430 | 1 | 33 | 152 | 60 | 127 |
| New Brunswick | 1 | 23 | 46 | 23 | 261 | . | . | . | . | 0 |
| Newfoundland | 3 | 46 | 47 | 33 | 129 | 1 | 12 | 55 | 21 | 75 |
| Nova Scotia | 4 | 78 | 83 | 51 | 324 | 7 | 70 | 140 | 73 | 152 |
| Ontario | 3 | 350 | 1286 | 586 | 3872 | 1 | 322 | 1738 | 538 | 697 |
| Prince Edward Island | 10 | 19 | 23 | 17 | 38 | 8 | 46 | 69 | 49 | 27 |
| Quebec | 3 | 895 | 979 | 589 | 2236 | 5 | 328 | 1230 | 540 | 422 |
| Saskatchewan | 5 | 39 | 55 | 37 | 292 | 1 | 15 | 64 | 22 | 129 |

**(b) Number of Banks**

| | Urban 15 km | | | | | Rural 50 km | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Min | Median | Max | Mean | Obs | Min | Median | Max | Mean | Obs |
| Alberta | 2 | 10 | 11 | 9 | 1077 | 1 | 6 | 11 | 6 | 183 |
| British Columbia | 1 | 11 | 14 | 10 | 1528 | 1 | 6 | 14 | 6 | 157 |
| Manitoba | 3 | 10 | 11 | 9 | 430 | 1 | 4 | 11 | 4 | 127 |
| New Brunswick | 1 | 7 | 8 | 5 | 261 | . | . | . | . | 0 |
| Newfoundland | 2 | 7 | 7 | 5 | 129 | 1 | 3 | 7 | 3 | 75 |
| Nova Scotia | 1 | 6 | 7 | 5 | 324 | 1 | 5 | 7 | 4 | 152 |
| Ontario | 2 | 8 | 12 | 8 | 3872 | 1 | 8 | 12 | 7 | 697 |
| Prince Edward Island | 5 | 6 | 6 | 5 | 38 | 2 | 6 | 7 | 5 | 27 |
| Quebec | 1 | 9 | 12 | 8 | 2236 | 1 | 8 | 12 | 7 | 422 |
| Saskatchewan | 4 | 8 | 10 | 8 | 292 | 1 | 3 | 10 | 3 | 129 |

Data sources: CFM 2017, FCAC 2017

Note: The upper (lower) table shows the summary statistics for the number of branches (banks) that are within 15km from urban households' locations and 50km from rural households' locations in each province. Rural area is defined as the second digit of the Canadian postal code being zero.

at other banks. Summary statistics of some key variables are shown in Table 6 of Appendix A.2.

## 4.2 Estimation Results

Following the discussion in Section 3, we estimate the demand parameters in three steps separately: (1) portfolio allocation choice, (2) bank choices for mortgage loans, credit cards, and GICs, and (3) deposit bank choice taking into account the utilities from the portfolio of liquidity holding and from potentially bundling other financial products with the deposit accounts. We first discuss the results from each step in order and then we discuss the estimates of banks' marginal costs.

Table 2 shows the estimated parameters for the deposit rates and the branch network measures (i.e., $\tilde{\alpha}^b$, $\tilde{\boldsymbol{\beta}}^b$) in the CES aggregator. The parameters for the household characteristics, bank fixed effects, and the deposit-specific constant (i.e., $\tilde{\boldsymbol{\gamma}}^b$, $\tilde{\eta}_j^b$, $\tilde{\zeta}^b$) are shown in Table 7 in Appendix B. We include bank fixed effects to absorb the unobserved bank quality, such as the potential effects of the withdrawal fees and transaction fees. Because there is not much over-time variation in the deposit rates for some banks during the sample period of 2010–2017, we do not include a fixed effect for each bank. Instead, we include indicators for different groups of banks, i.e., big five banks, small banks, online banks, the Desjardins credit union, and the big credit unions.

The deposit rate has a significantly positive effect on the allocation of liquid assets. If the after-tax deposit rate increases by 1 percentage point, the deposit-to-cash ratio would increase by 52% from a median of around 20 to 30. Easier access to bank branches increases the deposit-to-cash ratio, which is consistent with the classic Baumol-Tobin model. Interestingly, this effect manifests itself in different ways in urban and rural areas. An urban household is not concerned about the distance to the closest branch but cares about the number of local branches, while the opposite is true for a rural household. This may arise because households in urban and rural areas use branches in different ways. Urban households may use branches that are close to their workplaces more frequently than those that are close to where they live. Therefore, the number of a bank's local branches, which also captures the distance from workplaces to branches, may better measure the convenience of branch access for urban households. Rural households, however, may use the branches close to their residences for the majority of the time because other branches can be too far away. Therefore, they care only about the distance from residences to branches.

Table 3 shows the estimates for the home bank preference $\kappa^k$ and bank branch network $\boldsymbol{\beta}^k$ in the households' choices of the credit card issuers, mortgage banks, and GIC companies.

Table 2: Estimated Parameters in Portfolio Allocation Choice

| Dependent variable: Log of deposit-to-cash ratio | |
|---|---|
| Post-tax deposit rate | 0.522*** |
| | (0.193) |
| ln(Distance to branch) | 0.004 |
| | (0.010) |
| ln(Distance to branch) × Live in rural area | -0.053*** |
| | (0.015) |
| ln(Number of branches + 1) | 0.024*** |
| | (0.008) |
| ln(Number of branches + 1) × Live in rural area | -0.026 |
| | (0.017) |
| Observations | 62,504 |

Robust standard errors in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Data sources: CFM 2010–2017, CANNEX 2010–2017, FCAC 2010–2017, Government of Canada website
Note: The table shows a selection of the estimated parameters from regressing the log of deposit-to-cash ratio on the post-tax deposit rates, bank branch network, grouped bank fixed effects, and household characteristics (including region and year fixed effects).

Bank fixed effects are also included to absorb the bank-level prices of a given product, which are shown in Table 8 in Appendix B. The estimate $\hat{\kappa}^k$ shows that households have a strong preference for getting the considered financial product from their deposit banks. This is not surprising since 45% of credit card holders get their credit cards from their home banks and more than half of mortgage borrowers borrow from their home banks, as shown in Table 4. Interestingly, the home preference parameters are similar in magnitude across the products. The estimates $\hat{\boldsymbol{\beta}}^k$ in each column of Table 3 suggest that households value the branch network when choosing these financial products. A longer distance to the nearest branch and a lower number of nearby branches reduce the likelihood of choosing a particular bank for the financial products.

To estimate the deposit bank choice problem, we first obtain the weighted sum of the expected utilities from different financial products, $\sum_{k\in\mathcal{K}} \omega^k E[V_{i,j}^k]$, using the estimates from Table 3 together with the probabilities of needing financial products, $\omega^k$'s, measured by the fractions of households that have the corresponding product in Table 4. Using these estimates, we obtain Table 5, which shows the estimated parameters for the utilities from liquidity holding, the expected utilities from other financial products, and the branch networks in the deposit bank choice problem. The branch network affects the choice probabilities of the deposit bank through three channels. First, there is a direct channel captured by $\boldsymbol{\beta}^f$, where the preference over the branch networks directly affects the deposit bank choice. The

Table 3: Estimated Parameters from Bank Choices of Different Financial Products

| | (1) Credit Card | (2) Mortgage | (3) GIC |
|---|---|---|---|
| Home bank preference | 2.351*** | 2.671*** | 2.916*** |
| | (0.010) | (0.016) | (0.018) |
| ln(Distance to branch) | -0.117*** | -0.123*** | -0.156*** |
| | (0.008) | (0.015) | (0.015) |
| ln(Distance to branch) × Live in rural area | 0.003 | -0.026 | -0.055** |
| | (0.013) | (0.024) | (0.025) |
| ln(Number of branches + 1) | 0.083*** | 0.132*** | 0.086*** |
| | (0.007) | (0.014) | (0.014) |
| ln(Number of branches + 1) × Live in rural area | 0.030** | 0.044* | -0.026 |
| | (0.014) | (0.026) | (0.026) |
| Observations | 1,075,719 | 314,230 | 292,732 |
| Number of choice sets | 72,449 | 24,603 | 22,858 |

Robust standard errors in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Data sources: CFM 2010–2017, CANNEX 2010–2017, FCAC 2010–2017, Government of Canada website
Note: Each column in the table shows the selected estimated parameters from a conditional logit regression of the bank choice of a given financial product (i.e., credit card, mortgage loan, guaranteed investment certificate GIC) on the home bank indicator, branch network, and all bank fixed effects. For each column, the dependent variable equals one if a bank is chosen for the given product and zero for all the non-chosen banks in a household's choice set.

Table 4: Fraction of Households with Different Financial Products

| | Have the product | Have the product from home bank |
|---|---|---|
| Credit Card | 0.90 | 0.45 |
| Mortgage | 0.30 | 0.56 |
| Garanteed Investment Certificates | 0.29 | 0.55 |

Data sources: CFM 2010–2017
Note: The table shows the fraction of households that have a credit card, mortgage loan, or guaranteed investment certificate in the second column. Conditional on the households that have a given product, the last column shows the fraction of households that bundle the product with their home banks that they have deposit accounts with.

other two channels are indirect, where the branch networks affect the deposit bank choice indirectly through affecting the utility from holding liquid assets and from other financial products, respectively. For the direct channel, we find that for urban households, an increase in 1km of the branch distance would reduce the choice probability by around 10% on average. If a bank's local branch number increases by one, this would increase the probability of choosing the bank by around 14%. Rural households are more tolerant to distance, so a 1km increase in distance barely reduces the likelihood of choosing a bank. However, given the

low number of branches in rural areas, adding one more branch would increase their choice probabilities by around 25% on average.

Table 5: Estimated Parameters in Deposit Bank Choice

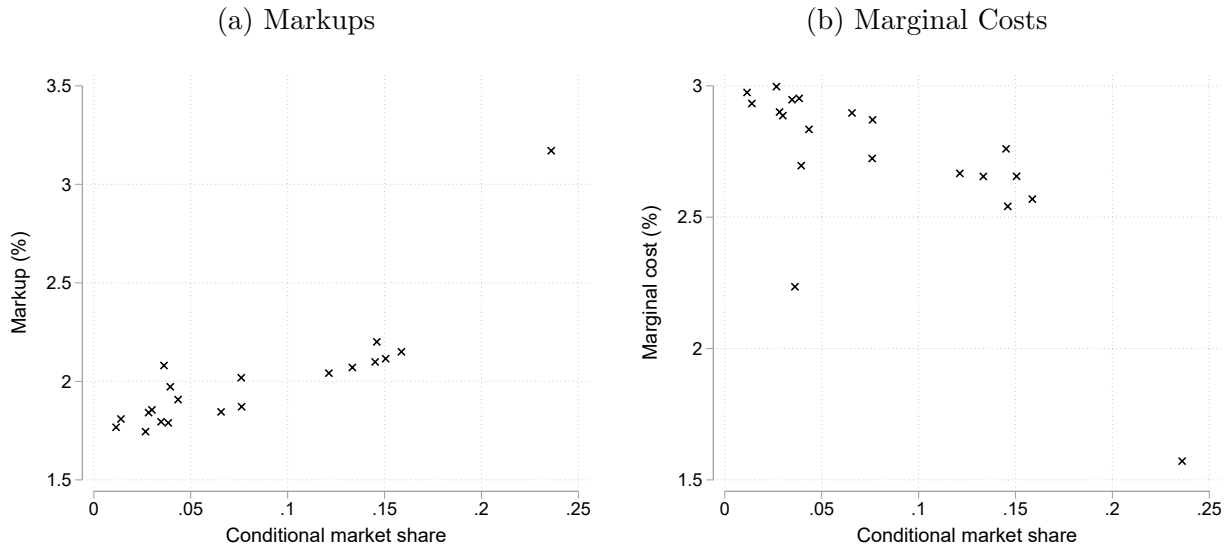
| Dependent variable: Indicator of deposit bank choice | |
|---|---|
| Utility from liquidity holding $\ln L^b_{i,j}$ | 1.661*** |
| | (0.179) |
| Weighted sum of expected utilities from financial products | 1.368*** |
| | (0.038) |
| ln(Distance to branch) | -0.175*** |
| | (0.008) |
| ln(Distance to branch) × Live in rural area | 0.113*** |
| | (0.015) |
| ln(Number of branches + 1) | 0.439*** |
| | (0.011) |
| ln(Number of branches + 1) × Live in rural area | 0.229*** |
| | (0.021) |
| Observations | 674,536 |
| Number of choice sets | 62,504 |

Robust standard errors in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Data sources: CFM 2010–2017, CANNEX 2010–2017, FCAC 2010–2017, Government of Canada website
Note: The table shows a selection of the estimated parameters from a conditional logit regression of the deposit bank choice on the utilities from liquidity holding $\ln L^b_{i,j}$, the weighted sum of expected utilities from financial products $\sum_{k\in\mathcal{K}} \omega^k E[V^k_{i,j}]$, the branch network measures, and grouped bank fixed effects. The estimated bank fixed effects can be found in Table 9 in Appendix B. The dependent variable equals one if a given bank is chosen for deposits and zero for all non-chosen banks in a household's choice set.

With the estimates of the demand side, we obtain the estimated markups, or equivalently, the inverse semi-elasticities of deposit demand. Using (13), we then obtain the supply-side parameters, i.e., banks' marginal costs. Figure 2 plots the banks' markups and marginal costs against their market shares in the year 2017.[12] There is considerable heterogeneity in both market shares and markups. The former ranges from around 1% to more than 20% and the latter ranges from 1.7% to around 3.2%. The estimated marginal costs range from 1.6% to 3.0%, with a mean of around 2.7% in 2017. The markups are positively correlated with market shares, while the marginal costs are negatively correlated with market shares. We next treat the demand-side parameters and the marginal costs of banks as primitives and conduct counterfactuals to assess the effects of introducing a CBDC.

[12]The market share of a bank is the average market share across all local markets served by the bank.

Figure 2: Estimated Markup and Marginal Cost for Each Bank in 2017




Data sources: CFM 2010–2017, CANNEX 2010–2017, FCAC 2010–2017, Government of Canada website
Note: The figure plots the estimated markups against the banks' market shares for each bank in 2017. The conditional market share refers to each bank's market share conditional on its presence in the local markets, which is calculated using the estimated probabilities of choosing this bank averaged across the local markets that the bank operates in.

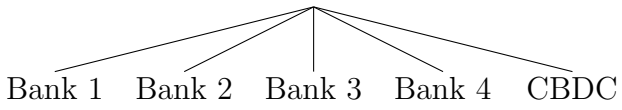
# 5 Counterfactual CBDC Issuance

This section evaluates what would have been the impact of introducing a CBDC in 2017 on the Canadian banking sector. The CBDC is a liquid digital money that is similar to bank deposits. Therefore, we model it as a new product that is added to every household's choice set for digital liquid money, as shown in Figure 3. We consider different designs of the CBDC in terms of interest rates, service locations, and holding limits. From CFM data on bank branch usage habits, we find that people value in-person customer service and support. Therefore, we anticipate that these services would also matter for CBDC despite CBDC being digital.[13] We assume that central bank does not provide other financial products such as mortgage loans and credit cards. If a household chooses CBDC instead of an incumbent

[13]Figure 9 in Appendix A.1 shows that while branch usage fell slightly over our sample period, the majority of households visited a bank branch in the past month. Figure 10 in Appendix A.1 shows the fraction households using various channels (i.e., branches, phone calls, online banking, mobile banking, etc.) for getting different types of services from their financial institution. We observe customer service/support and withdrawing cash remain important reasons to go to the physical locations offered by banks. Similarly, Allen et al. (2008) argue that even while banks offer online services, the offline services offered at bank branches remain important for retaining and attracting customers. Our paper maintains such patterns would carry over to a digital product that the central bank may issue.

bank to deposit their digital money, it still has to obtain other financial products from private banks and thus does not enjoy the home bank preference.

Figure 3: Choice Set for Holding Liquid Digital Assets after CBDC Issuance




Assuming that the preference and cost parameters remain unchanged after the CBDC issuance, we calculate the counterfactual equilibrium for a given CBDC design using these estimated parameters. More specifically, we use the estimated preference parameters and the exogenously chosen CBDC design attributes to obtain each household's utility from depositing their digital money in CBDC.[14] The household chooses to deposit its digital money in either the CBDC or an incumbent bank by comparing the utility from each institution. Banks take the CBDC attributes as given and adjust their deposit rates in response to the change in deposit demand. More details can be found in Appendix C.1.

Section 5.1 shows the aggregate effect of a CBDC. Section 5.3 shows how the impact of the CBDC differs across banks, and Section 5.4 shows the impact of imposing a holding limit on the CBDC. Section 5.5 shows the changes in consumer surplus due to CBDC issuance.

## 5.1 Impact of CBDC on Aggregate Outcomes

We start with the design options in terms of the interest rate and the network of service locations and assume there is no holding limit. Four designs for the service location network are considered: (1) no service location, in which case the CBDC is analogous to an online bank; (2) all Canada Post offices; (3) all bank branches; (4) all bank branches and the Canada Post Offices. For this exercise, we use the locations of all open Canada Post offices in 2021 obtained from the Canada Post Corporation.[15]

Figure 4 shows the aggregate CBDC shares, the changes in average deposit rates, and the average percentage changes in bank deposits and profitability, under each design of the CBDC. There are two main findings: first, the network of CBDC service locations matters a lot for the take-up of CBDC and its impact on banks; second, the effect of the CBDC

[14]To obtain the utility from CBDC, we also need to make assumptions on the CBDC fixed effect that captures the unobserved quality of CBDC. In this section, we assume the CBDC fixed effect takes the value of the estimated fixed effect for the largest banks. We show the results using the worst fixed effect in Figure 14 and 15 in Appendix C.2.

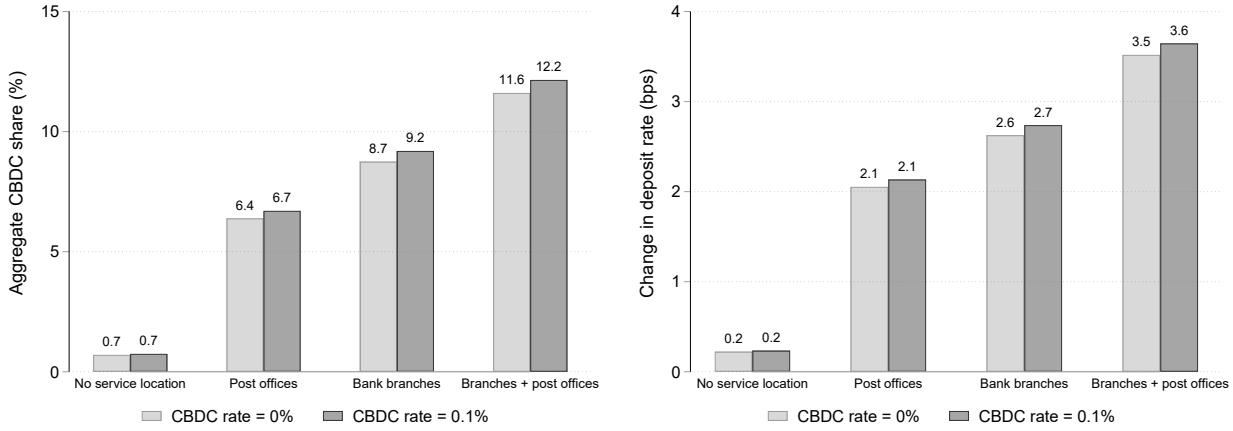
[15]Here we take the participation of the post offices as given and make no claim about the viability of such arrangements. Further research may consider the incentives of these businesses to enter into such contracts. Since the post office network is relatively stable over time, not using the 2017 location data due to availability should not bias our results much.

interest rate is rather limited compared to the CBDC network. The CBDC interest rate needs to be sufficiently high to have a noticeable impact on the CBDC take-up.

Figure 4: Impacts of CBDC Designs on Equilibrium Outcomes

(a) Aggregate CBDC share

(b) Change in bank interest rates

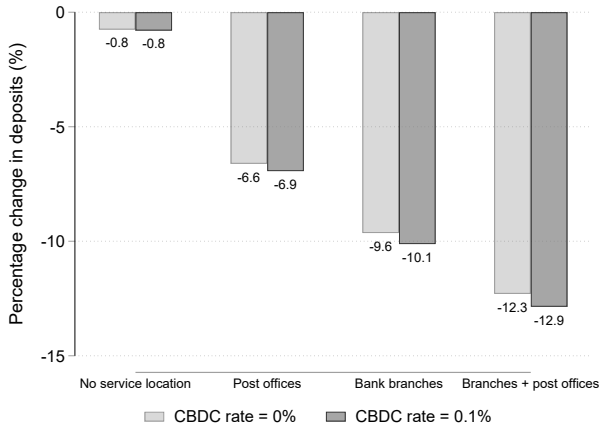


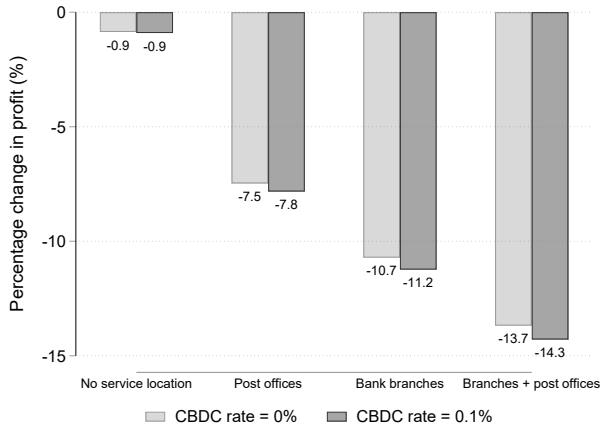




(c) Percentage change in deposits

(d) Percentage change in profits




Data sources: CFM 2017, FCAC 2017, Canada Post 2021

Note: This figure plots (a) the aggregate CBDC share calculated as the share of liquid assets allocated in equilibrium by households to CBDC, (b) the endogenous changes in deposit rates (in percentage points) on average across banks after CBDC issuance, (c) the percentage drop in deposits, and (d) the percentage drop in profits on average across banks relative to the pre-CBDC equilibrium. In each subfigure, the given equilibrium outcome is plotted under four designs of branch network for CBDC (i.e., no service location, all Canada Post offices as service locations, all bank branches as service locations, and all bank branches plus all Canada Post offices as service locations), combined with two different remuneration for CBDC: 0 and 10 basis points. In this figure, we use the fixed effect for the big five banks as the CBDC fixed effect. We show the results where CBDC fixed effect takes the estimated fixed effect of the small banks in Figure 14 in Appendix C.2.

Figure 4a shows the aggregate CBDC share under each design. We consider two interest rates on the CBDC: 0 and 10 basis points. The former is the consensus among many central banks, which decide not to pay interest on the CBDC. The latter reflects the average of the interest rates paid on deposits in 2017. In addition, we vary the network of service locations at which the households can access in-person services for the CBDC. If there are no CBDC service locations, consumers barely adopt CBDC. Only around 1% of total households' liquid assets are allocated to CBDC even if the CBDC pays an interest rate of 10 basis points. If all Canada post offices provide in-person services for the CBDC, the aggregate CBDC share increases to about 6%. This leads to a CBDC-to-deposits ratio that is comparable to the cash-to-deposit ratio of 4.8% in the data. If the goal is to make the market share of the CBDC close to the current market share of cash, providing CBDC service at post offices would achieve it. If all the bank branches provide services for the CBDC, the CBDC share increases to around 9%. The market share of CBDC increases further under more extensive network of service locations.

For each network, increasing the interest rate on CBDC to 10 basis points (i.e., the level of the average deposit rate) barely impacts its adoption. However, when the CBDC rate is sufficiently attractive, it can have a large impact on the aggregate CBDC share. As shown in Figure 12 in Appendix C.2, when the CBDC rate is 1.5%, the aggregate CBDC share doubles relative to the non-interest-bearing case within each network design. If the CBDC rate is 4%, the aggregate share of a CBDC with no service location can reach the same level of a non-interest-bearing CBDC but with all Canada Post offices as service locations.

Figure 4b plots the average change in deposit rates across banks under the same set of CBDC designs. In response to CBDC issuance, banks tend to raise deposit rates to retain customers. The magnitude of the responses depends on the CBDC design. If the CBDC offers no network, the banks barely respond. However, If it offers an attractive network, the average deposit rate increases by 2–4 basis points, which is about 20-40 percent of the average deposit rate in 2017. Moreover, there is substantial heterogeneity in the responses across banks, ranging from around 0 to 20 basis points, as we will show in the next section.

Figure 4c shows the percentage changes in deposits after CBDC issuance. The effects are similar in magnitude to the negative value of the market share of the CBDC in Figure 4a. Intuitively, since the market share of cash is low, the CBDC gains market share mainly by reducing the market share of deposits. As shown in Figure 4c, even when all existing branches and Canada Post offices are used as service locations, CBDC reduces the liquid deposits by slightly more than 10%. Since the liquid bank deposits (that a CBDC directly competes with) are around 16% of total bank deposits and 5% of total bank assets (García et al., 2020), the CBDC is likely to have a limited crowding out effect on bank deposits.

Finally, in Figure 4d we study how the CBDC affects the average profit across banks. The change in profit comes from two sources: (1) the decrease in the bank's markup, which in our model is solely driven by the increase in the deposit rate shown in Figure 4b, and (2) the decrease in the quantity of deposits shown in Figure 4c. Here, the quantity effect dominates. Similar to the other panels, the impact of CBDC increases as the network of service locations improves, while the interest on CBDC with a similar magnitude to the deposit rate has a limited consequence. Notice that our profit measure only captures the profits from lending funded by liquid deposits. Given such lending activities usually generate a small portion of a bank's total profit, the impact on the overall profitability of banks can be much lower.

## 5.2 Model Misspecification: No Complementarity

Section 5.1 has shown the importance of service location design for CBDC. Here, we demonstrate the importance of capturing the complementarity feature, i.e., deposits come with complementary financial products while a CBDC does not. More specifically, we estimate the misspecified model where the home bank preference $\kappa^k = 0$ for all financial product $k \in \mathcal{K}$ and the expected utilities from different financial products no longer affect the deposit bank choice.

Using the estimates from the misspecified model, we find that the aggregate CBDC share can be substantially overestimated when neglecting the difference in complementarity between CBDC and deposits.[16] As shown in Figure 13 in Appendix C.2, the aggregate CBDC share is around 23% for a non-interest-bearing CBDC that uses all Canada Post offices as service locations, and around 38% under the most extensive network where both Canada Post offices and bank branches are used as service locations.

## 5.3 Heterogeneous Impact of CBDC on Banks

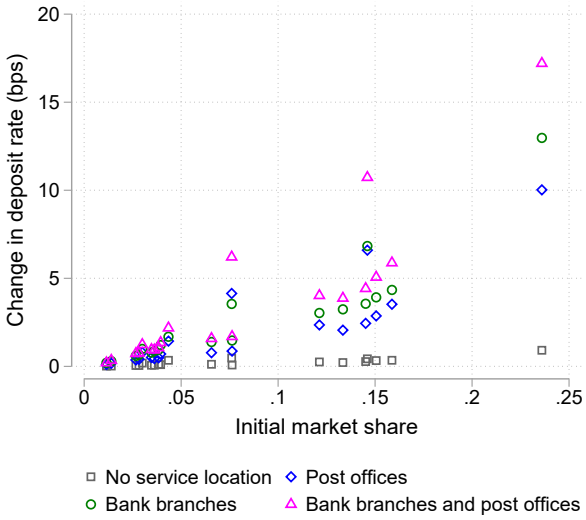
We now study how the impact of a non-interest-bearing CBDC differs across banks. We are particularly interested in how the impact depends on the market power of the bank prior to the CBDC issuance, which is measured by its average market share across the markets it serves. Alternatively, using the bank's markup to measure its degree of market power gives similar results, since the market share and the markup are positively correlated as shown in Figure 2a. Figure 5 shows the changes in deposit rate, markup, deposit quantity, and profit for each bank with a different initial market share.

Figure 5a shows how the adjustments in the deposit rates by banks vary with their initial market shares. Under a given service location network for the CBDC, banks with higher

[16] Estimates in the deposit bank choice are reported in Table 10 in Appendix B.

Figure 5: Impacts of CBDC on Banks with Different Initial Market Shares

(a) Level Change in Deposit Rate




(b) Percentage Change in Markup


(c) Percentage Change in Deposits


(d) Percentage Change in Profit


Data sources: CFM 2017, FCAC 2017, Canada Post 2021

Note: This figure plots each bank's optimal response in deposit rates (in basis points), the percentage changes in markups, deposits, and profits for different CBDC network designs. The x-axis is the bank's initial market share, measured as the local market-level probabilities of choosing the particular bank averaged across all local markets in which the bank is present. Here, we assume the CBDC is non-interest-bearing and has a fixed effect that is identical to that of the big five banks. We show the results where CBDC fixed effect takes the estimated fixed effect of the small banks in Figure 15 in Appendix C.2.

initial market shares tend to raise their deposit rates by more in response to the CBDC. Intuitively, these larger banks with greater market power are threatened by the CBDC by more, while those smaller banks are already dominated by big banks in the world without the CBDC and hence would not respond as much. Consistent with the aggregate effect discussed in Section 5.1, better service locations for the CBDC lead to larger increases in deposit rates by banks.

Interestingly, changes in deposit rates are more heterogeneous across banks when the CBDC has better service locations. In other words, the standard deviation of the interest rate increases is larger when all bank branches and post offices become CBDC service locations compared to the case when the CBDC has no service location. This is driven by banks with higher initial market shares that are very responsive to changes in the CBDC service network design. Intuitively, if the CBDC does not have any service location, banks with high market shares would have a big competitive advantage over the CBDC due to their extensive branch networks. Therefore, these banks do not have to increase their deposit rates by much even though their markups are high, leading to relatively homogeneous responses to the CBDC across banks. In contrast, if the CBDC has many service locations, these banks are facing severe competition and have to respond aggressively, resulting in relatively heterogeneous responses.

Figure 5b shows how the percentage changes in markups depend on the initial market shares. It is more or less a reverse image of Figure 5a. This is not surprising because changes in markups are purely driven by changes in deposit rates in our model. Similarly, banks' markups are reduced by more when the CBDC has more service locations. The markup changes are more heterogeneous across banks if the CBDC has a more extensive service location network and banks with high market shares are the main drivers of the increased heterogeneity.

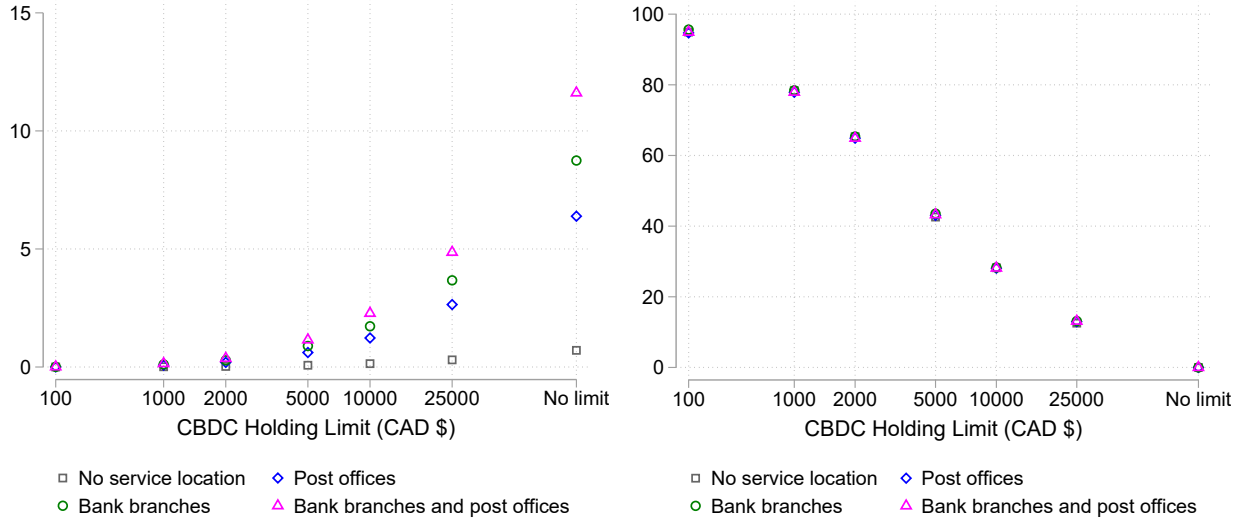
Since banks with higher initial market shares tend to raise their deposit rates by more, they would lose fewer deposits, as shown in Figure 5c. Interestingly, there is no clear relationship between the percentage change in profit and the initial market share, as shown in Figure 5d. Banks with higher market shares tend to sacrifice more in markups but retain more deposits. These two effects largely cancel out. Similar pattern of heterogeneity holds here. If the CBDC has no service location, changes in deposits and profits are more or less the same across banks. But if the CBDC has many service locations, the changes are more heterogeneous across banks.

## 5.4 Impact of Imposing Limits on CBDC Holdings

Recently, several central banks are considering imposing a limit on CBDC holdings. The proposed digital euro legislation (European Commission, 2023) argues the ECB should develop limits to the holdings of a CBDC. The purpose of this policy is to prevent depositors from running from the banking sector to the CBDC in the time of systemic financial distress, but a side effect is that the limit can also discourage the uptake of the CBDC in normal times. It remains a question as to how big the negative effect on adoption is during the normal time. To answer this question in the Canadian context, we take our estimated model and impose a constraint on how much CBDC a household can hold. We vary the limit between $100 and $25,000 and calculate the market share of the CBDC and the percentage of households that would be constrained by the limit in each case. As in the previous sections, we consider four different service location networks.

Figure 6: The Impact of Imposing Different Limits on CBDC Holdings

(a) Percentage change in aggregate CBDC share (b) Percentage of constrained households




Data sources: CFM 2017, FCAC 2017, Canada Post 2021
Note: This figure shows the percentage change in aggregate CBDC share and the percentage of constrained households across different CBDC holding limits for four service location network designs. The aggregate CBDC share is the share of households' total liquid assets allocated into the CBDC in equilibrium. The x-axis is on a compressed log scale for clarity. Here, we assume the CBDC is non-interest-bearing and has a fixed effect that is identical to that of the big five banks.

Figure 6a shows how the market share of a CBDC changes with the limit. As a benchmark, we report the market share without a limit at the right end of the x-axis. Under all service location networks, a limit as high as 25,000 CAD still reduces the market share of a

CBDC to less than half of its level without a limit. This implies that even if the limit is very high, the reduction in CBDC adoption can still be substantial. If the limit is $5000 CAD, which is close to the 3000 euro limit suggested by a speech from an ECB executive (Panetta, 2022), the CBDC would take around 1% of the market. This is much lower than the market share of cash. In the scenario where only post offices are used as the CBDC service locations, the limit needs to be higher than $65,000 to reach the current market share of the cash.

Figure 6b shows the fraction of households constrained by the limit. If the limit is $25,000, only slightly more than 10% of households are constrained. However, these households hold the majority of the total liquidity assets. Figure 16 in Appendix C.3 shows that the upper 10% of households hold 50% of the total liquid assets. As a result, the limit forces these households to hold much less CBDC than they wanted and greatly reduces the market share of the CBDC.

To sum up, the central bank should be cautious in designing the holding limit to avoid the potential negative effect on the adoption of the CBDC. If the target market share of the CBDC is the current market share of cash, the holding limit should be higher than $65,000 when Canada Post offices are service locations, or at least $35,000 when bank branches are service locations.

## 5.5 Change in Consumer Surplus

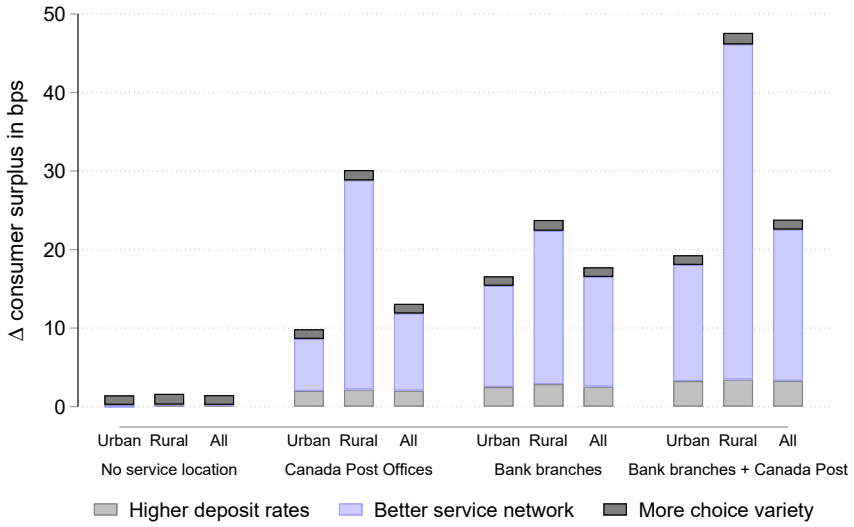
Lastly, we study the effects of introducing a CBDC on consumer surplus.[17] We measure the change in consumer surplus using the equivalent variation, that is, the additional deposit rate that would be needed in an economy without a CBDC to make the aggregate utility the same as in an economy with a CBDC.

Figure 7 shows the changes in consumer surplus under four designs of CBDC service locations. In each case, we decompose the changes in consumer surplus into three parts to study the contributing factors: (1) increased deposit rates induced by competition from the CBDC; (2) changes in the service location network; and (3) increased variety of choices due to the new product CBDC. We report results for the urban, rural, and all households, respectively.

If the CBDC does not have service locations, deposit rates would barely change and thus almost all of the increase in consumer surplus is due to adding a new product, which is very small. As the service location network becomes better, the increase in consumer surplus becomes larger. If the CBDC only uses post offices as service locations, the consumer surplus increases by slightly more than 10 basis points on average across all households. If it uses all

[17] Here, the consumer refers to a depositor instead of a borrower. Since we focus on the impact of a CBDC on the deposit market, we cannot discuss how a borrower's welfare is affected by the CBDC issuance.

Figure 7: Decompose the Change in Consumer Surplus into Different Channels

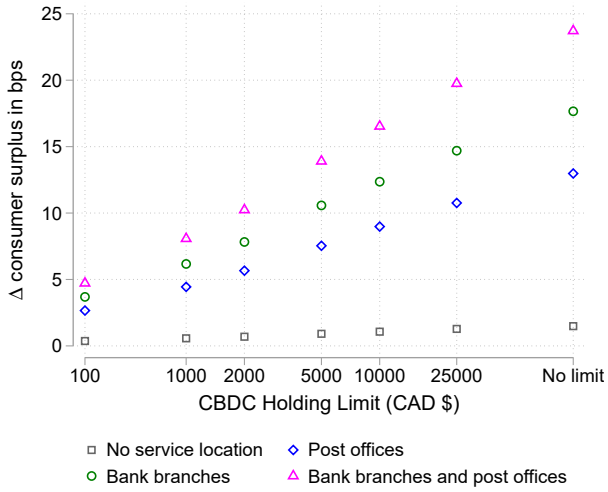



Data sources: CFM 2017, FCAC 2017, Canada Post 2021
Note: This figure plots the changes in consumer surplus (in basis points) under four designs of CBDC service network (i.e., no service location, all Canada Post Offices, all bank branches, or both branches and post offices). Within each service network design, each bar represents the average change in consumer surplus across urban, rural, or all households, respectively. The change in consumer surplus is decomposed into three different channels that drive the change: higher deposit rates, improvement in service network brought by CBDC, and increase in choice variety due to the presence of CBDC in the choice set. Here, we assume CBDC is non-interest-bearing and has a fixed effect that is identical to that of the big five banks.

bank branches, the increase is about 18 basis points. If it uses both the bank branches and the post offices, the gain can be close to 25 basis points. In these cases, the service location network is the main contributor to the gain in consumer surplus.

Rural households would benefit much more from a CBDC that uses post offices as service locations than a CBDC that uses bank branches. This is because post offices are more evenly distributed across the country compared to bank branches, which are more concentrated in urban areas. As shown in Figure 17a in Appendix C.4, the distance from a rural household to the nearest Canada Post Office is around 1.9km on average, while the distance to the nearest bank branch is 6.8km. Therefore, including Canada Post offices as service locations may be useful for promoting financial inclusion.

Figure 8: Change in Consumer Surplus under Different Limits on CBDC Holdings




Data sources: CFM 2017, FCAC 2017, Canada Post 2021
Note: This figure shows the changes in consumer surplus (in basis points) across different CBDC holding limits (in Canadian dollars) for four service location network designs. In each case, the change in consumer surplus reflects the average across all households. The x-axis is on a log scale for clarity. Here, we assume CBDC is non-interest-bearing and has a fixed effect that is identical to that of the big five banks.

Figure 8 shows how the holding limit affects the change in consumer surplus. When there is no limit, the results are identical to those shown in Figure 7. For example, consumer surplus increases by around 25 basis points under the most extensive CBDC service network. Introducing a holding limit of $25,000 reduces the gains in consumer surplus by less than 20%, much lower than the reduction in the market share of the CBDC (more than 50% as shown in Figure 6a). This suggests that although imposing a holding limit can substantially reduce the market share of CBDC in terms of the total households' liquid assets, its effect on the consumer surplus is much lower.

# 6 Conclusions

This paper brings two important aspects to the heated discussion on the impact of a CBDC on banks. First, we take into account that banks provide financial products that are complementary to deposits, which cannot be provided by the central bank. Second, we account for the fact that consumers value physical service locations. We develop a structural model that incorporates both features and estimate the model using a unique Canadian dataset which contains information on households' bank choices for a rich set of financial products.

This framework allows us to address a range of questions related to the CBDC. First, we find that the impact of a CBDC is much lower compared to the previous work after taking into account the complementarity between deposits and other financial products provided that gives banks a competitive advantage over the CBDC. Second, the impact of a CBDC depends crucially on its service location network. A CBDC that has no service locations can barely gain any attraction. A CBDC that uses Canada Post offices as service locations would lead to an uptake that is similar to cash and benefit rural households more than a CBDC that uses bank branches as service locations. Third, banks with larger market shares tend to respond more to the CBDC and hence retain more deposits. We also use the model to study the effect of introducing a limit on CBDC holdings, which is frequently discussed by policymakers. We find that a holding limit can significantly reduce the uptake of the CBDC but the effect on consumer surplus can be limited.

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# Appendices

## A Data

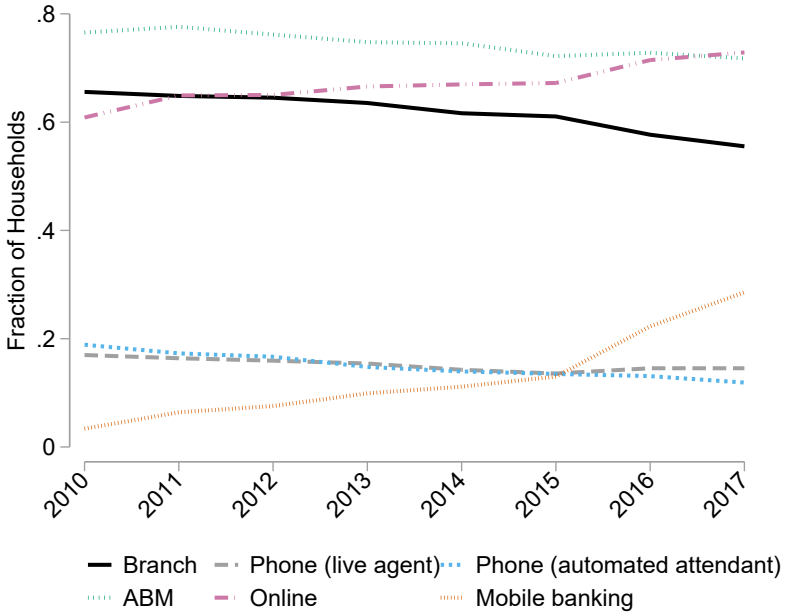
This section shows the data statistics. Section A.1 shows the frequency of branch visits by households and what services people use the branches for. Section A.2 shows the summary statistics of the key variables and the bank-level interest rates.

### A.1 Branch Usage Habits

Figure 9 shows that from the CFM data during 2010–2017, around 60% of the households reported that they visited their branches at least once in the past month. Households use branches, ABMs, and online banking more often than other channels. From 2010 to 2017, the branch usage frequency has declined slightly but it still remained high in 2017.

Figure 10 shows different categories of services that households use each channel for. For transaction-related services such as cash withdrawal and bill payments, households often use ABMs and online banking respectively, which is not surprising as these transactions can be easily done without visiting a branch. However, for other services such as the customer service/support, applying for a new product and complaining about something, households still prefer to use branches over other channels.

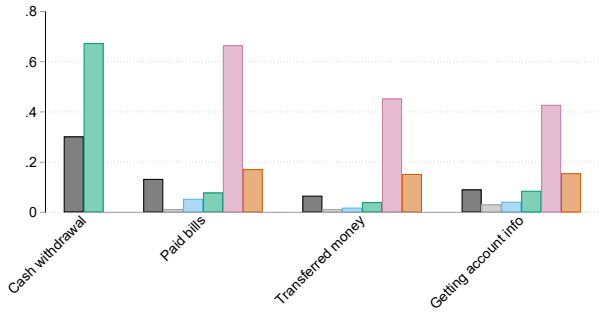
Figure 9: Usage of Branches vs Other Channels over Time



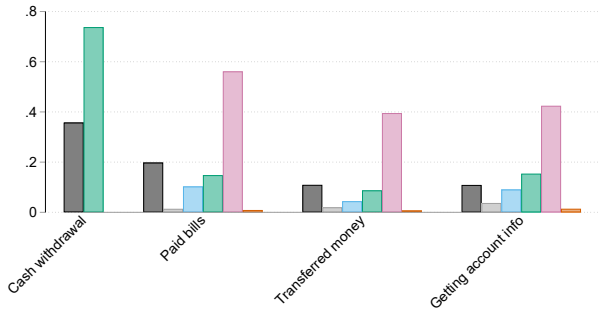

Data sources: CFM 2010–2017
Note: The y-axis refers to the fraction of households that used each given channel for banking services at least once in the past month. The x-axis shows the year in which the respondents reported the usage. Each line refers to a different method/channel used to obtain the banking services. The channels include branches (e.g., teller), phone (live agent), phone (automated attendant), ABM (automatic banking machine), online, or mobile banking.

Figure 10: Usage of Branches vs Other Channels for Different Banking Services

(a) Transaction-related services in 2017

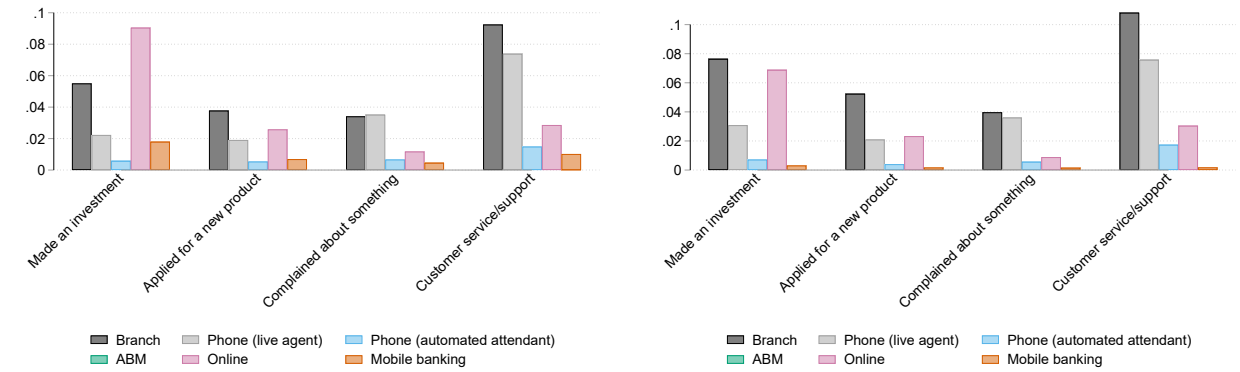



(b) Transaction-related services in 2010




(c) Other service categories in 2017

(d) Other service categories in 2010




Data sources: CFM 2010–2017

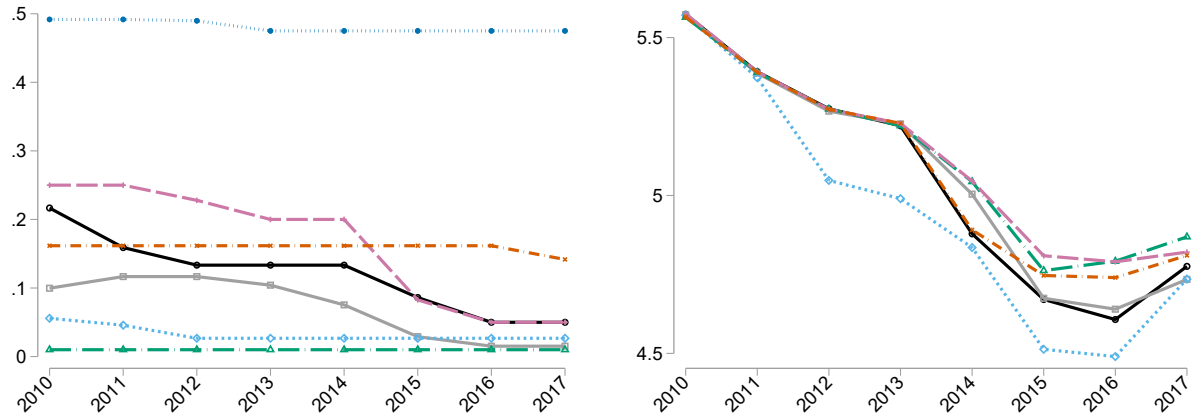
Note: This figure shows the fractions of households that need to use branches versus other channels (i.e., phone calls, ABM, online banking, mobile banking) for each service category in year 2010 and year 2017, ranging from cash withdrawal to customer service/support. The y-axis shows the fraction of households that used a given channel at least once in the past month in order to get the specific service indicated by the x-axis.

## A.2 Summary Statistics

Figure 11 plots the demand deposit rates and the five-year closed mortgage rates for each bank over time from 2010 to 2017. Table 6 shows the summary statistics of some key variables.

Figure 11: Bank Interest Rates During 2010–2017

(a) Demand deposit rates (%) (b) Five-year closed mortgage rates (%)




Data sources: CANNEX 2010–2017
Note: This figure shows the bank-level demand deposit rates and the five-year closed mortgage rates in percentage points during 2010 and 2017. The latter are used to measure the exogenous bank-specific returns on loans.

# B Estimation Results

Table 7 shows the estimated parameters for the household characteristics in the portfolio allocation choice that are not shown in Table 2. Table 8 and 9 show all the estimated parameters (including the bank fixed effects that are not shown in the main text) in the bank choices of different financial products (i.e., credit card, mortgage loan, GIC) and deposits, respectively. Table 10 compares the baseline estimates with the estimates where complementarity is neglected.

Table 6: Summary Statistics of Selected Variables

| Variable | Obs | Mean | sd | Min | p25 | p50 | p75 | Max |
|---|---|---|---|---|---|---|---|---|
| ln(deposit/cash) | 66834 | 2.91 | 1.91 | -4.76 | 1.67 | 2.97 | 4.16 | 12.43 |
| Deposit rate (before tax) | 66834 | 0.09 | 0.07 | 0.01 | 0.05 | 0.09 | 0.13 | 0.49 |
| Deposit rate (after tax) | 65162 | 0.06 | 0.05 | 0.00 | 0.03 | 0.06 | 0.08 | 0.34 |
| Distance to the nearest branch | 66834 | 5.17 | 8.08 | 0.01 | 0.92 | 1.81 | 5.24 | 50.00 |
| Number of local branches | 66834 | 21.96 | 32.39 | 0.00 | 2.00 | 9.00 | 28.00 | 296.00 |
| Household head age | 66834 | 55.07 | 15.48 | 18.00 | 44.00 | 57.00 | 66.00 | 106.00 |
| Household income | 65162 | 7.75 | 3.18 | 1.00 | 6.00 | 9.00 | 10.00 | 12.00 |
| Household size | 66834 | 2.15 | 1.14 | 1.00 | 1.00 | 2.00 | 3.00 | 8.00 |
| Household head education | 66413 | 3.67 | 1.35 | 1.00 | 2.00 | 4.00 | 5.00 | 6.00 |
| Dislike investing in stock market | 65950 | 6.04 | 2.95 | 1.00 | 4.00 | 6.00 | 9.00 | 10.00 |
| Have difficulty in paying off debt | 65835 | 3.39 | 2.88 | 1.00 | 1.00 | 2.00 | 5.00 | 10.00 |
| Behind debt obligations in the past year | 65078 | 0.06 | 0.23 | . | . | . | . | . |
| Rent a home | 65251 | 0.26 | 0.44 | . | . | . | . | . |
| Household has a female head | 66833 | 0.87 | 0.33 | . | . | . | . | . |
| Live in rural area | 66834 | 0.18 | 0.38 | . | . | . | . | . |
| Big 5 indicator | 66834 | 0.67 | 0.47 | . | . | . | . | . |
| Small bank indicator | 66834 | 0.05 | 0.21 | . | . | . | . | . |
| Online bank indicator | 66834 | 0.07 | 0.26 | . | . | . | . | . |
| Desjardins credit union indicator | 66834 | 0.09 | 0.28 | . | . | . | . | . |

Data sources: CFM 2010–2017, CANNEX 2010–2017, FCAC 2010–2017, Government of Canada website
Note: This table shows the summary statistics of the selected variables that are used in the estimation. The column "Obs" refers to the number of household-year observations in the estimation sample for the portfolio allocation choice.

Table 7: Estimated Parameters in Portfolio Allocation Choice

| Dependent variable: Log of deposit-to-cash ratio | coefficients | se |
|---|---|---|
| Post-tax deposit rate | 0.522*** | (0.193) |
| ln(Distance to branch) | 0.004 | (0.010) |
| ln(Distance to branch) × Live in rural area | -0.053*** | (0.015) |
| ln(Number of branches + 1) | 0.024*** | (0.008) |
| ln(Number of branches + 1) × Live in rural area | -0.026 | (0.017) |
| Dislike investing in stock market | 0.019*** | (0.003) |
| Having difficulty in paying off debt | -0.063*** | (0.003) |
| Behind debt obligations in the past year | -0.280*** | (0.036) |
| Household income $15,000 - $19,999 | 0.183*** | (0.053) |
| Household income $20,000 - $24,999 | 0.289*** | (0.052) |
| Household income $25,000 - $29,999 | 0.339*** | (0.052) |
| Household income $30,000 - $34,999 | 0.473*** | (0.049) |
| Household income $35,000 - $44,999 | 0.457*** | (0.046) |
| Household income $45,000 - $54,999 | 0.474*** | (0.046) |
| Household income $55,000 - $59,999 | 0.510*** | (0.050) |
| Household income $60,000 - $69,999 | 0.512*** | (0.047) |
| Household income $70,000 - $99,999 | 0.577*** | (0.044) |
| Household income $100,000 - $149,999 | 0.632*** | (0.046) |
| Household income $\geqslant$ $15,000 | 0.677*** | (0.051) |
| Grade 9-13 | 0.092 | (0.057) |
| Community College | 0.141** | (0.058) |
| Diploma | 0.230*** | (0.057) |
| Undergraduate | 0.387*** | (0.058) |
| Post-graduate | 0.498*** | (0.061) |
| Household head age 35–44 | -0.225*** | (0.031) |
| Household head age 45–54 | -0.331*** | (0.029) |
| Household head age 55–64 | -0.291*** | (0.028) |
| Household head age $\geqslant$ 65 | -0.079*** | (0.028) |
| Household size = 2 | -0.083*** | (0.021) |
| Household size = 3 | -0.123*** | (0.029) |
| Household size $\geqslant$ 4 | -0.127*** | (0.029) |
| Household has a female head=1 | 0.295*** | (0.025) |
| Rent a home=1 | -0.266*** | (0.021) |
| Live in rural area=1 | 0.088* | (0.053) |
| Alberta | 0.029 | (0.032) |
| Saskatchewan | 0.042 | (0.043) |
| Manitoba | 0.006 | (0.039) |
| Ontario | -0.053** | (0.024) |
| Quebec | -0.200*** | (0.033) |
| New Brunswick | -0.158*** | (0.056) |
| Prince Edward Island | -0.109 | (0.112) |
| Nova Scotia | -0.377*** | (0.042) |
| Newfoundland | -0.335*** | (0.066) |
| Year 2011 | -0.021 | (0.028) |
| Year 2012 | -0.030 | (0.029) |
| Year 2013 | 0.001 | (0.030) |
| Year 2014 | 0.016 | (0.029) |
| Year 2015 | 0.061* | (0.032) |
| Year 2016 | 0.022 | (0.031) |
| Year 2017 | 0.033 | (0.031) |
| Big 5 bank indicator | -0.133*** | (0.026) |
| Small bank indicator | -0.196*** | (0.048) |
| Online bank indicator | -0.098** | (0.042) |
| Desjardins Credit Union indicator | -0.025 | (0.044) |
| Constant | 2.473*** | (0.088) |
| Observations | 62,504 | |

Robust standard errors in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Data sources: CFM 2010–2017, CANNEX 2010–2017, FCAC 2010–2017, Government of Canada website
Note: The table shows the estimated parameters from regressing the log of deposit-to-cash ratio on the post-tax deposit rates, bank branch network, bank fixed effects, and household characteristics (including the region and year fixed effects).

Table 8: Estimated Parameters in Bank Choices of Different Financial Products

| | (1) Credit Card | | (2) Mortgage | | (3) GIC | |
|---|---|---|---|---|---|---|
| bankid | | | | | | |
| Home bank preference | 2.351*** | (0.010) | 2.671*** | (0.016) | 2.916*** | (0.018) |
| ln(Distance to branch) | -0.117*** | (0.008) | -0.123*** | (0.015) | -0.156*** | (0.015) |
| ln(Distance to branch) × Live in rural area | 0.003 | (0.013) | -0.026 | (0.024) | -0.055** | (0.025) |
| ln(Number of branches + 1) | 0.083*** | (0.007) | 0.132*** | (0.014) | 0.086*** | (0.014) |
| ln(Number of branches + 1) × Live in rural area | 0.030** | (0.014) | 0.044* | (0.026) | -0.026 | (0.026) |
| TD indicator | 0.768*** | (0.029) | 0.032 | (0.041) | -0.318*** | (0.043) |
| RBC indicator | 1.161*** | (0.028) | 0.078** | (0.038) | -0.387*** | (0.042) |
| Scotiabank indicator | 0.688*** | (0.030) | 0.388*** | (0.039) | -0.281*** | (0.043) |
| BMO indicator | 1.519*** | (0.029) | -0.356*** | (0.041) | -0.713*** | (0.044) |
| CIBC indicator | 1.345*** | (0.029) | 0.110*** | (0.040) | -0.635*** | (0.044) |
| National Bank indicator | 0.324*** | (0.035) | -0.099** | (0.046) | -1.052*** | (0.055) |
| Laurentian Bank indicator | -0.042 | (0.059) | -0.298*** | (0.079) | -1.215*** | (0.091) |
| HSBC indicator | -1.043*** | (0.064) | -1.383*** | (0.081) | -1.805*** | (0.089) |
| Canadian Western Bank indicator | -5.677*** | (1.000) | -2.618*** | (0.247) | -1.412*** | (0.127) |
| Desjardins Credit Union indicator | 0.976*** | (0.032) | 0.062 | (0.047) | -0.832*** | (0.054) |
| Vancity Credit Union indicator | -0.057 | (0.075) | -0.643*** | (0.105) | -0.672*** | (0.124) |
| ATB Financial indicator | -0.295*** | (0.073) | -0.469*** | (0.095) | -0.546*** | (0.093) |
| Coast Capital Credit Union indicator | -0.969*** | (0.097) | -0.532*** | (0.099) | -0.226** | (0.094) |
| Envision Credit Union indicator | -1.548*** | (0.212) | -1.166*** | (0.195) | -0.988*** | (0.196) |
| Prospera Credit Union indicator | -2.638*** | (0.352) | -1.050*** | (0.148) | -1.265*** | (0.191) |
| Meridian Credit Union indicator | -2.421*** | (0.170) | -1.212*** | (0.094) | -1.098*** | (0.093) |
| Tangerine indicator | -1.128*** | (0.061) | -0.694*** | (0.060) | 0.303*** | (0.046) |
| PC Financial indicator | 1.517*** | (0.030) | -1.206*** | (0.058) | -1.815*** | (0.073) |
| Other bank indicator | 0.770*** | (0.045) | 0.025 | (0.073) | -0.804*** | (0.090) |
| AMEX indicator | 1.578*** | (0.031) | | | | |
| MBNA indicator | 1.185*** | (0.033) | | | | |
| Canadian Tire indicator | 1.564*** | (0.031) | | | | |
| Capital One indicator | 1.595*** | (0.031) | | | | |
| Other financial institutions indicator | | | 1.353*** | (0.038) | 1.708*** | (0.038) |
| Trust companies indicator | | | -0.125** | (0.053) | -0.229*** | (0.055) |
| Observations | 1,075,719 | | 314,230 | | 292,732 | |
| Number of choice sets | 72,449 | | 24,603 | | 22,858 | |

Robust standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Data sources: CFM 2010–2017, CANNEX 2010–2017, FCAC 2010–2017, Government of Canada website

Note: Each column in the table shows the selected estimated parameters from a conditional logit regression of the bank choice of a given financial product (i.e., credit card, mortgage loan, guaranteed investment certificate GIC) on the home bank indicator, branch network, and all bank fixed effects. For each column, the dependent variable equals one if a bank is chosen for the given product and zero for all the non-chosen banks in a household's choice set.

Table 9: Estimated Parameters in Deposit Bank Choice

| Dependent variable: Indicator of deposit bank choice | |
|---|---|
| bankid | |
| Utility from liquidity holding $\ln L^b_{i,j}$ | 1.661*** |
| | (0.179) |
| Weighted sum of expected utilities from financial products | 1.368*** |
| | (0.038) |
| ln(Distance to branch) | -0.175*** |
| | (0.008) |
| ln(Distance to branch) × Live in rural area | 0.113*** |
| | (0.015) |
| ln(Number of branches + 1) | 0.439*** |
| | (0.011) |
| ln(Number of branches + 1) × Live in rural area | 0.229*** |
| | (0.021) |
| Big 5 bank indicator | -0.259*** |
| | (0.033) |
| Small bank indicator | -0.454*** |
| | (0.033) |
| Online bank indicator | 0.389*** |
| | (0.027) |
| Desjardins Credit Union indicator | 0.109*** |
| | (0.026) |
| Observations | 674,536 |
| Number of choice sets | 62,504 |

Robust standard errors in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Data sources: CFM 2010–2017, CANNEX 2010–2017, FCAC 2010–2017, Government of Canada website
Note: The table shows the estimated parameters from a conditional logit regression of the deposit bank choice on the estimated utilities from liquidity holding $\ln L^b_{i,j}$, potential bundling other financial products with deposit accounts, branch network, and bank fixed effects. The dependent variable equals one if a given bank is chosen for deposits and zero for all non-chosen banks in a household's choice set.

Table 10: Deposit Bank Choice Estimation With and Without Complementarity

| | Baseline | Misspecified |
|---|---|---|
| bankid | | |
| Utility from liquidity holding $\ln L^b_{i,j}$ | 1.661*** | 1.892*** |
| | (0.179) | (0.182) |
| Weighted sum of expected utilities from financial products | 1.368*** | |
| | (0.038) | |
| ln(Distance to branch) | -0.175*** | -0.287*** |
| | (0.008) | (0.008) |
| ln(Distance to branch) × Live in rural area | 0.113*** | 0.082*** |
| | (0.015) | (0.015) |
| ln(Number of branches + 1) | 0.439*** | 0.470*** |
| | (0.011) | (0.011) |
| ln(Number of branches + 1) × Live in rural area | 0.229*** | 0.261*** |
| | (0.021) | (0.021) |
| Big 5 bank indicator | -0.259*** | 0.335*** |
| | (0.033) | (0.027) |
| Small bank indicator | -0.454*** | -0.593*** |
| | (0.033) | (0.034) |
| Online bank indicator | 0.389*** | 0.580*** |
| | (0.027) | (0.027) |
| Desjardins Credit Union indicator | 0.109*** | 0.540*** |
| | (0.026) | (0.023) |
| Observations | 674,536 | 674,536 |
| Number of choice sets | 62,504 | 62,504 |

Robust standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Data sources: CFM 2010–2017, CANNEX 2010–2017, FCAC 2010–2017, Government of Canada website

Note: The column "baseline" shows the estimated parameters from a conditional logit regression of the deposit bank choice on the estimated utilities from liquidity holding $\ln L^b_{i,j}$, potential bundling other financial products with deposit accounts, branch network, and bank fixed effects. The last column shows the results when complementarity is neglected. The dependent variable in both specifications equals one if a given bank is chosen for deposits and zero for all non-chosen banks in a household's choice set.

# C Counterfactual Analysis

Section C.1 explains how we conduct the counterfactual analysis on CBDC. Section C.2 shows more counterfactual results. Section C.3 shows the distribution of households' liquid assets, which is used in the discussion on the CBDC holding limits. Section C.4 compares the service networks of bank branches and Canada Post offices.

## C.1 Introducing a CBDC into the Model

Section C.1.1 shows how we obtain the utility from a CBDC using the demand parameters and Section C.1.2 explains how the introduction of the CBDC affects the banks.

### C.1.1 Obtain the Utility from CBDC

After CBDC is introduced, we assume that each household's choice set would contain this new alternative. The household chooses to deposit their digital liquid assets in CBDC or one of the existing banks by comparing the utility from each option. Based on (18), a household $i$'s probability of depositing the digital balance in CBDC is:

$$P(j_i^* = cbdc|r_j, \boldsymbol{r}_{-j}) = \frac{\exp\left(\tilde{\theta}\ln\tilde{L}^b_{i,cbdc} + \phi\sum_{k\in\mathcal{K}}\omega^k E[V^k_{i,cbdc}] + \boldsymbol{X}_{i,cbdc}\boldsymbol{\beta}^f + \eta^f_{cbdc}\right)}{\sum_{m\in\mathcal{J}_i}\exp\left(\tilde{\theta}\ln\tilde{L}^b_{i,m} + \phi\sum_{k\in\mathcal{K}}\omega^k E[V^k_{i,m}] + \boldsymbol{X}_{i,m}\boldsymbol{\beta}^f + \eta^f_{m}\right)}, \quad (19)$$

where the choice set $\mathcal{J}_i$ now also contains a CBDC and the subscript $m$ can refer to a bank or a CBDC. For each household, the probabilities of choosing different options $m$ for their digital money sum to one, so a positive probability of choosing the CBDC implies a reduction in the probabilities of choosing the banks. We use the estimated demand parameters together with the exogenous CBDC design choices to obtain the CBDC choice probability above. We discuss how we obtain each element in (19) below.

**Value from Aggregate Liquid Assets.** We first obtain the utility from liquidity holding $\ln\tilde{L}^b_{i,cbdc}$ in cash and CBDC using the estimates of parameters $(\tilde{\alpha}^b, \tilde{\boldsymbol{\beta}}^b, \tilde{\eta}^b_j, \tilde{\zeta}^b, \tilde{\varepsilon}^b_i)$:

$$\ln\tilde{L}^b_{i,cbdc} = \ln\left[1 + \exp\left(\tilde{\alpha}^b r_{i,cbdc} + \boldsymbol{X}_{i,cbdc}\tilde{\boldsymbol{\beta}}^b + \tilde{\eta}^b_{cbdc} + \tilde{\zeta}^b + \tilde{\varepsilon}^b_i)\right)\right], \quad (20)$$

where $r_{cbdc}$ is the CBDC rate and $r_{i,cbdc} = r_{cbdc}(1-\tau_i)$ is the post-tax CBDC rate. The vector $\boldsymbol{X}_{i,cbdc}$ consists of the branch network measures for CBDC. In the counterfactual analyses, we study different designs of CBDC in terms of the interest rate and the network of service locations. Assuming the preference parameters for attributes, $\tilde{\alpha}^b$ and $\tilde{\boldsymbol{\beta}}^b$, remain unchanged after CBDC issuance, the remaining unknowns are the CBDC fixed effect $\tilde{\eta}^b_{cbdc}$

and the unobserved idiosyncratic preferences for CBDC ($\tilde{\zeta}^b + \tilde{\varepsilon}_i^b$). Intuitively, we do not know how consumers will value a product that is not yet offered. We consider a range of possibilities for the fixed effect of the CBDC, namely among the estimated fixed effects for the big five banks, the small banks, the online banks, and the regional credit unions. For the unobserved idiosyncratic preferences, we assume that they are identical to those of bank deposits since they are both digital money.

If a household chooses to deposit their digital balance in CBDC, then based on (7), the desired holding of CBDC would be:

$$d_{i,cbdc} = \frac{\left(u_{i,cbdc}^b\right)^{\frac{\sigma}{1-\sigma}}}{1 + \left(u_{i,cbdc}^b\right)^{\frac{\sigma}{1-\sigma}}} w_i, \tag{21}$$

where $u_{i,cbdc}^b = \exp\left(\alpha^b r_{i,cbdc} + \boldsymbol{X}_{i,cbdc}\boldsymbol{\beta}^b + \eta_{cbdc}^b + \zeta^b + \varepsilon_i^b\right)$ is the per dollar value from holding the digital balance in CBDC. In our model, once a household chooses CBDC for their digital balance, it will only hold the liquid assets in cash and CBDC. As a result, the cash holding is $c_{i,cbdc} = w_i - d_{i,cbdc}$.

Suppose a central bank would like to impose a limit $\bar{d}_{cbdc}$ on the holdings of a CBDC. When the optimal holding of CBDC exceeds this limit, then household $i$'s CBDC holding is constrained at the limit $d_{i,cbdc} = \bar{d}_{cbdc}$ and the household holds the rest of the liquid assets in cash $c_{i,cbdc} = w_i - \bar{d}_{cbdc}$. This tends to reduce the utility from holding the portfolio of liquid assets in cash and CBDC, and thus reduces the probability of choosing CBDC in the first place.

**Value from Financial Products.** Based on (10), we obtain the expected utility from obtaining the financial product $k$ when the home institution is CBDC:

$$E[V_{i,cbdc}^k] = \ln\left(\sum_{n\in\mathcal{J}_i^k} \exp\left(\kappa \mathbb{1}(n = cbdc) + \boldsymbol{X}_{i,n}\boldsymbol{\beta}^k + \eta_n^k\right)\right). \tag{22}$$

Since CBDC does not come with other complementary financial products, the indicator $\mathbb{1}(n = cbdc)$ is zero no matter which bank $n$ is chosen for the financial product. In other words, if CBDC is the home institution, the household does not enjoy the extra utility $\kappa$ because it still needs to obtain the financial product from some other bank. As a result, the expected utility $E[V_{i,cbdc}^k]$ would be lower compared to the case when the home institution is a bank. We use the estimated parameters $(\kappa, \boldsymbol{\beta}^k, \eta_n^k)$ to calculate $E[V_{i,cbdc}^k]$.

**Service Location Network for CBDC.** As shown above, the service network for CBDC indirectly affects the choice probability of CBDC through the utility from liquidity holding and the expected utility from the other financial products. In addition, we assume

the service location network $\boldsymbol{X}_{i,cbdc}$ for CBDC can directly affect the utility from CBDC since it reflects the convenience of getting in-person customer services for CBDC.

**CBDC Fixed Effect.** We assume the estimated preference parameters $\tilde{\theta}$, $\phi$, and $\boldsymbol{\beta}^f$ are unchanged when CBDC is introduced. The only unknown parameter in the CBDC choice probability (19) is the CBDC fixed effect $\eta^f_{cbdc}$. As discussed above, we consider a range of CBDC fixed effects based on the estimated fixed effects $\eta^f_j$ for different banks $j$.

### C.1.2 Effect of CBDC on Banks

Introducing a CBDC would shift the demand for deposits at each bank. Upon issuance at the previous equilibrium deposit rates, the deposit demand for bank $j$ would be reduced due to a lower probability $P_{i,j}$ of choosing bank $j$ by a household $i$. A lower $P_{i,j}$ tends to make the deposit demand more elastic, according to (14), which would induce banks to raise their deposit rates to compete with CBDC and maintain their deposits.

We assume banks' marginal costs estimated in Section 4.2 are unchanged by CBDC issuance. Therefore, the extent of deposit rate adjustments is only driven by the demand shift and the resulting change in the deposit demand elasticity. With the estimated demand parameters and the constructed expected utility from CBDC, the deposit demand for each bank is a function of the deposit rates. Using the estimated marginal costs and the banks' first-order conditions (13), we solve for the new equilibrium deposits rates in the presence of CBDC. As we vary the design of the CBDC (i.e., $r_{cbdc}, \boldsymbol{X}_{i,cbdc}, \bar{d}_{cbdc}$), we can predict how banks would adjust their deposit rates in response to the CBDC with a given design.

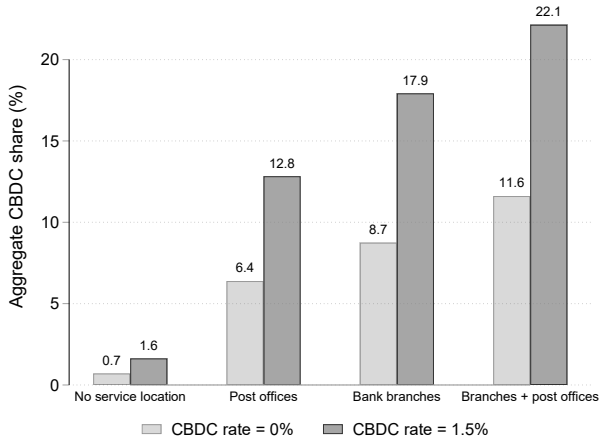
## C.2 Counterfactual Results

Figure 12 shows the aggregate CBDC shares when the interest rate paid on CBDC is 1.5% or 4%, which is substantially higher than the average deposit rate of 10 basis points in 2017. Figure 13 shows the aggregate effects of a CBDC using the estimates from a misspecified model where complementarity is neglected.

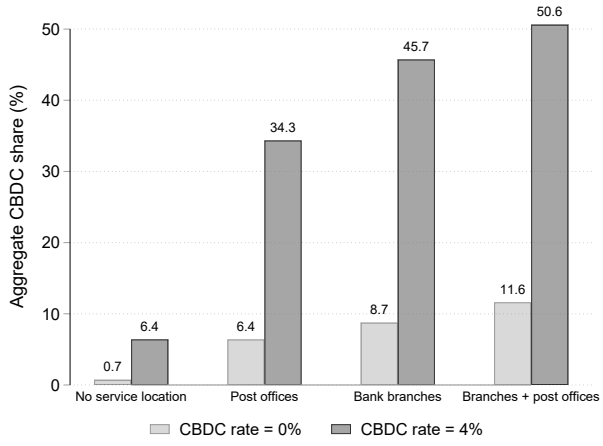
Figure 14 and 15 show the aggregate effects of a CBDC on the equilibrium outcomes and the impact of the CBDC on different banks when assuming the CBDC fixed effect equals the estimated fixed effect for small banks. Except for this different assumption, all else is identical to the corresponding figures in the main text.

Figure 12: Aggregate CBDC Shares under Different CBDC Interest Rates

(a) CBDC rate equals 0 % or 1.5%

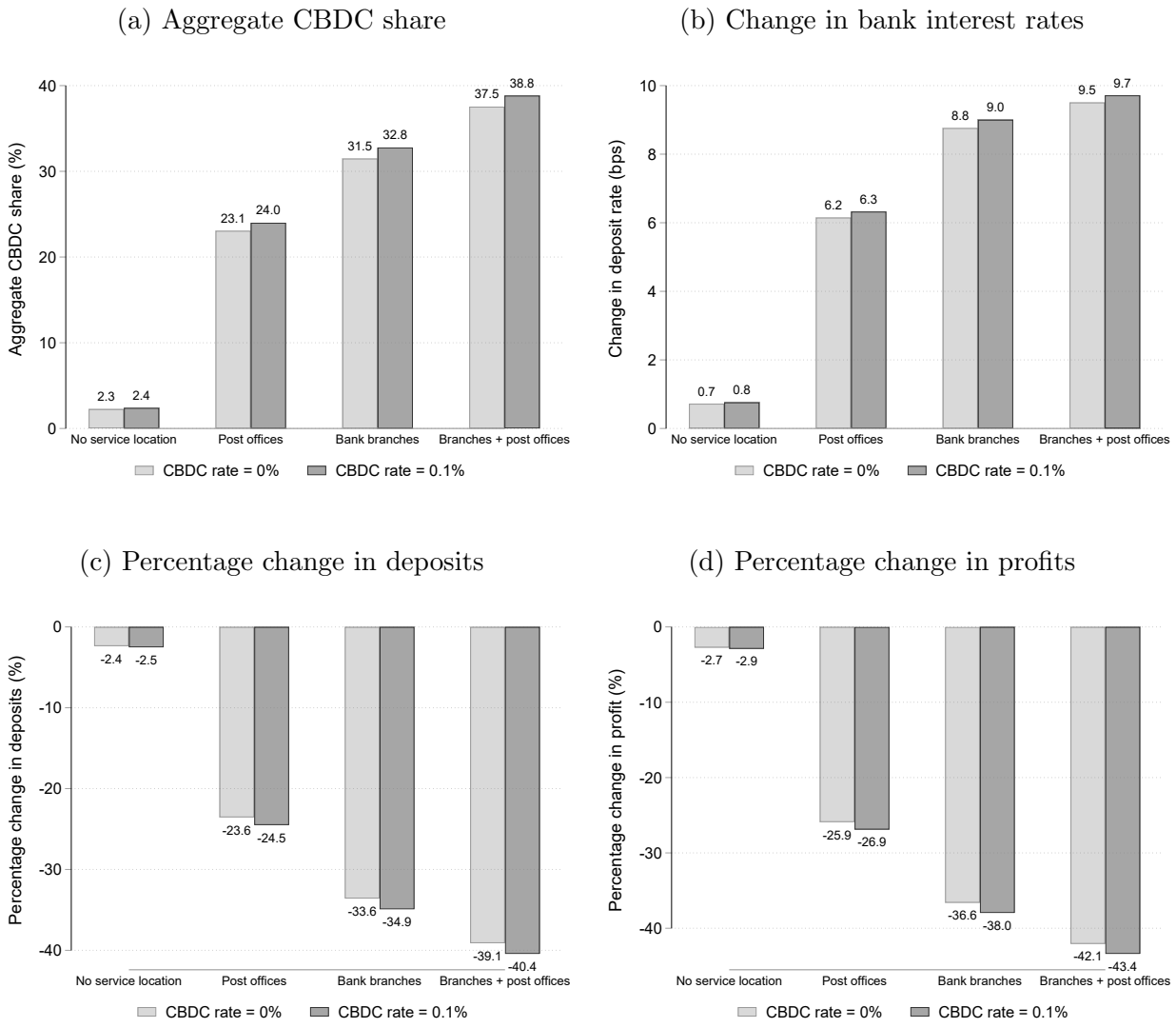



(b) CBDC rate equals 0 % or 4%




Data sources: CFM 2017, FCAC 2017, Canada Post 2021
Note: This figure plots the aggregate CBDC share, calculated as the share of liquid assets allocated in equilibrium by households to CBDC, under different interest rates paid on CBDC. In each subfigure, the given equilibrium outcome is plotted under four designs of branch network for CBDC (i.e., no service location, all Canada Post offices as service locations, all bank branches as service locations, and all bank branches plus all Canada Post offices as service locations), combined with two different remuneration for CBDC. In this figure, we use the fixed effect for the big five banks as the CBDC fixed effect.

Figure 13: The Aggregate Effects of CBDC When Neglecting the Complementarity



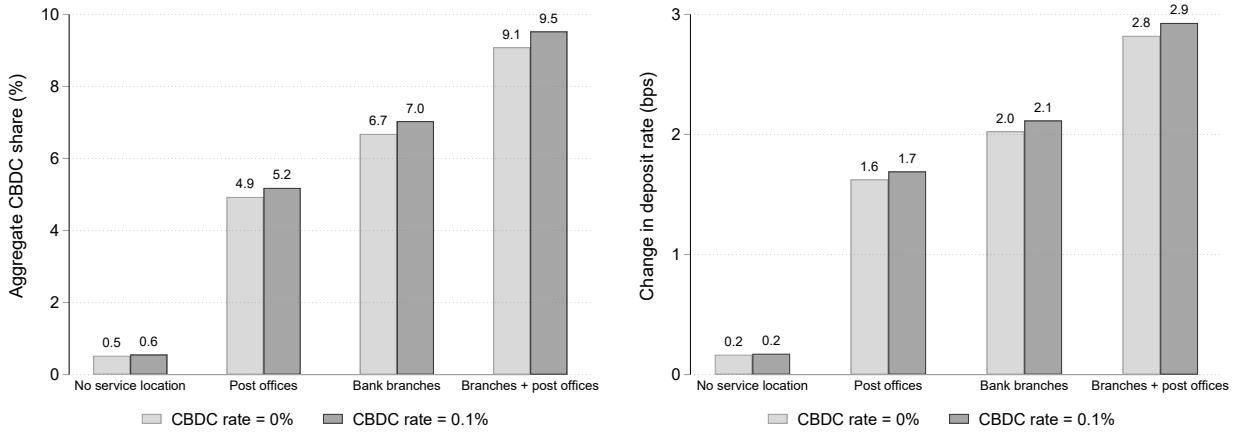

Data sources: CFM 2017, FCAC 2017, Canada Post 2021

Note: This figure is based on the model that is estimated without taking into account the complementarity feature. This figure plots (a) the aggregate CBDC share calculated as the share of liquid assets allocated in equilibrium by households to CBDC, (b) the endogenous changes in deposit rates (in percentage points) on average across banks after CBDC issuance, (c) the percentage drop in deposits, and (d) the percentage drop in profits on average across banks relative to the pre-CBDC equilibrium. In each subfigure, the given equilibrium outcome is plotted under three designs of branch network for CBDC (i.e., no service location, all Canada Post offices as service locations, all bank branches as service locations, and all bank branches plus all Canada Post offices as service locations), combined with two different remuneration for CBDC: 0 and 10 basis points. In this figure, we use the fixed effect for the small banks as the CBDC fixed effect.

Figure 14: Impact of CBDC Designs on Equilibrium Outcomes When CBDC Fixed Effect Equals the Small Bank Fixed Effect

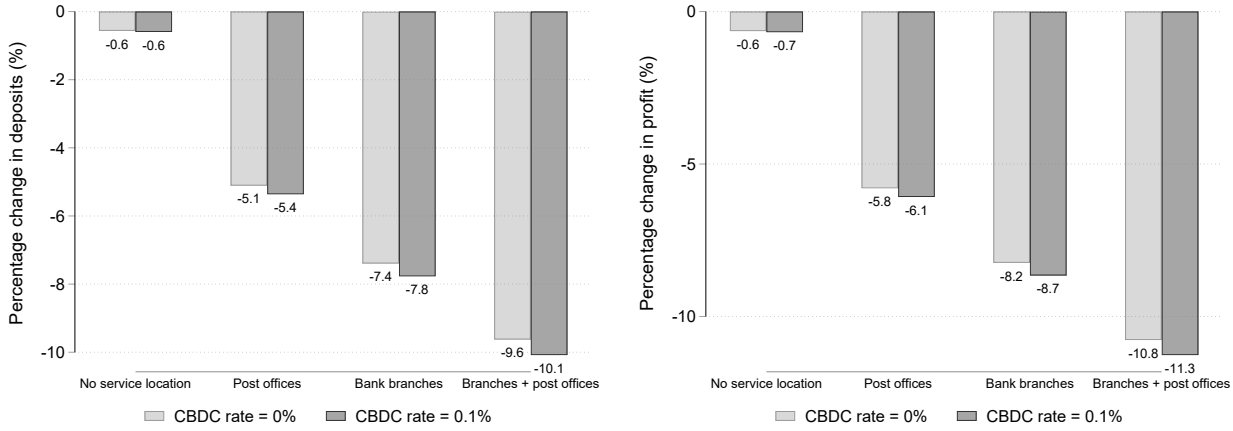
(a) Aggregate CBDC share

(b) Change in bank deposit rates




(c) Percentage change in deposits

(d) Percentage change in profits



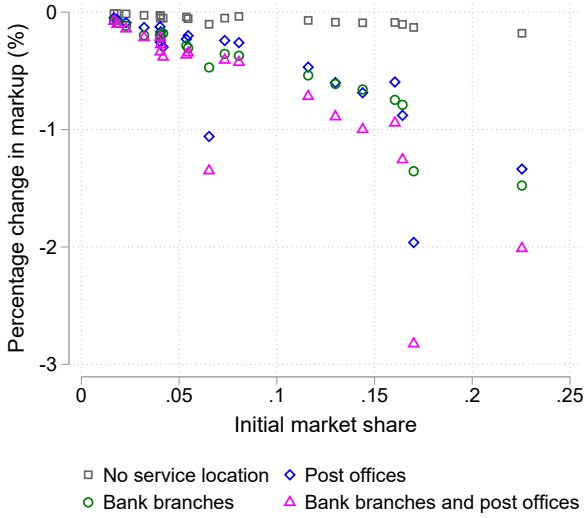

Data sources: CFM 2017, FCAC 2017, Canada Post 2021

Note: This figure plots (a) the aggregate CBDC share calculated as the share of liquid assets allocated in equilibrium by households to CBDC, (b) the endogenous changes in deposit rates (in percentage points) on average across banks after CBDC issuance, (c) the percentage drop in deposits, and (d) the percentage drop in profits on average across banks relative to the pre-CBDC equilibrium. In each subfigure, the given equilibrium outcome is plotted under three designs of branch network for CBDC (i.e., no service location, all Canada Post offices as service locations, all bank branches as service locations, and all bank branches plus all Canada Post offices as service locations), combined with two different remuneration for CBDC: 0 and 10 basis points. In this figure, we use the fixed effect for the small banks as the CBDC fixed effect.

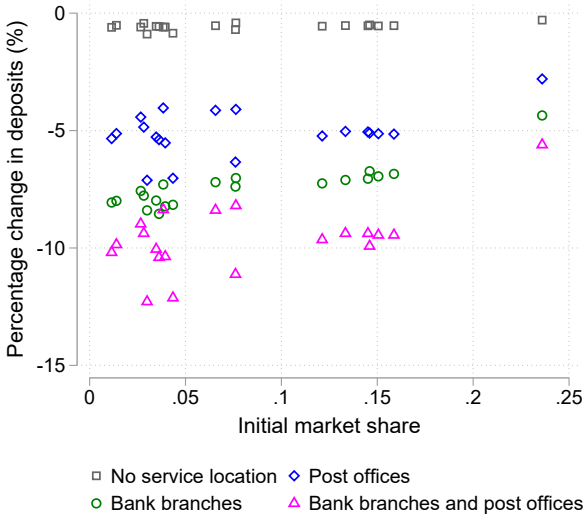
Figure 15: Impact of CBDC on Different Banks under Small Bank Fixed Effect

(a) Level Change in Deposit Rate


(b) Percentage Change in Markup




(c) Percentage Change in Deposits




(d) Percentage Change in Profit

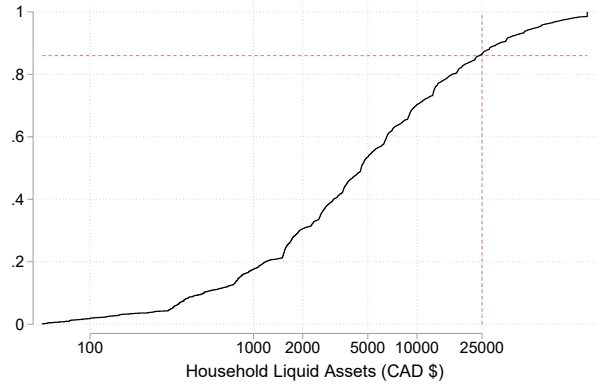

Data sources: CFM 2017, FCAC 2017, Canada Post 2021
Note: This figure plots each bank's optimal response in deposit rates (in basis points), the percentage changes in deposits, markups, and profits for different CBDC network designs. The x-axis is the bank's initial market share, measured as the local market-level probabilities of choosing the particular bank averaged across all local markets in which the bank is present. Here, we assume CBDC is non-interest-bearing and has a fixed effect that is identical to that of the small banks.

## C.3 Distribution of Household Liquid Assets

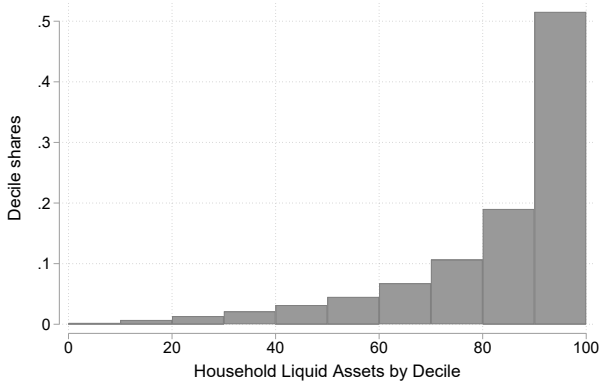
Figure 16 shows the distribution of households' liquid assets.

Figure 16: Distribution of Household Liquid Assets

(a) Empirical CDF




(b) Percentage of total liquid assets by decile



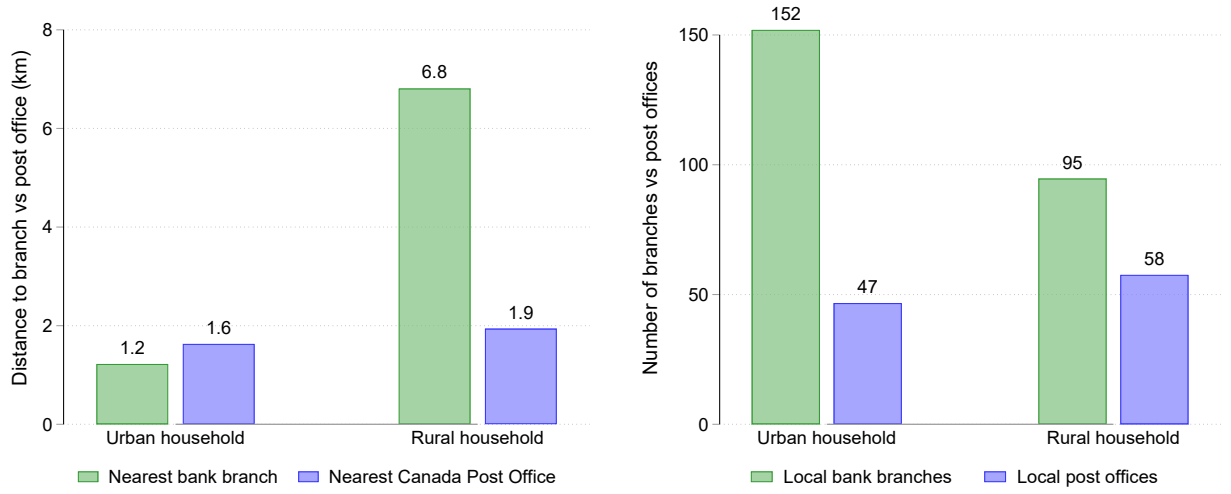

Data sources: CFM 2017

Note: This figure shows the distribution of liquid assets that our model takes as input. In panel (a) we show the empirical cumulative distribution function for 2017 from the CFM. For a given level of assets on the x-axis, the corresponding level on the y-axis refers to the percentage of households holding less than that amount. In panel (b) we show the percentage of total liquid assets held by each decile. For example, the height of the 3rd bar means that households from the 20th to 30th percentile hold 1.3% of the total liquid assets, while the 10th bar shows that the 90th to 100th percentile households hold 51% of total liquid assets.

## C.4 Comparing the Location Networks of Banks and Canada Post

Figure 17: Comparing the Location Networks of Banks and Canada Post

(a) Distance to the nearest branch or post office (b) Number of local branches or post offices




Data sources: CFM 2017, FCAC 2017, Canada Post 2021

Note: The first (last) two bar in figure (a) show the great-circle distance from each urban (rural) household to the nearest bank branch or the nearest Canada Post Office, which is then averaged across all urban (rural) households. The first (last) two bars in figure (b) show the total number of bank branches or Canada Post Offices in each urban (rural) household's local market, which is then averaged across urban (rural) households. The local market of an urban (a rural) household includes all the banks with branches available that are within 15km (50km) from the household's location.