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# Central Bank Digital Currency and Banking Choices

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## Abstract

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

*Topics: Central bank research; Digital currencies and fintech*

*JEL codes: E50, E58*

## Résumé

Dans quelle mesure une monnaie numérique de banque centrale (MNBC) concurrence-t-elle les dépôts bancaires? Pour répondre à cette question, nous élaborons et estimons un modèle structurel dans lequel chaque ménage choisit l'institution financière où déposer son argent numérique. Les ménages évaluent les intérêts servis sur l'argent numérique, la possibilité d'obtenir des produits financiers complémentaires et l'accès aux services en succursale. Une MNBC ne portant pas intérêt et non assortie de produits financiers complémentaires ne peut évincer dans une large mesure les dépôts bancaires que si elle est associée à un réseau de services étendu. L'imposition d'une limite élevée à la détention de MNBC atténuerait efficacement cet effet d'éviction.

*Sujets : Recherches menées par les banques centrales, Monnaies numériques et technologies financières*

*Codes JEL : E50, E58*

# 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.<sup>1</sup> By offering the public the option to hold the digital money in a CBDC instead of bank deposits, the CBDC would directly compete with bank deposits in the market for digital money. As a consequence, 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 addressing 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 differentiating features between a CBDC and bank deposits: (i) banks provide products complementary to deposits, such as mortgages and credit cards,<sup>2</sup> while a CBDC would likely be a stand-alone central bank product; (ii) most banks have extensive branch networks for in-person service, while depending on the design, the service location network of a CBDC can be very different from banks' branch networks. For example, a CBDC can be designed to be entirely digital with no physical branch, or it can be designed to have a network of branches like banks.

Incorporating these two features is important for studying the crowding out effects of a CBDC, because households have strong preferences for obtaining complementary financial products from their deposit banks and for conveniently accessing in-person services at physical locations (bank branches). According to Canadian household survey data 2010–2017, 56% of mortgage borrowers and 45% of credit card holders choose their deposit banks for the respective product.<sup>3</sup> Additionally, both urban and rural households prefer banks with branches closer to their residences. The same survey data show that around 60% of depositors

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<sup>1</sup>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. 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 have already started their pilots, including China, India, Singapore, South Korea, and Sweden.

<sup>2</sup>We focus on the complementarity between deposits and other financial products within the same bank that is enjoyed by consumers, which differs from the complementarity between credit lines and deposits that is enjoyed by banks in [Piazzesi and Schneider \(2020\)](#) or the complementarity between print and online newspapers in [Gentzkow \(2007\)](#). The complementarity in our paper could reflect the convenience of managing the different products in the same bank, the ease of making bill payments from the deposit account, or the better deals from bundling different products at the same bank, for instance.

<sup>3</sup>In our sample, 30% of households have a mortgage loan and 90% of households have a credit card.

reported that they had visited their branches at least once in the past month. In particular, depositors prefer to use bank branches for non-transaction related services, such as obtaining customer service and support and making complaints, compared to other banking methods such as online and mobile banking.

To incorporate these two features, we develop a structural model where households obtain utility from holding their endowed liquid assets in physical cash and digital money. In the absence of a CBDC, the only available digital money is deposits provided by private banks. To hold deposits, a household first needs to choose one of the private banks, taking into account that banks offer different deposit rates, complementary financial products, and service locations (bank branches). Each bank faces a deposit demand that aggregates each individual household's deposit demand and competes in the deposit rate. We estimate the model primitives, which include households' preference parameters for different attributes (e.g., deposit rate, complementarity, and branch network) and banks' marginal costs. These model primitives are assumed to be unchanged after CBDC issuance.

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 use a unique Canadian household survey dataset that contains detailed information on households' bank choices for each financial product, which allows us to estimate how much households value obtaining a given financial product from their deposit bank. In addition, we combine the households' residential locations from the household survey data with the bank branch location data to measure the branch network that is specific to each household's local area and estimate households' preferences towards the branch network when choosing their deposit banks.

After obtaining the estimates of the model primitives, we then introduce a CBDC into the model and study its impact on banks in counterfactual analyses. We model the CBDC as a new product with attributes that are exogenously chosen by the central bank. In the presence of a CBDC, each household chooses to deposit their digital money in either an existing bank or the CBDC based on their utilities from each product, which in turn depend on how households value the attributes of each product as well as the household-specific tastes for each product. Introducing a CBDC would reduce the fraction of households that choose existing banks because there will always be some households with tastes in favor of a CBDC. This leads to a lower deposit demand for each bank. Moreover, the CBDC increases the deposit demand elasticity with respect to the deposit rate because households now have more options.

Facing a more elastic deposit demand, banks optimally raise their deposit rate to maintain their attractiveness. With the better deposit rate, a household would hold more deposits

relative to cash if they were to choose an existing bank. However, this intensive margin change is dominated by the extensive margin change (i.e., fewer households choose existing banks). Therefore, in equilibrium, households' deposit demand is lower and the CBDC would crowd out bank deposits.

When a CBDC is designed to be more attractive, it would lead to more crowding out. Apart from the CBDC interest rate, we consider design features such as complementarity, service location network, and a potential limit on CBDC holdings. We assume that the CBDC does not offer complementary financial products such as mortgage loans and credit cards.<sup>4</sup> Depending on the design, the CBDC may have no service location or may have a network of service locations that is identical to the network of all bank branches or the network of Canada Post offices.<sup>5</sup> Additionally, we use our model to study the effect of introducing a limit on CBDC holdings, which is a design choice frequently discussed by policymakers as a potential tool to reduce the crowding out effect of the CBDC.

The main findings are as follows. First, the network of service locations and the absence of complementary financial products are two key factors that determine the take-up of a CBDC and its crowding out effect on bank deposits. A non-interest-bearing CBDC that does not come with complementary financial products would require better service locations to be attractive. If it has no service location, it would have a negligible impact, crowding out bank deposits by only 1%. In contrast, if it uses both Canada Post offices and bank branches as service locations, it would crowd out 12% of bank deposits. Under this extensive network design, if we misspecify the model by neglecting the complementarity between deposits and other financial products, we would significantly overestimate the impact of a CBDC and conclude incorrectly that a CBDC can crowd out 39% of bank deposits. Therefore, it is crucial to account for these two differentiating factors when quantifying the effects of the CBDC on bank deposits.

Second, a large limit on CBDC holdings can substantially reduce the crowding out, while its impact on reducing the depositors' welfare gains is much smaller. By solving the model for a range of different limits, we find that even a large holding limit of 25,000 Canadian

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<sup>4</sup>As a consequence, if a household chooses the CBDC for their digital money, they still need to go to a private bank for a mortgage loan or a credit card and would not enjoy the synergy between the CBDC and these financial products. We think this is a realistic design feature since the central bank is unlikely to make loans to the public.

<sup>5</sup>These counterfactual location choices are motivated by the policy discussions on whether a central bank should directly deliver the CBDC to the public (i.e., single-tier system) or partner with the private sector (i.e., two-tier system). The 2022 BIS survey shows that 87% of central banks engaged in retail CBDC work are considering a two-tier system that involves a role for the private sector ([Kosse and Mattei, 2023](#)). We highlight the implications of the delivery arrangement on service locations. While a single-tier system is likely to imply no service location for the CBDC, a two-tier system would imply a network of CBDC service locations similar to those of the private sector providers.

dollars, which is much higher than the limit of 3,000 euros considered by the ECB (Panetta, 2022), would reduce the share of liquid assets held in the CBDC by half regardless of the service location network. This is because the constrained households, while representing only around 10% of households, are from the top end of the liquid asset distribution and thus tend to hold a large amount of liquid assets. Since this large limit only affects a small proportion of households, the reduction in households' welfare gains from the CBDC is much smaller. This suggests policymakers can reduce the crowding out while making CBDC attractive to most households.

Third, impacts of a CBDC on both banks and households are heterogeneous. 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.<sup>6</sup> 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 access to banks in rural areas. The difference is larger when the service locations of the 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 perspective, it might be desirable to consider locations as broad as Canada Post offices as service locations for the CBDC.

This paper complements the growing theoretical literature that studies the effects of a CBDC on banking (e.g., Chang et al., 2023; Chiu et al., 2023; Keister and Sanches, 2023; Garratt, Yu and Zhu, 2022; Andolfatto, 2021).<sup>7</sup> This literature typically assumes that the CBDC is a perfect substitute for bank deposits.<sup>8</sup> Most papers in this stream also have limited discussions on the designs of the CBDC, focusing mainly on the interest rate. 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 we use

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<sup>6</sup>Similarly, Whited, Wu and Xiao (2023) find that when the banking sector is more concentrated, banks lose fewer deposits to a one dollar increase in CBDC. Garratt, Yu and Zhu (2022) find that the large bank raises its deposit rate by more in response to a higher CBDC interest rate. In contrast, with the household-level data, we can also study the heterogeneous impact of a CBDC on households.

<sup>7</sup>Existing theoretical literature also studies the impact of CBDC on financial stability (e.g., Ahnert et al., 2023; Fernández-Villaverde et al., 2021; Williamson, 2021; Schilling, Fernández-Villaverde and Uhlig, 2020; Brunnermeier and Niepelt, 2019; Skeie, 2019), monetary policy (e.g., Abad, Nuño and Thomas, 2023; Davoodalhosseini, 2022; Jiang and Zhu, 2021; Bordo and Levin, 2017), macroeconomic volatility (e.g., Assenmacher, Bitter and Ristiniemi, 2023; Barrdear and Kumhof, 2022; George, Xie and Alba, 2022; Minesso, Mehl and Stracca, 2022), payment platform competition (Liu, Reshidi and Rivadeneyra, 2023), 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.

<sup>8</sup>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.



these preferences to predict the substitution patterns between deposits and the CBDC with different designs.<sup>9</sup>

This paper is most closely related to the empirical literature on CBDC, which is scarce at this point due to the lack of data on CBDC. To address this issue, one approach is to develop a structural model and estimate the households’ preferences for product attributes using the data on existing products that are close substitutes for the CBDC. The estimated model is then used to conduct counterfactual analysis on the CBDC. Using this approach, [Li \(2023\)](#) studies the households’ potential holdings of the CBDC relative to cash and demand deposits, and [Huynh et al. \(2020\)](#) study the consumer adoption and usage of the CBDC as a payment instrument relative to cash, debit cards, and credit cards, using the Canadian consumer survey data. More recently, [Whited, Wu and Xiao \(2023\)](#) 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 the complementarity between deposits and other financial products from the consumers’ point of view and the service locations when studying the impact of a CBDC on bank deposits.<sup>10</sup>

Another approach is to conduct surveys or experiments to directly ask people about their intention to adopt a hypothetical CBDC.<sup>11</sup> For example, surveys have been conducted in the Netherlands ([Bijlsma et al., 2021](#)), in Austria ([Abramova et al., 2022](#)), and by the European Central Bank (ECB) ([Kantar Public, 2022](#)). In the absence of a CBDC or a concrete design for CBDC, this survey approach is challenging because the results would rely heavily on consumers’ understanding of the CBDC based on a broad description for the CBDC. [Choi et al. \(2022\)](#) use a discrete choice experiment approach, where each respondent is asked to choose between a pair of hypothetical payment methods (constructed by varying the values of nine product attributes). Again, the accuracy of the results relies on consumers’ understanding of each hypothetical payment instrument. Different from the survey or the

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<sup>9</sup>While there are a few papers studying the non-price design features of a CBDC, such as anonymity ([Cheng and Izumi, 2023](#); [Chiu and Monnet, 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 to quantify the impact of the CBDC designs in terms of the network of service locations and the complementarity.

<sup>10</sup>This paper also adds to the literature on deposit market competition using structural estimation (e.g., [Albertazzi et al., 2022](#); [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 financial product bundling within the same bank. 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 the impact of geographical and cultural proximity on households’ choices of credit products and the pricing received, while we focus on the deposit market competition in this paper.

<sup>11</sup>[Grodecka-Messi and Zhang \(2023\)](#) use a historical event, the opening of the Bank of Canada in 1935, to study how the issuance of central bank (physical) money could affect the chartered banks, which offers insights for the potential effect of the digital money issued by the central bank.

experimental approach, we use households’ preferences that are revealed from their choices of deposit products from different banks.

The rest of the paper is organized as follows. Section 2 presents the model without a CBDC. Section 3 discusses identification and estimation of the model. Section 4 presents our data sources and estimation results. Section 5 shows the counterfactual analyses for different CBDC designs, including the network of service locations as well as a hard limit on CBDC holdings. Section 6 concludes.

## 2 Model

The model consists of two types of agents: households and banks. Each household first chooses which bank  $j$  to go to for depositing their digital money. Conditional on the deposit bank choice, they then allocate their endowed liquid assets between digital money and physical cash based on the relative attributes of the two assets. Households’ utilities from holding the liquid assets depend on their deposit bank choice because banks offer different deposit rates, for instance. After the deposit bank choice, a household may need to get a financial product  $k$ . In this case, they choose a bank  $n$ , which can be different from the deposit bank  $j$ . However, they enjoy some extra utility if they get this product from their deposit bank due to the complementarity between deposits and the financial product within the same bank.

We solve the households’ problem using backward induction. We first solve the portfolio allocation problem and the bank choice problems for other financial products to obtain households’ utilities from liquidity holding and from complementary financial products, respectively. Then we solve households’ deposit bank choice problem, taking into account these two utilities and the utility from branch networks that different deposit banks provide.

By solving the households’ problem, we obtain each household’s deposit demand. We then aggregate to obtain the deposit demand for each bank at the national level. Banks take the deposit demand functions as given and engage in Bertrand competition with differentiated products in the deposit market. Each bank chooses their deposit rate to maximize their profit. To focus on the deposit market where a CBDC will have the most direct impact, we simplify the bank’s problem by abstracting from banks’ lending decisions and how the complementarity affects the loan demand. We discuss the bank’s problem and the implications of these simplifying assumptions in Section 2.2. We now discuss the household’s problem in Section 2.1.

## 2.1 Household's Problem

Each household  $i$  is endowed with  $w_i$  liquid asset balance, which they would like to hold in both the physical form (cash) and the digital form (deposits). Bank deposits are the only digital liquid asset available in the absence of a CBDC. To hold deposits, the household first chooses a bank  $j$  that gives them the highest utility from their choice set  $\mathcal{J}_i$ . We denote the set of all banks by  $\mathcal{J}$ .

Conditional on choosing a deposit bank  $j$ , the household optimally allocates  $w_i$  between cash and deposits and obtains utility  $V_{i,j}^b$  from holding the liquid assets. Given that  $V_{i,j}^b$  depends on bank  $j$ 's attributes, such as the deposit rate and the branch network, it affects a household's deposit bank choice.

After choosing the deposit bank, the household may need to obtain a financial product  $k \in \mathcal{K}$ , such as a mortgage loan and a credit card, with an exogenous probability  $\omega^k$ .<sup>12</sup> For each product  $k \in \mathcal{K}$ , the household would need to choose a bank  $n$  from their choice set  $\mathcal{J}_i^k$ . To capture the complementarity between deposits and other financial products within the same bank, we allow the household to have a home bank preference for each financial product. That is, they enjoy extra utility if they obtain the financial product from their deposit bank. Because of this home bank preference, the expected value  $E[V_{i,j}^k]$  from obtaining the financial product  $k$  depends on the deposit bank choice  $j$ .

We solve the household's problem using backward induction. We first solve for each household's utility from holding the portfolio of liquid assets  $V_{i,j}^b$  and their expected value from obtaining the complementary product  $E[V_{i,j}^k]$ . These factors then enter into the household's utility  $V_{i,j}^f$  from opening a deposit account at bank  $j$ , which also depends on the branch network  $\mathbf{X}_{i,j}$ , unobserved quality captured by the bank fixed effect  $\eta_j^f$ , and the idiosyncratic taste  $\varepsilon_{i,j}^f$  for bank  $j$ :

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

The term  $\omega^k E[V_{i,j}^k]$  is the expected utility from obtaining the financial product  $k$ , which is the product of the probability of requiring the financial product,  $\omega^k$ , and the expected value from the financial product,  $E[V_{i,j}^k]$ . At the time of choosing the deposit bank, the household does not know their bank-specific taste for the financial product; therefore, they take the future expected value  $E[V_{i,j}^k]$  into account. The parameters,  $\theta$  and  $\phi$ , capture the importance of the utility from liquidity holding and from complementary financial products, respectively. The

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<sup>12</sup>This timing assumption is supported by the Canadian household survey data from 2010–2017, where around 80% of the mortgage borrowers take out a mortgage after getting the deposit account. A median household takes out a mortgage 8 years after having the deposit account.

vector  $\mathbf{X}_{i,j}$  contains the branch network measures of bank  $j$  that are specific to household  $i$ 's local area, and  $\beta^f$  consists of the preference parameters for each branch network measure.

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 probability of choosing a given bank  $j$  is

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

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

**Value from Liquid Assets.** Household  $i$  obtains utility from holding cash  $c_{i,j}$  and deposits  $d_{i,j}$  in bank  $j$ , through a constant-elasticity-of-substitution (CES) aggregator:

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

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  $r_j$ , branch network measures  $\mathbf{X}_{i,j}$ , household characteristics  $\mathbf{Z}_i$ , the bank fixed effect  $\eta_j^b$ , a deposit-specific constant  $\zeta^b$ , and a household's idiosyncratic taste for deposits  $\varepsilon_i^b$ :

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

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  $\beta^b$  measure how much the households value the respective bank-specific characteristics. The parameters  $\gamma^b$  capture the effects of household characteristics on  $u_{i,j}^b$ . The household chooses  $c_{i,j}$  and  $d_{i,j}$  to maximize their utility from liquid asset holdings by solving

$$V_{i,j}^b = \max_{c_{i,j}, d_{i,j}} \ln [c_{i,j}^\sigma + (u_{i,j}^b d_{i,j})^\sigma]^{1/\sigma} \quad \text{st} \quad c_{i,j} + d_{i,j} = w_i. \quad (5)$$

One can solve this problem and obtain

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

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

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

Therefore, household  $i$ 's expected demand for deposits at bank  $j$  is  $d_{i,j}(r_j)$  multiplied by the choice probability (2).

**Value from Financial Products.** If household  $i$  needs a financial product  $k \in \mathcal{K}$ , they will choose a bank  $n$  from their choice set  $\mathcal{J}_i^k$ . Denote the set of all banks providing product  $k$  by  $\mathcal{J}^k$ . If their deposit bank is  $j$ , the utility of obtaining the product from bank  $n$  is

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

where  $\kappa$  is the extra utility household  $i$  gets from obtaining the financial product from their deposit bank,  $\mathbf{X}_{i,n}$  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. We assume that  $\varepsilon_{i,n}^k$  is independent across financial products and banks and is independent of all the other idiosyncratic tastes in the model. 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 their deposit bank if  $\kappa^k > 0$ . This home bank preference could reflect the convenience in managing different products at the same bank, or potentially better deals offered by banks, for instance.<sup>13</sup> The parameters  $\boldsymbol{\beta}^k$  reflect the importance of the branch network measures in the bank choice for product  $k$ . Let  $E[V_{i,j}^k]$  denote the expected value from getting the product  $k$  if the home bank is  $j$ :

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

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 the following closed-form expression:

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

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<sup>13</sup>Mester, Nakamura and Renault (2007) show that banks use payments information from small business borrowers' transaction accounts to adjust their monitoring intensity. Similarly, banks may use information from households' deposit accounts to give them better deals for other products. However, better deals are not necessary for households to prefer their home banks. They may get worse deals from their home banks but still prefer their home banks due to convenience.

If  $\kappa^k = 0$  for all  $k \in \mathcal{K}$ , the expected value from each financial product is identical across potential deposit banks  $j$  and thus would not affect the choice of the 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  $\mathbf{r}_{-j}$ . This deposit demand is obtained by summing across each household's expected demand:

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

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

Banks set their deposit rates to compete for deposits. We assume they only invest in loans, which give an exogenous return  $r_j^l$ .<sup>14</sup> Let  $mc_j$  denote bank  $j$ 's marginal cost. Bank  $j$  takes the deposit rates of other banks  $\mathbf{r}_{-j}$  as given and chooses a deposit rate  $r_j$  to maximize its profit:

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

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

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

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 the 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  $P_{i,j} \equiv P(j_i^* = j | r_j, \mathbf{r}_{-j})$ , and the deposit shares  $\frac{d_{i,j}}{w_i}$

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<sup>14</sup>We abstract from modeling how the loan supply is affected by a CBDC or how the loan demand is affected by the complementarity with deposits. These simplifications do not affect the estimation of the households' demand side or how a CBDC affects the deposit demand. They only affect the equilibrium loan rate, which in turn changes the magnitude of banks' endogenous responses in deposit rates. We find that the change in equilibrium deposits is not very sensitive to the magnitude of the endogenous rate responses. As a result, abstracting from the loan side is unlikely to substantially change our results on the crowding out effects of the CBDC.

across households:

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

where  $P_{i,j} d_{i,j}(r_j)/D_j(r_j, \mathbf{r}_{-j})$  can be viewed as the weight on household  $i$ . Once a CBDC is introduced, a household can choose to hold their digital money in either the CBDC or an incumbent bank. The CBDC will be a new alternative in each household's choice set  $\mathcal{J}_i$ . Given the idiosyncratic taste for the CBDC, the probability of choosing the CBDC is always positive, meaning that the probability  $P_{i,j}$  of choosing an incumbent bank  $j$  decreases. As shown in (14), a smaller  $P_{i,j}$  tends to make the deposit demand more elastic (i.e., semi-elasticity increases) and induces banks to raise their deposit rate.<sup>15</sup>

### 3 Identification and Estimation

The demand side of the model has four sets of unknown parameters: parameters in the CES aggregator of liquid assets,  $(\alpha^b, \beta^b, \gamma^b, \eta^b, \zeta^b, \sigma)$ , parameters in the bank choice for a financial product  $k \in \mathcal{K}$ ,  $(\kappa^k, \beta^k, \eta^k)$ , the probabilities of demanding each financial product  $k$ ,  $\omega^k$ , and the weights on different components in the utility for the deposit bank  $(\theta, \phi, \beta^f, \eta^f)$ . Here  $\eta^b = \{\eta_j^b\}_{j \in \mathcal{J}}$ ,  $\eta^k = \{\eta_j^k\}_{j \in \mathcal{J}^k}$ ,  $\eta^f = \{\eta_j^f\}_{j \in \mathcal{J}}$  are the vectors of fixed effects for all banks in the portfolio allocation choice, the bank choice for financial product  $k$ , and the bank choice for the deposit account, respectively. The supply side has a set of unknown parameters, i.e., each bank's marginal cost  $mc_j$ .

Suppose we observe an independent sample of households indexed by  $i \in \mathcal{I}$ . For each household  $i$ , we observe a vector  $(\mathcal{J}_i, j_i^*, c_i^*, d_i^*, \tau_i, \{\mathcal{J}_i^k\}_{k \in \mathcal{K}}, \{n_{i,k}^*\}_{k \in \mathcal{K}}, \{\mathbf{X}_{i,j}\}_{j \in \mathcal{J}_i}, \mathbf{Z}_i)$ , where  $c_i^*$  and  $d_i^*$  are household  $i$ 's cash and deposit holdings at their chosen deposit bank  $j_i^*$ , and  $n_{i,k}^*$  is their chosen bank for financial product  $k$ . For each bank  $j$ , we observe  $(r_j, r_j^l)$ , which implies that we observe  $r_{i,j} = (1 - \tau_i)r_j$  for all  $i$  and  $j$ . This section studies how to identify and estimate the unknown parameters of the model with the above information. We focus our discussion on the demand side of the model. Once we obtain the demand-side parameters, we can identify  $D_j(r_j, \mathbf{r}_{-j})$  and use banks' first-order conditions (13) to identify

<sup>15</sup>The semi-elasticity for bank  $j$  is a sum over all households' semi-elasticities of their expected deposit demand. Therefore, how a household's weight  $P_{i,j} d_{i,j}(r_j)/D_j(r_j, \mathbf{r}_{-j})$  is affected by  $P_{i,j}$  is not important. The impact of a CBDC on the elasticity is through the term  $(1 - P_{i,j})$ , where for each household  $i$ ,  $P_{i,j}$  is smaller due to the CBDC.

their marginal costs,  $mc_j$ .

### 3.1 Identification

Identification of the demand-side parameters involves three steps. First, we use households' portfolio allocations to identify the parameters in the CES aggregator of liquid assets. Second, we use households' bank choices for different financial products to identify their home bank preference and other preference parameters for each financial product. Lastly, we combine these two sets of parameters with households' deposit bank choices to identify the parameters in choosing the deposit bank.

#### Parameters in the CES Aggregator

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

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

In particular, this implies that

$$\ln \frac{d_i^*}{c_i^*} = \frac{\sigma}{1-\sigma} (\alpha^b r_{i,j_i^*} + \mathbf{X}_{i,j_i^*} \boldsymbol{\beta}^b + \mathbf{Z}_i \boldsymbol{\gamma}^b + \eta_{j_i^*}^b + \zeta^b + \varepsilon_i^b). \quad (16)$$

This is a linear regression model, so the coefficients and residuals are identifiable if explanatory variables have enough variation (i.e., the design matrix is invertible). However, there are two caveats. First, we can identify  $\eta_j^b$  only if bank  $j = j_i^*$  for some household  $i$ . Therefore, to identify  $\boldsymbol{\eta}^b$ , we assume that  $j_i^*$  in our sample has sufficient variation and every bank  $j \in \mathcal{J}$  is chosen by some households. 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  $\tilde{v} = \frac{\sigma v}{1-\sigma}$  for every  $v \in \{\alpha^b, \boldsymbol{\beta}^b, \boldsymbol{\gamma}^b, \boldsymbol{\eta}^b, \zeta^b, \varepsilon_i^b\}$ . However, as will be shown later in this section, this is sufficient for our counterfactual analysis.

#### Preference Parameters in Bank Choices for Other Financial Products

If a household needs a financial product  $k$  (i.e., mortgage loan, credit card, guaranteed investment certificate), they select a bank  $n$  from their choice set to maximize their utility given their 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, the household's probability of choosing a bank  $n \in \mathcal{J}_i^k$  is

$$P(n_{i,k}^* = n) = \frac{\exp(\kappa^k \mathbb{1}(n = j_i^*) + \mathbf{X}_{i,n} \boldsymbol{\beta}^k + \eta_n^k)}{\sum_{m \in \mathcal{J}_i^k} \exp(\kappa^k \mathbb{1}(m = j_i^*) + \mathbf{X}_{i,m} \boldsymbol{\beta}^k + \eta_m^k)}. \quad (17)$$

We identify the parameters  $(\kappa^k, \boldsymbol{\beta}^k, \boldsymbol{\eta}^k)$  by matching the conditional choice probabilities predicted by (17) with those implied from the data for each product  $k$ . Similarly,  $\mathbf{X}_{i,m}$  and  $n_{i,k}^*$  need to have sufficient variation (e.g., every bank  $n \in \mathcal{J}^k$  is chosen by some households) for the parameters to be identifiable.

### Preference Parameters in Deposit Bank Choice

To identify the parameters  $(\theta, \phi, \boldsymbol{\beta}^f, \boldsymbol{\eta}^f)$  in the conditional choice probability of each deposit bank (2), we first need to know  $V_{i,j}^b$  and  $\sum_{k \in \mathcal{K}} \omega^k E[V_{i,j}^k]$ . We can calculate the expected value from getting a financial product  $E[V_{i,j}^k]$  using (10) because all the unknown parameters are identified in the step above.<sup>16</sup> The utility  $V_{i,j}^b$ , defined by (6), affects deposit bank choices only through the term:

$$\frac{1 - \sigma}{\sigma} \ln [1 + (u_{i,j}^b)^{\sigma/(1-\sigma)}], \quad (18)$$

which is specific to bank  $j$ . The term  $\ln w_i$  in (6) is the same for all banks and thus does not affect the conditional choice probabilities of deposit banks. Therefore, we can drop it without loss of generality. By (4),  $(u_{i,j}^b)^{\sigma/(1-\sigma)}$  equals the exponential of the right-hand side of (15). Since  $\tilde{v} = \frac{\sigma v}{1-\sigma}$  is identified in the first step for every  $v \in \{\alpha^b, \boldsymbol{\beta}^b, \boldsymbol{\gamma}^b, \boldsymbol{\eta}^b, \zeta^b, \varepsilon_i^b\}$ , we can identify  $(u_{i,j}^b)^{\sigma/(1-\sigma)}$  for every bank  $j$  that is chosen by some households. As discussed before,  $\sigma$  is unidentifiable, so we obtain (18) up to the scaling factor  $(1 - \sigma)/\sigma$ .

To proceed, define  $\tilde{V}_{i,j}^b = \ln[1 + (u_{i,j}^b)^{\sigma/(1-\sigma)}]$  and  $\tilde{\theta} = (1 - \sigma)\theta/\sigma$ . We can then rewrite the choice probability (2) as

$$P(j_i^* = j | r_j, \mathbf{r}_{-j}) = \frac{\exp(\tilde{\theta} \tilde{V}_{i,j}^b + \phi \sum_{k \in \mathcal{K}} \omega^k E[V_{i,j}^k] + \mathbf{X}_{i,j} \boldsymbol{\beta}^f + \eta_j^f)}{\sum_{m \in \mathcal{J}_i} \exp(\tilde{\theta} \tilde{V}_{i,m}^b + \phi \sum_{k \in \mathcal{K}} \omega^k E[V_{i,m}^k] + \mathbf{X}_{i,m} \boldsymbol{\beta}^f + \eta_m^f)}. \quad (19)$$

The parameters  $(\tilde{\theta}, \phi, \boldsymbol{\beta}^f, \boldsymbol{\eta}^f)$  are identified by matching the conditional choice probabilities of deposit banks predicted by (19) with those implied by the data. Notice that 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.

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<sup>16</sup>We calibrate  $\omega^k$  using the fraction of households that have obtained the financial product  $k$ .

### 3.2 Estimation

The estimation strategy closely follows the identification strategy. The estimation of the demand side involves three steps. First, we apply ordinary least squares to (16) to estimate  $\tilde{v} = \frac{\sigma v}{1-\sigma}$  for  $v \in \{\alpha^b, \beta^b, \gamma^b, \eta^b, \zeta^b, \varepsilon_i^b\}$ . Second, given that we observe which bank is chosen by household  $i$  for deposits and for each product  $k$ , we apply the maximum likelihood estimation (MLE) to (17) to estimate  $(\kappa^k, \beta^k, \eta^k)$ , i.e., the estimator is defined as

$$(\hat{\kappa}^k, \hat{\beta}^k, \hat{\eta}^k) = \arg \max_{\kappa, \beta, \eta} \sum_{i \in \mathcal{I}} \ln \frac{\exp \left( \kappa \mathbb{1}(n_{i,k}^* = j_i^*) + \mathbf{X}_{i,n_{i,k}^*} \beta + \eta_{n_{i,k}^*} \right)}{\sum_{m \in \mathcal{J}_i^k} \exp \left( \kappa \mathbb{1}(m = j_i^*) + \mathbf{X}_{i,m} \beta + \eta_m \right)}.$$

In the third step, we estimate  $\tilde{V}_{i,j}^b$  and  $E[V_{i,n}^k]$  using the estimates from the first two steps. Let  $\widehat{\tilde{V}_{i,j}^b}$  and  $\widehat{E[V_{i,n}^k]}$  denote the resulting estimators. We can then apply the MLE to (19) to estimate  $(\tilde{\theta}, \phi, \beta^f, \eta^f)$  and the estimator is defined as

$$(\hat{\tilde{\theta}}, \hat{\phi}, \hat{\beta}^f, \hat{\eta}^f) = \arg \max_{\theta, \phi, \beta, \eta} \sum_{i \in \mathcal{I}} \ln \frac{\exp \left( \theta \widehat{\tilde{V}_{i,j_i^*}^b} + \phi \sum_{k \in \mathcal{K}} \omega^k \widehat{E[V_{i,j_i^*}^k]} + \mathbf{X}_{i,j_i^*} \beta + \eta_{j_i^*} \right)}{\sum_{m \in \mathcal{J}_i} \exp \left( \theta \widehat{\tilde{V}_{i,m}^b} + \phi \sum_{k \in \mathcal{K}} \omega^k \widehat{E[V_{i,m}^k]} + \mathbf{X}_{i,m} \beta + \eta_m \right)}.$$

With the estimates of all the demand-side parameters, we can obtain bank  $j$ 's deposit demand as a function of the deposit rates,  $D_j(r_j, \mathbf{r}_{-j})$ . Then the estimates of banks' marginal costs  $mc_j$  are obtained from (13) once we replace  $D_j(r_j, \mathbf{r}_{-j})$  by their estimates.

## 4 Data and Estimation Results

Section 4.1 provides a detailed discussion on the data used for estimating the model. Section 4.2 then presents the estimation results for the households' banking choices and banks' marginal costs.

### 4.1 Data

Estimating the model requires (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 their bank choices for other financial products, including mortgage loans, credit cards, and guaranteed investment certificates (GICs).<sup>17</sup> This allows us to estimate the home bank preference for each of these financial products. 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 is measured using the sum of cash in the wallet and precautionary holdings of cash. Demand deposits are measured as the sum of chequing, chequing/saving, and saving account balances. In our sample, a median household holds \$3,500 in demand deposits and \$195 in cash.<sup>18</sup> 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 from each household to each branch location, allowing us to construct the branch network that 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 of their residence and a rural household considers banks with a branch within 50 kilometers. For online banks that do not have branches, we assume they are present in every household’s choice set.<sup>19</sup>

Table 1 shows the summary statistics on the numbers of branches and banks available to each household based on the constructed choice set. As can be seen, there is a large difference

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<sup>17</sup>More than 70% of households go to one bank for their demand deposits, as shown in Table A1 in Appendix A.2. The fraction of households that have a single mortgage bank, credit card issuer, and GIC issuer is 98%, 42%, and 78%, respectively. For households that have multiple deposit banks, we use their main financial institution where they have the largest deposit balance. Similarly, we assume their main mortgage bank, credit card issuer, and GIC issuer are the ones with the largest remaining mortgage payment, the highest current balance, or the highest GIC balance, respectively.

<sup>18</sup>Approximately 99% of households hold demand deposits worth less than \$100,000 and thus are fully covered by the deposit insurance. Therefore, there is not enough variation in the data to allow us to estimate households’ preferences towards safety, which is another differentiating feature between a CBDC and bank deposits.

<sup>19</sup>For the estimation in Section 4.2, we assume the distance to an online bank is 15 km (50 km) for an urban (a rural) household.

in the accessibility of banks and branches across provinces and regions. In particular, urban households can access more banks and branches than rural households. Figure 1 shows that both urban and rural households prefer to choose banks with branches closer to their residential locations.

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

<b>(a) Number of Branches</b>										
	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>(b) Number of Banks</b>										
	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

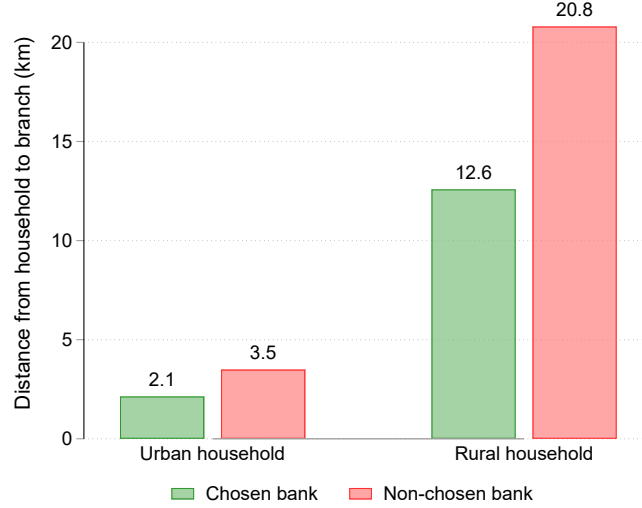
Data sources: CFM 2017, FCAC 2017

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

CANNEX provides bank-level interest rates of demand deposits and mortgage loans.<sup>20</sup>

<sup>20</sup>Cross-bank variation in these rates are shown in Figure A3 in Appendix A.3. These rates are at the national level, as we do not observe branch-level interest rates in Canada. In fact, none of the major institutions post different deposit rates by province. Therefore, banks in our model compete in the national deposit market rather than the local market around a household's residential location. For local deposit market competition in US, see Granja and Paixao (2021) and Drechsler, Savov and Schnabl (2017).

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 15 km (50 km) of the household's location. Online banks are excluded in this figure.

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.<sup>21</sup> 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 the CFM data and the 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 at other banks. Summary statistics of some key variables are shown in Table A2 of Appendix A.3.

## 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,

<sup>21</sup>In our sample, 70% of households choose the big six banks as their main financial institutions. Since Laurentian Bank is a small bank that mostly operates in Quebec, we exclude its rates in calculating the average deposit rates.

and GICs, and (3) deposit bank choice taking into account the utilities from holding a portfolio of liquid assets and from obtaining complementary financial products. We first discuss the results from each step in order and then discuss the estimates of banks’ marginal costs.

Table 2 shows the estimated parameters for the deposit rates and the branch network measures (i.e.,  $\tilde{\alpha}^b$ ,  $\tilde{\beta}^b$ ) in the CES aggregator. The parameters for the household characteristics, bank fixed effects, and the deposit-specific constant (i.e.,  $\tilde{\gamma}^b$ ,  $\tilde{\eta}^b$ ,  $\tilde{\zeta}^b$ ) are shown in Table B3 in Appendix B. We include year fixed effects to absorb the unobserved aggregate shocks and bank fixed effects to absorb the unobserved bank quality that is time-invariant.<sup>22</sup> We mostly use the cross-bank variation in the deposit rates, so 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 other big credit unions.

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) $\times$ Live in rural area	-0.053*** (0.015)
ln(Number of branches + 1)	0.024*** (0.008)
ln(Number of branches + 1) $\times$ 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 subset of the estimated parameters from the OLS regression of 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). The “Observations” shows the number of households in the CFM sample from 2010 to 2017.

<sup>22</sup>The year and bank fixed effects can control for unobserved demand shocks to some extent. More importantly, with the (micro) household-level data on deposit holdings, there is no simultaneous causality in the sense that a household’s deposit holdings would not affect a bank’s deposit rate. Therefore, endogeneity in deposit rate is less of a concern than the literature that uses bank-level data for demand estimation. However, we also tried using banks’ heterogeneous pass-through of policy rates to instrument for the deposit rate, following Egan, Hortaçsu and Matvos (2017), and we obtained a similar estimate for  $\tilde{\alpha}^b$ .

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. Overall, easier access to bank branches increases the deposit-to-cash ratio, which is consistent with the classic Baumol-Tobin model.<sup>23</sup>

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

	(1) Credit Card	(2) Mortgage	(3) GIC
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) $\times$ 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) $\times$ Live in rural area	0.030** (0.014)	0.044* (0.026)	-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 corresponds to a conditional logistic regression of the bank choice for a given financial product (i.e., credit card, mortgage loan, guaranteed investment certificate GIC) on the home bank indicator, branch network variables, and bank fixed effects. Only the estimated parameters for the home bank indicator and the branch network measures are presented in this table. The “Number of choice sets” denotes the number of households in the sample, while “Observations” represents the cumulative total of alternatives/banks within each household’s choice set.

Table 3 shows the estimates for the home bank preference  $\kappa^k$  and bank branch network  $\beta^k$  in the households’ bank choices for credit cards, mortgage loans, and GICs.<sup>24</sup> Bank fixed effects are also included to absorb the unobserved bank quality, which are shown in Table B4 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

<sup>23</sup>Interestingly, the distance from the residence to the closest branch does not have a significant effect on an urban household’s portfolio decisions. This could be because urban households can easily withdraw cash at branches close to their workplaces.

<sup>24</sup>Note that the choice set  $\mathcal{J}_i^k$  is different across households  $i$  and products  $k$ . In addition,  $\mathcal{J}_i^k$  tends to include more choice alternatives than the choice set  $\mathcal{J}_i$  for deposits. For example, on top of the banks that households can choose for deposits, the choice sets for credit cards also include other credit card issuers such as American Express and Capital One.

mortgage borrowers borrow from their home banks, as shown in Table 4. Interestingly, the home bank preference parameters are similar in magnitude across these products. The estimates  $\hat{\beta}^k$  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 of a given bank and a lower number of the bank’s nearby branches reduce the likelihood of choosing that bank for the financial product.

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
Guaranteed Investment Certificates	0.29	0.55

Data sources: CFM 2010–2017

Note: The table shows the fraction of households that have a credit card, a mortgage loan, or a guaranteed investment certificate (GIC) 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 where they have deposit accounts.

To estimate the deposit bank choice problem, we first obtain the 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 demanding the 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 (i.e.,  $\tilde{\theta}, \phi, \beta^f$ ) for the utilities from liquidity holding, the sum of expected utilities from other financial products, and the branch networks, respectively, in the deposit bank choice problem. The estimated bank fixed effects  $\eta^f$  are shown in Table B5 in Appendix B. As seen in Table 5, the estimates of  $\tilde{\theta}$  and  $\phi$  indicate that households value the utility from liquidity holding and from complementary financial products when choosing their deposit banks.

The branch network affects the choice probabilities of the deposit bank through one direct and two indirect channels. It directly affects choice probabilities through the preference over the branch network, which is captured by  $\beta^f$ . Additionally, it indirectly affects the choice probabilities through the utility from liquidity holding and the utility from complementary financial products. Through the direct channel, an increase in 1 km of the branch distance would reduce their choice probabilities by around 10% on average in urban areas. 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 of distance, so a 1 km 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



Table 5: Estimated Parameters in Deposit Bank Choice

Variables	Estimates
Utility from liquidity holding	1.661*** (0.179)
Sum of expected utilities from financial products	1.368*** (0.038)
$\ln(\text{Distance to branch})$	-0.175*** (0.008)
$\ln(\text{Distance to branch}) \times \text{Live in rural area}$	0.113*** (0.015)
$\ln(\text{Number of branches} + 1)$	0.439*** (0.011)
$\ln(\text{Number of branches} + 1) \times \text{Live in rural area}$	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 subset of the estimated parameters from a conditional logistic regression of the deposit bank choice on the utilities from liquidity holding  $V_{i,j}^b$ , the sum of expected utilities from financial products  $\sum_{k \in \mathcal{K}} \omega^k E[V_{i,j}^k]$ , the branch network measures, and grouped bank fixed effects. The “Number of choice sets” denotes the number of households in the sample, while “Observations” represents the cumulative total of alternatives/banks within each household’s choice set.

by around 25% on average.

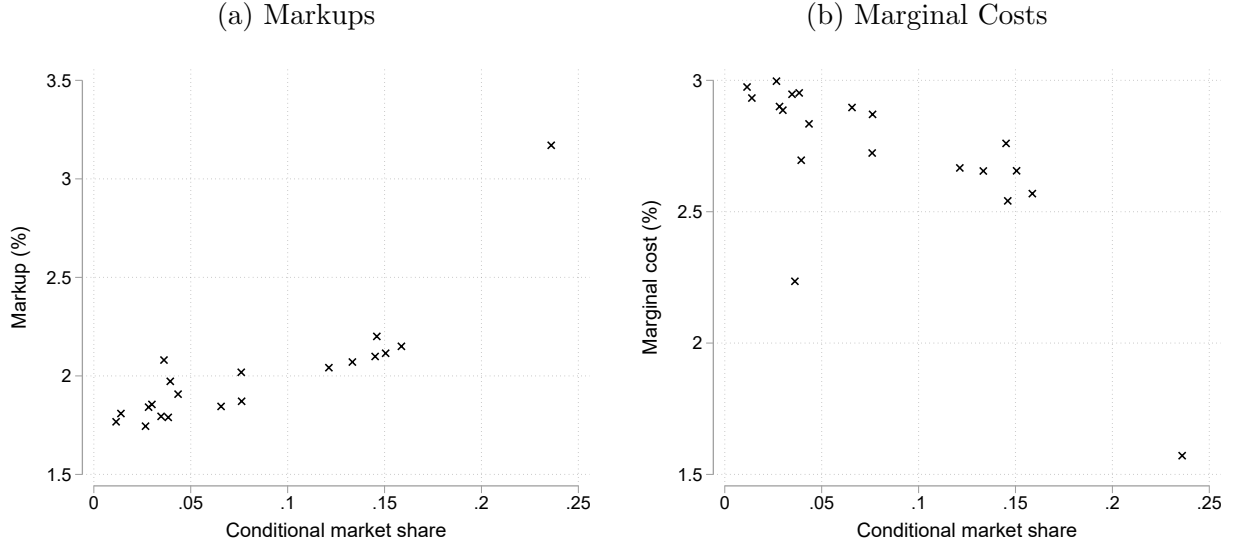
With the estimates of the demand side, we obtain the estimated markups, or equivalently, the inverse semi-elasticities of deposit demand. We then use (13) to obtain the supply-side parameters, i.e., banks’ marginal costs. Figure 2 plots banks’ markups and marginal costs against their market shares in the year 2017.<sup>25</sup> There is considerable heterogeneity in both market shares and markups, with the former ranging from around 1% to more than 20% and the latter ranging from 1.7% to around 3.2%. The markup estimates are comparable to those found in the literature for the US.<sup>26</sup> The estimated marginal costs range from 1.6%

<sup>25</sup>The market share of a bank is the average market share across all local markets served by the bank, where the bank’s market share in a local market (around a household’s residence) is measured using the estimated probability of the household choosing this bank.

<sup>26</sup>The estimated markup or, equivalently, the inverse semi-elasticity of deposit demand aligns with the findings in the literature that uses US bank-level data to estimate the deposit demand. For example, the deposit demand elasticity is around 0.73, with an average deposit rate of 1.7% in Xiao (2020) and 0.56 at a deposit rate of 1% in Egan, Hortaçsu and Matvos (2017). This implies a markup of around 2.3% and 1.8%, respectively. Our estimated markup is around 2.0% on average across banks, which is similar to those found in the literature.

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.

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 and marginal costs of banks against their market shares in 2017. A bank's conditional market share refers to its market share conditional on its presence in the local markets, which is calculated using the estimated probabilities of choosing the bank averaged across all the local markets that the bank operates in.

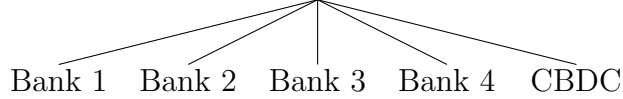
## 5 Counterfactual CBDC Issuance

This section evaluates what would have been the impact of introducing a CBDC in 2017 on the Canadian banking sector. In the presence of a CBDC, households can choose to hold their digital money in either the CBDC or an incumbent bank. Therefore, we model the CBDC as a new product that is added to every household's choice set for digital money, as illustrated in Figure 3. We consider different designs of the CBDC in terms of interest rates, service locations, and holding limits. According to the CFM data on bank branch usage, Canadians value in-person customer service and support. Therefore, we anticipate that these services would also be relevant for the CBDC even though it is digital.<sup>27</sup> We assume that

<sup>27</sup>Figure A1 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 A2 in Appendix A.1 shows the

the central bank does not provide complementary financial products such as mortgage loans and credit cards. If a household chooses to deposit their digital money in the CBDC instead of an incumbent bank, they still have to obtain other financial products from private banks and thus do 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. 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 the CBDC.<sup>28</sup> The household chooses either the CBDC or one of the incumbent banks based on the utilities from these products. The presence of the CBDC in the choice set leads to a lower probability of choosing the banks and thus reduces each household’s expected deposit demand. Banks take the CBDC attributes as given and adjust their deposit rates in response to the change in deposit demand. More details on how the CBDC enters into the model are shown in Appendix C.1.

Section 5.1 shows the aggregate effect of a CBDC. Section 5.2 demonstrates the importance of the complementarity feature. Section 5.3 shows how the impact of a CBDC differs across banks. Section 5.4 examines the impact of imposing a limit on the holdings of a CBDC. Finally, Section 5.5 discusses the changes in the consumer surplus after the issuance of a CBDC.

## 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, while assuming the CBDC does not have complementary financial products and

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fraction of households using various channels (i.e., branches, phone calls, online banking, mobile banking, etc.) for getting different types of services from their banks. We observe that customer service/support and withdrawing cash remain important reasons for visiting the physical branches. Similarly, [Allen, Clark and Houde \(2008\)](#) 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 that such patterns would carry over to a digital product that the central bank may issue.

<sup>28</sup>To obtain the utility from the CBDC, we also need to make assumptions on the CBDC fixed effect that captures the unobserved quality of the 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 C7 and C8 in Appendix C.2.

there is no limit on CBDC holdings. Four designs for the service location network are considered: (1) no service location, in which case the CBDC is analogous to an online narrow bank; (2) all Canada Post offices; (3) all bank branches; (4) all bank branches and Canada Post offices. For this exercise, we use the locations of all open Canada Post offices in 2021 obtained from the Canada Post Corporation.

Figure 4 shows the aggregate CBDC share, the average change in deposit rates across banks, 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 the CBDC and its impact on banks. Second, the effect of the CBDC 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 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 that propose a non-interest-bearing CBDC,<sup>29</sup> while the latter is the average deposit rate during 2010–2017. In addition, we vary the network of in-person service locations for the CBDC. If there is no service location, consumers barely adopt the CBDC. Only around 1% of total households’ liquid assets are allocated to the 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%. If the target market share of the CBDC is close to the current share of cash (4.5%), then providing CBDC services at the Canada Post offices is sufficient. When all bank branches provide services for the CBDC, the CBDC share increases to around 9%. The market share of CBDC increases further under a more extensive network of service locations that includes all Canada Post offices and bank branches.

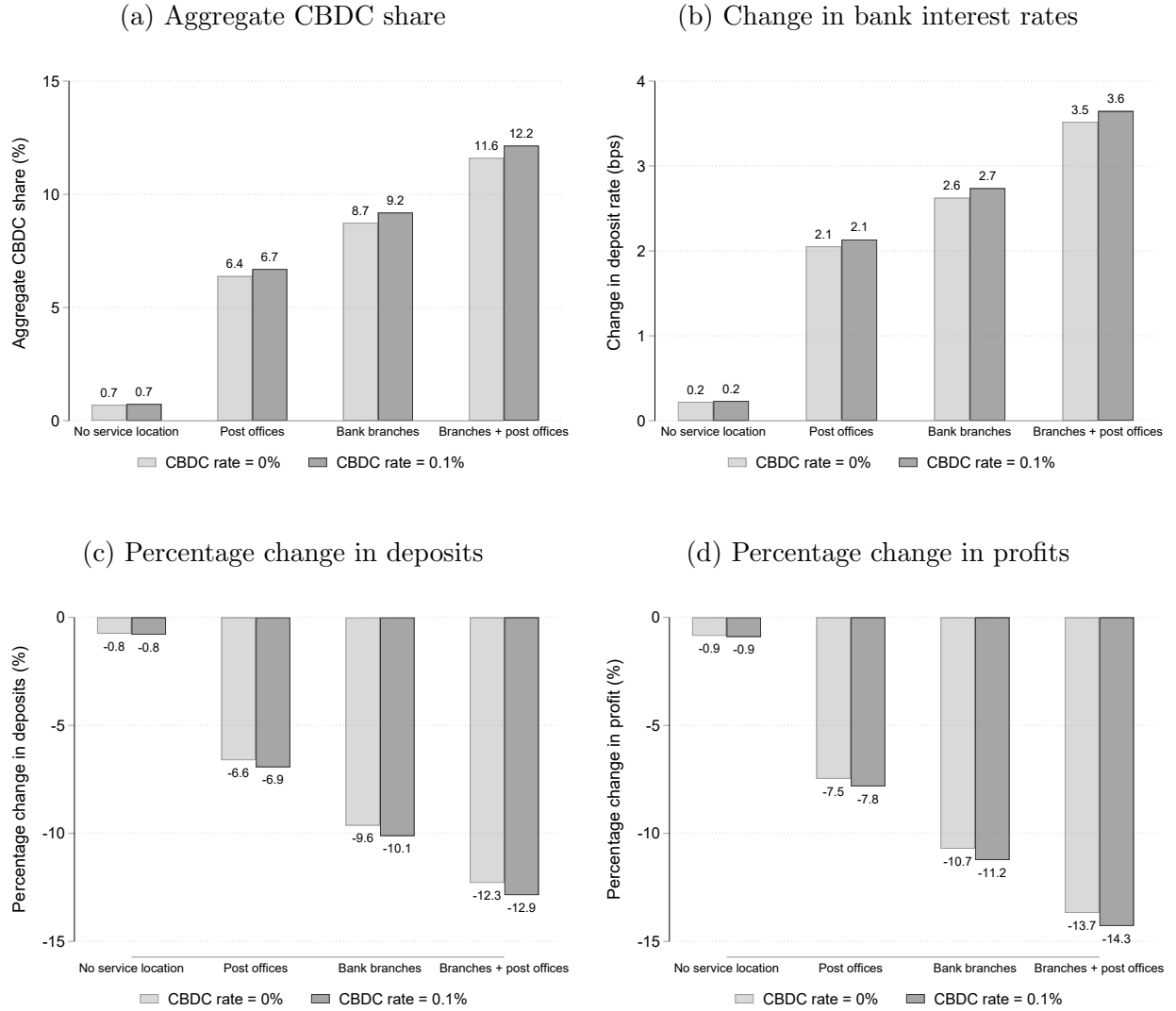
Interest on the CBDC can have a significant impact only if the rate is sufficiently attractive compared to deposit rates. As shown in Figure 4a, paying 0.1% interest barely impacts the adoption of the CBDC. However, the market share of the CBDC can double if we raise its interest rate to 1.5%, which is 15 times the average deposit rate in our data, as shown in Figure C4 in Appendix C.2. A CBDC with no service locations needs to pay 4% interest to obtain the same market share as a non-interest-bearing CBDC 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 the CBDC issuance, banks tend to raise deposit rates to retain

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<sup>29</sup>See the ECB report on the digital euro (ECB, 2023) and the speech by Sir Jon Cunliffe on the digital pound (Cunliffe, 2023).

Figure 4: Impacts of CBDC Designs on Equilibrium Outcomes



Data sources: CFM 2017, FCAC 2017, Canada Post 2021, Government of Canada website

Note: This figure plots (a) the aggregate CBDC share calculated as the share of liquid assets allocated in equilibrium by households to the CBDC, (b) the average endogenous change in deposit rate (in basis points) across banks, (c) the average percentage drop in deposits across banks, and (d) the average percentage drop in profits across banks relative to the pre-CBDC equilibrium. In each graph, the given equilibrium outcome is plotted under four designs of service locations 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 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 C7 in Appendix C.2.

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 to 4 basis points, which is about 20 to 40 percent of the average deposit rate during 2010–2017. Moreover, there is substantial heterogeneity in the responses across banks, ranging from around 0 to 20 basis points, as will be shown in Section 5.3.

Figure 4c shows the average percentage change in deposits across banks after the CBDC issuance. The magnitude is similar to the market share of the CBDC in Figure 4a. Intuitively, since the market share of cash is small, the CBDC gains its market share mainly by reducing the market share of deposits.<sup>30</sup> As shown in Figure 4c, even when all existing branches and Canada Post offices are used as service locations, the CBDC reduces the demand deposits by slightly more than 10%. Since the demand deposits (that a CBDC directly competes with) are around 33% of total bank deposits and 10% of total bank assets (García et al., 2020), the crowding out effect of the CBDC on bank deposits is likely to be manageable.<sup>31</sup>

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,<sup>32</sup> 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 graphs, the impact of the CBDC increases as the network of service locations improves, while paying interest on the CBDC has limited effects if the rate is similar to the average deposit rate.

## 5.2 Model Misspecification: No Complementarity

Section 5.1 has shown the importance of service location design for a CBDC. Here, we demonstrate the importance of capturing the difference in 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 is absent

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<sup>30</sup>As shown in Figure C5 in Appendix C.2, the CBDC also crowds out the market share of cash, but to a lesser extent than that of deposits. This is because households will hold cash regardless of whether they choose the CBDC or an incumbent bank for their digital money. The crowding out on cash is solely through the change in the intensive margin, i.e., a greater portion of liquid assets is allocated into digital money due to higher deposit rates or better CBDC attributes.

<sup>31</sup>These numbers are based on the regulatory filings of the deposit liabilities in 2019, where 33% is the total Canadian dollar personal demand deposits by the big six banks as a percentage of their total deposits. Total deposits also include demand deposits held by other entities, term deposits, and foreign currency deposits.

<sup>32</sup>The change in a bank’s markup is equivalent to the change in its inverse semi-elasticity of deposit demand, as seen in (13). Introducing the CBDC makes banks’ deposit demand more elastic, which induces banks to raise their deposit rates, leading to a drop in their markups.

(i.e.,  $\kappa^k = 0$ ) for all financial product  $k \in \mathcal{K}$  and thus the expected utilities from different financial products no longer affect the deposit bank choice. The new estimates in the deposit bank choice problem are reported in Table B6 in Appendix B.

Using the estimates from the misspecified model, we find that the aggregate CBDC share can be substantially overestimated when neglecting the difference in the complementarity feature of a CBDC and deposits. As shown in Figure C6 in Appendix C.2, this misspecified model predicts that the aggregate CBDC share is around 23% for a non-interest-bearing CBDC if all Canada Post offices are used as service locations, and around 38% if both Canada Post offices and bank branches are used as service locations, compared to about 9% and 12% when the complementarity is correctly taken into account.

### 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 local 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. Banks with higher initial market shares tend to raise their deposit rates by more in response to the CBDC. Intuitively, larger banks with greater market power are more substantially threatened by the CBDC, whereas smaller banks, which are already dominated by larger banks in the absence of the CBDC, would not respond as strongly. 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.

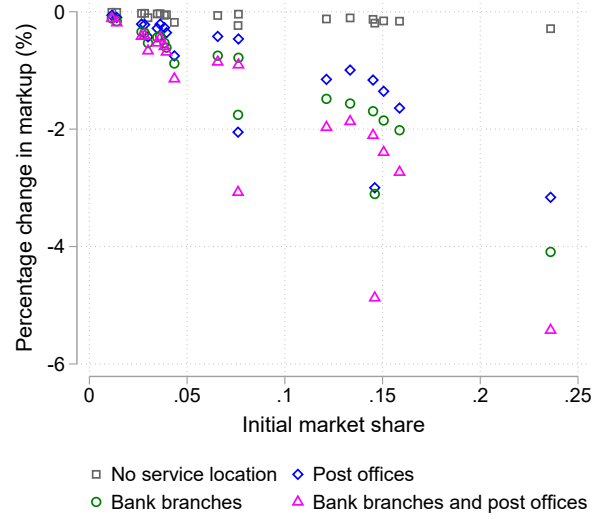
Interestingly, changes in deposit rates are more heterogeneous across banks when the CBDC has a better service location network. For example, the standard deviation of the deposit rate increases is significantly larger if the CBDC has all bank branches and post offices as service locations than if it 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. Intuitively, if the CBDC does not have any service location, banks with high market shares enjoy a considerable competitive advantage due to their extensive branch networks. Consequently, they do not need to markedly increase their deposit rates, even if their markups are high, resulting in relatively uniform responses to the CBDC across banks. In contrast,

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, Government of Canada website

Note: This figure plots each bank's optimal response in deposit rates (in basis points), the percentage changes in markups, deposits, and profits for four different CBDC network designs (i.e., no service location, all Canada Post offices, all bank branches, both bank branches and Canada Post offices). The x-axis is the bank's initial market share, calculated by averaging the estimated probabilities of households choosing the bank across all local markets (around households' residences) in which the bank operates. 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 C8 in Appendix C.2.



if the CBDC has many service locations, these banks face intensified competition and have to respond aggressively, resulting in relatively heterogeneous responses.

Figure 5b illustrates the relationship between percentage changes in markups and initial market shares. This pattern is more or less a mirrored image of Figure 5a. This is not surprising, as changes in markups are solely driven by changes in deposit rates in our model. Similarly, banks' markups are reduced by more when the CBDC has more attractive designs. 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.

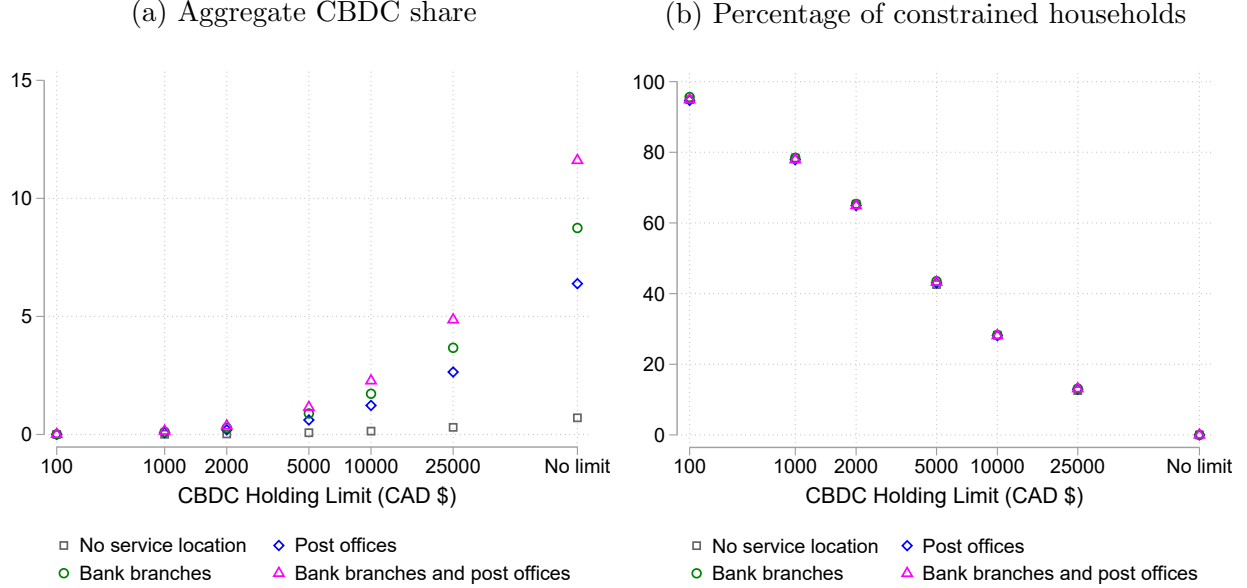
Given that banks with higher initial market shares tend to raise their deposit rates by more, they also experience fewer deposit losses, as shown in Figure 5c. There is no apparent relationship between the percentage change in profit and the initial market share, as shown in Figure 5d. Banks with higher market shares tend to sacrifice more on markups but retain more deposits. These two effects largely offset each other. A 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. In contrast, 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. For example, the proposed digital euro legislation (European Commission, 2023) suggests that the ECB should establish a limit on CBDC holdings to avoid excessive crowding out. To study the effectiveness of this policy tool in the Canadian context, we use our estimated model and impose a constraint on how much CBDC a household can hold. We vary the limit from \$100 to \$25,000 and calculate the aggregate CBDC share and the percentage of households constrained by the limit in each case.

Figure 6a shows how the market share of a CBDC changes with the limit. As a benchmark, the right end of the x-axis shows the market share without any limit. Across all service location networks, even with a limit as high as \$25,000, the market share of the CBDC still drops to less than half of its level without a limit. This suggests that even with a very high limit, the reduction in CBDC holdings can still be substantial. If the limit is \$5,000, which is close to the 3,000-euro limit suggested by an ECB executive in a speech (Panetta, 2022), the CBDC would capture around 1% of the market, significantly lower than the market share of cash. If the goal is to achieve a CBDC market share similar to that of cash, the holding limit should be higher than \$65,000 if Canada Post offices are service locations, or at least

Figure 6: Imposing Different Limits on CBDC Holdings



Data sources: CFM 2017, FCAC 2017, Canada Post 2021, Government of Canada website

Note: This figure shows the aggregate CBDC share and the percentage of constrained households under different CBDC holding limits for four service location network designs (i.e., no service location, all Canada Post offices, all bank branches, both bank branches and Canada Post offices). The aggregate CBDC share is the share of households' total liquid assets allocated into the CBDC in equilibrium. The x-axis is displayed on a 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.

\$35,000 if bank branches are service locations.

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 more than 50% of the total liquid assets, as shown in Figure C9 in Appendix C.3. As a result, the limit forces these households to hold much less CBDC than they wanted and thus greatly reduces the market share of the CBDC.

Our results suggest that a large holding limit is likely to be sufficient to avoid excessive crowding out without damaging the usefulness of the CBDC as a payment instrument.<sup>33</sup> A limit as high as \$25,000 can keep the aggregate CBDC share under 5%, while only affecting a small fraction of households.

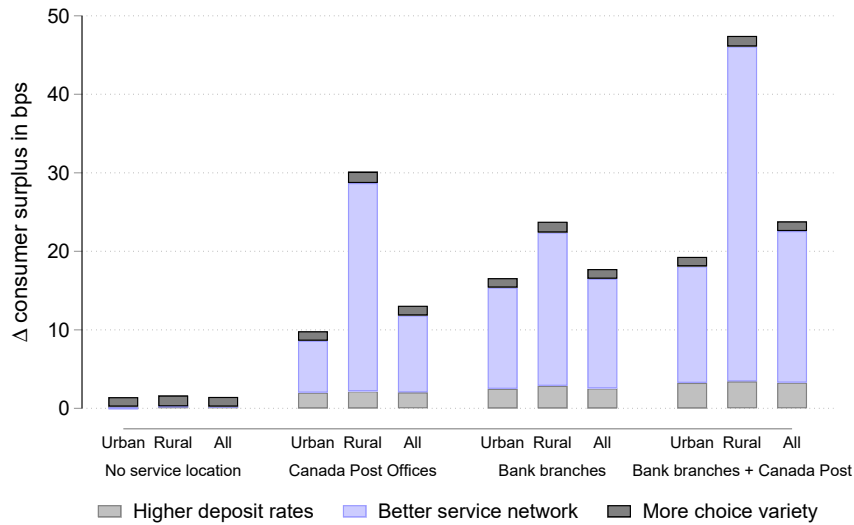
<sup>33</sup>According to the 2018 Diary of Consumer Payment Choice in the US, above 99% of the transaction values are below 5,000 USD, which is far below a holding limit of 25,000 CAD.

## 5.5 Change in Consumer Surplus

Lastly, we study the effects of introducing a CBDC on consumer surplus.<sup>34</sup> We measure the change in consumer surplus using the equivalent variation, that is, the increase in deposit rate required to compensate a household in an economy without a CBDC to make their utility the same as in an economy with a CBDC.

Figure 7 shows the average change in consumer surplus across households under four designs of the CBDC service locations. In each case, we decompose the changes in consumer surplus into three components 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 separately for urban, rural, and all households.

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



Data sources: CFM 2017, FCAC 2017, Canada Post 2021, Government of Canada website

Note: This figure plots the changes in consumer surplus (in basis points) across four designs of CBDC service network: no service location, all Canada Post offices, all bank branches, or both branches and Canada Post offices. Within each service network design, each bar represents the average change in consumer surplus for 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 the CBDC, and increase in choice variety due to the presence of the CBDC in the choice set. Here, we assume the CBDC is non-interest-bearing and has a fixed effect that is identical to that of the big five banks.

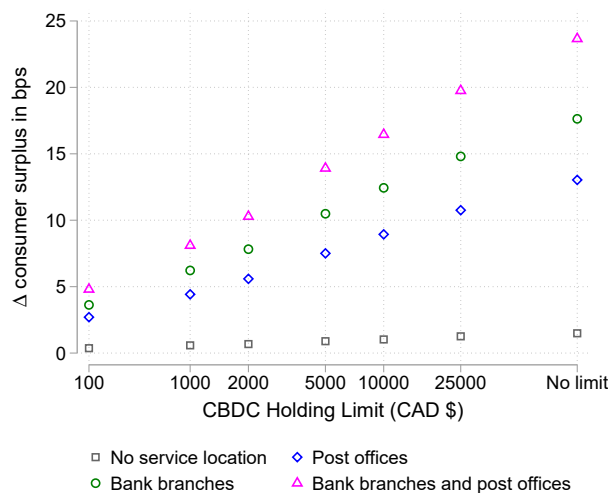
If the CBDC does not have service locations, deposit rates would barely change and thus almost all of the increase in consumer surplus is due to the introduction of a new

<sup>34</sup>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.

product, which is very small. As the service location network becomes better, the increase in consumer surplus becomes larger. Specifically, if the CBDC only uses post offices as service locations, the consumer surplus increases by slightly over 10 basis points on average across all households. If it uses all bank branches, the increase is about 18 basis points. If it uses both bank branches and Canada Post offices, the gain can approach 25 basis points. In these cases, the service location network is the main contributor to the gain in consumer surplus.

Rural households would benefit more from a CBDC that uses Canada Post offices as service locations than from one 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 C10a in Appendix C.4, the average distance from a rural household to the nearest Canada Post office is around 1.9 km, while the distance to the nearest bank branch is considerably greater at 6.8 km. 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, Government of Canada website

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: no service location, all Canada Post offices, all bank branches, or both branches and Canada Post offices. In each case, the change in consumer surplus represents the average across all households. The x-axis is displayed on a 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 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 CBDC’s share of total household liquid assets (more than 50% as shown in Figure 6a). This suggests that although imposing a holding limit can substantially reduce the market share of the CBDC, its effect on the consumer surplus is much lower.

## 6 Conclusions

This paper brings two important aspects to the ongoing 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 a CBDC. First, we find that the impact of a CBDC is much lower after taking into account that households enjoy the complementarity between deposits and other financial products within the same bank, which 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 location can barely gain any traction. A CBDC that uses Canada Post offices as service locations would lead to a take-up that is similar to the market share of 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 while a holding limit can significantly reduce the take-up of the CBDC, its effect on consumer surplus is relatively smaller.

## References

- Abad, Jorge, Galo Nuño, and Carlos Thomas.** 2023. “CBDC and the operational framework of monetary policy.” BIS Working Paper No. 1126.
- Abramova, Svetlana, Rainer Böhme, Helmut Elsinger, Helmut Stix, and Martin Summer.** 2022. “What can CBDC designers learn from asking potential users? Results from a survey of Austrian residents.” Oesterreichische Nationalbank Working Paper No. 241.
- Abrams, Eliot.** 2019. “Assessing bank deposit market power given limited consumer consideration.” Available at SSRN 3431374.
- Aguirregabiria, Victor, Robert Clark, and Hui Wang.** 2019. “The geographic flow of bank funding and access to credit: Branch networks, local synergies, and competition.” CEPR Discussion Paper No. DP13741.
- Agur, Itai, Anil Ari, and Giovanni Dell’Ariccia.** 2022. “Designing central bank digital currencies.” *Journal of Monetary Economics*, 125: 62–79.
- Ahnert, Toni, Peter Hoffmann, Agnese Leonello, and Davide Porcellacchia.** 2023. “CBCD and financial stability.” ECB Working Paper No. 2783.
- Ahnert, Toni, Peter Hoffmann, and Cyril Monnet.** 2022. “The digital economy, privacy, and CBDC.” ECB Working Paper No. 2662.
- Albertazzi, Ugo, Lorenzo Burlon, Tomas Jankauskas, and Nicola Pavanini.** 2022. “The shadow value of unconventional monetary policy.” CEPR Discussion Paper No. DP17053.
- Allen, Jason, Robert Clark, and Jean-François Houde.** 2008. “Market structure and the diffusion of e-commerce: Evidence from the retail banking industry.” Bank of Canada Working Paper 2008-32.
- Andolfatto, David.** 2021. “Assessing the impact of central bank digital currency on private banks.” *The Economic Journal*, 131(634): 525–540.
- Assenmacher, Katrin, Aleksander Berentsen, Claus Brand, and Nora Lamersdorf.** 2021. “A unified framework for CBDC design: Remuneration, collateral haircuts and quantity constraints.” Available at: [https://www.snb.ch/en/ifor/research/conf/other\\_academic\\_conferences/id/sem\\_2021\\_05\\_20](https://www.snb.ch/en/ifor/research/conf/other_academic_conferences/id/sem_2021_05_20).

- Assenmacher, Katrin, Lea Bitter, and Annukka Ristiniemi.** 2023. “CBDC and business cycle dynamics in a New Monetarist New Keynesian model.” ECB Working Paper No. 2023/2811.
- Barrdear, John, and Michael Kumhof.** 2022. “The macroeconomics of central bank digital currencies.” *Journal of Economic Dynamics and Control*, 142: 104148.
- Berentsen, Aleksander, and Fabian Schar.** 2018. “The case for central bank electronic money and the non-case for central bank cryptocurrencies.” Available at SSRN 3194981.
- Bijlsma, Michiel, Carin van der Crujsen, Nicole Jonker, and Jelmer Reijerink.** 2021. “What triggers consumer adoption of central bank digital currency?” De Nederlandsche Bank Working Paper No. 709.
- Bordo, Michael D, and Andrew T Levin.** 2017. “Central bank digital currency and the future of monetary policy.” National Bureau of Economic Research Working Paper 23711.
- Brunnermeier, Markus K, and Dirk Niepelt.** 2019. “On the equivalence of private and public money.” *Journal of Monetary Economics*, 106: 27–41.
- Carbo-Valverde, Santiago, Hector Perez-Saiz, and Hongyu Xiao.** 2023. “Geographical and cultural proximity in retail banking.” Bank of Canada Working Paper 2023-2.
- Chang, Huifeng, Federico Grinberg, Lucyna Gornicka, Marcello Miccoli, and Brandon Joel Tan.** 2023. “CBDC and banking disintermediation in a portfolio choice model.” IMF Working Paper WP/23/236.
- Cheng, Yuteng, and Ryuichiro Izumi.** 2023. “CBDC: Banking and anonymity.” Available at SSRN 4340866.
- Chiu, Jonathan, and Cyril Monnet.** 2023. “Money creation for distributed ledgers: Stablecoins, tokenized deposits, or central bank digital currencies?” Mimeo.
- Chiu, Jonathan, Seyed Mohammadreza Davoodalhosseini, Janet Hua Jiang, and Yu Zhu.** 2023. “Bank market power and central bank digital currency: Theory and quantitative assessment.” *Journal of Political Economy*, 131(5): 1213–1248.
- Choi, Syngjoo, Young Sik Kim, Bongseop Kim, and Ohik Kwon.** 2022. “Central bank digital currency and privacy: A randomized survey experiment.” Bank of Korea Working Paper No. 2022-13.

- Cunliffe, Jon.** 2023. “The digital pound.” Speech by Jon Cunliffe, Former Deputy Governor of the Bank of England for Financial Stability, at the UK Finance. Retrieved from: <https://www.bankofengland.co.uk/speech/2023/february/jon-cunliffe-speech-at-uk-finance-update-on-central-bank-digital-currency>.
- Davoodalhosseini, Seyed Mohammadreza.** 2022. “Central bank digital currency and monetary policy.” *Journal of Economic Dynamics and Control*, 142: 104150.
- Davoodalhosseini, Seyed Mohammadreza, Francisco Rivadeneyra, and Yu Zhu.** 2020. “CBDC and monetary policy.” Bank of Canada Staff Analytical Notes 2020-4.
- Dick, Astrid A.** 2008. “Demand estimation and consumer welfare in the banking industry.” *Journal of Banking & Finance*, 32(8): 1661–1676.
- Drechsler, Itamar, Alexi Savov, and Philipp Schnabl.** 2017. “The deposits channel of monetary policy.” *The Quarterly Journal of Economics*, 132(4): 1819–1876.
- ECB.** 2023. “A stocktake on the digital euro: Summary report on the investigation phase and outlook on the next phase.” ECB. Available at: [https://www.ecb.europa.eu/paym/digital\\_euro/investigation/profuse/shared/files/dedocs/ecb.dedocs231018.en.pdf](https://www.ecb.europa.eu/paym/digital_euro/investigation/profuse/shared/files/dedocs/ecb.dedocs231018.en.pdf).
- Egan, Mark, Ali Hortaçsu, and Gregor Matvos.** 2017. “Deposit competition and financial fragility: Evidence from the US banking sector.” *American Economic Review*, 107(1): 169–216.
- Engert, Walter, and Ben Siu-Cheong Fung.** 2017. “Central bank digital currency: Motivations and implications.” Bank of Canada Staff Discussion Paper No. 2017-16.
- European Commission.** 2023. “Regulation of the European Parliament and of the Council on the establishment of the digital euro.” Available from: <https://perma.cc/36VB-QLGE>.
- Fernández-Villaverde, Jesús, Daniel Sanches, Linda Schilling, and Harald Uhlig.** 2021. “Central bank digital currency: Central banking for all?” *Review of Economic Dynamics*, 41: 225–242.
- García, Alejandro, Bena Lands, Xuezhi Liu, and Joshua Slive.** 2020. “The potential effect of a central bank digital currency on deposit funding in Canada.” Bank of Canada Staff Analytical Note 2020-15.
- Garratt, Rodney, Jiaheng Yu, and Haoxiang Zhu.** 2022. “How central bank digital currency design choices impact monetary policy pass-through and market composition.” Available at SSRN 4004341.



- Gentzkow, Matthew.** 2007. “Valuing new goods in a model with complementarity: Online newspapers.” *American Economic Review*, 97(3): 713–744.
- George, Ammu, Taojun Xie, and Joseph D Alba.** 2022. “Central bank digital currency with adjustable interest rate in small open economies.” Available at SSRN 3605918.
- Granja, João, and Nuno Paixao.** 2021. “Market concentration and uniform pricing: Evidence from bank mergers.” Bank of Canada Working Paper 2021-9.
- Grodecka-Messi, Anna, and Xin Zhang.** 2023. “Private bank money vs central bank money: A historical lesson for CBDC introduction.” *Journal of Economic Dynamics and Control*, 154: 104707.
- Gross, Marco, and Elisa Letizia.** 2023. “To demand or not to demand: On quantifying the future appetite for CBDC.” IMF Working Paper No. 2023/009.
- Ho, Katherine, and Joy Ishii.** 2011. “Location and competition in retail banking.” *International Journal of Industrial Organization*, 29(5): 537–546.
- Huynh, Kim, Jozsef Molnar, Oleksandr Shcherbakov, and Qinghui Yu.** 2020. “Demand for payment services and consumer welfare: The introduction of a central bank digital currency.” Bank of Canada Staff Working Paper 2020-7.
- Jiang, Janet Hua, and Yu Zhu.** 2021. “Monetary policy pass-through with central bank digital currency.” Bank of Canada Staff Working Paper 2021-10.
- Kahn, Charles M, Maarten RC van Oordt, and Yu Zhu.** 2021. “Best before? Expiring central bank digital currency and loss recovery.” Bank of Canada Staff Working Paper 2021-67.
- Kantar Public.** 2022. “Study on new digital payment methods.” Commissioned by the European Central Bank. Available at: [https://www.ecb.europa.eu/paym/digital\\_euro/investigation/profuse/shared/files/dedocs/ecb.dedocs220330\\_report.en.pdf](https://www.ecb.europa.eu/paym/digital_euro/investigation/profuse/shared/files/dedocs/ecb.dedocs220330_report.en.pdf).
- Keister, Todd, and Daniel R Sanches.** 2023. “Should central banks issue digital currency?” *The Review of Economic Studies*, 90(1): 404–431.
- Kosse, Anneke, and Ilaria Mattei.** 2022. “Gaining momentum: Results of the 2021 BIS survey on central bank digital currencies.” BIS No. 125.
- Kosse, Anneke, and Ilaria Mattei.** 2023. “Making headway: Results of the 2022 BIS survey on central bank digital currencies and crypto.” BIS No. 136.

- Li, Jiaqi.** 2023. “Predicting the demand for central bank digital currency: A structural analysis with survey data.” *Journal of Monetary Economics*, 134: 73–85.
- Liu, Youming, Edona Reshidi, and Francisco Rivadeneyra.** 2023. “CBDC and platform competition.” Bank of Canada mimeo.
- Mancini-Griffoli, Tommaso, Maria Soledad Martinez Peria, Itai Agur, Anil Ari, John Kiff, Adina Popescu, and Celine Rochon.** 2018. “Casting light on central bank digital currency.” IMF Staff Discussion Notes 18-08.
- Meaning, Jack, Ben Dyson, James Barker, and Emily Clayton.** 2018. “Broadening narrow money: Monetary policy with a central bank digital currency.” Bank of England Working Paper No. 724.
- Mester, Loretta J, Leonard I Nakamura, and Micheline Renault.** 2007. “Transactions accounts and loan monitoring.” *The Review of Financial Studies*, 20(3): 529–556.
- Minesso, Massimo Ferrari, Arnaud Mehl, and Livio Stracca.** 2022. “Central bank digital currency in an open economy.” *Journal of Monetary Economics*, 127: 54–68.
- Panetta, Fabio.** 2022. “The digital euro and the evolution of the financial system.” Introductory statement by Fabio Panetta, Member of the Executive Board of the ECB, at the Committee on Economic and Monetary Affairs of the European Parliament. Retrieved from: <https://www.ecb.europa.eu/press/key/date/2022/html/ecb.sp220615~0b859eb8bc.en.html>.
- Piazzesi, Monika, and Martin Schneider.** 2020. “Credit lines, bank deposits or CBDC? Competition and efficiency in modern payment systems.” Working Paper, Stanford University.
- Schilling, Linda, Jesús Fernández-Villaverde, and Harald Uhlig.** 2020. “Central bank digital currency: When price and bank stability collide.” National Bureau of Economic Research Working Paper 28237.
- Skeie, David R.** 2019. “Digital currency runs.” Available at SSRN 3294313.
- Wang, Yifei, Toni M Whited, Yufeng Wu, and Kairong Xiao.** 2020. “Bank market power and monetary policy transmission: Evidence from a structural estimation.” National Bureau of Economic Research Working Paper No. 27258.
- Whited, Toni M., Yufeng Wu, and Kairong Xiao.** 2023. “Will central bank digital currency disintermediate banks?” Available at SSRN: 4112644.

- Williamson, Stephen D.** 2021. “Central bank digital currency and flight to safety.” *Journal of Economic Dynamics and Control*, 142: 104146.
- Williamson, Stephen D.** 2022. “Central bank digital currency: Welfare and policy implications.” *Journal of Political Economy*, 130(11): 2829–2861.
- Xiao, Kairong.** 2020. “Monetary transmission through shadow banks.” *The Review of Financial Studies*, 33(6): 2379–2420.

# Appendices

## A Data

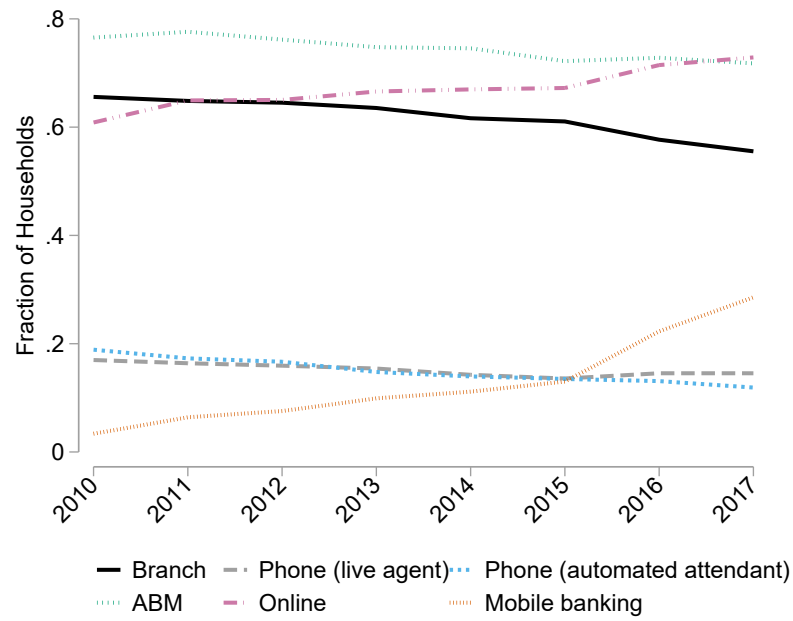
This section shows the summary statistics for the major datasets used in this paper as well as supporting evidence for some of our modeling choices. Section A.1 shows the frequency of branch visits by households and what services they use the branches for. Section A.2 explains how we construct the main financial institution for a product when a household has multiple banks for that product. Section A.3 shows the summary statistics of the key variables and the bank-level interest rates.

### A.1 Branch Usage Habits

Figure A1 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 A2 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 customer service/support, applying for a new product, and complaining about something, households still prefer to use branches over other channels.

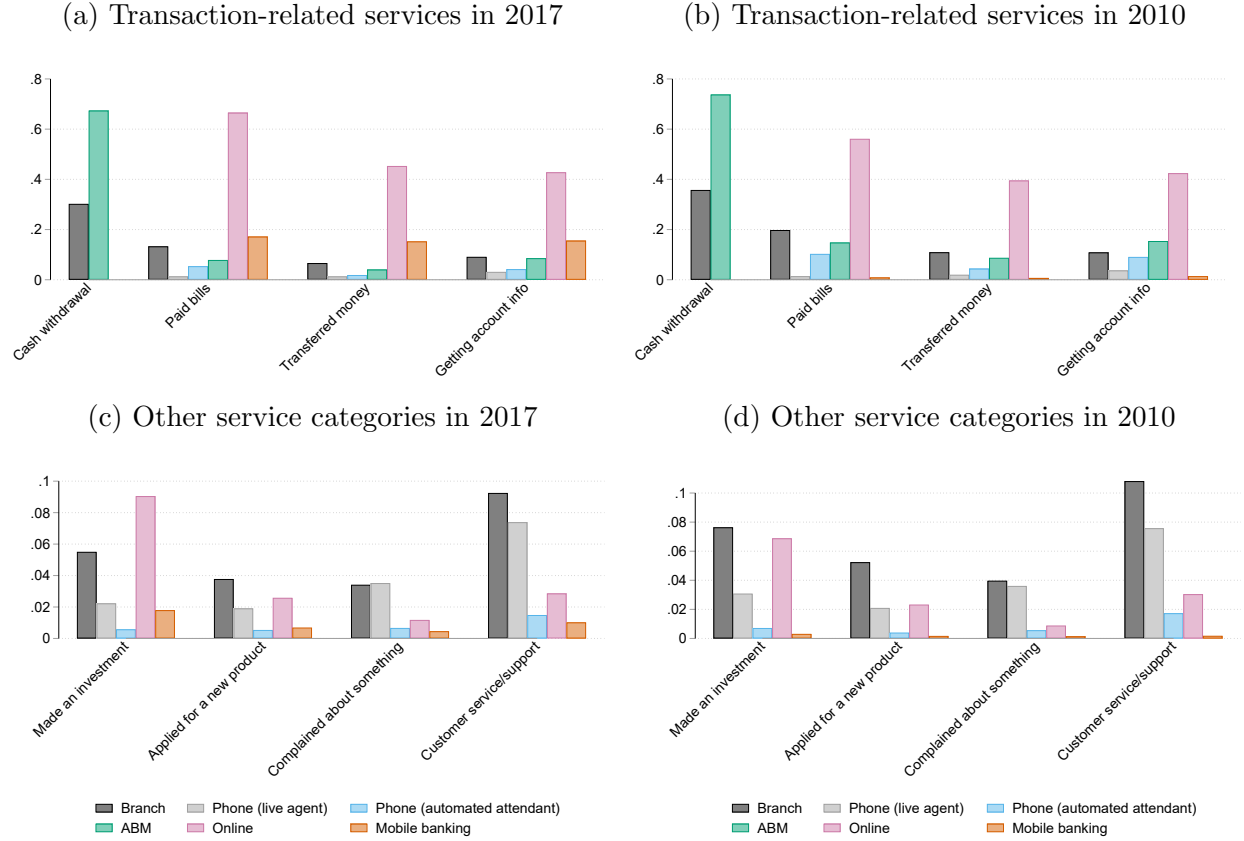
Figure A1: Usage of Branches vs Other Channels over Time



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 A2: Usage of Branches vs Other Channels for Different Banking Services



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. The x-axis shows the service categories, 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 obtain the specific service indicated by the x-axis.

## A.2 Main Financial Institution

This section shows the fraction of households with a single bank for each product, i.e., demand deposits, mortgage loans, credit cards, and guaranteed investment certificates (GICs). It also shows how we construct the main financial institution for a given product in cases where households report to have multiple banks for that product.

Table A1 shows that 73% of households go to a single bank for demand deposits. This fraction is 98% for mortgage loans, 42% for credit cards, and 78% for GICs. These numbers are even higher by looking at different household members (i.e., female household head, male household head, joint ownership) separately. For example, more than 85% of female household heads go to a single bank for their demand deposits, and the number is similar for male household heads. Conditional on the female or male household heads, more than 60% of them go to a single credit card issuer.

In our model and estimation, we assume each household only chooses one bank for each product. Therefore, if a household has multiple banks for a given product, we assume one of these banks is their main financial institution and is their chosen bank. More specifically, if a household has multiple banks for demand deposits, we assume their main financial institution is the one where they deposit the largest balance. Similarly, for households choosing multiple banks for the other financial products, we assume their main financial institutions for the mortgage loans, credit cards, and GICs are the ones with the largest remaining mortgage payment, the largest current outstanding balance, and the highest balance, respectively.

Table A1: Number of Banks that Households Choose for Different Products

	Number of Banks			
	1	2	3	more than 3
Demand Deposits	0.73	0.23	0.04	0.00
Mortgage	0.98	0.02	0.00	0.00
Credit Card	0.42	0.31	0.17	0.11
Guaranteed Investment Certificates	0.78	0.16	0.03	0.02

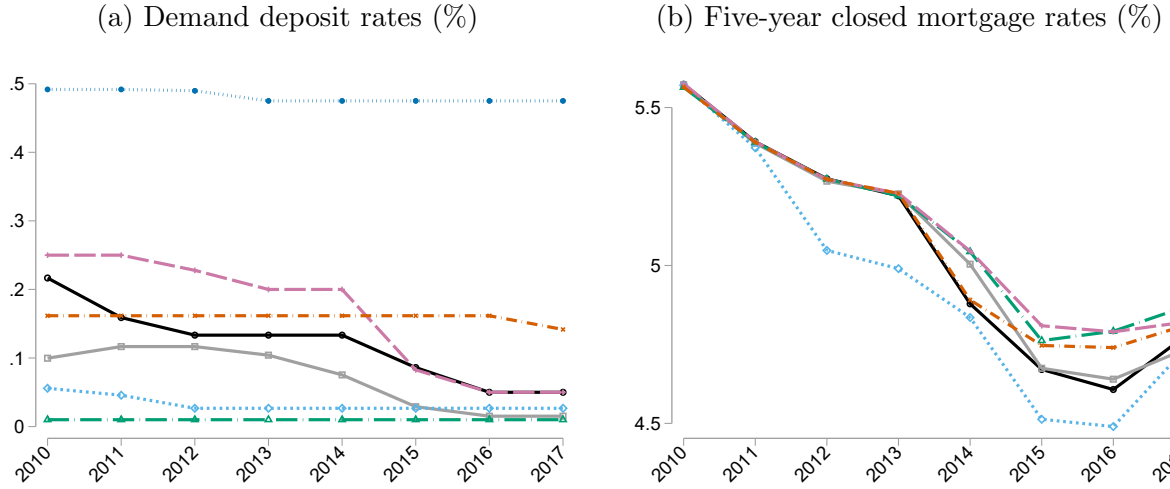
Data sources: CFM 2010–2017

Note: This table shows how many financial institutions that households go to for each product, including the demand deposits, mortgage loans, credit cards, and GICs. Each cell shows the fraction of households that go to 1/2/3/more than 3 banks for a given product.

### A.3 Summary Statistics

Figure A3 plots the demand deposit rates and the five-year closed mortgage rates for each bank over time from 2010 to 2017. Table A2 shows the summary statistics of some key variables.

Figure A3: Bank Interest Rates During 2010–2017



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 B3 shows the estimated parameters for household characteristics in the portfolio allocation choice that are not shown in Table 2. Table B4 and B5 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 B6 compares the baseline estimates with the estimates from the misspecified model where complementarity is neglected.



Table A2: 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 B3: 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) $\times$ Live in rural area	-0.053***	(0.015)
ln(Number of branches + 1)	0.024***	(0.008)
ln(Number of branches + 1) $\times$ 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 $\geq$ \$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 $\geq$ 65	-0.079***	(0.028)
Household size = 2	-0.083***	(0.021)
Household size = 3	-0.123***	(0.029)
Household size $\geq$ 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 the OLS regression of 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). The “Observations” shows the number of households in the CFM sample from 2010 to 2017.

Table B4: Estimated Parameters in Bank Choices of Different Financial Products

	(1) Credit Card		(2) Mortgage		(3) GIC	
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) $\times$ 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) $\times$ 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 estimated parameters from a conditional logistic 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. The “Number of choice sets” denotes the number of households in the sample, while “Observations” represents the cumulative total of alternatives/banks within each household’s choice set.

Table B5: Estimated Parameters in Deposit Bank Choice

Variables	Estimates
Utility from liquidity holding	1.661*** (0.179)
Sum of expected utilities from financial products	1.368*** (0.038)
ln(Distance to branch)	-0.175*** (0.008)
ln(Distance to branch) $\times$ Live in rural area	0.113*** (0.015)
ln(Number of branches + 1)	0.439*** (0.011)
ln(Number of branches + 1) $\times$ 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 logistic regression of the deposit bank choice on the utilities from liquidity holding  $\tilde{V}_{i,j}^b$ , the sum of expected utilities from financial products  $\sum_{k \in \mathcal{K}} \omega^k E[V_{i,j}^k]$ , the branch network measures, and grouped bank fixed effects. The “Number of choice sets” denotes the number of households in the sample, while “Observations” represents the cumulative total of alternatives/banks within each household’s choice set.

Table B6: Deposit Bank Choice Estimation With and Without Complementarity

	Baseline	Misspecified
Utility from liquidity holding	1.661*** (0.179)	1.892*** (0.182)
Sum of expected utilities from financial products	1.368*** (0.038)	
ln(Distance to branch)	-0.175*** (0.008)	-0.287*** (0.008)
ln(Distance to branch) $\times$ Live in rural area	0.113*** (0.015)	0.082*** (0.015)
ln(Number of branches + 1)	0.439*** (0.011)	0.470*** (0.011)
ln(Number of branches + 1) $\times$ Live in rural area	0.229*** (0.021)	0.261*** (0.021)
Big 5 bank indicator	-0.259*** (0.033)	0.335*** (0.027)
Small bank indicator	-0.454*** (0.033)	-0.593*** (0.034)
Online bank indicator	0.389*** (0.027)	0.580*** (0.027)
Desjardins Credit Union indicator	0.109*** (0.026)	0.540*** (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 logistic regression of the deposit bank choice on the utilities from liquidity holding  $\tilde{V}_{i,j}^b$ , the sum of expected utilities from financial products  $\sum_{k \in \mathcal{K}} \omega^k E[V_{i,j}^k]$ , the branch network measures, and grouped bank fixed effects. The column “misspecified” shows the estimated parameters for the misspecified model where complementarity is neglected and thus  $\sum_{k \in \mathcal{K}} \omega^k E[V_{i,j}^k]$  no longer affects the deposit bank choice. The “Number of choice sets” denotes the number of households in the sample, while “Observations” represents the cumulative total of alternatives/banks within each 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 CBDC holding limits. Section C.4 compares the service networks of bank branches and Canada Post offices.

### C.1 Introducing 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 a CBDC affects the banks. Section C.1.3 shows how we construct the aggregate asset holdings from the households' asset holdings.

#### C.1.1 Obtain the Utility from CBDC

After a 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 the CBDC or one of the existing banks by comparing the utility from each option. Based on (19), a household  $i$ 's probability of depositing the digital money in the CBDC is

$$P(j_i^* = cbdc | r_j, \mathbf{r}_{-j}) = \frac{\exp \left( \tilde{\theta} \tilde{V}_{i,cbdc}^b + \phi \sum_{k \in \mathcal{K}} \omega^k E[V_{i,cbdc}^k] + \mathbf{X}_{i,cbdc} \boldsymbol{\beta}^f + \eta_{cbdc}^f \right)}{\sum_{m \in \mathcal{J}_i} \exp \left( \tilde{\theta} \tilde{V}_{i,m}^b + \phi \sum_{k \in \mathcal{K}} \omega^k E[V_{i,m}^k] + \mathbf{X}_{i,m} \boldsymbol{\beta}^f + \eta_m^f \right)}, \quad (\text{C1})$$

where the choice set  $\mathcal{J}_i$  now also contains the CBDC and the subscript  $m$  refers 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 each household's probability of choosing the CBDC (C1). We discuss how we obtain each element in (C1) below.

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

$$\tilde{V}_{i,cbdc}^b = \ln \left[ 1 + \exp \left( \tilde{\alpha}^b r_{i,cbdc} + \mathbf{X}_{i,cbdc} \tilde{\boldsymbol{\beta}}^b + \tilde{\eta}_{cbdc}^b + \tilde{\zeta}^b + \tilde{\varepsilon}_i^b \right) \right], \quad (\text{C2})$$

where  $r_{cbdc}$  is the CBDC rate and  $r_{i,cbdc} = r_{cbdc}(1 - \tau_i)$  is the post-tax CBDC rate. The vector  $\mathbf{X}_{i,cbdc}$  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  $\tilde{\eta}_{cbdc}^b$  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 money in the CBDC, then based on (7), the desired holding of the CBDC would be

$$d_{i,cbdc} = \frac{(u_{i,cbdc}^b)^{\frac{\sigma}{1-\sigma}}}{1 + (u_{i,cbdc}^b)^{\frac{\sigma}{1-\sigma}}} w_i, \quad (C3)$$

where  $u_{i,cbdc}^b = \exp(\alpha^b r_{i,cbdc} + \mathbf{X}_{i,cbdc} \boldsymbol{\beta}^b + \eta_{cbdc}^b + \zeta^b + \varepsilon_i^b)$  is the per dollar value from holding the digital balance in the CBDC. Note that  $(u_{i,cbdc}^b)^{\frac{\sigma}{1-\sigma}}$  is equivalent to the exponential term in (C2), so  $d_{i,cbdc}$  can be calculated in a similar way as discussed above. In our model, once a household chooses the CBDC for their digital money, they will only hold the liquid assets in cash and the 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 the CBDC. When the desired holding of the CBDC exceeds this limit, then household  $i$ 's CBDC holding is constrained at the limit  $d_{i,cbdc} = \bar{d}_{cbdc}$  and they hold the rest of the liquid assets in cash  $\bar{c}_{i,cbdc} = w_i - \bar{d}_{cbdc}$ . In this case, the utility from liquidity holding is

$$\tilde{V}_{i,cbdc}^b = \ln \left[ 1 + \frac{\bar{d}_{cbdc}}{\bar{c}_{i,cbdc}} \right], \quad (C4)$$

which is lower than that of the unconstrained case (C2). A lower  $\tilde{V}_{i,cbdc}^b$  reduces the probability of choosing the CBDC in the first place.

**Value from Financial Products.** Based on (10), we obtain the expected value from obtaining the financial product  $k \in \mathcal{K}$  when the home institution is the CBDC:

$$E[V_{i,cbdc}^k] = \ln \left( \sum_{n \in \mathcal{J}_i^k} \exp(\kappa \mathbb{1}(n = cbdc) + \mathbf{X}_{i,n} \boldsymbol{\beta}^k + \eta_n^k) \right). \quad (C5)$$

Since the 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 the household chooses the CBDC for their digital money, they will not enjoy the

extra utility  $\kappa$  because they still need to obtain the financial product from some other bank. As a result, the expected value  $E[V_{i,cdbc}^k]$  would be lower compared to the case when they choose a bank to deposit their digital money. We use the estimated parameters  $(\kappa, \beta^k, \eta^k)$  to calculate  $E[V_{i,cdbc}^k]$ .

**Service Location Network for CBDC.** As shown above, the service network for the CBDC indirectly affects the choice probability of the CBDC through the utility from liquidity holding and the expected utility from the other financial products. In addition, we assume the service location network  $\mathbf{X}_{i,cdbc}$  for the CBDC can directly affect the utility from the CBDC since it reflects the convenience of getting in-person customer services for CBDC. Depending on the designs of the service location network, the values of  $\mathbf{X}_{i,cdbc}$  will be different.

**CBDC Fixed Effect.** We assume the estimated preference parameters  $\tilde{\theta}$ ,  $\phi$ , and  $\beta^f$  are unchanged when the CBDC is introduced. The only unknown parameter in the CBDC choice probability (C1) is the CBDC fixed effect  $\eta_{cdbc}^f$ . As discussed above, we consider a range of CBDC fixed effects based on the estimated fixed effects  $\eta_j^f$  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, 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 that 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 the 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 deposit rates in the presence of the CBDC. As we vary the design of the CBDC (i.e.,  $r_{cdbc}$ ,  $\mathbf{X}_{i,cdbc}$ ,  $\bar{d}_{cdbc}$ ), we can predict how banks adjust their deposit rates in response to the CBDC with a given design.



### C.1.3 Aggregate Asset Holdings

The new equilibrium deposit rates affect the households' utilities from liquidity holding if they deposit their digital money with a bank  $j$ :

$$\tilde{V}_{i,j}^b = \ln \left[ 1 + \exp \left( \tilde{\alpha}^b r_{i,j} + \mathbf{X}_{i,j} \tilde{\boldsymbol{\beta}}^b + \tilde{\eta}_j^b + \tilde{\zeta}^b + \tilde{\varepsilon}_i^b \right) \right], \quad (\text{C6})$$

which in turn affect the choice probabilities for both banks and the CBDC. A higher new equilibrium deposit rate means that conditional on choosing a bank  $j$ , the household will allocate more of their endowed liquid assets into deposits than cash. In addition, it leads to a higher  $\ln \tilde{L}_{i,j}^b$ , which raises the probability of choosing the bank  $j$  and lowers the probability of choosing the CBDC, compared to the case when there is no endogenous response in deposit rates.

The equilibrium aggregate CBDC holdings can be obtained using the new equilibrium deposit rates, together with (C1) and (C3):

$$d_{cbdc} = \sum_{i \in \mathcal{I}} P(j_i^* = cbdc | r_j, \mathbf{r}_{-j}) d_{i,cbdc}(r_{cbdc}). \quad (\text{C7})$$

Similarly, the new equilibrium aggregate deposit ( $D$ ) and cash ( $C$ ) holdings can be obtained using

$$D = \sum_{j \in \mathcal{J}_i \& j \neq cbdc} \sum_{i \in \mathcal{I}} P(j_i^* = j | r_j, \mathbf{r}_{-j}) d_{i,j}(r_j), \quad (\text{C8})$$

$$C = \sum_{j \in \mathcal{J}_i} \sum_{i \in \mathcal{I}} P(j_i^* = j | r_j, \mathbf{r}_{-j}) c_{i,j}(r_j), \quad (\text{C9})$$

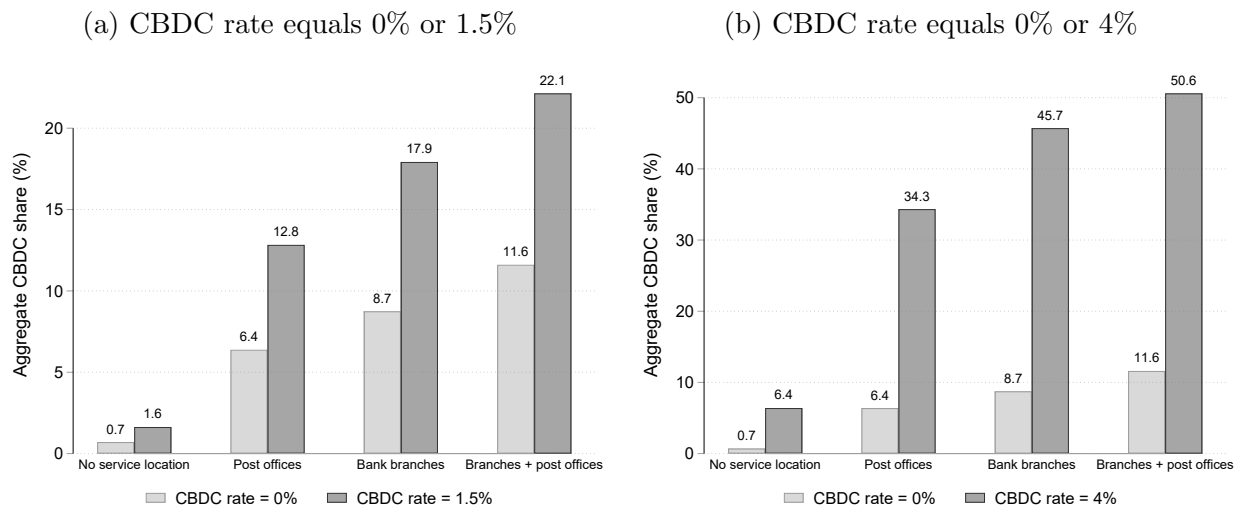
where  $\mathcal{J}_i$  contains both incumbent banks and the CBDC. The total liquid assets ( $d_{cbdc} + D + C$ ) is the same as the total liquid assets  $\sum_i w_i$  before the CBDC issuance.

## C.2 Counterfactual Results

This section shows additional counterfactual results. Figure C4 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 during 2010–2017. Figure C5 shows the percentage changes in aggregate deposits and aggregate cash under different designs of a CBDC. Figure C6 shows the aggregate effects of a CBDC using the estimates from a misspecified model where complementarity is neglected.

Figures C7 and C8 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.

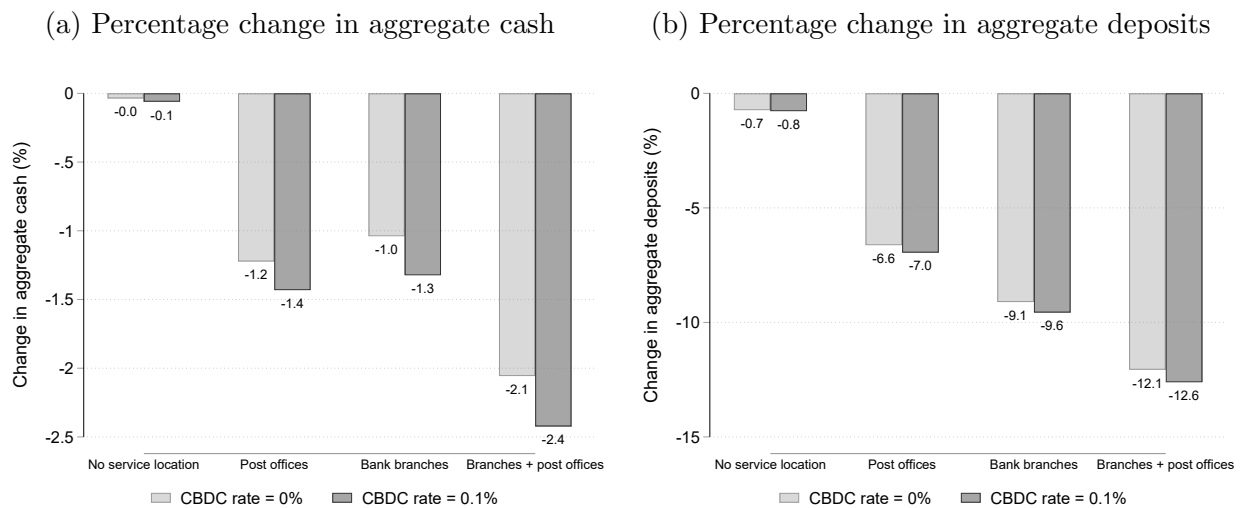
Figure C4: Aggregate CBDC Shares under Different CBDC Interest Rates



Data sources: CFM 2017, FCAC 2017, Canada Post 2021, Government of Canada website

Note: Each figure plots the aggregate CBDC share, calculated as the share of liquid assets allocated in equilibrium by households to the CBDC, 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. Here, we assume the CBDC fixed effect is identical to that of the big five banks.

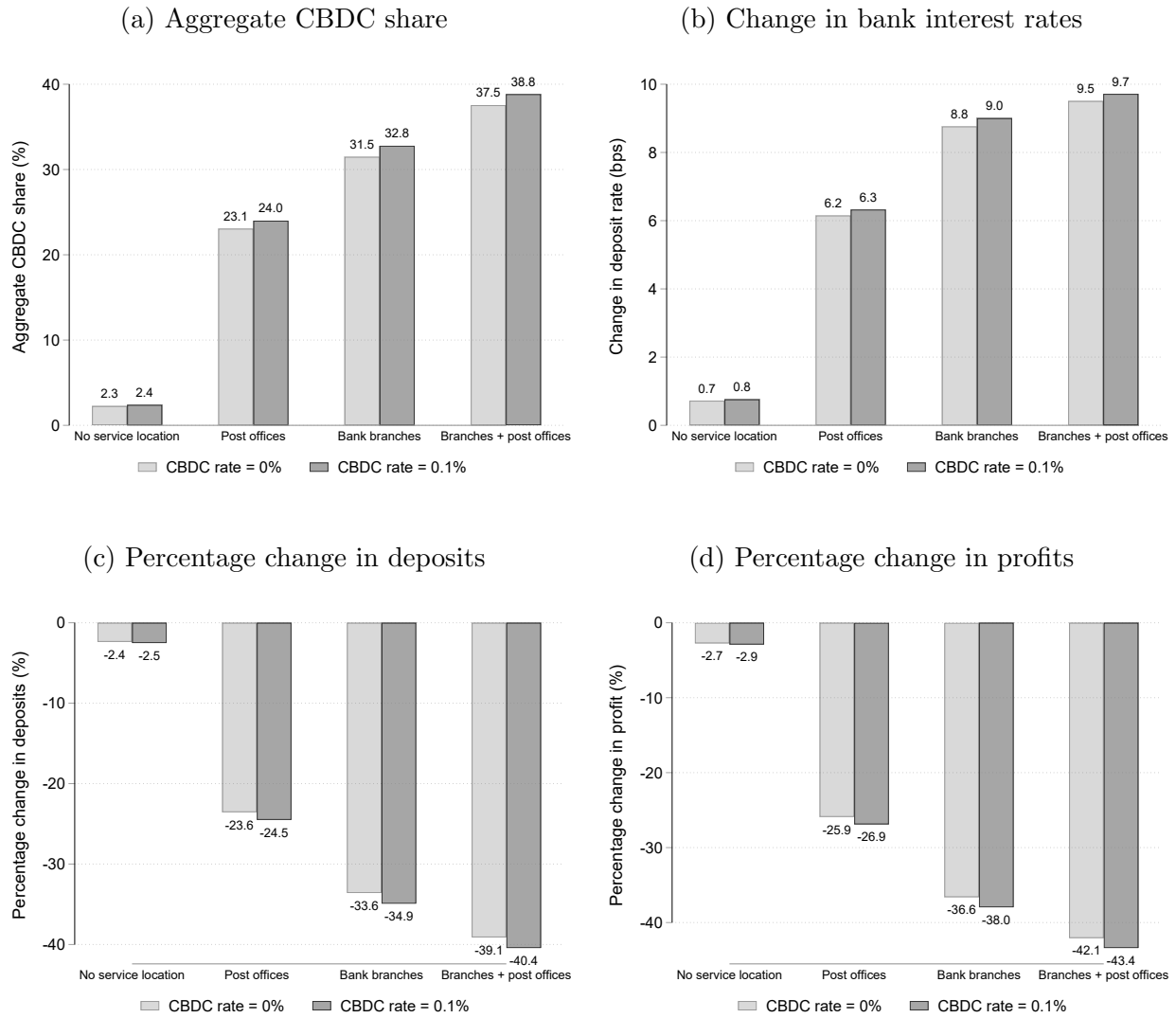
Figure C5: Impact of CBDC Designs on Aggregate Cash and Aggregate Deposits



Data sources: CFM 2017, FCAC 2017, Canada Post 2021, Government of Canada website

Note: This figure plots the percentage changes in the aggregate cash and the aggregate deposit holdings relative to their pre-CBDC values, 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. Here, we assume the CBDC fixed effect is identical to that of the big five banks. Before CBDC issuance, the aggregate cash share is around 4.5% and the aggregate deposit share is around 95.5%.

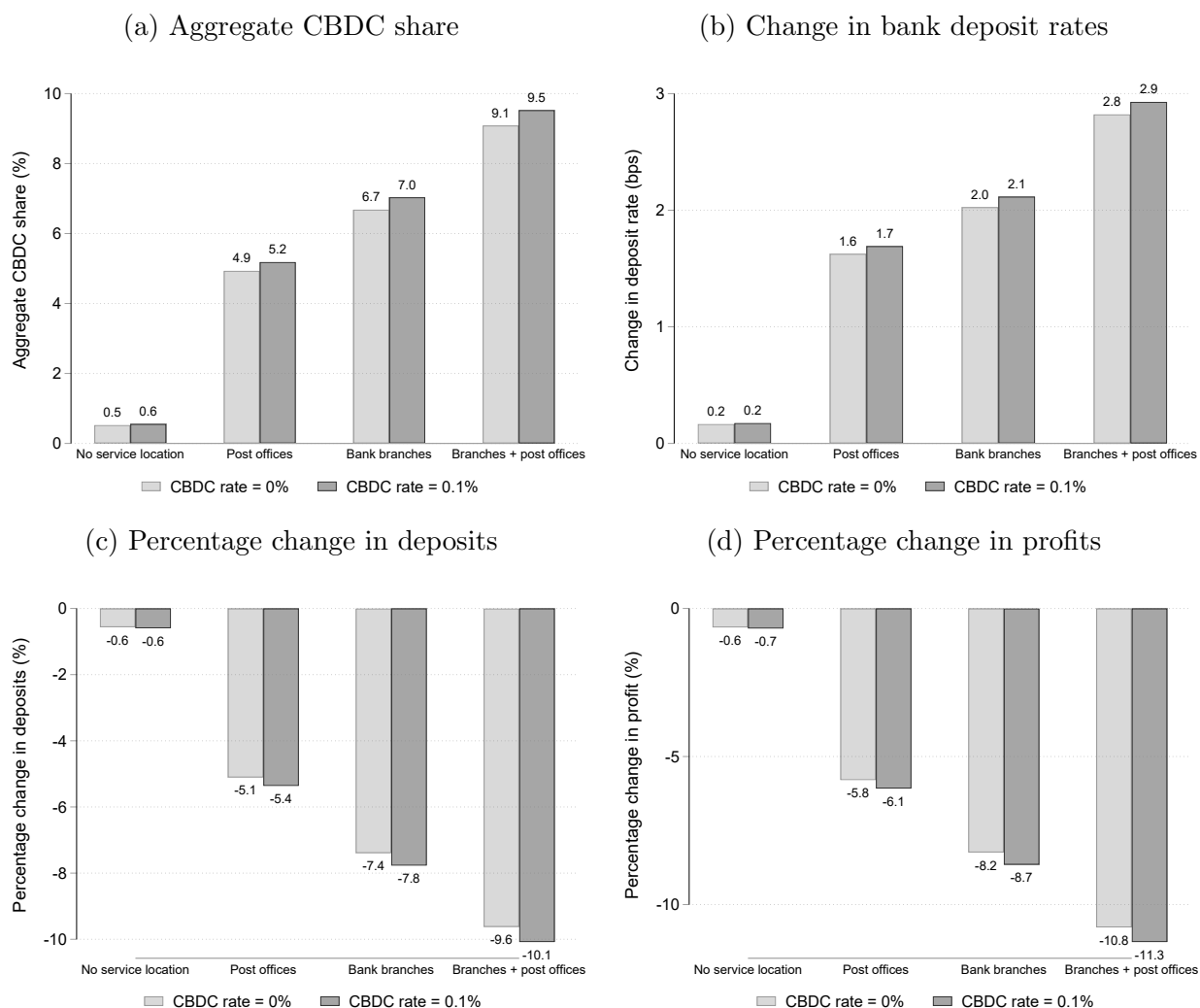
Figure C6: The Aggregate Effects of CBDC When Neglecting the Complementarity



Data sources: CFM 2017, FCAC 2017, Canada Post 2021, Government of Canada website

Note: This figure is based on the misspecified 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 the CBDC, (b) the average endogenous change in deposit rate (in basis points) across banks, (c) the average percentage drop in deposits across banks, and (d) the average percentage drop in profits across banks relative to the pre-CBDC equilibrium. In each graph, the given equilibrium outcome is plotted under four designs of service locations 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.

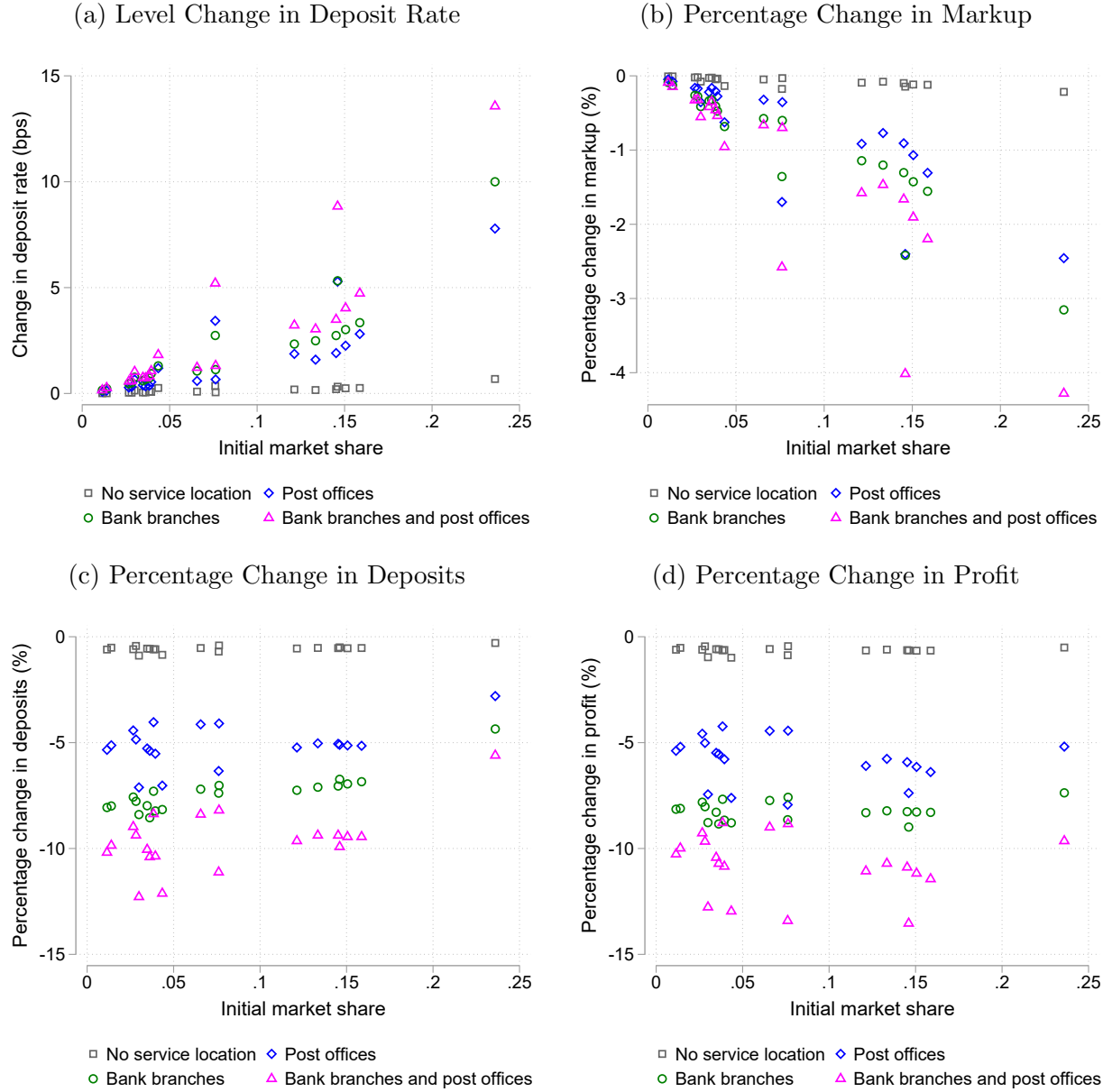
Figure C7: Impact of CBDC Designs on Equilibrium Outcomes When CBDC Fixed Effect Equals the Small Bank Fixed Effect



Data sources: CFM 2017, FCAC 2017, Canada Post 2021, Government of Canada website

Note: This figure plots (a) the aggregate CBDC share calculated as the share of liquid assets allocated in equilibrium by households to the CBDC, (b) the average endogenous change in deposit rate (in basis points) across banks, (c) the average percentage drop in deposits across banks, and (d) the average percentage drop in profits across banks relative to the pre-CBDC equilibrium. In each graph, the given equilibrium outcome is plotted under four designs of service locations 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 C8: Impact of CBDC on Different Banks Under Small Bank Fixed Effect



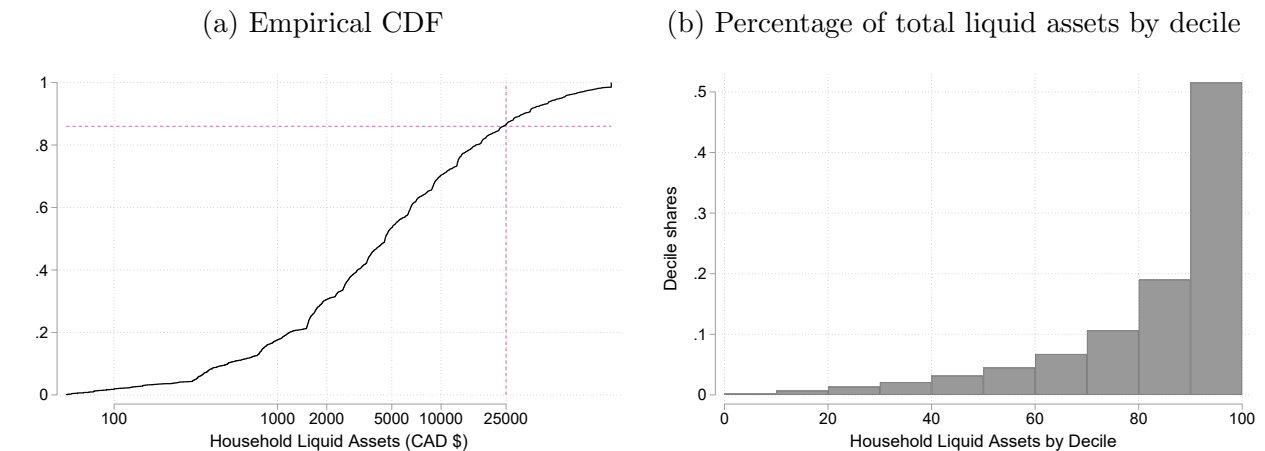
Data sources: CFM 2017, FCAC 2017, Canada Post 2021, Government of Canada website

Note: This figure plots each bank's optimal response in deposit rates (in basis points), the percentage changes in markups, deposits, and profits for four different CBDC network designs (i.e., no service location, all Canada Post offices, all bank branches, both bank branches and Canada Post offices). The x-axis is the bank's initial market share, calculated by averaging the estimated probabilities of households choosing the bank across all local markets (around households' residences) in which the bank operates. Here, we assume the 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 C9 shows the distribution of households' liquid assets.

Figure C9: Distribution of Household Liquid Assets



Data sources: CFM 2017

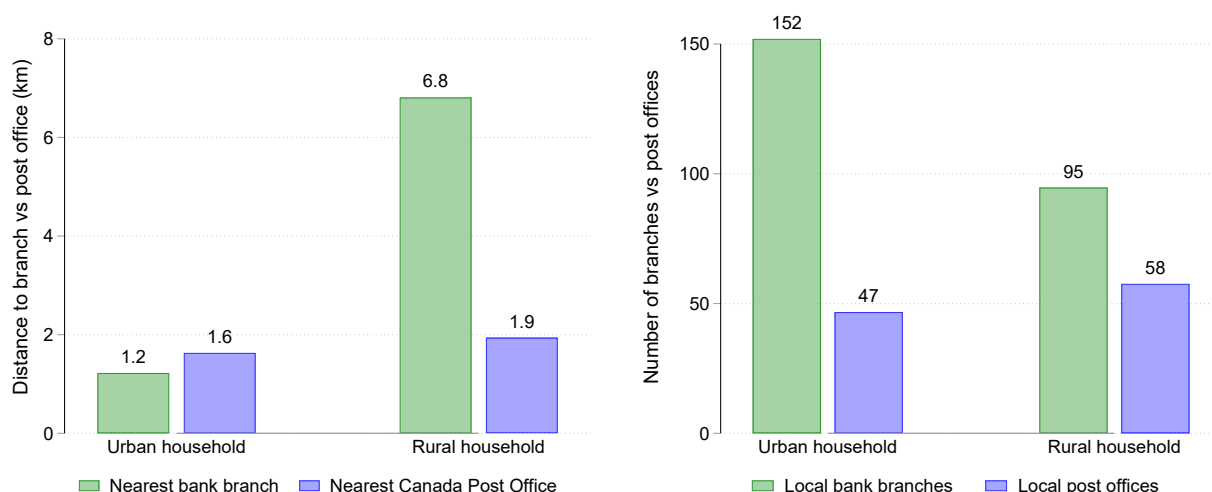
Note: This figure shows the distribution of liquid assets that our model takes as input. In panel (a) we show the empirical cumulative distribution function for 2017 from the CFM. For a given level of assets on the x-axis, the corresponding level on the y-axis refers to the percentage of households holding 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 C10 compares the service networks of bank branches and Canada Post offices.

Figure C10: 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 bars 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 15 km (50 km) of the household's location. Online banks are excluded in this figure.