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Liquidity regulation and banks: Theory and evidence ☆

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ABSTRACT

This paper theoretically and empirically investigates the effects of liquidity regulation on the banking system. We document that the current quantity-based liquidity rule has reduced banks' liquidity risks. However, the mandated liquidity buffer appears to crowd out bank lending and lead to a migration of liquidity risks to banks that are not subject to liquidity regulation. These findings motivate a model of liquidity regulation with endogenous liquidity premiums and heterogeneous banks. The model shows that the current liquidity rule can improve upon the unregulated equilibrium but can also have distortionary effects because of the dual role of the liquidity buffer as an implicit tax and a costly mitigator of liquidity risks. The fixed quantity mandate can interact with the uncertain liquidity demand, amplifying the volatility in the liquidity premium. A central bank committed liquidity facility could improve the current quantity-based regulation by introducing a price-based mechanism.

1. Introduction

Before the 2007–2009 financial crisis, bank regulation primarily focused on capital requirements. However, despite adequate capital levels, many banks still experienced significant liquidity problems during the crisis.[1] In response, the Basel Committee introduced global liquidity standards to reduce risks associated with excessive liquidity transformation. In 2013, U.S. bank regulators implemented the liquidity coverage ratio (LCR) requirement. This regulation requires banks with more than \$50 billion in total assets (LCR banks) to hold a portfolio of high-quality liquid assets at least as large as expected total net cash outflows over a 30-day stress period. The LCR requirement marks one of the most important regulatory reforms in the post-crisis banking system.

Unlike capital regulation, which has received extensive academic scrutiny, liquidity regulation is new and has run ahead of research (Diamond and Kashyap, 2016). The idea of the LCR builds on traditional liquidity "coverage ratio" methodologies used internally by banks. However, there is a lack of consensus on whether such a regulatory design is optimal. A key question often raised in the policy debate is whether this liquidity regulation can negatively affect other bank functions such as credit provision.[2]

This paper sheds light on this question using insights from public interest theory (Pigou, 1932; Weitzman, 1974; Laffont and Tirole, 1993; Dewatripont and Tirole, 1994). First, we show that the current LCR rule can improve the unregulated equilibrium but also has distortionary effects. The key insight is that the mandated liquidity buffer serves a dual role, first as an implicit tax on liquidity transformation and second as a costly mitigator of liquidity risks. As a result, the LCR rule cannot simultaneously achieve the first-best liquidity and lending. Moreover, the distortion worsens when heterogeneous intermediaries are not subject to the same liquidity rule and when the demand for liquidity is uncertain.

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[1] See "Basel III: The liquidity coverage ratio and liquidity risk monitoring tools," Basel Committee on Banking Supervision, 2013.

[2] For instance, a report by the Basel Committee titled "Literature review on integration of regulatory capital and liquidity instruments" suggests that the introduction of the LCR may reduce bank credit and lower aggregate output. However, theoretically, excessive credit growth fueled by unrestricted liquidity transformation can also be suboptimal, so reducing credit does not necessarily mean the regulation is distortionary.

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Our analysis is motivated by new empirical patterns that arose after the LCR was implemented. Using U.S. bank data, we find that the liquidity condition of LCR banks has significantly improved since the introduction of the LCR: the average liquidity ratios of LCR banks have increased by around 20% since 2013. Moreover, in the cross-section of LCR banks, banks with greater exposure to liquidity regulation, measured by a larger gap between their preregulation liquidity ratios and the mandated level, have improved their liquidity by a larger margin. The increase in liquidity ratios is mainly driven by an increase in high-quality liquid assets and, to a lesser degree, an increase in stable funding sources.

While LCR banks have improved their liquidity condition, the required liquidity buffers appear to have crowded out the illiquid assets. By exploiting granular data on small business loans and mortgage origination, we find that more-exposed banks, measured by the gap between their pre-regulation liquidity ratio and the required level, have experienced lower lending growth. The reduction in lending is robust to controlling for the differences in demand, business models, and exposures to other regulations, such as capital requirements, stress testing, supplementary leverage ratio (SLR) requirements, and global systemically important banks (GSIB) regulation. Consistent with the crowding-out hypothesis, the reduction in lending is present in balance sheet–based lending but is absent in securitization-based lending.

Furthermore, we find that some liquidity risks appear to have migrated to banks that are not subject to liquidity regulation. Specifically, non-LCR banks—banks whose assets are below the $50 billion threshold—experienced a significant deterioration in their liquidity ratios after the introduction of the LCR. The deterioration is more severe for non-LCR banks that operate in markets with more LCR banks, suggesting a migration of illiquidity from LCR banks to non-LCR banks.[3]

These empirical findings raise important questions about welfare implications. On the one hand, the laissez-faire liquidity and credit supply could be excessive, and the LCR could have brought them closer to the social optimum. On the other hand, it is unclear whether the current LCR rule, which mandates a fixed liquidity buffer in an environment with unregulated intermediaries and uncertain liquidity demand, strikes the best balance between promoting stability and maintaining credit supply.

To understand these issues, we develop a model of liquidity regulation with endogenous liquidity premiums and heterogeneous banks. Following Stein (2012), we assume that unregulated liquidity transformation can lead to an externality in which intermediaries issue too much short-term debt and leave the system excessively vulnerable to liquidity risks. This market failure motivates liquidity regulation. The current LCR rule is a quantity-based regulation, in the terminology of Weitzman (1974), in that banks are required to hold a fixed liquidity buffer relative to their short-term debt. This requirement imposes an implicit tax on liquidity transformation because liquid assets generate lower returns than illiquid assets. This tax forces banks to internalize the externality of liquidity transformation and brings the quantity of short-term debt closer to the socially optimal level.

However, the LCR rule cannot achieve the first-best outcome because of the dual role of the liquidity buffer. On the one hand, the liquidity buffer serves as an implicit tax through which the private and social costs of liquidity transformation are aligned. On the other hand, it serves as a costly mitigator of liquidity risks because it occupies banks' balance sheets but generates low returns. As a result, the LCR rule faces a trade-off between achieving the first-best liquidity and lending. If the regulator sets the liquidity buffer to socially optimal, the short-term debt issuance will still be larger than the socially optimal as the fire-sale externality is still not fully internalized; if the regulator sets the liquidity buffer to be so high that the short-term debt issuance equals the socially optimal amount, the mandated liquid assets would exceed the socially optimal amount and crowd out too much lending.

Furthermore, as regulated banks hold more liquid assets, the liquidity premium rises, incentivizing unregulated intermediaries to ramp up liquidity transformation. Such migration is distortionary because the marginal costs of liquidity transformation are not equalized across intermediaries. The trade-off also worsens in the presence of uncertain liquidity demand because the fixed quantity mandate of the LCR induces a pro-cyclical tax. If the liquidity demand is unexpectedly high, the liquidity premium rises, which drives up the implicit tax on liquidity transformation. As a result, liquidity regulation becomes more punitive exactly when liquidity transformation is needed. The pro-cyclicality, in turn, exacerbates the migration of liquidity transformation.

Although these distortions do not necessarily negate the positive effects of the LCR on welfare, they suggest possible room for improvement. Inspired by the classic result in Weitzman (1974) on quantity-based versus price-based regulation, we consider a central bank committed liquidity facility (CLF) that allows banks to pay the central bank an upfront fee for a loan commitment.[4] The unused capacity of the loan commitment can be counted toward a bank's liquidity requirements without occupying banks' balance sheets, eliminating the crowding-out effects of liquidity buffers on bank lending. Furthermore, the committed liquidity facility can also eliminate the pro-cyclicality of the implicit tax imposed by the current LCR rule because banks have the option to pay a flat commitment fee to obtain a loan commitment instead of purchasing liquid assets at an elevated liquidity premium. Note that the committed liquidity facility does not undo liquidity regulation because the commitment fee effectively functions as a Pigovian tax to discourage excessive liquidity transformation.

Liquidity regulation is one policy that addresses market failures associated with liquidity transformation. However, it is not the only policy. The central bank has long acted as the lender of last resort (LOLR) to address liquidity issues in the banking system. We show that liquidity regulation is complementary to the LOLR because as a preventative policy, it can alleviate the moral hazard problem induced by ex post interventions of the LOLR.

We also discuss the roles of the central bank as the LOLR and as the provider of the CLF. Although both roles involve using public liquidity to support private liquidity transformation, the goals of the policy instruments are quite different, with the CLF charging a commitment fee ex ante as Pigovian taxation on liquidity transformation, and the LOLR charging a cost ex post to discourage over-reliance on a public liquidity backstop. Additionally, the quantity of liquidity commitment from the CLF is determined by the LCR, while the borrowing capacity from the LOLR is determined by available collateral and haircuts. These differences mean that the LOLR cannot be used to replace the CLF for price-based liquidity regulation.

Finally, we calibrate the model to data to evaluate the welfare implications of various regulatory designs. We simulate five scenarios: a laissez-faire approach, a first-best solution, the LCR, a stricter LCR with a 10% higher required liquidity ratio, and the LCR combined with the CLF. The results show that the LCR could close around 50% of the welfare gap between the laissez-faire and first-best equilibrium, but it causes significant distortions due to crowding-out and migration effects. A stricter LCR does not improve social welfare as the distortions are further exacerbated. On the other hand, the CLF improves the regulatory outcome of the LCR by reducing the crowding-out effect and migration

[3] Although the average liquidity ratio of non-LCR banks is still higher than that of the LCR banks, non-LCR banks are generally smaller and have poorer access to the funding market. Thus, the migration of liquidity risks from LCR banks to non-LCR banks may increase the average fragility.

[4] The committed liquidity facility was initially introduced by the Reserve Bank of Australia to address the structural shortage of high-quality liquid assets in the Australian banking system during the LCR implementation. However, this facility can be useful in other countries where the shortage of high-quality liquid assets is less of an issue.

effect. When the LCR is combined with a CLF, it can close up to 70% of the welfare gap between the laissez-faire and first-best equilibrium.

This paper contributes to the growing literature on liquidity regulation. On the theory side, Farhi et al. (2009) show that the private market cannot provide liquidity efficiently, so government intervention is needed. Carletti et al. (2018) use a global game model to analyze the interdependent effects of bank capital and liquidity on the likelihood of solvency- and liquidity-driven crises. Calomiris et al. (2015) provide a theory of liquidity regulation based on the idea that it is much easier to verify the value of cash on the asset side than capital on the liability side. Diamond and Kashyap (2016) show that the existence of the liquidity buffers may forestall certain panic-driven runs even if the required liquidity buffers are not allowed to be deployed to meet the withdrawals. Dewatripont and Tirole (2018) develop a conceptual framework on the consistency between liquidity and solvency regulations. Kashyap et al. (2020) show that joint implementation of capital and liquidity regulation is needed to correct the distortions in the private market. Hachem and Song (2021) show theoretically that liquidity regulation can trigger unintended credit booms in the presence of interbank market power. Our paper contributes to the literature by bringing insights from public interest theory (Pigou, 1932; Weitzman, 1974; Laffont and Tirole, 1993; Dewatripont and Tirole, 1994) to study the regulatory design of liquidity regulation. The key insight is that the quantity-based LCR rule may crowd out bank lending and interact negatively with uncertain liquidity demand. A price-based mechanism could help overcome the distortions caused by the current quantity-based liquidity rule.

This paper relates to the growing empirical literature on liquidity regulation. Berger and Bouwman (2009) develop a comprehensive empirical measure of bank liquidity creation that accounts for both off-balance-sheet and on-balance-sheet items. Bai et al. (2018) examine the measurement of liquidity mismatch in the banking sector. Ihrig et al. (2019) provide a descriptive analysis of how banks' management of high-quality liquid assets (HQLAs) has changed since the 2007-2009 financial crisis. Anderson et al. (2021) show that post-crisis regulation has induced global banks to shift their use of wholesale funding from financing illiquid assets to financing near risk-free arbitrage positions. Gete and Reher (2021) use the LCR as a regulatory shock to study the effect of secondary market prices on the supply of credit by nonbank lenders in the mortgage market. Banerjee and Mio (2018) find that liquidity regulation improves the liquidity condition for U.K. banks. Gorton et al. (2022) draw lessons from the U.S. National Banking Era and argue that the LCR could make collateral immobile but is unlikely to reduce financial fragility. A key study closely related to our paper is Roberts et al. (2018), which provides one of the first analyses on the impact of liquidation regulation on U.S. banks, focusing on liquidity creation by banks. Our paper builds on this literature by exploiting several new sources of variations to sharpen the identifications, including differences in regulatory exposure *within* LCR banks, differences between conforming and non-conforming mortgages, and variations in the geographic footprint of the LCR banks. Using these variations, we document two new facts regarding the crowding-out and migration effects. Additionally, our model predicts that the current liquidity rule can increase the volatility of the liquidity premium, which is consistent with the findings of Afonso et al. (2020), Correa et al. (2020), Avalos et al. (2019), and D'Avernas and Vandeweyer (2020).

Our paper builds on and extends the literature that studies price-versus quantity-based financial stability regulations. Stein (2012) develops a model in which monetary policy is used as a financial stability regulation, drawing a parallel between the financial-stability-motivated monetary policy and Pigovian taxation. Our model addresses the same market failure, but explores how liquidity regulation can address this market failure. Jeanne and Korinek (2010) examine how Pigovian taxation in the form of taxes on capital flows can reduce the externalities associated with deleveraging and potentially improve welfare. Jeanne and Korinek (2019) study Pigovian taxation in a dynamic model to address the feedback between debt accumulation and asset prices. Keister (2016) develops a model of bailouts and argues that taxing short-term liabilities can improve the allocation of resources and promote financial stability. Our paper applies the conceptual framework of the public interest theory to analyze the regulatory design of liquidity regulation, which is crucial to understand given the central role it plays in post-crisis regulatory reform. We show that the LCR cannot achieve the first-best outcome, given the dual role of the liquidity buffer and the predetermined run-off rate. In contrast, the commitment fee associated with the CLF effectively functions as a Pigovian tax to discourage excessive liquidity transformation.

Our paper connects to a large body of research on the role of the central bank as a lender of last resort (LOLR). On the empirical side, the literature has documented important facts about the effects of liquidity injections by central banks on banks (e.g., Alves et al. (2021), Taylor and Williams (2009), and Anbil and Vossmeyer (2021)). On the theory side, the literature has explored the importance of the public provision of liquidity to private entities such as banks and firms (Diamond and Dybvig, 1983; Holmström and Tirole, 1998), the optimal intervention policies of central banks in their role as LOLR (e.g., Acharya and Thakor (2016)), and the moral hazard issue induced by the ex post intervention by the LOLR (e.g., Buser et al. (1981); Acharya and Yorulmazer (2007); Farhi and Tirole (2012)). We contribute to the literature by examining a new set of tools possessed by regulators after the 2007–2009 financial crisis, such as the LCR and the CLF. We show the LCR differs from the LOLR because it is an ex ante preventative measure. The LCR complements the LOLR because it can alleviate the moral hazard problem resulting from ex post interventions. Our paper also formally examines the pricing of the CLF whereby banks can meet their mandated liquidity requirements by accessing the CLF by paying the commitment fee without necessarily drawing any liquidity. Finally, in terms of modeling, the above literature mainly focuses on regulated banks, while we explore the spillover effects by simultaneously modeling both LCR banks and non-LCR banks in the economy.

Our paper also contributes to the literature on the aggregate supply and demand for liquidity. Holmström and Tirole (1998, 2011) show theoretically that when a shortage of government-supplied liquid assets exists, a liquidity premium arises in the equilibrium, which induces the private sector to conduct liquidity transformation. Dang et al. (2017) show that banks provide private liquidity by keeping information about the underlying assets secret. Krishnamurthy and Vissing-Jorgensen (2012) and Nagel (2016) show that Treasury supply and monetary policy affect the economy's liquidity premium. Sunderam (2014) shows that commercial paper issuance responds to the supply of public debt. Our paper contributes to this literature by studying the interaction between liquidity regulation and liquidity provision by private banks.

Finally, our paper connects to a theoretical literature on loan commitments. One of the early contributions by Boot et al. (1993) sheds light on why the material adverse clause (MAC), granting the bank the right to revoke commitments under certain circumstances, may indeed be optimal. Dinç (2000) explores how increased bank competition could motivate banks to extend loan commitments to their corporate borrowers and fulfill them in bad states of the world. Kashyap et al. (2002) make the point that offering loan commitments simultaneously with deposit-taking create synergies associated with the holding balances of liquid assets to meet the draws on loan commitments and deposit withdrawals. Thakor (2005) offers a theory of loan commitments as an insurance against shortage on loans in the future during crisis states of the economy as a welfare-improving contract. In these papers the focus is on loan commitments offered by banks to their corporate clients. Our paper focuses on the possible use of loan commitments by the central bank to the banks, in the context of meeting their LCR requirements. Our model also considers an economy with regulated and unregulated banks in the context of committed loan facilities, in a general equilibrium setting with endogenous liquidity premium.

The remainder of the paper is organized as follows. In Section 2, we describe the institutional background. We then present the motivating evidence in Section 3. In Section 4, we develop a model to interpret these results. Section 5 concludes.

2. Institutional background

2.1. Liquidity coverage ratio (LCR)

The liquidity coverage ratio (LCR) is one of the key post-crisis regulatory reforms proposed by the Basel Committee on Banking Supervision.[5] The LCR was proposed by the Basel Committee on Banking Supervision in December 2010 as part of the Basel III global regulatory framework and was scheduled to be implemented by member countries in January 2013. A revised LCR rule was issued by the Basel Committee in January 2013. The U.S. version of the LCR was first proposed in October 2013, and was finalized in September 2014, and had a final compliance deadline of December 2017. In the United States, banks with assets above $50 billion are subject to the LCR.[6] In the following analysis, we refer to banks with assets above $50 billion as LCR banks and banks with assets below $50 billion as non-LCR banks. We define 2011Q1–2012Q4 as the pre-liquidity regulation period and 2013Q1–2017Q4 as the post-liquidity regulation period. The cutoff date, 2013Q1, corresponds to the quarter when the Basel Committee issued the revised LCR rule.[7] This choice is also consistent with other work such as Roberts et al. (2018). We acknowledge that it could be challenging to pinpoint one particular event date for major regulatory reforms such as the LCR because there could be anticipation effects or delayed responses. In the Online Appendix, we also conduct robustness checks by refining the post variable using the finalization of the U.S. rule in September 2014.

The LCR builds on traditional liquidity "coverage ratio" methodologies used internally by banks to assess exposure to contingent liquidity events (BCBS, 2013). The LCR is defined as the ratio of high-quality liquid assets (HQLA) to total net cash outflows over the next 30 calendar days:

$$LCR = \frac{\textit{High-quality liquid assets}}{\textit{Net expected cash outflows}}. \tag{1}$$

HQLAs in the numerator are calculated by multiplying a liquidity factor for each type of liquid asset and then adding them:

$$\textit{High-quality liquid assets} = \sum_k \textit{Liquidity weight}_k \times \textit{Asset}_k. \tag{2}$$

The liquidity weights represent the fire-sale values banks can recover from these assets in the middle of a severe financial crisis. Table OA.1 presents the detailed liquidity weights. Cash, central bank reserves, and government securities are classified as "level 1 HQLA" and receive a liquidity weight of 100%. GSE securities are classified as "level 2a HQLA" and receive a liquidity weight of 85%. Investment corporate and municipal bonds and Russell 1000 equities are classified as "level 2b HQLA" and receive a liquidity weight of 50%. Loans and other fixed assets are not qualified as HQLA and receive a liquidity weight of 0%.

In the denominator, the net expected cash outflows are defined as the difference between expected cash outflows and inflows. Expected cash outflows are calculated by multiplying run-off rates by the portion of liabilities that mature within the next 30 days:

$$\textit{Expected cash outflows} = \sum_k \textit{Run-off rate}_k \times \textit{Cash outflows in 30 days}_k, \tag{3}$$

where $\textit{Cash outflows in 30 days}_k = \textit{Liability}_k / \textit{Maturity}_k$. $\textit{Liability}_k$ is the value of a liability and $\textit{Maturity}_k$ is the maturity in a unit of months. Two factors affect the expected cash outflows. First, the shorter the maturity, the greater the fraction of the debt that will mature within the next 30 days, which results in larger cash outflows. Second, holding the maturity constant, a liability with a higher run-off rate leads to greater expected cash outflows. The run-off rates represent the portion of the liability that remains a source of funding during the next 30 days.

The run-off rates measure the instability of the liability. Table OA.2 presents the detailed run-off rates assigned by the LCR rule. Deposits generally have lower run-off rates (ranging from 3% to 40%) compared to wholesale funding because deposits are generally viewed as sticky. Unsecured wholesale funding generally has higher run-off rates than secured funding because unsecured creditors are not protected by collateral and, consequently, are more prone to run. Within the secured funding, the run-off rates also depend on the underlying collateral. Wholesale funding secured by level 1 HQLAs has a run-off rate of 0%, while wholesale funding secured by non-HQLAs has run-off rates ranging from 25% to 100%. Finally, the run-off rates also depend on the counterparty. For instance, loan commitments for secured underwriting have a run-off rate of 100% because the counterparties are sophisticated investors who are likely to draw down liquidity in a period of distress. In contrast, loan commitments of credit cards have a run-off rate of 5% because the counterparty is unsophisticated retail customers who are less likely to draw down liquidity.

Finally, total expected cash inflows are calculated by multiplying the outstanding balances of various categories of contractual receivables by the rates at which they are expected to flow. The outstanding balances include securities borrowed, reverse repos, loans maturing within one month, and positive fair value of derivatives. The expected cash inflows are then used to offset part of the expected cash outflows to calculate the net expected cash outflows.

2.2. Data

Our first data set is a panel of U.S. commercial banks and bank holding companies from 2011 to 2017, compiled using the Call Reports and FR Y-9C. We use the highest level ownership as the observation unit because the LCR applies to both banks and bank holding companies (BHCs). In other words, if a bank is a stand-alone bank, we include it as an observation; if a bank belongs to a BHC as a subsidiary, we include the BHC but not the subsidiary bank. In the following discussion, we refer to our observations as banks.[8] In our analysis, we drop custodial banks and investment banks such as Bank of New York Mellon and Goldman Sachs because their business models are completely different from other commercial banks. However, the results are robust if these banks are included. Call Reports and FR Y-9C do not directly disclose the liquidity coverage ratio. We follow Hong et al. (2014) to construct the liquidity ratio using banks' balance sheet composition. Note that LCR can be more accurately estimated at daily frequency using the Federal Reserve's Form FR2052a. However, Form FR2052a has been required only for the six largest banks since December 2015 (Correa et al., 2020). As a result, we use Call Reports and FR Y-9C, which

[5] Another component of the Basel III liquidity standards is the Net Stable Funding Ratio (NSFR) requirement, which is intended to ensure that banks have a robust funding profile over a one-year horizon. The NSFR has not been implemented in the United States as of 2022. In addition to the LCR and the NSFR, the Federal Reserve in the United States also introduced the Comprehensive Liquidity Assessment Review (CLAR) in 2012. The CLAR covers 16 systematically important institutions, including banks, insurance companies, and broker-dealers supervised by the Large Institution Supervision Coordinating Committee (LISCC). Although we focus on the LCR in this paper, the discussion can be generalized to all liquidity regulations.

[6] Note that banks with assets below $250 billion but above $50 billion are subject to a modified LCR in which the requirements are 70% lower than that for banks with assets above $250 billion.

[7] In Figure OA.1 we show that Google searches on LCR also peaked in January 2013 in the United States.

[8] The results are robust if we only use bank-level or only use BHC-level data.

Table 1
Summary Statistics of the Bank Balance Sheet Data.

Panel A: LCR banks

	mean	sd	p5	p25	p50	p75	p95
Liquidity coverage ratio	0.822	0.449	0.304	0.482	0.752	1.012	1.688
Capital ratio	9.928	2.497	7.110	8.860	9.893	10.910	12.469
Log assets	25.821	1.066	24.630	25.138	25.522	26.200	28.148
HQLA growth	0.108	0.245	-0.206	-0.010	0.038	0.178	0.748
Illiquid asset growth	0.032	0.068	-0.090	-0.002	0.017	0.064	0.184
Deposit growth	0.049	0.056	-0.036	0.000	0.044	0.082	0.160
Non-interest income	0.017	0.010	0.007	0.011	0.016	0.021	0.032
Leverage	0.099	0.026	0.065	0.084	0.094	0.107	0.154
Leverage (risk-weighted)	0.536	0.433	0.103	0.123	0.188	1.000	1.000
CCAR	0.947	0.223	0.000	1.000	1.000	1.000	1.000
SLR	0.077	0.267	0.000	0.000	0.000	0.000	1.000
GSIB	0.192	0.394	0.000	0.000	0.000	0.000	1.000

Panel B: Non-LCR banks

	mean	sd	p5	p25	p50	p75	p95
Liquidity coverage ratio	2.736	2.788	0.328	0.916	1.812	3.477	8.561
Capital ratio	9.989	4.081	6.050	8.550	9.650	10.970	14.410
Log assets	19.148	1.262	17.321	18.310	19.031	19.834	21.433
HQLA growth	0.072	0.309	-0.346	-0.129	0.000	0.207	0.784
Illiquid asset growth	0.036	0.077	-0.091	-0.004	0.019	0.086	0.184
Deposit growth	0.034	0.060	-0.051	0.000	0.018	0.069	0.160
Non-interest income	0.007	0.008	0.001	0.003	0.005	0.009	0.019
Leverage	0.106	0.033	0.072	0.088	0.100	0.116	0.161
Leverage (risk-weighted)	0.861	0.313	0.126	1.000	1.000	1.000	1.000
CCAR	0.000	0.013	0.000	0.000	0.000	0.000	0.000
SLR	0.000	0.000	0.000	0.000	0.000	0.000	0.000
GSIB	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Note: This table reports the summary statistics of the bank data from Call Reports and FR Y-9C. The unit of observation is a bank-quarter combination. The sample period is from 2011 to 2017.

allow us to estimate the LCR for all banks. Panels A and B of Table 1 provide summary statistics of the bank data for LCR and non-LCR banks, respectively. Note that we define the LCR status as of 2012Q4. The sample period is from 2011Q1 to 2017Q4. The median liquidity ratio is 0.75 for LCR banks and 1.81 for non-LCR banks. Non-LCR banks, on average, maintain higher liquidity ratios because they are generally smaller and have poorer access to the funding market.

We complement the bank-level data with small business loan origination data collected under the Community Reinvestment Act (CRA). This data set contains information on small business lending at the bank-MSA-year level. The granularity of the data allows us to trace the spillover of liquidity regulation from LCR banks to non-LCR banks through local loan markets. This data set covers 751 banks in 361 MSA markets. The sample period is from 2011 to 2017. The unemployment rates are from the Bureau of Labor Statistics. Panels A and B of Table 2 report the summary statistics of this data set. During our sample period, the LCR banks experienced a −2.6% loan growth rate on average, while the non-LCR banks experienced a 6.5% loan growth rate.

Finally, we use mortgage data collected by the Home Mortgage Disclosure Act (HMDA). The data set includes the lender, loan type, purpose, loan amount, year of origination, and location information. We classify a loan as a conforming loan if the loan amount is less than the conforming limit. Otherwise, the loan is classified as a non-conforming loan. Then, we collapse the data to the bank level and compute the growth rate in conforming and non-conforming loans. Panels A and B of Table 3 report the summary statistics of this data set. The sample includes all mortgages, including those for home purchases or home refinances. The sample period is from 2011 to 2017.

3. Motivating evidence

3.1. Aggregate trends

We first examine the aggregate trends in the U.S. banking system during the implementation period of the LCR. As shown in Fig. 1(a), the average liquidity ratio of LCR banks was around 95% before the LCR. After the introduction of the LCR in 2013, the average liquidity ratio substantially increased and reached around 120% by the end of 2017. One may wonder why banks hold an additional liquidity buffer above the 100% minimum liquidity requirements. This behavior is reminiscent of banks' response to capital regulation: they usually maintain an additional buffer relative to the minimum requirement to avoid hitting the hard regulatory constraint when there is an unexpected shock.[9]

Banks can improve their liquidity ratios by increasing high-quality liquid assets or reducing unstable funding. Fig. 2(a) shows the high-quality liquid assets held by LCR banks and non-LCR banks, normalized by the level in 2013Q1, which is the quarter when the LCR was introduced. LCR banks increased their holdings of high-quality liquid assets by around 35% from 2013 to 2017. The total HQLAs held by the LCR have increased by more than $1 trillion since the implementation of the LCR. As a benchmark, the total government debt outstanding was $16.7 trillion as of 2013. The LCR thus constitutes an economically significant increase in the demand for HQLAs. In contrast to the massive increase in the holdings of HQLAs by LCR banks, the holdings of HQLAs by non-LCR banks stayed largely flat.

Fig. 2(b) compares the illiquid assets of LCR banks and non-LCR banks. A priori, it is unclear what would happen for illiquid assets because the LCR requirements do not explicitly constrain them. One possibility is that LCR banks can become LCR-compliant by increasing the quantity of HQLAs and decreasing the run-prone short-term debt while keeping illiquid assets intact. The other possibility is that increased liquid assets may crowd out illiquid assets if banks face certain balance sheet capacity limits. Consistent with the "crowding-out hypothesis," Fig. 2(b) shows that LCR banks' illiquid assets appear to grow significantly slower than non-LCR banks.

[9] The result is robust if we consider the asset-weighted average liquidity ratio, as shown in Figure OA.2.

Table 2
Summary Statistics of the CRA Loan Origination Data.

Panel A: LCR banks

	mean	sd	p5	p25	p50	p75	p95
Loan growth	-0.026	0.868	-1.524	-0.581	-0.027	0.481	1.600
LCR-bank share	0.501	0.200	0.165	0.359	0.506	0.647	0.827
Stress-test-bank share	0.645	0.197	0.263	0.515	0.681	0.795	0.917
Log Assets	19.380	1.244	17.713	18.335	19.117	20.959	21.425
Non-interest income	0.018	0.011	0.007	0.011	0.017	0.020	0.057
Mortgage share	0.238	0.136	0.000	0.148	0.250	0.319	0.424
Comm. loan share	0.158	0.102	0.003	0.096	0.136	0.198	0.410
Leverage	0.096	0.020	0.077	0.084	0.091	0.102	0.136
Leverage (risk-weighted)	0.545	0.437	0.101	0.119	0.201	1.000	1.000
CCAR	0.946	0.226	0.000	1.000	1.000	1.000	1.000
GSIB	0.264	0.441	0.000	0.000	0.000	1.000	1.000
SLR	0.150	0.357	0.000	0.000	0.000	0.000	1.000

Panel B: Non-LCR banks

	mean	sd	p5	p25	p50	p75	p95
Loan growth	0.060	0.994	-1.669	-0.612	0.002	0.750	1.778
LCR-bank share	0.503	0.195	0.167	0.359	0.517	0.649	0.799
Stress-test-bank share	0.653	0.187	0.279	0.535	0.696	0.795	0.905
Log Assets	15.635	1.205	13.777	14.571	15.684	16.720	17.448
Non-interest income	0.014	0.012	0.002	0.006	0.011	0.017	0.052
Mortgage share	0.386	0.180	0.001	0.271	0.415	0.518	0.635
Comm. loan share	0.185	0.166	0.031	0.078	0.124	0.235	0.580
Leverage	0.101	0.027	0.073	0.086	0.094	0.110	0.158
Leverage (risk-weighted)	0.837	0.337	0.111	1.000	1.000	1.000	1.000
CCAR	0.016	0.124	0.000	0.000	0.000	0.000	0.000
GSIB	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SLR	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Note: This table reports the summary statistics of the CRA data. The unit of observation is a bank-MSA-year combination. The sample period is from 2011 to 2017.

Table 3
Summary Statistics of the Mortgage Loan Origination Data.

Panel A: LCR banks

	mean	sd	p5	p25	p50	p75	p95
Jumbo growth	0.055	0.646	-1.071	-0.356	0.061	0.481	1.127
Conforming growth	-0.130	0.687	-1.276	-0.481	-0.111	0.195	1.011
Log Assets	19.642	1.217	18.054	18.621	19.367	21.037	21.455
Non-interest income	0.017	0.005	0.008	0.013	0.017	0.021	0.025
Mortgage share	0.268	0.104	0.108	0.190	0.277	0.329	0.421
CI loan share	0.144	0.065	0.061	0.102	0.130	0.190	0.262
Leverage	0.091	0.015	0.070	0.083	0.089	0.097	0.115
Leverage (risk-weighted)	0.561	0.440	0.098	0.117	1.000	1.000	1.000
CCAR	0.991	0.089	1.000	1.000	1.000	1.000	1.000
GSIB	0.378	0.485	0.000	0.000	0.000	1.000	1.000
SLR	0.137	0.308	0.000	0.000	0.000	0.000	1.000

Panel B: Non-LCR banks

	mean	sd	p5	p25	p50	p75	p95
Jumbo growth	0.103	0.712	-1.113	-0.374	0.083	0.618	1.277
Conforming growth	0.046	0.770	-1.250	-0.355	0.023	0.424	1.515
Log Assets	14.426	1.637	12.064	13.168	14.086	15.758	17.239
Non-interest income	0.014	0.014	0.002	0.006	0.009	0.015	0.057
Mortgage share	0.507	0.152	0.229	0.417	0.516	0.610	0.734
CI loan share	0.106	0.073	0.023	0.054	0.089	0.140	0.244
Leverage	0.096	0.019	0.072	0.085	0.093	0.104	0.129
Leverage (risk-weighted)	0.902	0.273	0.127	1.000	1.000	1.000	1.000
CCAR	0.001	0.014	0.000	0.000	0.000	0.000	0.000
GSIB	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SLR	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Note: This table reports the summary statistics of the HMDA data. The unit of observation is a bank-MSA-year combination. The sample period is from 2011 to 2017.

Next, we turn our attention to the liability side. Fig. 2(c) shows deposits of LCR banks and non-LCR banks, respectively. Deposits are generally treated as stable funding sources in the LCR because of the deposit insurance. Surprisingly, we find that deposits of LCR banks did not expand much faster than non-LCR banks. This result could be explained by the fact that deposits are sticky, so banks did not use them as the main margin of adjustment. Fig. 2(d) shows the wholesale funding of LCR banks and non-LCR banks, respectively. After the LCR, LCR banks' wholesale funding grows slower than the non-LCR banks, which is consistent with the fact that unstable funding receives higher run-off rates in the LCR rules.

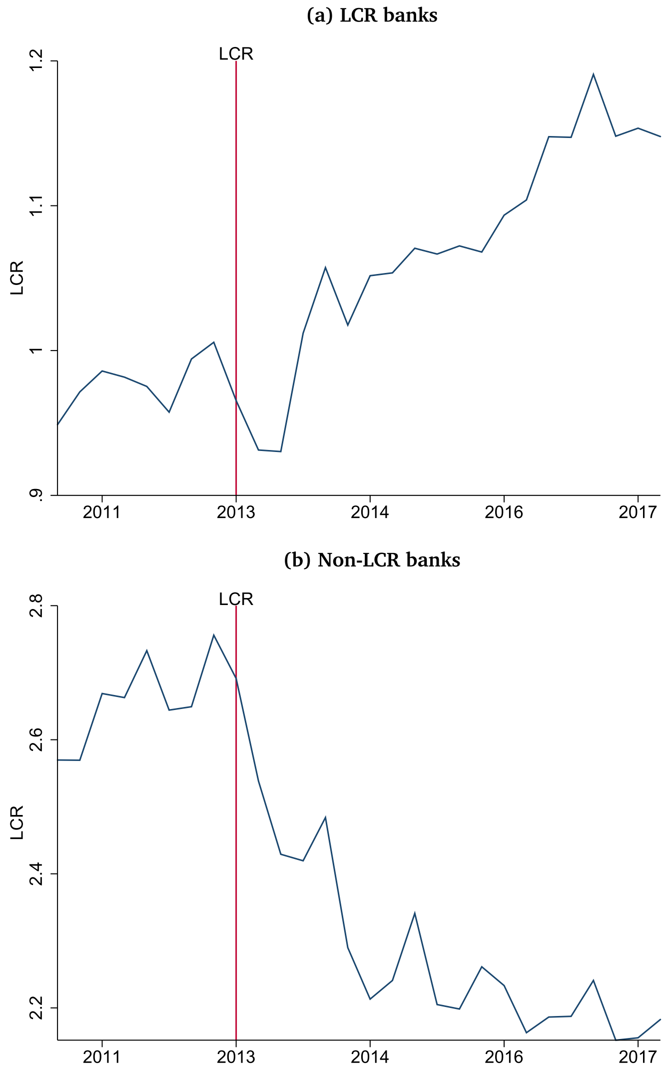

Fig. 1. Liquidity Coverage Ratio of U.S. Banks. This figure plots the liquidity coverage ratios of LCR banks and non-LCR banks. The vertical line indicates 2013Q1, the start of the post-liquidity regulation period. The sample period is from 2011 to 2017. Data source: Call Reports, FR Y-9C. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

While the liquidity ratios of LCR banks have significantly improved, the liquidity ratios of non-LCR banks appear to have deteriorated since the introduction of the LCR, as shown in Fig. 1(b). The deterioration of liquidity ratios of non-LCR banks is consistent with the rapid growth of illiquid assets and unstable funding, as shown in Fig. 2. Note that the LCR banks control around 80% of the assets, so the overall liquidity ratio of the banking sector still improves. However, because non-LCR banks are generally smaller and have poorer access to the funding market, the deterioration in their liquidity ratios could increase the liquidity risks of these institutions even if the average liquidity ratio of non-LCR banks is still higher than that of the LCR banks. Furthermore, the migration of liquidity risks may potentially compromise the goal of reducing the aggregate liquidity risks of the whole banking system.

3.2. Micro-level evidence

The aggregate trends presented in the previous section are revealing. However, many confounding policy changes also occurred at the same time as liquidity regulation. Therefore, this section uses micro-level data to identify the effects of post-crisis liquidity regulation.

3.2.1. High-quality liquid assets of LCR banks

When analyzing the aggregate trends in Section 3.1, we compare LCR banks with non-LCR banks. One concern about this comparison is that LCR banks are generally much larger than non-LCR banks, and therefore the differences between these two groups of banks could be attributed to factors other than liquidity regulation. To address this concern, we exploit the variation in the regulatory exposure *within* LCR banks to identify the effect of liquidity regulation in a spirit similar to Cortés et al. (2020). We construct a *liquidity ratio gap*$_i$ for each bank, defined as the following:

$$\textit{Liquidity ratio gap}_i = \textit{Required ratio}_i - \textit{Pre-regulation ratio}_i, \tag{4}$$

where *Required ratio* is 100% for banks with assets above \$250 billion and 70% for banks with assets between \$50 billion and \$250 billion, *Pre-regulation ratio*$_i$ is the liquidity ratio in 2012Q4, the last quarter before the introduction of the LCR. Using the pre-regulation ratio alleviates the concern that the outcome variables could be mechanically correlated with the treatment variable.

A trade-off of using *liquidity ratio gap* as the treatment variable is that the sample is restricted to a panel of 30 LCR banks. The small number of banks is a typical constraint for studies of post-crisis regulations because these regulations mostly target big banks.[10] Another caveat is that measuring banks' liquidity ratio could be subject to measurement errors, which may bias against us finding significant results.[11]

We first examine the effect of liquidity regulation on the HQLAs of LCR banks. The regression model is the following:

$$HQLA_{i,t} = \beta Post_t * Liquidity\ ratio\ gap_i + \gamma X_{i,t} + \tau_t + \tau_i + \epsilon_{i,t}. \tag{5}$$

$HQLA$ is the growth rate of high-quality liquid assets.[12] *Post* is a dummy variable that equals one if the time is after 2013Q1. The sample period is from 2011Q1 to 2017Q4. To control for banks' exposure to other regulations, we include the following control variables, $X_{i,t}$: (1) leverage ratios (based on both risk-weighted and unweighted assets); (2) an indicator for whether the bank is subject to the supplementary leverage ratio (SLR) requirement; (3) an indicator for whether the bank is subject to CCAR stress tests; and (4) an indicator for whether a bank is a global systemically important banks (GSIB). Furthermore, the exposure to liquidity regulation may correlate with banks' business model, such as the mix of investment banking versus commercial banking. Therefore, we use the non-interest income normalized by asset as a proxy for banks' business model. Note that the interaction of these controls with the "post" dummy are also included to control for possible differential trends for banks with different characteristics. Next, we include bank fixed effects to absorb unobservable time-invariant bank characteristics and time fixed effects to absorb macroeconomic shocks. Finally, we include category-time fixed effects, where "category" indicates whether the bank's size is between \$50 billion and \$250 billion or is above \$250 billion. The former group is required to have an LCR of 70%, while for the latter, it is 100%, so mechanically *liquidity ratio gap* could be bigger for the latter. We include these category-time fixed effects to avoid *Post*Liquidity ratio gap* from picking up how banks of different sizes trend differently.

Table 4 shows the results. We find that a 10% higher gap between the pre-regulation liquidity ratio and the required level is associated with a 3.1% higher growth rate in high-quality liquid assets after the LCR introduction based on column (1). Moreover, the magnitudes are

[10] For instance, Cortés et al. (2020) study 28 banks that are subject to stress testing. Correa et al. (2020) study six U.S. global systemically important banks covered by the Complex Institution Liquidity Monitoring Report, FR2052a.

[11] Our results are robust to an alternative identification strategy that compares LCR banks with non-LCR banks in a difference-in-differences regression. See Online Appendix Table OA.4.

[12] The results are robust using the share of assets as the dependent variable as shown in the Online Appendix Table OA.5.

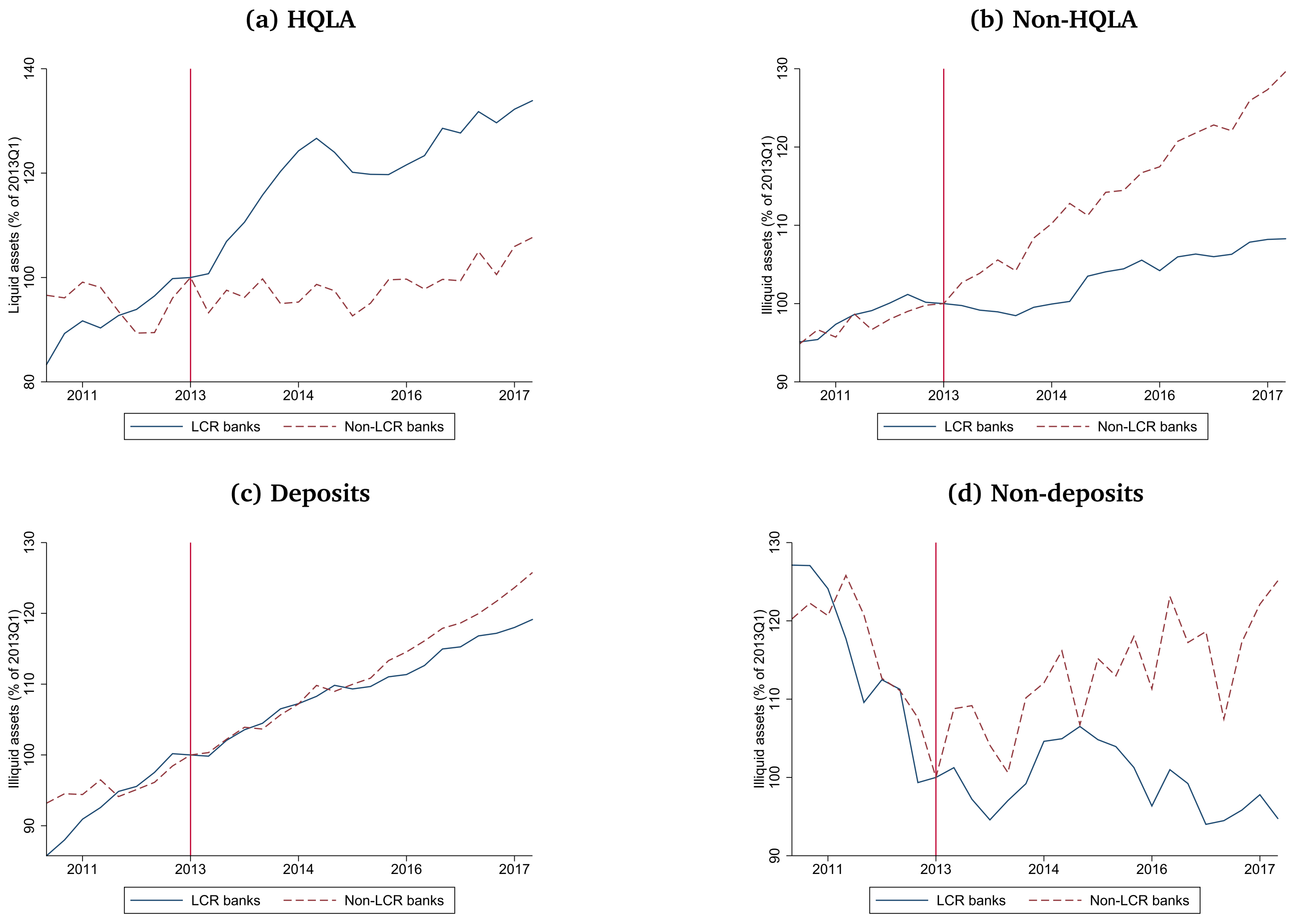

Fig. 2. U.S. Bank Balance Sheets During the LCR Implementation. This figure shows the composition of U.S. bank balance sheets over time. The solid blue line presents LCR banks, and the red dashed line represents non-LCR banks. The vertical line indicates 2013Q1, which is the start of the post-liquidity regulation period. High-quality liquid assets include cash, central bank reserves, government securities, GSE securities, corporate and municipal bonds, and Russell 1000 equities. The non-HQLAs include loans, derivatives, and real estate holdings. The sample period is from 2011 to 2017. Data source: Call Reports, FR Y-9C.

robust when more fixed effects are included in the regression as shown in columns (2) and (3). Furthermore, it's worth noting that the coefficient of the interaction between the "Post" and "Leverage" variables is negative and significant. This suggests that the increase of HQLAs appears to be restricted by the available balance sheet space, a constraint that becomes particularly acute for banks with high leverage.

Next, we estimate the dynamic treatment effects of liquidity regulation on the fraction of HQLAs over assets. We augment the empirical model (5) with interactions of the treatment variables and indicators for each quarter in the sample period. Fig. 3 plots the estimated coefficients. Banks trended similarly before the regulation, but started to diverge after the introduction of the LCR. This result alleviates the concern that unobservable time trends are causing the change.

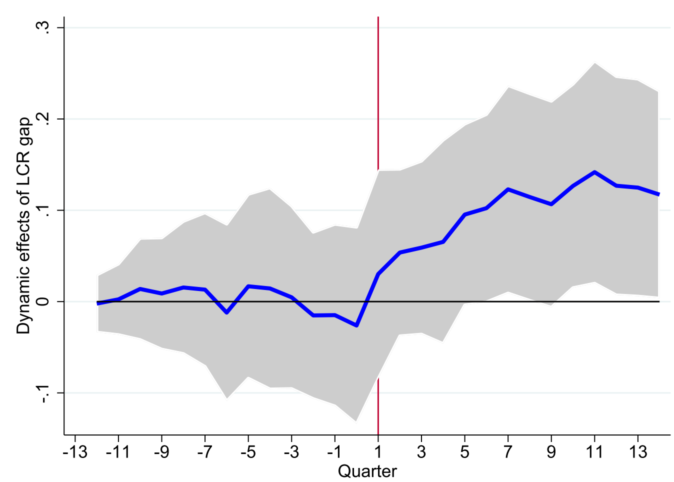

Fig. 3. Dynamic Effects of the Liquidity Regulation on HQLAs. This figure plots the estimates of the LCR gap interacting with indicators for each quarter. The sample includes only LCR banks. The vertical line indicates 2013Q1, which is the start of the post-liquidity regulation period. Data source: Call Reports, FR Y-9C.

3.2.2. *Illiquid assets of LCR banks*

Although the LCR has increased banks' holding of high-quality liquid assets, it may crowd out banks' illiquid assets. To test this hypothesis, we estimate regression model (5) for illiquid assets and present the results in Table 5. Indeed, more-exposed banks experienced lower growth rates in illiquid assets after the LCR introduction. A 10% higher gap between the pre-regulation liquidity ratio and the required level is associated with a 0.8% lower growth rate in illiquid assets after the LCR introduction based on column (1). The effects are robust to controlling for bank fixed effects, time fixed effects, and banks' exposure to capital regulation.

The change in LCR banks' illiquid assets, which mainly consist of loans, could be driven by changes in either loan supply or loan demand. Therefore, we control for various bank characteristics that may correlate with loan demand, such as bank business model and size. Still, the liquidity ratio gap could correlate with unobservable variations in

Table 4
LCR Banks' HQLAs Holdings.

	(1) HQLA	(2) HQLA	(3) HQLA
Post * Liquidity ratio gap	0.307***	0.372***	0.369***
	[0.107]	[0.131]	[0.120]
Post * Non-interest income	0.163	-1.544	-1.673
	[2.778]	[2.903]	[3.013]
Post * Leverage	-2.581**	-3.089**	-3.081*
	[1.239]	[1.508]	[1.571]
Post * Leverage (risk-weighted)	0.254*	0.110	0.132
	[0.137]	[0.114]	[0.122]
Post * CCAR	0.102	0.053	0.048
	[0.159]	[0.170]	[0.170]
Post * GSIB	-0.142*	-0.046	-0.050
	[0.082]	[0.095]	[0.118]
Post * SLR	-0.017	0.042	0.062
	[0.030]	[0.041]	[0.085]
Control	Yes	Yes	Yes
Bank F.E.	Yes	Yes	Yes
Time F.E.	No	Yes	No
Category-Time F.E.	No	No	Yes
Observations	832	832	832
Adj. R-squared	0.275	0.291	0.275

Note: This table shows the effect of liquidity regulation on LCR banks' asset holdings. The sample includes banks with assets above \$50 billion from 2011Q1 to 2017Q4. The dependent variable is the growth rates of high-quality liquid assets. *Post* is a dummy variable that equals one if the time is after 2013Q1. *Liquidity ratio gap* is the difference between the required liquidity ratio and the pre-regulation liquidity ratio. *Non-interest income* is the non-interest income normalized by assets. *Leverage* is the leverage ratio with unweighted assets. *Leverage (risk-weighted)* is the leverage ratio with risk-weighted assets. *CCAR* is a dummy variable that equals one if a bank is subject to CCAR stress tests, and zero otherwise. *GSIB* is a dummy variable that equals one if a bank is a global systemically important bank, and zero otherwise. *SLR* is a dummy variable that equals one if a bank is subject to the supplementary leverage ratio requirement, and zero otherwise. The control variables also include log assets, the share of real estate loans, and the share of commercial and industrial loans. Standard errors shown in parentheses are clustered at the bank level. ***, **, and * represent 1%, 5%, and 10% significance levels, respectively.

Table 5
LCR Banks' Illiquid Assets Holdings.

	(1) Illiquid assets	(2) Illiquid assets	(3) Illiquid assets
Post * Liquidity ratio gap	-0.084***	-0.055*	-0.061*
	[0.022]	[0.027]	[0.030]
Post * Non-interest income	-0.256	-0.726	-0.593
	[0.717]	[0.643]	[0.619]
Post * Leverage	-0.451*	-0.292	-0.333
	[0.221]	[0.308]	[0.315]
Post * Leverage (risk-weighted)	0.038**	0.013	0.012
	[0.015]	[0.018]	[0.020]
Post * CCAR	-0.058	-0.050	-0.043
	[0.048]	[0.041]	[0.043]
Post * GSIB	-0.001	0.026	0.031
	[0.019]	[0.033]	[0.033]
Post * SLR	-0.016**	0.005	-0.010
	[0.007]	[0.009]	[0.012]
Control	Yes	Yes	Yes
Bank F.E.	Yes	Yes	Yes
Time F.E.	No	Yes	No
Category-Time F.E.	No	No	Yes
Observations	832	832	832
Adj. R-squared	0.339	0.417	0.403

Note: This table shows the effect of liquidity regulation on LCR banks' asset holdings. The sample includes banks with assets above \$50 billion from 2011Q1 to 2017Q4. The dependent variable is the growth rates of illiquid assets. *Post* is a dummy variable that equals one if the time is after 2013Q1. *Liquidity ratio gap* is the difference between the required liquidity ratio and the pre-regulation liquidity ratio. *Non-interest income* is the non-interest income normalized by assets. *Leverage* is the leverage ratio with unweighted assets. *Leverage (risk-weighted)* is the leverage ratio with risk-weighted assets. *CCAR* is a dummy variable that equals one if a bank is subject to CCAR stress tests, and zero otherwise. *GSIB* is a dummy variable that equals one if a bank is a global systemically important bank, and zero otherwise. *SLR* is a dummy variable that equals one if a bank is subject to the supplementary leverage ratio requirement, and zero otherwise. The control variables also include log assets, the share of real estate loans, and the share of commercial and industrial loans. *Category* indicates whether a bank is subject to full LCR or modified LCR. Standard errors shown in parentheses are clustered at the bank level. ***, **, and * represent 1%, 5%, and 10% significance levels, respectively.

loan demand even after controlling for these characteristics. To sharpen the identification, we exploit two more granular data sets.

First, we use small business lending data from the CRA. This data set provides small business loan origination information at the bank-MSA-year level. We follow the identification strategy of Cortés et al. (2020) to include MSA-year fixed effects to absorb the time-varying local demand shocks. This test essentially compares two LCR banks in the same MSA market and the same year with different pre-LCR liquidity ratio gaps. Specifically, the regression model is the following:

$$Loans_{i,m,t} = \beta Post_t * Liquidity\ ratio\ gap_i + \gamma X_{i,m,t} + \tau_i + \tau_{m,t} + \epsilon_{i,t}, \tag{6}$$

where $Loans_{i,m,t}$ is the annual growth rate of loans of bank i in MSA m in year t; $Post_t$ is a dummy variable that equals one if the time is after 2013. The sample includes only LCR banks, so the regression exploits the variations in the regulatory exposure *within* LCR banks. The sample period is from 2011 to 2017. $X_{i,m,t}$ is a set of control variables as in equation (5) to control for different exposure to other regulations and banks' business models. $\tau_{m,t}$ is the MSA-year fixed effect. Table 6 shows the results. We find that lending decreases more for banks that are more exposed to the LCR. The effects are economically significant: a 10% higher gap between the pre-regulation liquidity ratio and the required level leads to 10% lower annual loan growth rates after the introduction of the LCR based on column (1). The results are robust to adding various fixed effects. Our findings are related to Chen et al. (2017), who document that small business lending by the four largest banks fell sharply relative to others after the global financial crisis in 2008. We document an additional decline in lending for LCR banks after the 2013 implementing of the LCR.

Second, we use mortgage lending data from the HMDA. The mortgage data allow us to exploit the different likelihood of securitization between conforming and non-conforming mortgages. Because conforming mortgages are typically securitized and sold, the LCR would not be expected to constrain lending in the conforming mortgage segment. In contrast, non-conforming mortgages usually stay on bank balance sheets. Thus the LCR would have a crowding-out effect similar to that for small business lending. To test this hypothesis, we repeat regression (6) for conforming and non-conforming mortgages separately. The sample includes only LCR banks, so the regression exploits the variations in the regulatory exposure *within* LCR banks. We also included MSA-time fixed effects to absorb the variation in local demand, following Cortés et al. (2020). Table 7 shows the results. Consistent with our hypothesis, the LCR appears only to reduce the non-conforming mortgages: a 10% higher gap between the pre-regulation liquidity ratio and the required level leads to 3%–5% lower annual non-conforming mortgage growth rates after the introduction of the LCR, as shown in columns (1) and (2). We do not find any significant differences in lending in the conforming mortgage market across banks with different liquidity ratio gaps, as shown in columns (3) and (4). These results further confirm our findings in the small business loan market that the LCR has a crowding-out effect on bank lending that uses bank balance sheet capacity.

Table 6
Small Business Lending of LCR Banks.

	(1) Loans	(2) Loans	(3) Loans
Post * Liquidity ratio gap	-1.001***	-1.008***	-1.056***
	[0.320]	[0.317]	[0.319]
Post * Non-interest income	-2.588	-1.999	-3.656
	[8.181]	[7.971]	[8.180]
Post * Leverage	-1.422	-1.313	-1.614
	[3.483]	[3.495]	[3.885]
Post * Leverage (risk-weighted)	0.055	0.070	0.109
	[0.265]	[0.256]	[0.256]
Post * CCAR	0.119	0.167	0.123
	[0.333]	[0.345]	[0.379]
Post * GSIB	-0.655**	-0.657**	-0.746**
	[0.308]	[0.312]	[0.322]
Post * SLR	0.107	0.124	0.141
	[0.104]	[0.101]	[0.109]
Control	Yes	Yes	Yes
Bank F.E.	Yes	Yes	No
MSA F.E.	Yes	No	No
Time F.E.	Yes	No	No
MSA-Time F.E.	No	Yes	Yes
MSA-Bank F.E.	No	No	Yes
Observations	34,051	34,051	33,145
Adj. R-squared	0.075	0.079	0.036

Note: This table shows the effect of liquidity regulation on LCR banks' CRA lending. The sample includes banks with assets above $50 billion from 2011Q1 to 2017Q4. The dependent variable is the growth rate of small business loans. $Post$ is a dummy variable that equals one if the time is after 2013Q1. *Liquidity ratio gap* is the difference between the required liquidity ratio and the pre-regulation liquidity ratio. *Non-interest income* is the non-interest income normalized by assets. *Leverage* is the leverage ratio with unweighted assets. *Leverage (risk-weighted)* is the leverage ratio with risk-weighted assets. *CCAR* is a dummy variable that equals one if a bank is subject to CCAR stress tests, and zero otherwise. *GSIB* is a dummy variable that equals one if a bank is a global systemically important bank, and zero otherwise. *SLR* is a dummy variable that equals one if a bank is subject to the supplementary leverage ratio requirement, and zero otherwise. The control variables also include log assets, the share of real estate loans, and the share of commercial and industrial loans. Standard errors shown in parentheses are clustered at both the MSA and the bank level. ***, **, and * represent 1%, 5%, and 10% significance levels, respectively.

3.2.3. Spillover effects on non-LCR banks

In this section, we study the spillover effects of liquidity regulation on non-LCR banks. As shown in Fig. 1(b), the average liquidity coverage ratio of non-LCR banks has deteriorated substantially since the introduction of the LCR. We hypothesize that, as LCR banks shed their illiquid loans to hold more high-quality liquid assets, non-LCR banks may respond by expanding their lending. To test this hypothesis, we exploit geographical variations in the presence of LCR banks. Specifically, we calculate the *LCR-bank share* in a metropolitan statistical area (MSA), defined as the total CRA loans of LCR banks within the MSA over the total CRA loans of all commercial banks within the same district. We use the loans in the final year of the pre-LCR period to compute the *LCR-bank share*:

$$\textit{LCR-bank share}_m = \frac{\sum_j \textit{LCR bank}_j \times \textit{Loans}_{m,j}}{\sum_j \textit{Loans}_{m,j}}, \tag{7}$$

where $Loans_{m,j}$ is the loans of bank j in MSA m, and $\textit{LCR bank}_j$ is a dummy variable that equals one if the bank is an LCR bank. We estimate the following regression model in the sample of non-LCR banks:

$$Loan_{i,m,t} = \beta Post_t * \textit{LCR-bank share}_m + \gamma X_{i,m,t} + \tau_{i,t} + \tau_m + \epsilon_{i,m,t}, \tag{8}$$

where $Loan_{i,m,t}$ is the annual growth rate of loans of bank i in MSA m in year t. The sample includes the non-LCR banks in the CRA data from 2011 to 2017. We include MSA fixed effects to absorb the time-invariant local market characteristics. We also include bank-year fixed effects, which absorb any time-varying supply shocks at the bank level. Therefore, the identification is obtained by comparing the lending of the same non-LCR banks in two MSAs with different LCR-bank shares.

Panel A of Table 8 shows the results: non-LCR banks have significantly expanded lending in regions formerly more reliant on LCR banks. Moreover, the effects are economically significant: a 10% higher LCR-bank share before the regulation is associated with a 3% higher loan growth rate after the introduction of the LCR, as shown in column (1). The results are also robust to controlling for MSA fixed effects, local stress-test-bank share, local unemployment rates, and their interactions with *Post* dummy, as shown in columns (2) and (3), respectively.

Although the increase in lending by non-LCR banks cushions the impact of liquidity regulation on loan supply, it may lead to a deterioration in the liquidity of non-LCR banks. To test this hypothesis, we measure non-LCR banks' exposure to liquidity regulation through their geographical overlaps with LCR banks using the following measure:

$$\textit{Average LCR-bank share}_i = \frac{\sum_m \textit{LCR-bank share}_m \times \textit{Loans}_{m,i}}{\sum_m \textit{Loans}_{m,i}}, \tag{9}$$

where $\textit{LCR-bank share}_m$ is defined in equation (7). $Loans_{m,i}$ is the loans originated by non-LCR bank i in MSA m. We use the loans in the final year of the pre-LCR period to compute this variable. Intuitively, a non-LCR bank is more exposed to liquidity regulation if it has more LCR banks in its operating markets. We then estimate the following regression model in the sample of non-LCR banks:

$$Liquidity_{i,t} = \beta Post_t * \textit{Average LCR-bank share}_i + \gamma X_{i,t} + \tau_t + \tau_i + \epsilon_{i,t}, \tag{10}$$

where $Liquidity_{i,t}$ is measured by the liquidity coverage ratios of non-LCR banks. Panel B of Table 8 shows the results. The more exposed non-LCR banks' liquidity ratios have deteriorated more than their less exposed peers. A 10% increase in the average LCR-bank share in the markets in which a non-LCR bank operated before the LCR is associated with a 5% decrease in the liquidity ratios after the LCR introduction, as shown in column (1). The results are also robust to controlling for bank fixed effects, the local stress-test-bank share, and its interaction with the *Post* dummy, as shown in columns (2) and (3), respectively. The result shows that some liquidity risks have migrated from LCR banks to non-LCR banks.

The migration effect seems to stem from inconsistent regulation across banks. It might raise the question as to why larger banks are subject to the LCR, while smaller banks are exempt. Several explanations could account for this. Firstly, the externalities of illiquidity may be more severe for larger financial institutions, necessitating stricter regulatory measures. Secondly, the costs of compliance could potentially be higher for smaller banks, making exemptions more practical. A third explanation could hinge on the "too big to fail" perception often associated with larger banks, which allows them to transform liquidity at lower costs. Evidence of this can be seen in the average liquidity ratios, which are noticeably lower for larger banks compared to smaller ones. Given this scenario, the blanket application of the LCR to small banks might not necessarily curb migration, as these regulations would not be binding.

4. Model

The above empirical analysis shows that post-crisis liquidity regulation has reduced the liquidity risks of regulated banks. However, it has also constrained LCR banks' lending and led to a migration of liquidity transformation from LCR banks to non-LCR banks. These empirical findings raise important questions on the welfare implications.

In this section, we present a model to conceptualize our findings. The model differs from the existing work on liquidity regulation in two dimensions. First, the existing models often assume the liquidity

Table 7
Mortgage Lending of LCR Banks.

	(1) Non-conforming	(2) Non-conforming	(3) Conforming	(4) Conforming
Post * Liquidity ratio gap	-0.313**	-0.474**	0.095	0.305
	[0.136]	[0.207]	[0.109]	[0.216]
Post * Non-interest income		6.671		-4.777
		[8.552]		[9.283]
Post * Leverage		-2.324		-3.005
		[3.254]		[4.159]
Post * Leverage (risk-weighted)		0.180		-0.714*
		[0.303]		[0.392]
Post * CCAR		-0.790*		-0.559
		[0.435]		[0.490]
Post * GSIB		-0.054		0.089
		[0.090]		[0.145]
Post * SLR		-0.199*		-0.013
		[0.110]		[0.117]
Control	No	Yes	No	Yes
MSA-Time F.E.	Yes	Yes	Yes	Yes
MSA-Bank F.E.	Yes	Yes	Yes	Yes
Observations	16,790	16,790	16,356	16,356
Adj. R-squared	-0.074	-0.064	0.114	0.127

Note: This table shows the effect of liquidity regulation on LCR banks' mortgage lending. The sample includes banks with assets above $50 billion from 2011Q1 to 2017Q4. The dependent variables are the growth rate of non-conforming mortgages (columns 1–2) and conforming mortgages (columns 3–4). *Post* is a dummy variable that equals one if the time is after 2013Q1. *Liquidity ratio gap* is the difference between the required liquidity ratio and the pre-regulation liquidity ratio. *Non-interest income* is the non-interest income normalized by assets. *Leverage* is the leverage ratio with unweighted assets. *Leverage (risk-weighted)* is the leverage ratio with risk-weighted assets. *CCAR* is a dummy variable that equals one if a bank is subject to CCAR stress tests, and zero otherwise. *GSIB* is a dummy variable that equals one if a bank is a global systemically important bank, and zero otherwise. *SLR* is a dummy variable that equals one if a bank is subject to the supplementary leverage ratio requirement, and zero otherwise. The control variables also include log assets, the share of real estate loans, and the share of commercial and industrial loans. Standard errors shown in parentheses are clustered at both the MSA and the bank level. ***, **, and * represent 1%, 5%, and 10% significance levels, respectively.

premium is exogenous, while we endogenize the liquidity premium to analyze the general equilibrium effects of liquidity regulation. As a trade-off, we do not delve into the microfoundation of the externality of liquidity transformation. Instead, we take it as given and analyze its implications on liquidity regulation. One could micro-found such externality using models of firesale externality. Second, the existing models of liquidity regulation often focus on regulated banks.[13] Our model introduces intermediaries not subject to liquidity regulation to study the endogenous migration of liquidity transformation.[14]

4.1. Setting

There are three dates, $T = 0$, 1, and 2. At date 0, intermediaries decide the assets and liabilities. On the asset side, intermediaries hold i units of illiquid assets and l units of government securities as a liquidity buffer. The return of illiquid assets at date 2 is r. The return of the liquid assets at date 2 is $r - p$, while p is the liquidity premium endogenously determined in the equilibrium.

Intermediaries issue short-term debt d to finance the balance sheets.[15] The short-term debt carries the liquidity premium, p, so the funding cost of issuing short-term debt is $r - p$. Intermediaries also incur a convex issuance cost, $c(d)$, where $c' > 0$ and $c'' > 0$. In the following analysis, we assume that the issuance cost takes a quadratic form, $c(d) = \frac{1}{2}\gamma d^2$.

Issuing short-term debt, however, makes intermediaries susceptible to liquidity risks as a random fraction of short-term creditors $\tilde{\alpha}$ may withdraw their funds at date 1 before the illiquid assets mature. If the liquidity buffer of an intermediary is less than the early withdrawals, $l < \tilde{\alpha} d$, then the bank needs to liquidate $\tilde{\alpha} d - l$ of illiquid assets at a liquidation cost of ϕ. The early liquidation also imposes an externality η on society. This externality can be micro-founded by the pecuniary externality of the firesale. We assume the random withdrawal follows a binary distribution.[16] With probability $1 - \mu$, the good state occurs, and $a < 1$ short-term creditors want to withdraw early. With probability μ, the bad state occurs, and all short-term creditors want to withdraw early. We assume the following regularity condition holds: $\phi > p > \mu\phi$, $\phi + \eta > p > \mu(\phi + \eta)$, which ensures that intermediaries will not only hold illiquid assets or only hold liquid assets.

Because intermediaries do not internalize the fire-sale externality, there will be an excessive liquidity transformation in the economy. To address this market failure, regulators impose the LCR requirement, which requires banks to hold a fixed fraction of liquidity buffer for each dollar of short-term debt: $l \geq \rho d$. We refer to ρ as the "required liquidity ratio". ρ also corresponds to the "run-off rate" following the terminology of the LCR. We assume the LCR is binding, so $\rho > a$. This liquidity rule is akin to a quantity-based regulation in Weitzman (1974). We assume that a fraction w of banks is subject to the LCR, while $1 - w$ does not. We use subscript 1 to indicate regulated banks and subscript 0 to

[13] There is a large literature studying the unregulated intermediaries concerning capital regulation, such as Plantin (2015) and Begenau and Landvoigt (2020). However, models on liquidity regulation that feature unregulated intermediaries are still rare, with the notable exception of Hachem and Song (2021).

[14] Our empirical analysis studies non-LCR banks. However, one can also consider shadow banks and government-sponsored enterprises as entities that can conduct liquidity transformation but are not subject to liquidity regulation.

[15] The results are similar if we introduce stable funding sources such as long-term debt, insured deposits, and equity in addition to short-term debt.

[16] We allow the random withdrawal to follow a general continuous distribution in Appendix A.5.

Table 8
The Spillover Liquidity Regulation to Non-LCR Banks.

Panel A: Lending

	(1) Loan growth	(2) Loan growth	(3) Loan growth
Post * LCR-bank share	0.293***	0.306***	0.334***
	[0.061]	[0.061]	[0.087]
Control	No	No	Yes
MSA F.E.	No	Yes	Yes
Bank-Time F.E.	Yes	Yes	Yes
Observations	49,193	49,193	49,193
Adj. R-squared	0.098	0.097	0.097

Panel B: Liquidity ratio

	(1) Liquidity ratio	(2) Liquidity ratio	(3) Liquidity ratio
Post * LCR-bank share	-0.472**	-0.386*	-0.388*
	[0.206]	[0.197]	[0.201]
Control	No	No	Yes
Bank F.E.	No	Yes	Yes
Time F.E.	Yes	Yes	Yes
Observations	15,442	15,442	15,442
Adj. R-squared	0.801	0.815	0.816

Note: Panel A shows the spillover effect of liquidity regulation on the loan growth and liquidity ratio of non-LCR banks. The sample includes banks in the CRA data with assets below \$50 billion from 2011Q1 to 2017Q4. The dependent variable, *Loan growth*, is the growth rate in small business loan origination by bank i in MSA m at time t. $Post$ is a dummy variable that equals one if the time is after 2013Q1. *LCR-bank share* is defined as the share of loans originated by LCR banks in an MSA in 2012. Bank-time fixed effects and MSA fixed effects are added to the regressions, as shown in the table. Control variables include the local stress-test-bank share, local unemployment rates, and their interactions with *Post* dummy. Standard errors shown in parentheses are clustered at both the MSA level and the bank level. Panel B shows the spillover effect of liquidity regulation on the liquidity coverage ratio of non-LCR banks. The sample includes banks with assets below \$50 billion from 2011Q1 to 2017Q4. The dependent variable *Liquidity ratio* is the liquidity coverage ratio of bank i at time t. $Post$ is a dummy variable that equals one if the time is after 2013Q1. *LCR-bank share* is defined as the average share of LCR banks in the MSAs in which a non-LCR bank operates. Bank fixed and time fixed effects are added to the regressions, as shown in the table. Control variables include the local stress-test-bank share and the interaction with *Post* dummy. Standard errors shown in parentheses are clustered at the bank level. ***, **, and * represent 1%, 5%, and 10% significance levels, respectively.

indicate unregulated ones. The objective of regulated banks is the following:

$$\pi_1 = \max_{i_1, l_1, d_1} ri_1 + (r-p)l_1 - (r-p)d_1 - c(d_1) - \phi\mathbb{E}\left[\tilde{\alpha}d_1 - l_1\right]^+, \tag{11}$$

subject to

$$i_1 + l_1 = d_1, \tag{12}$$

$$l_1 \geq \rho d_1. \tag{13}$$

The objective of the unregulated intermediaries is similar to equation (11), except that they do not face the LCR requirement (13).

$$\pi_0 = \max_{i_0, l_0, d_0} ri_0 + (r-p)l_0 - (r-p)d_0 - c(d_0) - \phi\mathbb{E}\left[\tilde{\alpha}d_0 - l_0\right]^+, \tag{14}$$

subject to

$$i_0 + l_0 = d_0. \tag{15}$$

Assuming the total mass of intermediaries is 1, the aggregate short-term debt, liquidity buffer held by banks, and lending are given by

$$D = wd_1 + (1-w)d_0, \tag{16}$$

$$L = wl_1 + (1-w)l_0, \tag{17}$$

$$I = wi_1 + (1-w)i_0. \tag{18}$$

The liquidity premium is determined by an aggregate demand function for liquidity:

$$p = p(Q, \xi), \tag{19}$$

where Q is the total stock of liquid assets held by the representative household. An increase in Q lowers the liquidity premium that the representative household is willing to pay, so $p_Q < 0$. ξ is a random shock to the aggregate liquidity demand, $p_\xi > 0$. In the following quantitative analysis, we assume that the aggregate liquidity demand function is $p(Q,\xi) = \log\left(\xi Q^{-\frac{1}{\epsilon}}\right)$, where $\epsilon > 0$ is the elasticity of liquidity demand. The aggregate liquidity demand function can be derived from a standard macro-finance model in which a representative household derives convenience from holding liquid assets, such as Krishnamurthy and Vissing-Jorgensen (2012), Galí (2015), and Nagel (2016).[17]

4.2. Equilibrium

The equilibrium is defined as a set of quantities $i_1, l_1, d_1, i_0, l_0, d_0$ and liquidity premium p such that:

1. All banks optimally choose their balance sheets according to equations (11) and (14), taking the equilibrium liquidity premium, p, as given.
2. The equilibrium liquidity premium, p, adjusts such that the aggregate supply of liquidity equals the demand.

$$D - L + G = Q, \tag{20}$$

where $D - L$ is the aggregate net liquidity supply from the banking sector, G is the total government securities, which is exogenous, and Q is the aggregate demand for liquidity given by equation (19).

4.3. The laissez-faire equilibrium

We first discuss the laissez-faire equilibrium. Given the liquidation cost satisfies the following condition, $\phi > p > \mu\phi$, the private optimal quantity of government securities held by banks equals the expected withdrawal in the good state,

$$l = ad. \tag{21}$$

The private optimal lending is solved from the balance sheet capacity constraint,

$$i = (1-a)d. \tag{22}$$

Banks choose the private optimal short-term debt d that equalizes the private marginal benefit of supplying liquidity and the private marginal cost:

$$p = \underbrace{c' + (1-a)\mu\phi + ap}_{\text{Private marginal cost}}. \tag{23}$$

The left-hand side is the liquidity premium. The right-hand side is the marginal cost of liquidity transformation, which consists of the issuance cost c', the expected firesale cost $(1-a)\mu\phi$, and the opportunity cost of holding liquidity ap.

4.4. The first-best equilibrium

We now solve the first-best equilibrium as a benchmark, where banks internalize the externality of liquidity transformation when choosing the quantities of short-term debt and liquidity buffer. Given

[17] The details are in Appendix A.1.

the liquidation cost satisfies the following condition, $\phi+\eta > p > \mu(\phi+\eta)$, the socially optimal quantity of government securities held by banks equals the expected withdrawals in the good state,

$$l = ad. \tag{24}$$

Banks use $a < 1$ units of government securities to create one unit of short-term debt. We can define the liquidity multiplier of the banking system as the ratio between the aggregate liquidity supplied by banks and aggregate liquidity demanded by them, $\frac{D}{L}$. The liquidity multiplier in the socially optimal equilibrium is $\frac{1}{a}$. The socially optimal lending is solved from the balance sheet capacity constraint,

$$i = (1-a)d. \tag{25}$$

The socially optimal short-term debt equalizes the marginal social benefit of liquidity and the social marginal cost:

$$p = \underbrace{c' + (1-a)\mu\phi + ap}_{\text{Private marginal cost}} + \underbrace{(1-a)\mu\eta}_{\text{Externality}}. \tag{26}$$

Comparing equation (23) with equation (26), we can see excessive liquidity transformation in the laissez-faire equilibrium because banks do not internalize the social externality of liquidity transformation, $(1-a)\mu\eta$.

The following expression defines the social welfare of the liquidity market:

$$W \equiv \underbrace{\int_0^Q P(z,\xi)dz}_{\text{Value derived by households}} \underbrace{-(wc_1 + (1-w)c_0)}_{\text{Costs of issuing debt}} \underbrace{-(\phi+\eta)(w\mathbb{E}\left[\tilde{\alpha}d_1 - l_1\right]^+ + (1-w)\mathbb{E}\left[\tilde{\alpha}d_0 - l_0\right]^+)}_{\text{Expected social costs in meeting liquidity demands}}, \tag{27}$$

where the first term is the value derived by households from holding liquidity, the second term is the costs of issuing debt, and the third term is the expected social costs in meeting liquidity demand. It is easy to verify that social welfare is maximized in the first-best equilibrium.

Proposition 1. *A Pigovian tax on short-term debt can implement the first-best equilibrium with a tax rate equal to the social externality of liquidity transformation:*

$$\tau^{Pigovian} = (1-a)\mu\eta. \tag{28}$$

Proof. With the tax on liquidity transformation, the first-order condition of a bank is given by

$$p = \underbrace{c' + (1-a)\mu\phi + ap}_{\text{Private marginal cost}} + \underbrace{\tau}_{\text{Tax on liquidity transformation}}, \tag{29}$$

where the right-hand side is the after-tax marginal cost of liquidity transformation. Comparing equation (29) with equation (26), we can see that a tax rate of $(1-a)\mu\eta$ can force intermediaries to internalize the social externality. Furthermore, because this tax does not interact with other bank decisions, it implements the first best. □

Note that the liquidity rules implemented in practice are not formulated as a tax on short-term debt, at least not explicitly. Instead, they are devised as a quantity requirement on the liquidity buffer of banks, building on the "traditional liquidity coverage ratio" methodologies used internally by banks. Therefore, we would like to know to what extent the LCR requirement resembles the Pigovian tax and to what extent it differs.

4.5. Equilibrium with LCR requirement

Given the first-best benchmark, we discuss the equilibrium with the LCR requirement. We can show the following result:

Proposition 2. *The LCR imposes an implicit tax on liquidity transformation with the following tax rate:*

$$\tau^{LCR} = (\rho - a)(p - \mu\phi), \tag{30}$$

where $\rho - a$ is the liquidity buffer required by the regulation above the level that banks prefer to hold, $p - \mu\phi$ is the opportunity cost of holding a liquidity buffer adjusted for the benefits of reducing liquidation cost.

Proof. Under a binding LCR constraint, the first-order condition of a regulated bank is given by

$$p = \underbrace{c' + (1-a)\mu\phi + ap}_{\text{Private marginal cost}} + \underbrace{(\rho - a)(p - \mu\phi)}_{\text{Implicit tax}}, \tag{31}$$

where the right-hand side is the marginal cost of liquidity transformation with the LCR. Comparing equation (31) with equation (23), we can derive the effective tax rate imposed by the LCR as the difference. □

Proposition 2 shows that the LCR imposes an implicit tax on liquidity transformation by requiring banks to hold liquid assets, which generate lower returns than illiquid assets. This tax increases banks' marginal cost to conduct liquidity transformation so that it is more closely aligned with the social cost. The implicit tax of the LCR is increasing to the run-off rate, ρ. One may conjecture that if regulators set the run-off rate such that the implicit tax of the LCR equals the Pigovian tax in equation (28), then the LCR may achieve the first-best outcome. Unfortunately, this conjecture is untrue even if all intermediaries are subject to the LCR. The reason is that the implicit tax is implemented by a *quantity requirement on the liquid assets*.

4.5.1. Crowding-out effects

To simplify the discussion, we assume all banks are subject to the LCR requirement, $w = 1$. We can prove the following result:

Proposition 3. *The welfare under the LCR is lower than the first-best outcome for any run-off rate.*

Proof. See appendix A.2. □

Intuitively, the reason LCR cannot achieve the first-best outcome comes from the dual role of the liquidity buffer, L. It serves as an implicit tax to align banks' private cost of liquidity transformation with the social cost; it also serves as a costly mitigator of liquidity risks because it occupies banks' balance sheets and generates low returns. The dual role implies that regulators cannot adjust the implicit tax on liquidity transformation without affecting banks' capacity to lend. The regulators would like to reduce the excessive issuance of short-term debt, D. But to do so, the regulators would have to alter the equilibrium liquidity multiplier, $\frac{D}{L}$, which describes how efficiently banks use their balance sheets for liquidity transformation and lending. Note that the liquidity multiplier in the laissez-faire equilibrium is the same as the first-best equilibrium.[18] The LCR, however, changes the liquidity multiplier from $\frac{1}{a}$ to $\frac{1}{\rho}$, which leads to welfare distortion.

[18] Note that this result is only true when the random withdrawal follows a binary distribution. As shown in Section A.5, when the random withdrawal follows a continuous distribution, the share of liquid assets in the laissez-faire equilibrium will be generally smaller than that in the first-best equilibrium because banks do not internalize the firesale externality. However, the main

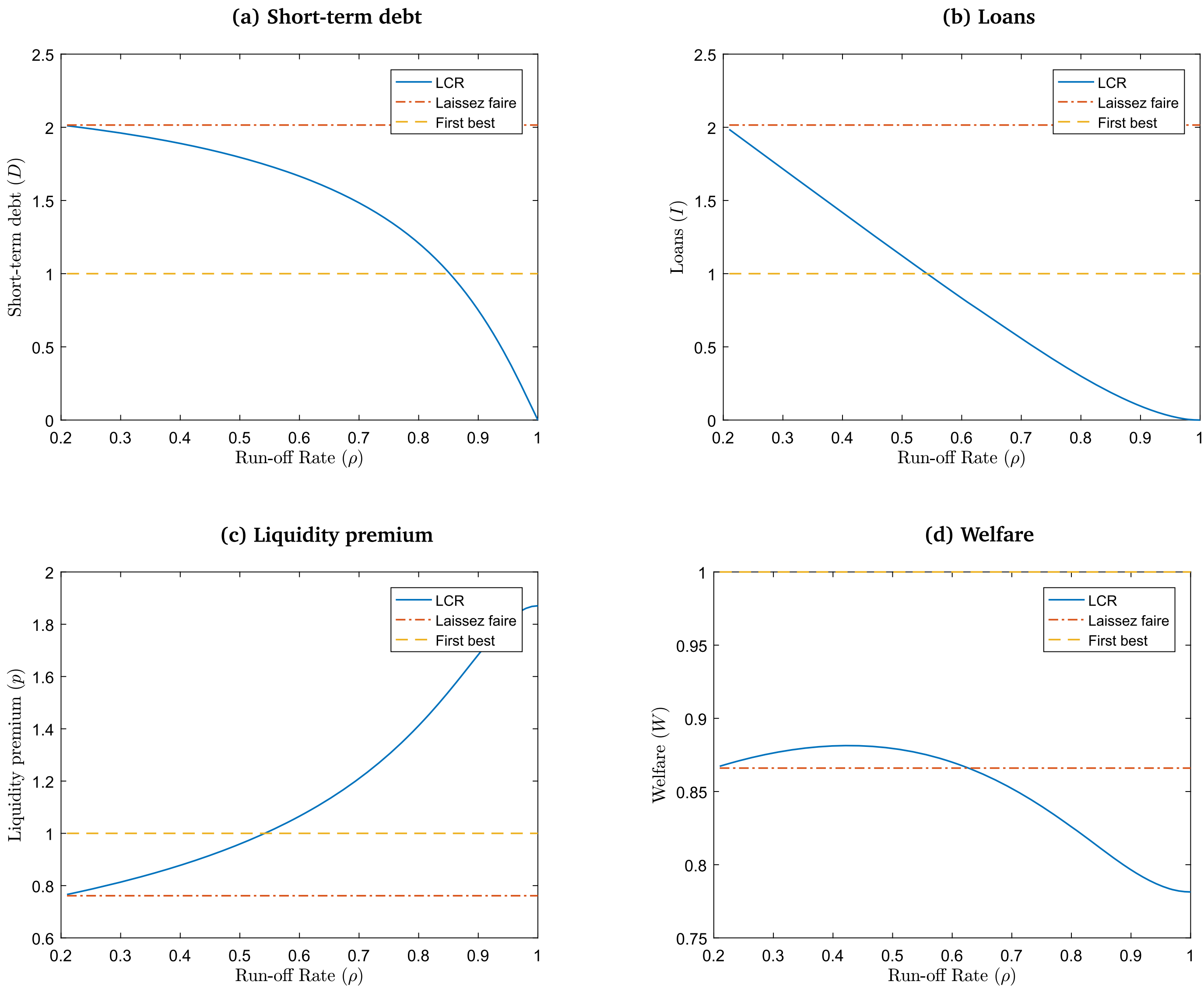

Fig. 4. Model Equilibrium with Different Run-off Rates. This figure plots equilibrium prices and quantities for different run-off rates. The fraction of withdrawal in good state a is 0.2. The demand for liquidity ξ is fixed at 1. The liquidity demand elasticity ϵ is 2. The issuance cost parameter γ is 1. The expected externality of liquidity transformation $\mu\eta$ is 0.8%. The expected liquidation costs borne by banks $\mu\phi$ is 0.5%. The fraction of regulated banks ω is 0.8. The supply of government securities G is 0.1.

We illustrate the crowding-out effect in Fig. 4, which shows the equilibrium for different run-off rates ρ. A higher value of run-off rate ρ indicates a tightening in liquidity regulation. The prices and quantities are normalized by the values in the first-best equilibrium, in which intermediaries internalize the externality of liquidity transformation. Therefore, a value of one indicates that the quantity of interest reaches the first-best level. Fig. 4(a) shows that the short-term debt in the laissez-faire equilibrium exceeds the first-best outcome, suggesting excessive liquidity transformation. Tightening liquidity regulation reduces the short-term debt issued by regulated banks, which brings the economy closer to the first-best equilibrium. The social welfare under the LCR exceeds the laissez-faire equilibrium when the run-off rate is not too high, as shown in Fig. 4(d). However, the LCR cannot bring social welfare to the first-best level. When the short-term debt reaches the social optimum, bank lending falls below the first-best level, as shown in Fig. 4(b). As a result, the liquidity premium rises above the socially optimal level, as shown in Fig. 4(c). If we impose a run-off rate that reduces the short-term debt to the first-best level, the social welfare under the LCR can fall below the laissez-faire equilibrium because the crowding-out effect would be too strong at this level of run-off rate.

To summarize, the model finds that the LCR that achieves the first-best liquidity supply reduces lending below the first-best level. Note that this result does not directly correspond to the empirical result, which simply suggests that the LCR reduces lending growth. It is ambiguous if reduced lending growth improves welfare because lending in the laissez-faire equilibrium could be excessive. We will evaluate the welfare implications of the LCR using a calibrated model in Section 4.10.

4.5.2. *Migration effects*

We now consider how the presence of unregulated intermediaries would affect the equilibrium outcome with the LCR. Intuitively, as liquidity regulation reduces the supply of short-term debt by regulated banks, the equilibrium liquidity premium rises. In response, unregulated banks increase their issuance of short-term debt. Such migration

results that there is an excessive issuance of short-term debt in the laissez-faire equilibrium and that the LCR cannot achieve the first-best equilibrium will be robust to the general distribution case.

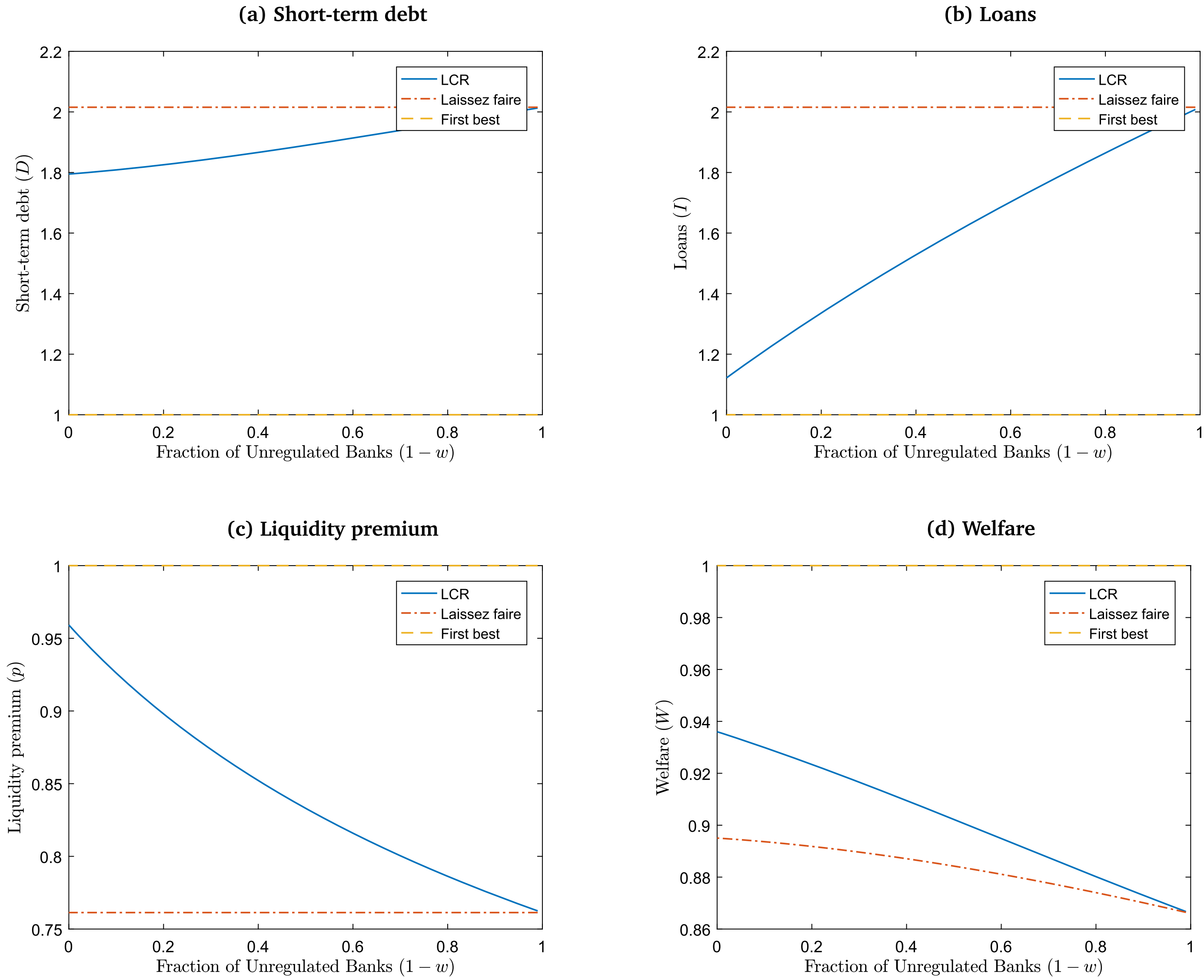

Fig. 5. Model Equilibrium with Different Fraction of Unregulated Banks. This figure plots equilibrium prices and quantities for different fractions of unregulated banks, $1-w$. The run-off rate ρ is fixed at 0.5. The fraction of withdrawal in good state a is 0.2. The liquidity demand elasticity ϵ is 2. The issuance cost parameter γ is 1. The expected externality of liquidity transformation $\mu\eta$ is 0.8%. The expected liquidation costs borne by banks $\mu\phi$ is 0.5%. The supply of government securities G is 0.1.

creates welfare distortion because the marginal issuance costs of short-term debt are not equalized across intermediaries. The extent of the migration depends on the elasticity of aggregate demand for liquidity, ϵ: a more inelastic demand leads to larger migration of liquidity transformation because the liquidity premium increases more for a given reduction in short-term debt. The extent of the migration also depends on the elasticity of the supply of liquidity, which is governed by γ: a more inelastic supply leads to smaller migration of liquidity transformation because the quantity of short-term debt adjusts less to a given increase in the liquidity premium.

We illustrate the migration effects in Fig. 5. We fix the run-off rate and solve the equilibrium with a different fraction of unregulated intermediaries, $1-w$. We find that more unregulated intermediaries dampen the effect of liquidity regulation in reducing the excessive liquidity transformation because some liquidity transformation migrates from the regulated banks to unregulated ones, as shown by Figs. 5(a) and 5(b). In addition, the equilibrium liquidity premium falls when there are more unregulated intermediaries, as shown by Fig. 5(c). Overall, more unregulated intermediaries reduce the welfare improvement created by liquidity regulation.

4.5.3. Uncertain liquidity demand

So far, we have held the liquidity demand as a constant. However, in reality, the liquidity demand varies over time. The LCR rule can interact with the uncertain liquidity demand and lead to a procyclical tax on liquidity transformation, exacerbating migration. Formally, we assume that the run-off rate ρ is determined *before* the realization of the uncertain liquidity demand, ξ. We can show the following result:

Proposition 4. *The implicit tax imposed by the LCR is increasing to the realized level of liquidity demand, ξ:*

$$\frac{\partial \tau^{LCR}}{\partial \xi} > 0. \tag{32}$$

Proof. Note that the equilibrium liquidity premium is increasing to the liquidity demand, $\frac{\partial p}{\partial \xi} > 0$. Also, note that the implicit tax is increasing to the liquidity premium according to Proposition 2. Therefore, the implicit tax imposed by the LCR is also increasing to the realized level of liquidity demand. □

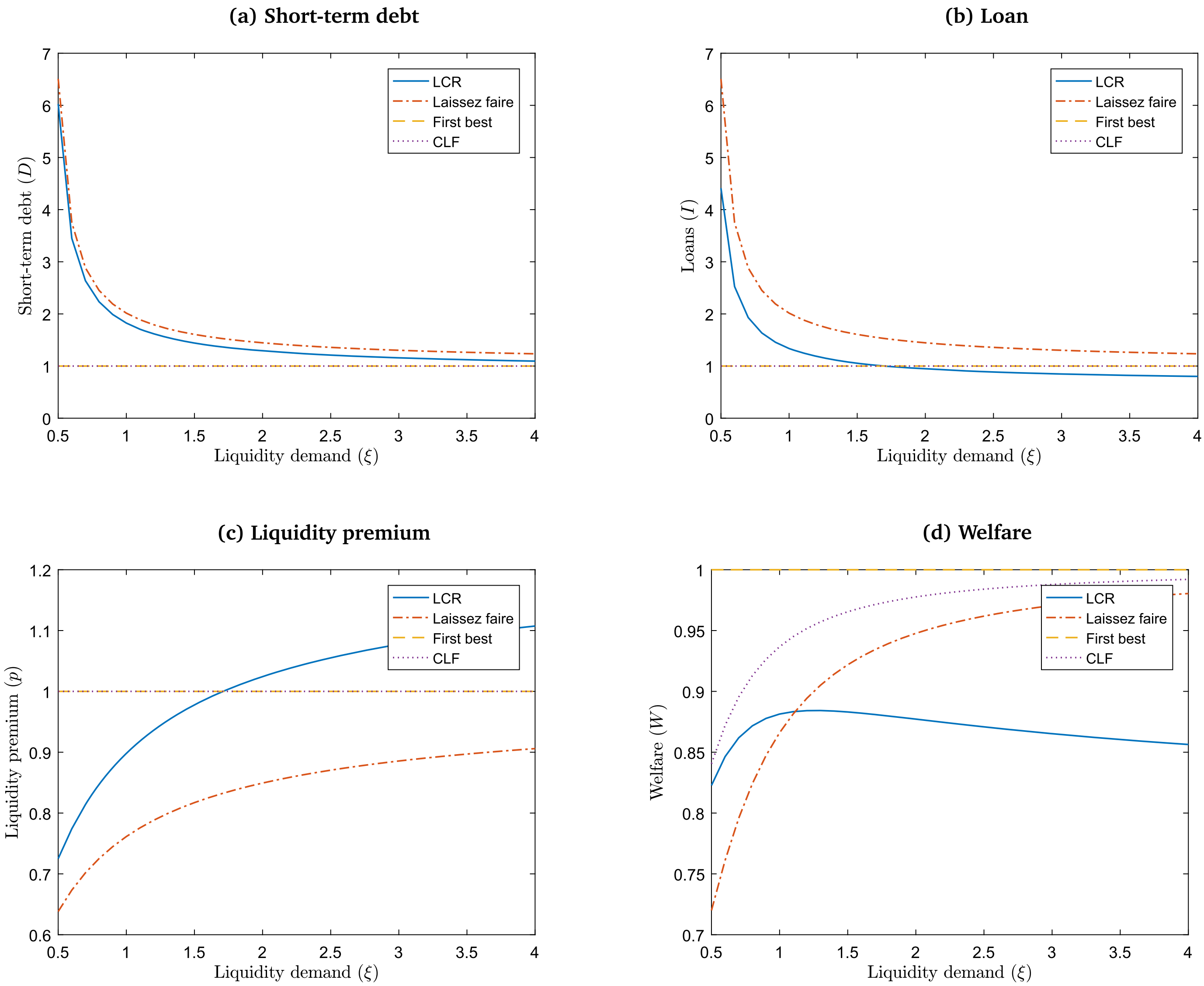

Fig. 6. Model Equilibrium with Different Liquidity Demands. This figure plots equilibrium prices and quantities for different liquidity demands, ξ. The run-off rate ρ is fixed at 0.5. The fraction of withdrawal in good state a is 0.2. The liquidity demand elasticity ϵ is 2. The issuance cost parameter γ is 1. The expected externality of liquidity transformation $\mu\eta$ is 0.8%. The expected liquidation costs borne by banks $\mu\phi$ is 0.5%. The fraction of regulated banks w is 0.8. The supply of government securities G is 0.1.

We illustrate the equilibrium outcomes with uncertain liquidity demand in Fig. 6. We set the run-off rate to 0.5 and vary the realized liquidity demands ξ. If the demand turns out to be quite low, the realized liquidity premium will be lower than expected. As a result, the regulation will be too soft, resulting in over-provision of liquidity and credit, as shown in Figs. 6(a) and 6(b). If the liquidity demand turns out to be quite high, the liquidity premium will be higher than expected, as shown in Fig. 6(c). The regulation will be more aggressive than socially desirable, leading to the under-provision of liquidity and credit. The social welfare under the LCR could fall below the lassie-fair equilibrium when the liquidity demand is too high, as shown in Fig. 6(d). These results are consistent with the predictions of the public interest theory that quantity-based regulations often lead to highly volatile regulatory costs when demand is uncertain (Weitzman, 1974).

4.6. Committed liquidity facility (CLF)

So far, we have shown that the current LCR rule may improve upon the unregulated equilibrium but can have distortionary effects. While these effects do not necessarily negate the benefits of liquidity regulation, they suggest room for welfare improvement. We study a potential policy to alleviate such distortions in the following discussion.

We consider a central bank committed liquidity facility complementing the existing LCR rule.[19] This facility allows banks to pay the central bank an upfront fee for a loan commitment. This loan commitment can then be counted toward the LCR liquidity requirement. The committed liquidity facility was initially adopted by the Reserve Bank of Australia to address the shortage of high-quality liquid assets faced by the Australian banking system. However, this facility can also be useful in countries without a structural scarcity of high-quality liquid assets because this facility introduces a price-based mechanism that can address the distortions caused by the purely quantity-based LCR rule.

[19] Many policymakers have advocated for this facility. For instance, see the speech by former Federal Reserve Governor Jeremy Stein, "Liquidity Regulation and Central Banking," at the 2013 Credit Markets Symposium (Stein, 2013). See also the speech by Benoît Cœuré, member of the Executive Board of the ECB, titled "Liquidity Regulation and Monetary Policy Implementation: From Theory to Practice" at the Toulouse School of Economics, Toulouse (Cœuré, 2013).

Formally, define $\lambda \geq 0$ as the upfront commitment fee and $q \geq 0$ as the quantity of committed liquidity that banks obtain from the committed liquidity facility. Regulated banks' problem is given by

$$\pi_1 = \max_{i_1, l_1, d_1, q_1} r i_1 + (r - p) l_1 - (r - p) d_1 - \phi \mathbb{E}\left[\tilde{\alpha} d_1 - l_1\right]^+ - \lambda q_1, \tag{33}$$

subject to

$$i_1 + l_1 = d_1, \tag{34}$$

$$l_1 + q_1 \geq \rho d_1. \tag{35}$$

Note that banks are still subject to an LCR requirement as indicated by equation (35). Otherwise, banks would not have incentives to obtain the loan commitment from the committed liquidity facility.

We focus on how the upfront fee λ at date 0 affects banks' incentives. In practice, the committed liquidity facility may also charge a draw fee if banks would like to draw the committed liquidity to meet redemptions. We assume that the draw fee is high enough so that banks do not draw from the committed liquidity to meet short-term creditors' withdrawal at date 1, even if they have unused commitments. Instead, banks only use the commitment to fulfill liquidity requirements at date 0. This assumption ensures that the committed liquidity facility only changes banks' regulatory environment without affecting the liquidity transformation technology that banks have access to.[20] Under this assumption, the expected liquidation cost only depends on the HQLAs that banks hold: $\phi \mathbb{E}\left[\tilde{\alpha} d_1 - l_1\right]^+$. Banks would at least hold a units of government securities. The question is what banks would do to meet the extra $\rho - a$ liquidity requirements from the LCR. If the commitment fee is lower than the cost of holding government securities, $\lambda \leq p - \mu\phi$, banks will obtain a commitment from the central bank to meet the liquidity requirement; otherwise, banks will hold more government securities. Therefore, the first-order condition of regulated banks is given by

$$p = \underbrace{c' + (1 - a)\mu\phi + ap}_{\text{Private marginal cost}} + \underbrace{(\rho - a)\min\left[\lambda, p - \mu\phi\right]}_{\text{Implicit tax}}. \tag{36}$$

A natural question is how the regulator should set the commitment fee. If the commitment fee is too low, the committed liquidity facility can undo liquidity requirements. If the commitment fee is too high, the committed liquidity facility will not be used. Formally, we can show the following results:

Proposition 5. *With the committed liquidity facility, the LCR can achieve the first-best level of supply of liquidity and credit if the commitment fee is set such that*

$$\lambda = \frac{\mu\eta(1 - a)}{w(\rho - a)} \leq p - \mu\phi, \tag{37}$$

where the inequality is the incentive compatibility constraint for banks to use the CLF.

Proof. See Appendix A.3. □

To understand how the committed liquidity facility alleviates the distortions caused by the current LCR rule, we solve the equilibrium with the committed liquidity facility for different realized liquidity demands ξ in Fig. 6. We find that under the commitment fee in Proposition 5, the equilibrium liquidity premium equals the first-best level, regardless of the realized liquidity demand. By doing so, the committed liquidity facility reduces the migration effects as the liquidity premium would not be elevated to induce unregulated banks to issue short-term debt. This pattern contrasts with the pure LCR case shown by the solid line, in which an unexpectedly high demand would drive the liquidity premium above the first-best level. The committed liquidity facility can also eliminate the crowding-out effects. As shown in Fig. 6(b), without the committed liquidity facility, banks would have to hold large liquidity buffers, which crowd out the loans. However, with the committed liquidity facility, the obtained loan commitment does not occupy banks' balance sheet space. Fig. 6(d) shows that the social welfare with the committed liquidity facility is always higher than the laissez-faire equilibrium. In contrast, under the current LCR rule, the social welfare with liquidity regulation could be lower than the laissez-faire equilibrium if the liquidity demand is unexpectedly high. Note that the committed liquidity facility does not bring welfare to the first-best level because there is still a distortionary migration of liquidity transformation from regulated banks to unregulated ones. A more comprehensive approach would be to impose a Pigovian tax on all forms of short-term debt, regardless of the issuers.

Note that the λ that equates the lending and supply of liquidity to the first-best level doesn't always achieve the maximum social welfare. A more nuanced consideration of the marginal costs of liquidity provision across regulated and unregulated banks is needed to achieve this maximum. We opt for this λ as the benchmark owing to its sufficiency in establishing the superiority of the CLF, and its relative simplicity. It is also important to note that the λ in Proposition 5 might not always exist if the probability of the bad state or the externality of liquidation is so large that banks' incentive compatibility constraint (the inequality in Proposition 5) is violated. In this case, banks prefer not to use the CLF and would hold HQLAs instead. To address this issue, the central bank can set a lower commitment fee than the level in Proposition 5 such that the incentive compatibility constraint is restored. This would result in a total liquidity supply exceeding the first-best level. Nevertheless, the lower commitment fee can still promote social welfare because the additional liquidity would be provided by regulated banks. These institutions, supplying less liquidity per bank in comparison to unregulated entities, would therefore have a lower marginal issuance cost.

To summarize, the current LCR rule is akin to a quantity-based regulation, which can crowd out bank lending and generate a procyclical tax on liquidity transformation. In contrast, the committed liquidity facility introduces a price-based mechanism, allowing banks to buy state-contingent liquidity from the central bank when the equilibrium liquidity premium is too high. This flexibility reduces the potential distortions caused by liquidity regulation.

We have discussed the role of the CLF in alleviating the uncertainty in liquidity demand. One could also consider the case in which the fire-sale externality is uncertain. There will be distortion associated with this uncertainty: when the realized externality is high, the social planner would like to reduce the short-term debt, but private banks would not. The LCR with a pre-determined run-off rate cannot address this uncertainty because the LCR does not become more or less stringent in the state with high externality, conditional on liquidity demand. In comparison, the CLF can mitigate the uncertain externality by charging a state-dependent fee according to Proposition 5: a higher realized externality should be countered by a higher commitment fee.

Note that unlike the case of uncertain liquidity demand in which the CLF can achieve a better outcome with a pre-determined commitment fee, in the case of uncertain externality, the commitment fee itself has to be state-dependent. One could argue that, in principle, regulators can also change the run-off rate of the LCR to address the uncertainty in externality, so there is no inherent advantage for the price-based mechanism in this case. However, in practice, changing the commitment fee is presumably easier than changing the required liquidity buffers because the commitment fee can be easily mapped to the externality while the run-off rates cannot.

[20] This assumption is to maintain a fair comparison with the LCR case. It does not mean that banks would not draw from committed liquidity to meet redemption ex-post in reality.

4.7. Liquidity regulation and LOLR

The previous section considers a policy proposal in which the central bank provides a CLF to reduce the distortion associated with the LCR. In this section, we step back and answer a more fundamental question: should we have the LCR in the first place, given the central bank can already function as a LOLR to avert liquidity crises?

To answer this question, it is important to note that the LCR regulates banks' liquidity transformation ex ante while the LOLR averts liquidity crisis ex post. Although there is no doubt that the LOLR is an effective policy tool, a common issue of ex post intervention is moral hazard. If banks expect to obtain liquidity from the central bank when they run out of liquidity, they would have little incentive to hold a liquidity buffer ex ante. Such moral hazard issues may lead to excessive risk-taking, resulting in losses for the central bank when banks use the LOLR facility. Although such losses can be avoided if the central bank only lends to fundamentally solvent banks, it may not be possible to distinguish insolvency from illiquidity during crises. Therefore, there is a limit to which the LOLR can resolve market failures of liquidity transformation, and some ex ante liquidity regulation, such as the LCR, is warranted.

We formally illustrate the connections and differences between the LOLR and LCR in the context of our model. Conditional on the realized state s, banks can borrow liquidity $q(s)$ from the discount window to meet the withdrawal. Given the usage of the LOLR, the realized firesale amount becomes $\alpha(s)d - l - q(s)$. Using the LOLR leads to a social cost of $\zeta q > 0$, which banks do not internalize. If this social cost is zero, banks should be allowed to use LOLR at no cost, and all the liquidity issues will be resolved. However, if using the LOLR is socially costly, the central bank would impose a cost $\nu > 0$ on the liquidity drawn from the discount window to discourage banks from overly relying on the LOLR. This cost captures the interest spread charged by the central bank and the stigma associated with borrowing from the discount window. For simplicity, we assume the collateral constraint of the LOLR is not binding. We first consider a bank that does not face the LCR requirement:

$$\pi_0 = \max_{i_0, l_0, d_0, q_0(s)} ri_0 + (r-p)l_0 - (r-p)d_0 - \phi\mathbb{E}\left[\tilde{\alpha}d_0 - l_0 - q_0(s)\right]^+ - \mathbb{E}\left[\nu q_0(s)\right], \tag{38}$$

subject to

$$i_0 + l_0 = d_0. \tag{39}$$

Banks' optimal strategy depends on the cost of borrowing from the discount window:

(1) $\nu > \phi$: the bank does not use the discount window. The option to use the discount window is worthless, and we get the same equilibrium as in the laissez-faire case. $d_{LOLR} = d_{LF}$.

(2) $\nu < \phi$ and $\nu > p$: the bank holds a fraction of a liquidity buffer and uses the discount window to meet the remaining withdrawal. As a result, the first-order condition (F.O.C.) with respect to the short-term debt is given by:

$$p = \underbrace{c' + \mu\nu(1-a) + ap}_{\text{Private marginal cost}}. \tag{40}$$

Comparing the above equation with the F.O.C. under the laissez-faire equilibrium, equation (23), the private marginal cost is lower under the LOLR because $\mu\nu < \mu\phi$, so banks issue more short-term debt when they have access to LOLR, $d_{LOLR} > d_{LF}$.

(3) $\nu < \phi$ and $\nu < p$: the bank holds no liquidity buffer and uses the discount window to meet all the withdrawals. The F.O.C. with respect to the short-term debt is given by:

$$p = \underbrace{c' + \mu\nu(1-a) + a\nu}_{\text{Private marginal cost}}. \tag{41}$$

Comparing the above equation with the F.O.C. under the laissez-faire equilibrium, equation (23), the private marginal cost is lower under the LOLR because $\mu\nu < \mu\phi$ and $\nu < p$, so banks issue more short-term debt when they have access to LOLR, $d_{LOLR} > d_{LF}$.

To summarize, although the LOLR can reduce the socially costly firesale ex post, it reduces banks' incentive to hold a liquidity buffer ex ante and leads to more issuance of short-term debt:

$$d_{LOLR} \geq d_{LF}. \tag{42}$$

The moral hazard issue of the LOLR is well understood in the literature. The extent the LCR can help address this issue is less clear. To study this problem, we consider a bank that has access to LOLR and faces the LCR requirement:

$$\pi_1 = \max_{i_1, l_1, d_1, q_1(s)} ri_1 + (r-p)l_1 - (r-p)d_1 - \phi\mathbb{E}\left[\tilde{\alpha}d_1 - l_1 - q_1(s)\right]^+ - \mathbb{E}\left[\nu q_1(s)\right], \tag{43}$$

subject to

$$i_1 + l_1 = d_1, \tag{44}$$

$$l_1 \geq \rho d_1. \tag{45}$$

We can derive the following result:

Proposition 6. *A stricter LCR reduces banks' reliance on the LOLR:*

$$\frac{\partial q_1}{\partial \rho} \leq 0. \tag{46}$$

Proof. Consider the non-trivial case in which the cost of accessing the discount window is smaller than the private firesale cost, $\nu < \phi$, so banks use the LOLR to meet the cash shortfalls. The LCR constraint implies that:

$$l_1 = \rho d. \tag{47}$$

The usage of the LOLR is given by

$$q_1(s) = \left[\alpha(s)d_1 - l_1\right]^+ = \left[(\tilde{\alpha} - \rho)d_1\right]^+. \tag{48}$$

Therefore, we have $\frac{\partial q_1}{\partial \rho} \leq 0$. □

The above proposition shows that the LCR requirement can alleviate the moral hazard problem due to the presence of the LOLR. Therefore, under the assumption that there is a non-zero social cost for using the LOLR, there is a role for ex ante preventative measures such as the LCR.

4.8. LOLR and CLF

So far, we have shown that the LCR can alleviate the moral hazard problem due to the presence of the LOLR. However, we have also noted that the LCR could crowd out bank lending and lead to distortionary migration. Our policy prescription is that the central bank should establish a CLF where banks can obtain liquidity commitments so liquidity regulation can be deployed without crowding out bank lending. A natural question is: instead of introducing a new committed liquidity facility, can we use existing LOLR facilities, such as the discount window, to complement the LCR rather than set up a new CLF facility? For instance, one could count the unused capacity of the discount window toward the LCR, and the cost of becoming a member bank to qualify for central bank liquidity access could be reinterpreted as a commitment fee.

Two major distinctions between the discount window and the proposed CLF make this proposal untenable. First, the commitment fee of the CLF needs to be chosen properly to restore the first-best outcome. In contrast, the membership fee associated with LOLR is presumably determined by other factors, such as the compliance costs associated with

Table 9
Calibrated parameters for policy experiments.

Parameter	Value	Targeted moments	Value
μ_α: mean of log random withdrawal	-0.019	mean of random withdrawal	0.000
σ_α: volatility of log random withdrawal	0.194	expected outflows in distress	0.300
μ_ξ: mean of log demand for liquidity	0.015	mean of liquidity premium	0.007
σ_ξ: volatility of log demand for liquidity	0.005	volatility of liquidity premium	0.005
γ: issuance cost of short-term debt	0.006	ratio of govt to bank liquidity	1.250
ϵ: elasticity of demand for liquidity	58.000	bank liquidity supply	0.800
ϕ: liquidation cost	0.115	pre-LCR liquidity share	0.270
η: firesale externality	0.259	post-LCR liquidity share	0.320
g: govt liquidity	1.000	normalized to one	1.000
ω: share of regulated banks	0.800	LCR bank share	0.800

Note: This table shows the calibrated parameters for the policy experiments. Columns (1) and (2) show the parameter value. Columns (3) and (4) show the targeted moments in the data.

bank supervision. Nor is the membership fee linked to the borrowing capacity from the LOLR. Second, the discount window has a stigma effect, so the real cost of borrowing from the discount window is much higher than the official spread. In contrast, the committed liquidity facility is unlikely to have such an effect as banks pay the committed liquidity facility ex ante for liquidity commitments they may need in the future.

4.9. Model extensions

This section discusses possible extensions of the baseline model. First, our baseline model assumes banks can use the mandated liquidity buffer to meet realized withdrawal ex post. This assumption differs from Diamond and Kashyap (2016), who assume that the LCR is not relaxed in the face of withdrawal by short-term debt holders. This difference reflects the policy environments in which these two papers are conceived. When the LCR was first proposed, there was substantial ambiguity in the regulation on whether regulators would allow banks to use the mandated liquidity buffers to meet the withdrawal in a crisis (see, e.g., Goodhart et al. (2008)). This ambiguity leads to a natural question: if the mandated liquidity buffer cannot be deployed in a crisis, could liquidity regulation have an effect? Diamond and Kashyap (2016) answer this question by showing that the mere existence of the liquidity buffers may forestall certain panic-driven runs.

Our paper is written in a context in which regulators have more clarity regarding using mandated liquidity buffers in a crisis. For instance, during the COVID-19 crisis, most authorities told banks they could operate below Basel III liquidity coverage ratios (Benediktsdóttir et al., 2020). This practice is consistent with our assumption that the mandated liquidity buffer can be used to cover an unanticipated withdrawal.

Nevertheless, the mechanism highlighted in our model is not incompatible with that in Diamond and Kashyap (2016). As pointed out by Diamond and Kashyap (2016), there are two ways to think about the purpose behind the mandated liquidity buffer. One is to reduce the likelihood of a withdrawal surge in the first place. The other is to ensure that banks can better withstand a surge in withdrawals should one occur. Diamond and Kashyap (2016) focus on the former while our model focuses on the latter. However, it is conceivable to incorporate the first channel into our model by allowing the mandated liquidity buffer to reduce the probability of the bad state, μ, as some panic-driven withdrawal becomes less likely to occur.

Second, our baseline model assumes banks only issue short-term debt. In Section A.4, we allow banks to choose between cheap unstable short-term debt and a more expensive stable funding source that does not face withdrawal in the interim period. The main results remain the same as the baseline model. Intuitively, even if banks can issue stable long-term claims, they would still issue too many short-term claims because of the liquidity premium.

Third, our baseline model assumes that random withdrawal follows a binary distribution for simplicity. In Section A.5, we allow a general continuous distribution for the withdrawal. In the general setting, neither short-term debt issuance nor the liquid asset share is socially optimal in the laissez-faire equilibrium. The gap in welfare between quantity-based regulation and the socially optimal one still exists because a single policy parameter, the run-off rate, cannot realign two F.O.C.'s for the short-term debt and the liquid asset shares. Therefore, the price-based regulation, the CLF, is still needed.

Fourth, our paper focuses on liquidity regulation. In practice, banks are also subject to other regulations, notably capital requirements. It is interesting to examine the possible interaction between capital and liquidity regulations (Carletti et al., 2018). Evidence has suggested that banks that were sufficiently well capitalized during the 2007–2009 crisis could continue to have access to liquidity (Thakor, 2018). The crisis ended up reallocating liquidity from the undercapitalized banks to strong banks (Berger and Bouwman, 2013; Pérignon et al., 2018). This observation raises the question of whether capital regulation, as opposed to liquidity regulation, could be a better prudential policy. Our findings illustrate certain distortions resulting from the current implementation of liquidity regulation, although some of these can be alleviated with better regulatory design. Understanding how liquidity regulation compares to other bank regulations would be an interesting question for future research.

4.10. Calibration

We calibrate a generalized model with continuous withdrawal to the data to better understand the welfare implications of different regulatory designs. Table 9 reports the key model parameters and the corresponding data moments. We assume that the following distribution generates the random withdrawal: $\ln(1-\tilde{\alpha}) \sim N(\mu_\alpha, \sigma_\alpha)$ so that $\tilde{\alpha}$ is bounded by 1. We calibrate μ_α such that the mean of the random withdrawal is zero. We then calibrate σ_α such that $\mathbb{E}\left[\tilde{\alpha}|\tilde{\alpha} > \alpha_{90}\right] = 0.3$, where α_{90} is the 90th percentile of the withdrawal distribution and 0.3 is banks' expected cash outflows in the data as defined in equation (3).[21] We then assume the liquidity demand shocks follow a log-normal distribution, $\ln\xi \sim N(\mu_\xi, \sigma_\xi)$. The mean of the liquidity demand is calibrated to match the average of liquidity premium, which is 0.73% based on Krishnamurthy and Vissing-Jorgensen (2012). The volatility of the liquidity demand is calibrated to match the residual volatility of liquidity premium after controlling for the log government debt to deposit ratio, which is 0.47%, using the data from Krishnamurthy and Li (2022). The elasticity of liquidity demand is calibrated to 58 based on the estimate of Jiang et al. (2022). The private liquidation cost ϕ is calibrated to match the liquidity ratios before the LCR. The firesale externality η is calibrated in such a way that the implicit tax on liquidity transformation

[21] The expected cash outflows are conditional on banks being in distress, which is assumed to be when the realized withdrawal is greater than the 90th percentile of its distribution.

Table 10
Counterfactual policy experiments.

Counterfactual	First-best	LCR	Stricter LCR	LCR + CLF
	Panel (a): Policy parameters			
Run-off rate (ρ)	-	0.383	0.421	0.383
Commitment fee (λ)	-	-	-	0.687
	Panel (b): Equilibrium outcomes			
Liquidity premium (p)	8.540	9.454	13.521	11.689
Liquidity premium volatility (σ_p)	8.528	13.568	17.060	-11.579
Aggregate private liquidity supply (D)	-0.512	1.366	0.465	0.388
Aggregate lending (I)	-9.962	-11.180	-15.729	-8.621
Short-term debt of regulated banks (d_1)	-0.512	-0.884	-3.126	-1.446
Short-term debt of unregulated banks (d_0)	-0.512	10.366	14.830	7.724
Liquidity ratio of regulated banks (r_1)	24.943	40.360	54.396	31.808
Liquidity ratio of unregulated banks (r_0)	24.943	-2.362	-3.403	-3.406
Lending of regulated banks (i_1)	-9.962	-16.843	-23.772	-12.977
Lending of unregulated banks (i_0)	-9.962	11.471	16.443	8.800
Welfare (W)	1.268	0.600	0.072	0.845

Note: This table shows the results of counterfactual policy experiments. The values in Panel A are expressed as in their raw levels. The values in Panel B are expressed as the percentage difference from the counterpart in the laissez-faire equilibrium.

(as defined in equation (84)) aligns the first-order condition concerning liquidity supply for regulated banks with that of the social planner. The issuance cost of short-term debt γ is calibrated to match the ratio of government liquidity to bank-supplied liquidity. The share of unregulated banks w is calibrated to the asset share of non-LCR banks, which is 0.8. Finally, the supply of government securities is normalized to 1.

We use the calibrated model to conduct a set of counterfactual policy experiments. We consider the following scenarios: (1) laissez-faire, (2) first-best, (3) LCR, (4) stricter LCR in which the required liquidity ratio is increased by 10%, and (5) LCR combined with CLF. Table 10 presents the results. The outcome variables are expressed as percentage differences from the laissez-faire level.

We first compare the first-best equilibrium with the laissez-faire equilibrium. The liquidity premium in the first-best is 8.5% higher than the laissez-faire equilibrium, as the social planner would cut back on the issuance of short-term debt. Banks hold 24.9% more liquidity buffer in the first-best equilibrium and make 10.0% fewer loans than in the laissez-faire equilibrium. The aggregate welfare is 1.3% higher in the first-best equilibrium than in the laissez-faire equilibrium.

Second, we consider the LCR case. We set the run-off rate according to equation (93) in the first-best case, which is 0.38.[22] After implementing the LCR, the average liquidity premium increases relative to the laissez-faire equilibrium while the private liquidity supply decreases. However, the volatility of the liquidity premium also increases substantially because of the pro-cyclical nature of the LCR requirement, as shown in Proposition 4. Furthermore, aggregate lending decreases by 11.2% relative to the laissez-faire equilibrium. Note that the decrease in lending is greater than that in the first-best equilibrium because of the crowding-out effects. Interestingly, the aggregate private liquidity supply increases slightly relative to the laissez-faire equilibrium because regulated banks buy up large quantities of government securities, which drives up the liquidity premium and short-term debt issuance by unregulated banks. Similar migration also emerges in the lending market, in which the lending of regulated banks decreases by 16.8% while the lending of unregulated banks increases by 11.5%. The overall welfare effect of the LCR is positive: it increases by 0.6%, which is around half of the increase in the first-best equilibrium.

Third, we consider a stricter version of the LCR in which the run-off rate is increased by 10%. The average liquidity premium increases further and becomes more volatile. The aggregate private liquidity supply and lending decrease further relative to the more relaxed version of LCR. However, it's important to note that private liquidity supply is still slightly above the laissez-faire case. The crowding-out and migration effects become stronger. Notably, with a stricter LCR, the welfare improvement becomes significantly smaller than the baseline LCR, only 0.1%. This counterfactual exercise shows that the choice of the required liquidity ratio is important for welfare.

Finally, we consider the scenario in which a price-based regulation, the CLF, is introduced alongside the LCR requirements. We set the commitment fee to 0.687% using equation (92), such that the F.O.C. of the private liquidity supply approximates the social planner's. We find the liquidity premium increases, but the volatility of the liquidity premium decreases relative to the laissez-faire equilibrium. This pattern is different from the pure quantity-based regulation, in which both the mean and the volatility of the liquidity premium increase due to regulation. The reason is that the CLF reduces the pro-cyclicality of the liquidity regulation as banks can use the CLF commitment to meet LCR requirements in states of high liquidity demand. The crowding-out effect on the lending of regulated banks becomes smaller because banks do not have to hold government securities on the balance sheets to meet the LCR. Consequently, the migration of lending to unregulated banks becomes smaller relative to the LCR scenario. Finally, the CLF alleviates the migration of short-term debt to unregulated banks. This result may appear surprising, given the average liquidity premium under the CLF is slightly higher than that under the LCR based on our calibration. This surprising result is because the CLF reduces the volatility of liquidity premiums, thus reducing the large migration of liquidity supply in high-demand states. Overall, around 70% of the gap between the laissez-faire and the first-best equilibrium can be closed by a combination of LCR and CLF. The welfare improvement is greater than that under a pure quantity-based regulation.

4.11. Policy implication

A central policy implication arising from our analysis pertains to the value of the CLF. The CLF is frequently discussed in the context of countries with a scarcity of HQLAs, but our results underscore its value even in nations with more abundant HQLAs. The CLF provides an alternative avenue for banks to meet liquidity requirements, enabling more efficient balance sheet management by reducing the costs to maintain extensive HQLA holdings. It also has the potential to mitigate the impact of significant demand shocks for HQLAs, such as shifts in foreign

[22] It is worth noting that the optimal level of the run-off rate is 0.33 under the LCR because the crowding-out effect would suggest a lower required liquidity ratio relative to that in the first-best equilibrium. We choose the first-best level, 0.38, as a benchmark because when the CLF is introduced, it would approximately restore the equilibrium to the first-best. The main results hold regardless of the run-off rate chosen for this analysis.

central banks' reserve holdings. Although not explicitly illustrated in our model, the CLF also gives the government greater flexibility in fiscal and monetary policy, which might influence the supply of HQLAs and consequently disrupt the implementation of the LCR.

Our analysis also offers practical guidance on determining the commitment fee. It considers the following parameters: (1) the proportion of liquidity buffers that banks would voluntarily maintain; (2) the required liquidity ratio; (3) the probability of facing withdrawals; (4) the externality of liquidity transformation; and (5) the fraction of banks covered by the LCR. In states of the world in which the firesale externality is higher, the commitment fee should increase accordingly. However, the commitment fee need not adjust to the changes in liquidity demand as banks' endogenous take-up from the CLF will act as a cushion for demand shocks. Finally, the commitment fee should be kept below a level linked to the liquidity premium of HQLAs and liquidity risk, as indicated in Proposition 5. If it exceeds this threshold, banks may not utilize this facility.

5. Conclusion

This paper studies how liquidity regulation interacts with the banking system. Empirically, we find that the LCR requirement implemented after the crisis has significantly reduced LCR banks' liquidity risks. However, the mandated liquidity buffer appears to crowd out bank lending and leads to a migration of liquidity risks to non-LCR banks. From a positive-economics perspective, we provide a model of liquidity regulation with endogenous liquidity premium and heterogeneous banks to explain the crowding-out and migration effects. The model also shows that the quantity-based LCR rule can interact with the uncertain liquidity demand, amplifying the volatility in the liquidity premium. Finally, from a normative perspective, we demonstrate that a central bank committed liquidity facility can alleviate these distortions by introducing a price-based mechanism.

Our findings should not be interpreted as evidence against liquidity regulation. The 2007–2009 financial crisis has made it clear that private liquidity transformation is subject to market failures, and some form of regulation is warranted. Our model also shows that the current LCR requirement can improve upon the laissez-faire equilibrium if the run-off rates are appropriately calibrated. Nevertheless, the current design of liquidity regulation is not perfect. The dual role of the liquidity buffer as an implicit tax and a costly mitigator of liquidity risks makes it impossible to achieve the first-best liquidity and credit simultaneously. The fixed quantity mandate also interacts with the uncertain liquidity demand and generates a procyclical regulatory burden. The limited reach of the current liquidity regulation leaves the possibility that liquidity risks can migrate from regulated entities to unregulated ones. The design of liquidity regulation should reflect these economic and regulatory environments to achieve better regulatory outcomes.

Our research bears significant policy implications, particularly in the wake of recent banking stress events involving regional banks such as Silicon Valley Bank. This bank's failure was in part due to its heavy reliance on uninsured deposit—a category of runnable liabilities that the LCR heavily penalizes. Notably, Silicon Valley Bank was exempted from the most stringent requirement of the LCR in 2019. This change followed the 2019 regulatory relief, which was driven, in part, by concerns about the high costs of regulatory compliance. Our paper proposes that the CLF could help reduce the compliance costs associated with the LCR. This would allow regulators to apply this rule more consistently across the banking sector, thereby mitigating the trade-off between fostering financial stability and the burden of high compliance costs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Code availability

The code and data packed for this article can be found at https://doi.org/10.17632/t6s7pcdsyw.2.

Data availability

Data will be made available on request.

Appendix A

A.1. Derivation of the aggregate liquidity demand

Following Galí (2015), we assume that households derive utility from holding a stock of liquid assets. The representative household seeks to maximize the objective

$$\mathbb{E}_0 \sum_{t=1}^{\infty} \beta^t u(C_t, Q_t), \tag{49}$$

subject to the budget constraint

$$\begin{aligned} &D_t + N_t + B_t + C_t \\ &= D_{t-1}\exp(r^d_{t-1}) + N_{t-1}\exp(r^g_{t-1}) + B_{t-1}\exp(r_{t-1}) + \Pi_{t-1} - T_{t-1} + Y_t, \end{aligned} \tag{50}$$

where D_t is the short-term debt issued by banks; N_t is government bonds held by the household; B_t is the net lending/borrowing of the household; C_t is consumption; Y_t is the income endowment; Π_t is the profits from the banking sector; T_t is the tax paid to the government; Q_t is the total stock of liquidity asset holdings that provide households with utility from liquidity services; and r^d_t, r^g_t, and r_t are the interest rates for short-term debt, government bonds, and illiquid bonds, respectively. The households' total stock of liquidity is the sum of short-term debt issued by banks, D_t, and government securities, N_t:

$$Q_t = D_t + N_t. \tag{51}$$

Consider the utility function takes the following functional form:

$$u(C_t, Q_t) = \frac{C_t^{1-\sigma}}{1-\sigma} + \frac{Q_t^{1-\nu}}{1-\nu}. \tag{52}$$

The first-order condition with respect to consumption yields the Euler equation:

$$\exp(r_t) = \frac{1}{\beta}\left\{\mathbb{E}_t\left[\frac{u_{c,t+1}}{u_{c,t}}\right]\right\}^{-1}. \tag{53}$$

The first-order condition with respect to short-term debt yields the following equation:

$$Q_t^{-\nu} = u_{c,t} - \beta E_t u_{c,t+1}\exp(r^d_t). \tag{54}$$

Plugging in the Euler equation to replace $\mathbb{E}_t\left[u_{c,t+1}\right]$ gives us

$$Q_t = C_t^{\sigma/\nu}(1-\exp(r^d_t - r_t))^{-1/\nu}. \tag{55}$$

Similarly, the first-order condition with respect to the government securities yields the following equation:

$$Q_t = C_t^{\sigma/\nu}(1-\exp(r^g_t - r_t))^{-1/\nu}. \tag{56}$$

Comparing the above equation with equation (54), we get that the liquidity premium of government securities is the same as the liquidity premium of short-term debt issued by banks:

$$r_t - r^g_t = r_t - r^d_t = p_t. \tag{57}$$

Define $p_t = r_t - r^d_t$. Using the first-order Taylor approximation $\log\left(\exp(-r^d_t) - \exp(-r_t)\right) \approx const. + \frac{1}{\exp(-r^d_t)-\exp(-r_t)} p_t$. Equation (56) can be written as

$$q_t = \frac{\sigma}{\nu} c_t - \epsilon p_t, \tag{58}$$

where $q_t \equiv \log Q_t$, $c_t \equiv \log C_t$, and $\epsilon \equiv \frac{1}{\nu(\exp(-r_t^d)-\exp(-r_t))} \approx \frac{1}{\nu p}$ is the implied semi-elasticity of demand for liquidity. Rearranging equation (58), we get

$$p_t = -\frac{1}{\epsilon} q_t + \frac{\sigma}{\nu\epsilon} c_t, \tag{59}$$

which gives rise to equation (19), $p = p(Q, \xi) = \log\left(\xi Q^{-\frac{1}{\epsilon}}\right)$.

To close the model, the tax paid to the government, T_t, is determined by the government's budget constraint:

$$G_t = G_{t-1} R^g_{t-1} - T_t + \eta(D_t - L_t), \tag{60}$$

where G_t is the government debt outstanding, which follows an exogenous process. $\eta(D_t - L_t)$ is the externality of liquidity transformation in terms of bailout costs for the government.

A.2. Proof of Proposition 3

We prove this result by contradiction. To obtain the socially optimal quantity of short-term debt, $D^{LCR} = D^{FB}$, the tax imposed by the LCR must equal the Pigovian tax:

$$(\rho - a)(p - \mu\phi) = (1 - a)\mu\eta. \tag{61}$$

The above equation requires that $\rho > a$. However, using $I^{FB} = (1 - a)D^{FB}$ and $I^{LCR} = (1 - \rho)D^{LCR}$, the lending in the LCR equilibrium is lower than that in the first-best equilibrium:

$$I^{LCR} < I^{FB}. \tag{62}$$

Furthermore, using $p^{FB} = p((1 - a)D^{FB} + G)$ and $p^{LCR} = p((1 - \rho)D^{LCR} + G)$, the liquidity premium in the LCR equilibrium is higher than that in the first-best equilibrium:

$$p^{LCR} > p^{FB}. \tag{63}$$

Therefore, the welfare under the LCR is lower than that of the first-best outcome. □

A.3. Proof of Proposition 5

Assuming the committee fee is low enough, $\lambda \le p - \mu\phi$, banks will use the committed liquidity facility to meet the liquidity requirement. The F.O.C. of the regulated banks is given by

$$p = c'(d_1) + (1 - a)\mu\phi + ap + (\rho - a)\lambda. \tag{64}$$

The F.O.C. of the unregulated banks is given by

$$p = c'(d_0) + (1 - a)\mu\phi + ap. \tag{65}$$

Multiplying the above two equations with the weights of regulated and unregulated intermediaries, w and $1 - w$, and then summing them, we obtain the following equation, which determines the aggregate supply of short-term debt:

$$p = c'(D) + (1 - a)\mu\phi + ap + w(\rho - a)\lambda, \tag{66}$$

where $c'(D) = wc'(d_1) + (1 - w)c'(d_0)$ by using the linearity assumption of the marginal issuance cost. Comparing this equation with equation (26), the aggregate supply of short-term debt under the CLF achieves the first-best outcome when $\lambda = \frac{\mu\eta(1-a)}{w(\rho-a)}$.

Furthermore, because the regulated banks use the committed liquidity facility to meet the LCR requirement rather than holding additional government securities, there is no crowding-out effect on loans, so that $D^{CLF} = D^{FB}$ implies $I^{CLF} = I^{FB}$. Finally, because the net liquidity supply, $D^{CLF} - L^{CLF}$, equals the first-best level, the liquidity premium also equals the first-best level. □

A.4. Extension: stable funding

In the baseline model, banks can only issue short-term debt. In this section, we allow banks to choose between a cheap unstable funding source subject to a liquidity coverage ratio and a more expensive stable funding source. Formally, banks can raise stable funding by issuing long-term bonds, b, with an interest rate higher than the short-term debt, $r - \delta > r - p$. δ is the exogenous interest spread between the illiquid assets and the long-term funding cost of the bank. δ is small and captures that banks have a unique advantage in finding and monitoring projects. Banks have an exogenous initial equity capital, e, and face a capital ratio requirement, ι. For simplicity, we assume that banks do not issue new equity capital due to high issuance costs. We also assume ι is small so that banks' long-term debt is non-zero. The objective of regulated banks is the following:

$$\pi_1 = \max_{i_1, l_1, d_1} ri_1 + (r - p)l_1 - (r - p)d_1 - (r - \delta)b_1 - c(d_1) - \phi\mathbb{E}\left[\tilde{\alpha}d_1 - l_1\right]^+, \tag{67}$$

subject to

$$i_1 + l_1 = d_1 + b_1 + e_1, \tag{68}$$

$$l_1 \ge \rho d_1, \tag{69}$$

$$i_1 + l_1 \le e_1/\iota, \tag{70}$$

where the last inequality is the capital requirement. On the margin, the bank earns a spread of δ to issue one more dollar of long-term debt to hold illiquid assets, so the capital requirement is binding.

In solving banks' problem, we have

$$b_1 = e_1/\iota - d_1 - e_1, \tag{71}$$

$$l_1 = \rho d_1, \tag{72}$$

$$i_1 = e_1/\iota - \rho d_1. \tag{73}$$

The issuance of the short-term debt, d_1, is determined by the first-order condition

$$p = \underbrace{c' + \delta + (1 - a)\mu\phi + ap}_{\text{Private marginal cost}} + \underbrace{(\rho - a)(p - \mu\phi)}_{\text{Implicit tax}}, \tag{74}$$

where the right-hand side is the marginal cost of liquidity transformation with the LCR. The F.O.C. differs from equation (31) of the baseline model in the term δ. Intuitively, the private marginal cost of issuing one dollar of short-term debt now includes the opportunity cost of issuing one fewer dollar of long-term debt, which generates a spread of δ. We can interpret δ broadly as part of the issuance cost of the short-term debt, c'. On the demand side, we assume that the liquidity premium of the short-term debt only depends on the supply of short-term debt. Therefore, the results of the baseline model remain the same.

A.5. Extension: continuous distribution of withdrawals

In the baseline model, we consider a binary distribution of withdrawal. This section allows $\tilde{\alpha}$ to follow a general and potentially continuous distribution. The expected liquidity shortfall can be written as follows:

$$\mathbb{E}\left[\tilde{\alpha}d - l\right]^+ = d \times \mathbb{E}\left[\tilde{\alpha} - \frac{l}{d}\right]^+ = d \times f(x), \tag{75}$$

where $x = \frac{l}{d}$ is the liquidity ratio; and $f(x)$ is the expected quantity of illiquid assets being liquidated, expressed as a fraction of short-term debt. A higher liquidity ratio reduces the expected liquidation amount, $f' < 0$. For instance, suppose the random withdrawal fraction $\tilde{\alpha}$ follows the binary distribution described in Section 4.1. Then, the expected fire-sale fraction is given by $f(x) = \mu(1 - x)$, where μ is the probability of the bad state.

Under the general setup, we can recast banks' decisions as choosing the quantity of short-term debt, d, and the liquidity ratio, x. Unregulated banks' objectives can be expressed as the following:

$$\pi_0 = \max_{i_0, x_0, d_0} ri_0 + (r-p)x_0 d_0 - (r-p)d_0 - c(d_0) - \phi f\left(x_0\right) d_0, \tag{76}$$

subject to

$$i_0 + x_0 d_0 = d_0. \tag{77}$$

The F.O.C.s with respect to d_0 and x_0 are

$$p = c' + \phi f(x_0) + x_0 p, \tag{78}$$

and

$$p = \phi(-f'(x_0)). \tag{79}$$

In contrast, the F.O.C.'s of the social planner with respect to d and x are

$$p = c' + (\phi + \eta) f(x) + xp, \tag{80}$$

and

$$p = (\phi + \eta)(-f'(x)). \tag{81}$$

Banks issue too much short-term debt and hold too little liquidity relative to the socially optimal level because they do not incorporate the social externality of firesale.

Note that in the binary distribution case, equation (81) (the F.O.C. with respect to the liquidity share) is an inequality between two possible levels of liquidity shares. As a result, the share of liquid assets on the balance sheet is the same in the socially optimal and the laissez-faire scenario. This result is not generally true for a continuous distribution of withdrawals. However, this change will not affect the main results, as discussed below. Now consider regulated banks, which have the same objective function as in equation (76) and face the following LCR constraint:

$$x_1 \geq \rho. \tag{82}$$

Since the LCR constraint is binding in the equilibrium, $x_1 = \rho$.

The F.O.C. with respect to d_1 gives

$$p = c' + \phi f(\rho) + \rho p. \tag{83}$$

Comparing equation (83) and equation (78), the LCR imposes an implicit tax on liquidity transformation with the following tax rate:

$$\tau^{LCR} = (\rho - x_0)p - \phi(f(x_0) - f(\rho)). \tag{84}$$

Equation (84) is a general case of Proposition 2. To see why this is true, note that when the random withdrawal follows a binary distribution, $x_0 = a$, $f(x_0) = \mu(1 - x_0)$, $f(\rho) = \mu(1 - \rho)$. Therefore, $\tau^{LCR} = (\rho - a)(p - \mu\phi)$ for the binary distribution case.

Proposition 3, which says the welfare under the LCR is lower than the first-best outcome for any run-off rate, still holds in this general case. Intuitively, because there are two wedges between the social planner's F.O.C.s and the laissez-faire ones, the run-off rate ρ that eliminates the wedge between the F.O.C.s of the short-term debt (equations (78) and (80)) does not generally eliminate the wedge between the F.O.C.s of the liquidity buffer (equations (79) and (81)). If the regulator sets the run-off rate to the socially optimal share, the quantity of short-term debt will still be greater than the socially optimal level as the firesale externality is still not fully internalized; if the regulator sets the run-off rate to be so high that the quantity of short-term debt equals the socially optimal level, the share of liquid assets has to be larger than the socially optimal. Hence, the gap in welfare between quantity-based regulation and the socially optimal regulation still exists for the same rationale, and price-based regulation is still needed.

Proposition 4 also holds in this general case, that is, the implicit tax imposed by the LCR is increasing to the realized level of liquidity demand, $\frac{\partial \tau^{LCR}}{\partial \xi} > 0$. The reason is that the equilibrium liquidity premium is increasing to the liquidity demand, $\frac{\partial p}{\partial \xi} > 0$, and the implicit tax is increasing to the liquidity premium.

Now consider the central bank committed liquidity facility. Define $y = q/d$ as the ratio of the liquidity commitment to the short-term debt. The problem of regulated banks becomes:

$$\pi_1 = \max_{i_1, x_1, d_1, y_1} ri_1 + (r-p)x_1 d_1 - (r-p)d_1 - c(d_1) - \phi f\left(x_1\right) d_1 - \lambda y_1 d_1, \tag{85}$$

subject to

$$i_1 + x_1 d_1 = d_1, \tag{86}$$

$$x_1 + y_1 \geq \rho. \tag{87}$$

Since the LCR constraint is binding in the equilibrium, $x_1 + y_1 = \rho$.

The F.O.C.s with respect to d_1 and x_1 are:

$$p = c' + \phi f(x_1) + x_1 p + \lambda(\rho - x_1), \tag{88}$$

$$p = \phi(-f'(x_1)) + \lambda. \tag{89}$$

Multiplying the F.O.C.s of regulated and unregulated banks, equations (88), (89), (78), and (79), with the corresponding weights of regulated and unregulated intermediaries, w and $1 - w$, and then sum them up, we can obtain the following equation, which determines the aggregate supply of short-term debt:

$$p = c'(D) + \phi\left(wf(x_1) + (1-w)f(x_0)\right) + p\left(wx_1 + (1-w)x_0\right) + w(\rho - x_1)\lambda, \tag{90}$$

$$p = -\phi\left(wf'(x_1) + (1-w)f'(x_0)\right) + w\lambda, \tag{91}$$

where $c'(D) = wc'(d_1) + (1 - w)c'(d_0)$ by using the linearity assumption of the marginal issuance cost. Comparing these two equations with the F.O.C.s of the social planner, equations (80) and (81), we can derive the following result: with the approximation that $wx_1 + (1 - w)x_0 \approx x$, $wf(x_1) + (1-w)f(x_0) \approx f(x)$, $wf'(x_1) + (1-w)f'(x_0) \approx f'(x)$, and $x \approx x_1$, where x is the first-best liquidity ratio, the commitment fee and the required liquidity ratio that achieve the first-best credit and liquidity supplies are given by

$$\lambda = \frac{\eta}{w}(-f'(x)), \tag{92}$$

$$\rho = x + \frac{f(x)}{-f'(x)}. \tag{93}$$

When all banks are regulated and there is no uncertainty in the liquidity demand, the approximation becomes exact. As a result, the above commitment fee and required liquidity ratio can achieve the first-best liquidity and credit supply. Note that when unregulated banks or uncertain liquidity demand are present, the commitment fee and liquidity ratio determined by equations (92) and (93) only approximate the optimal values and do not necessarily maximize the welfare.

Appendix B. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jfineco.2023.103747.

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