Liquidity Regulation and Banks: Theory and Evidence*

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Abstract

This paper investigates, theoretically and empirically, 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 premium 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 model also shows that the fixed quantity mandate can interact with the uncertain liquidity demand, amplifying the volatility in the liquidity premium. A central bank committed liquidity facility can improve the current quantity-based regulation by introducing a price-based mechanism.

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1 Introduction

Before the 2007–2009 financial crisis, bank regulation primarily focused on capital requirements. However, during the crisis, many banks—despite adequate capital levels—still experienced significant liquidity problems.[1] In response, the Basel Committee introduced global liquidity standards to reduce risks associated with excessive liquidity transformation. Since then, the U.S. bank regulators have implemented the Liquidity Coverage Ratio (LCR) requirement in 2013. 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 tries to shed light on this question using insights from public interest theory (Pigou, 1932; Weitzman, 1974; Laffont and Tirole, 1993; Dewatripont and Tirole, 1994). We show that the current LCR rule can improve upon the unregulated equilibrium but can also have 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

[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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mitigator of liquidity risks. As a result, the LCR rule cannot simultaneously achieve the first-best liquidity and lending. The distortion worsens when heterogeneous intermediaries are not subject to the same liquidity rule and when the demand for liquidity is uncertain.

Our analysis is motivated by new empirical patterns that arose after implementing the LCR. Using the 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 pre-regulation 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 experienced an improvement in their liquidity condition, the required liquidity buffers appear to have crowded out the illiquid assets. 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. Furthermore, we find that some liquidity risks appear to have migrated to banks that are not subject to liquidity regulation. Specifically, non-LCR banks, that is, 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.[3]

We develop a model of liquidity regulation with endogenous liquidity premium and heterogeneous banks to explain the findings. In the model, banks do not fully internalize

[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.

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the externality of liquidity transformation, so there is an excess liquidity transformation in the laissez-faire equilibrium. This market failure motives liquidity regulation. The current LCR rule is a quantity-based regulation in the terminology of Weitzman (1974) in the sense that banks are required to hold a fixed quantity of 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 also serves as a costly mitigator of liquidity risks in the sense that it occupies banks' balance sheets but generates low returns. As a result, the LCR rule cannot simultaneously achieve the first-best liquidity and credit supply. Instead, it faces a trade-off between achieving the first-best liquidity and lending. Furthermore, when not all of the intermediaries are subject to liquidity regulation, as regulated banks hold more liquid assets, the liquidity premium in the economy rises, which incentivizes 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. 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.

While these distortions do not necessarily negate the positive effects of the LCR on welfare, it suggests possible room for improvement. Inspired by the classic result in Weitzman

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(1974) on quantity-based vs. price-based regulation, we consider a central bank committed liquidity facility 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, which eliminates 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. It is worth noting 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.

This paper contributes to the growing literature on liquidity regulation. On the theory side, Farhi, Golosov, and Tsyvinski (2009) show that the private market cannot provide liquidity efficiently, so government intervention is needed. Carletti, Goldstein, and Leonello (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, Heider, and Hoerova (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) study the incentive properties of liquidity regulation. Kashyap, Tsomocos, and Vardoulakis (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

[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.

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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.

Our paper also relates to growing empirical research on liquidity regulation. Berger and Bouwman (2009) and Bai, Krishnamurthy, and Weymuller (2018) study the measurement of liquidity mismatch in the banking sector. Anderson, Du, and Schlusche (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. Roberts, Sarkar, and Shachar (2018) find that banks subject to the LCR requirement create less liquidity per dollar of assets in the post-LCR period. Banerjee and Mio (2018) find that liquidity regulation improves the liquidity condition for U.K. banks. We contribute to the literature by documenting the crowding-out and migration effects of the LCR rule and supplying a model to rationalize these findings. Furthermore, our model also predicts that the current liquidity rule can increase the volatility of liquidity premium, which is consistent with the findings by Afonso, Cipriani, Copeland, Kovner, La Spada, and Martin (2020), Correa, Du, and Liao (2020), Avalos, Ehlers, and Eren (2019), and D'Avernas and Vandeweyer (2020).

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, Gorton, Holm-

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ström, and Ordonez (2017) show that private liquidity is provided by banks by keeping the 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.

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 Committee.[5] The LCR builds on traditional liquidity "coverage ratio" methodologies used internally by banks to assess exposure to contingent liquidity events (Basel III, 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:

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

[5]Another component of 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 has 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.

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HQLA in the numerator are calculated by multiplying a liquidity factor for each type of liquid assets 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 that banks can recover from these assets in the middle of a severe financial crisis. 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 as well as 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%. The detailed liquidity weights can be found in Table OA.1.

The net expected cash outflows in the denominator are defined as the difference between expected cash outflows and inflows. Expected cash outflows are calculated by multiplying runoff rates to the portion of liabilities that mature within the next 30 days:

$$\textit{Expected cash outflows} = \sum_k \textit{Runoff rate}_k \times \textit{Cash outflows in 30 days.} \tag{3}$$

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 runoff rate leads to greater expected cash outflows. The runoff rates represent the portion of the liability that remains a source of funding during the next 30 days. The detailed runoff rates assigned by the LCR rule can be found in Table OA.2.

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The LCR was finalized in January 2013 with a final compliance deadline in 2017. In the United States, banks with assets above \$50 billion are subject to the LCR while banks with assets below \$50 billion are not.[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 LCR rule was finalized.

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 the bank level and bank holding company (BHC) level. 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 simply refer to our observations as banks.[7] 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, Huang, and Wu (2014) to construct the liquidity ratio using banks' balance sheet composition. It is worth noting 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, Du, and

[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 for banks with assets above \$250 billion.

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

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Liao, 2020). As a result, we use Call Reports and FR Y-9C, which 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. The sample period is from 2011Q1 to 2017Q4. The median liquidity ratio is 0.74 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 the 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 experience a -2.6% loan growth rate on average while the non-LCR banks experience a 6.5% loan growth rate.

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 Figure 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:

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they usually maintain an additional buffer relative to the minimum requirement to avoid hitting the hard regulatory constraint when there is an unexpected shock.

Banks can improve their liquidity ratios by increasing high-quality liquid assets or stable funding. Figure 2(a) shows the high-quality liquid assets held by LCR banks and non-LCR banks, normalized by the level in 2013Q1, the quarter when the LCR was introduced. We find that LCR banks have significantly increased their holdings of high-quality liquid assets by around 35% from 2013 to 2017. In comparison, the holdings of high-quality liquid assets by non-LCR banks stayed largely flat. Figure 2(b) compares the illiquid assets of LCR banks and non-LCR banks. We find that LCR banks' illiquid assets appear to grow significantly slower than those of non-LCR banks. This pattern suggests that banks have a limited balance sheet capacity and the mandated liquidity buffer appears to crowd out illiquid assets.

Next, we turn our attention to the liability side. Figure 2(c) shows deposits of LCR banks and non-LCR banks, respectively. Deposits are generally treated as stable funding sources in the LCR because most of them are insured. Somewhat 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. Figure 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 runoff rates in the LCR rules.

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 Figure 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 Figure 2. Because

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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, such as tightened capital requirements and quantitative easing, also occurred when liquidity regulation was implemented. This section uses micro-level data to identify the effects of post-crisis liquidity regulation.

3.2.1 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, Demyanyk, Li, Loutskina, and Strahan (2020). A trade-off 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.[8] Our results are robust to an alternative identification strategy

[8]For instance, Cortés, Demyanyk, Li, Loutskina, and Strahan (2020) study 28 banks that are subject to stress testing. Correa, Du, and Liao (2020) study six U.S. globally systemically important banks covered by the Complex Institution Liquidity Monitoring Report, FR2052a.

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that compares LCR banks with non-LCR banks in a difference-in-differences regression.[9] We construct a *liquidity ratio gap*$_i$ for each bank, defined as the following:

$$Liquidity\ ratio\ gap_i = Required\ ratio_i - Pre\text{-}regulation\ ratio_i, \tag{4}$$

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.

Using *Liquidity ratio gap* as a measure of the exposure to LCR, We examine the effect of liquidity regulation on the asset holdings of LCR banks. The regression model is the following:

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

The sample period is from 2011Q1 to 2017Q4. *Post* is a dummy variable that equals one if the time is after 2013Q1. *HQLA* is the growth rate of high-quality liquid assets. The control variables include *Log Assets*, *Capital ratio gap*, and the interaction term of *Capital ratio gap* and *Post*.[10] We include bank fixed effects to absorb unobservable differences in bank business models and time fixed effects to absorb macro-economic shocks such as quantitative easing.

[9] See Online Appendix Table OA.3.

[10] *Capital ratio gap* is defined analogously to *Liquidity ratio gap* as the difference between the required minimum capital ratio, 10.5%, and the actual ratio. Note that new capital requirements were introduced before the LCR so the interaction term between *Capital ratio gap* and the post LCR dummy does not measure the effect of tightened capital regulation. Instead, the interaction term allows the effects of capital requirement to be different before and after the LCR.

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We use the growth rate of HQLAs as the dependent variable instead of the share of HQLAs in total assets because changes in the relative share could be driven by changes in other assets in the denominator. This distinction will become crucial when we examine the crowding-out effect of HQLAs on illiquid assets. If banks increase HQLAs but do not reduce illiquid assets, we would observe a mechanical reduction in the relative share of illiquid assets, but such reduction in the relative share does not imply a crowding-out effect. Furthermore, our post-LCR sample features the transition period in which banks can gradually adjust their balance sheets before the compliance deadline in 2017. Using the growth rate is more appropriate to capture the transition dynamics in the compliance period as a positive estimate implies that more exposed banks experience higher growth rates in HQLAs during the compliance period after the LCR is introduced.[11] Panel A of Table 3 shows the results. We find that a 10% higher gap between the pre-regulation liquidity ratio and the required level is associated with a 4.6% higher growth rate in high-quality liquid assets after the LCR introduction. The magnitudes are robust when more fixed effects are included in the regression.

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 Panel B of Table 3. 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 0.4% lower growth rate in illiquid assets after the LCR introduction. The effects are robust to controlling for bank fixed effects, time fixed effects, and banks' exposure to capital regulation.

[11]The results are robust using the share of assets as the dependent variable as shown in the Online Appendix Table OA.4.

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We further examine lending of LCR banks using CRA loan origination data. We estimate the following regression in the sample of LCR banks:

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

$Loans_{i,m,t}$ is 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 period is from 2011 to 2017. $X_{i,m,t}$ is a set of control variables, including the log assets and deposit ratio. Table 4 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 1.7% lower annual loan growth rates after the introduction of the LCR.

One may also worry that the change in the loan growth rates could be driven by changes in demand rather than supply. To address this concern, we follow the identification strategy of Cortés, Demyanyk, Li, Loutskina, and Strahan (2020) to include MSA-year fixed effect $\tau_{m,t}$ to absorb the time-varying local demand shocks. This test essentially compares two banks in the same MSA market and in the same year. Table 4 shows that the results are robust in this specification.[12]

3.2.2 Non-LCR Banks

As shown in Figure 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

[12]Our findings are related to Chen, Hanson, and Stein (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 implementation of the LCR in 2013.

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variations in the presence of LCR banks. Specifically, we calculate the *LCR-bank share* in a metropolitan statistical area (MSA), defined as the total loans of LCR banks within the MSA over the total 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*:

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

where $\textit{Loans}_{m,j}$ is the loans of bank j in MSA m and $\textit{LCR bank}_{m,j}$ is a dummy variable which equals 1 if the bank is an LCR bank. We estimate the following regression model in the sample of non-LCR banks:

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

where $\textit{Loan}_{i,m,t}$ 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. Note that we include bank-year fixed effects to absorb the supply shocks. Therefore, the identification is obtained by comparing the lending of the same non-LCR banks in two MSAs with different LCR-bank shares.

Table 5 shows the results: non-LCR banks have significantly expanded lending in regions formerly more reliant on LCR banks. 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. Note that we include MSA fixed effects in all specifications, so the results are not driven by unobservable differences across MSAs. The results are also robust to controlling for the exposure to stress testing and local economic conditions.

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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:

$$Average\ LCR\text{-}bank\ share_i = \frac{\sum_m LCR\text{-}bank\ share_m \times Loans_{m,i}}{\sum_i Loans_{m,i}}, \tag{9}$$

where $LCR\text{-}bank\ share_m$ 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 the markets where it operates.

We then estimate the following regression model in the sample of non-LCR banks:

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

where $Liquidity_{i,t}$ is measured by the liquidity coverage ratios of non-LCR banks. Table 6 shows the results. We find that 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 4% decrease in the liquidity ratios after the LCR introduction. The result shows that some liquidity risks have migrated from LCR banks to non-LCR banks.

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

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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 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 that are 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.

[13] There is a large literature studying the unregulated intermediaries with respect to 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 think about shadow banks and government-sponsored enterprises as entities that can conduct liquidity transformation but are not subject to liquidity regulation.

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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 $T = 1$ 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 firesale. We assume the random withdrawal follows a binary distribution. 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 "runoff rate" following the terminology of the LCR. 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 ρ to indicate regulated banks and subscript 0 to indicate

[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.

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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

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

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

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

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

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

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

$$P = \xi v'(Q), \tag{19}$$

where Q is the total stock of liquid assets held by the representative household, v is the utility that the representative household derives from liquidity assets, and $\xi \geq 0$ is a random shock to the aggregate liquidity demand. An increase in Q lowers the liquidity premium that the representative household is willing to pay, so $v'' < 0$. In the following analysis, we assume that the indirect utility function is $v(Q) = \left(1 - \frac{1}{\sigma}\right)^{-1} Q^{1-\frac{1}{\sigma}}$, where σ is the elasticity of liquidity demand. The indirect utility 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) and Nagel (2016).[16]

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 equation (14), taking the equilibrium liquidity premium, P, as given.

2. The equilibrium liquidity premium, P, adjusts such that the aggregate supply of liquidity equals to the demand.

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

[16] The details can be found in Appendix A.1.

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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,

$$L = aD. \tag{21}$$

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

$$I = (1 - a)D. \tag{22}$$

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

$$P = \underbrace{c' + (1 - a)\mu\phi + aP}_{\text{Private marginal cost}}, \tag{23}$$

Compare equation (23) with equation (26), we can see that there is excessive liquidity transformation in the laissez-faire equilibrium because banks do not internalize the social externality of liquidity transformation.

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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 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,

$$L = aD. \tag{24}$$

Note that 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 $\frac{1}{a}$.

And 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 social marginal benefit of liquidity and the social marginal cost:

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

The left-hand side is the liquidity premium, which also equals the marginal utility of the representative household to liquidity, $P = \xi v'((1-a)D + G)$. The right-hand side is the social marginal cost of liquidity transformation. The first component, $c' + (1-a)\mu\phi + aP$ is the private marginal cost, which consists of the issuance cost c', the expected firesale

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cost $(1-a)\mu\phi$, and the opportunity cost of holding liquidity aP. The second component is the social externality, $(1-a)\mu\eta$.

The social welfare of the liquidity market is defined by the following expression:

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

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

Proposition 1. *The first-best equilibrium can be implemented by a Pigovian tax on short-term debt 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, so it implements the first best. ∎

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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. We would like to know to what extent the LCR requirement resembles the Pigovian tax and to what extent it is different.

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 in excess to the level that banks prefer to hold, $P - \mu\phi$ is the opportunity cost of holding liquidity buffer adjusted for the benefits of reducing liquidation cost.

Proof: 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 way that the LCR works is to impose an implicit tax on liquidity transformation by requiring banks to hold liquid assets, which generate lower

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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 not true even if all intermediaries are subject to the LCR. The reason has to do with the fact 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 why 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 in the sense that 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 the short-term debt issued, D. But to do so, the regulators would have to alter the equilibrium liquidity multiplier, $\frac{D}{L}$, which describes how efficient 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

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because it is determined by banks' optimal choice given the distribution of redemptions. The LCR, however, changes the liquidity multiplier from $\frac{1}{a}$ to $\frac{1}{\rho}$, which leads to welfare distortion.

We illustrate the crowding-out effect in Figure 3. We solve the equilibrium for different runoff rates ρ. A higher value of runoff 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. Figure 3(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 Figure 3(d). However, the LCR cannot bring the 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 Figure 3(b). The liquidity premium rises above the socially optimal level, as shown in Figure 3(c). In fact, 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 runoff rate.

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 creates wel-

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fare 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, σ: 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 Figure 4. 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 Figures 4(a) and 4(b). The equilibrium liquidity premium falls when there are more unregulated intermediaries, as shown by Figure 4(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, which can exacerbate the migration. Formally, we assume that the runoff rate ρ is determined *before* the realization of the uncertain liquidity demand, ξ. We can show the following result:

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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. ∎

We illustrate the equilibrium outcomes with uncertain liquidity demand in Figure 5. 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 Figures 5(a) and 5(b). If the liquidity demand turns out to be quite high, the liquidity premium will be higher than expected, as shown in Figure 5(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 Figure 5(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, it suggests possible room for welfare improvement. In the following discussion, we study a potential policy that can alleviate such distortions.

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We consider a central bank committed liquidity facility as a complement to the existing LCR rule.[17] 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.

Formally, define λ as the upfront commitment fee, and q as the quantity of committed liquidity that banks obtain from the committed liquidity facility. Regulated bank's problem is given by

$$\pi_1 = \max_{i_1,l_1,d_1,q_1} Ri_1 + (R-P)l_1 - (R-P)d_1 - \phi\mathbb{E}\left[\tilde{\alpha}d_1 - l_1\right]^+ - \lambda q_1, \tag{33}$$

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.

[17] 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).

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We focus on how the upfront fee λ at $T = 0$ 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 such that banks do not draw from the committed liquidity to meet short-term creditors' withdrawal at $T = 1$ even if they have unused commitments. Instead, banks only use the commitment to fulfill liquidity requirement $T = 0$. This assumption ensures that the committed liquidity facility only changes banks' regulatory environment without affecting the liquidity transformation technology that banks have access to. Under this assumption, the expected liquidation cost only depends on the government securities 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 of 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, then the committed liquidity facility could make the liquidity requirement too loose. If the commitment fee is too high, then the committed liquidity facility would not be used at all. 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*

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

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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 Figure 5. We find that under the optimal pricing of the commitment fee, the equilibrium liquidity premium always equals the first-best level, regardless of the realized liquidity demand. This pattern is in stark contrast to the pure LCR case shown by the solid line, where an unexpected 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 Figure 5(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. Figure 5(d) shows that the social welfare with the committed liquidity facility is always higher than the laissez-fair equilibrium. In contrast, under the current LCR rule, the social welfare with liquidity regulation could be lower than the laissez-fair equilibrium if the liquidity demand is unexpectedly high. Note that the committed liquidity facility does not bring the welfare to the first-best level because there is still a distortionary migration of liquidity transformation from regulated banks to unregulated ones.

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.

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Before we conclude, it would be helpful to discuss the similarities and differences between the committed liquidity facility and some existing central bank facilities, notably, the central bank discount window. First, under the discount window, liquidity must be drawn from the central bank to be counted as a liquidity buffer. The drawn liquidity occupies banks' balance sheets and crowds out loans. The central bank's balance sheet will also expand significantly. However, banks do not need to draw liquidity from the committed liquidity facility to meet the LCR requirement. Instead, the unused capacity of the loan commitment from the committed liquidity facility can be counted as a liquidity buffer.[18] 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 commitment that they may need in the future.

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. From a

[18] One may argue that the regulator could, in principle, count the unused capacity of the discount window toward the LCR. In other words, any discount-window-eligible assets should be counted as high-quality liquid assets. However, this policy proposal essentially undoes the liquidity regulation because banks do not need to pay upfront fees to obtain the capacity to borrow from the discount window.

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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 liquidity 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.

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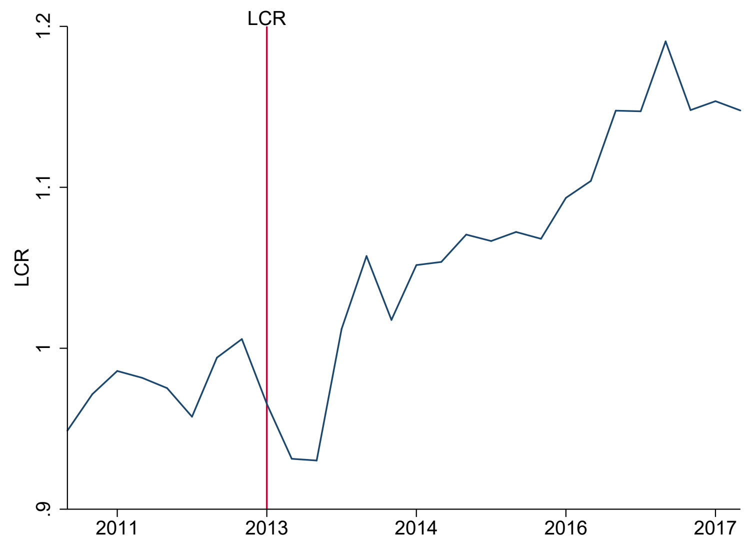
(a) LCR banks



(b) Non-LCR banks

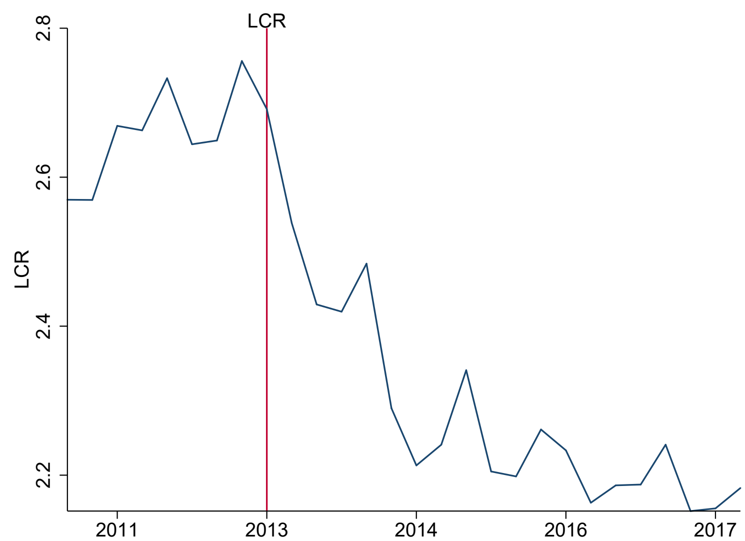


Figure 1: Liquidity Coverage Ratio of U.S. Banks

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.

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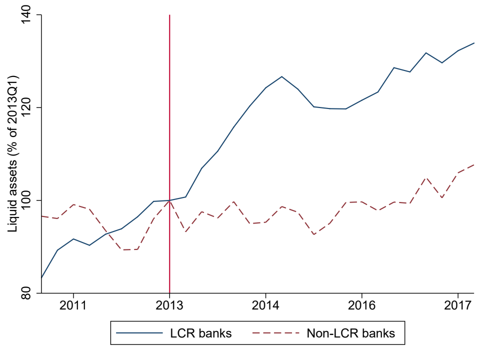
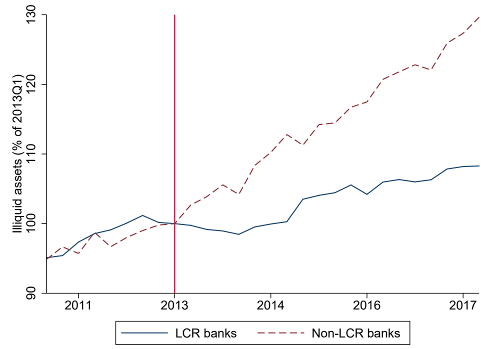
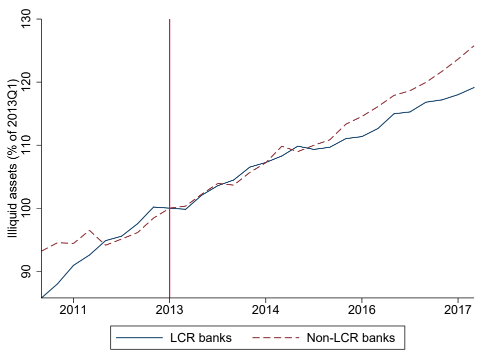
(a) HQLA



(b) Non-HQLA



(c) Deposits



(d) Non-deposits

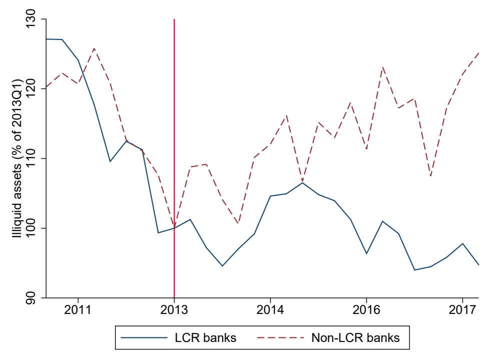


Figure 2: U.S. Bank Balance Sheets During the LCR Implementation

This figure shows the composition of U.S. bank balance sheets over time. The blue solid line presents LCR banks, and the red dashed line represents non-LCR banks. The vertical line indicates 2013Q1, 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-HQLA include loans, derivatives, and real estate holdings. The sample period is from 2011 to 2017. Data source: Call Reports, FR Y-9C.

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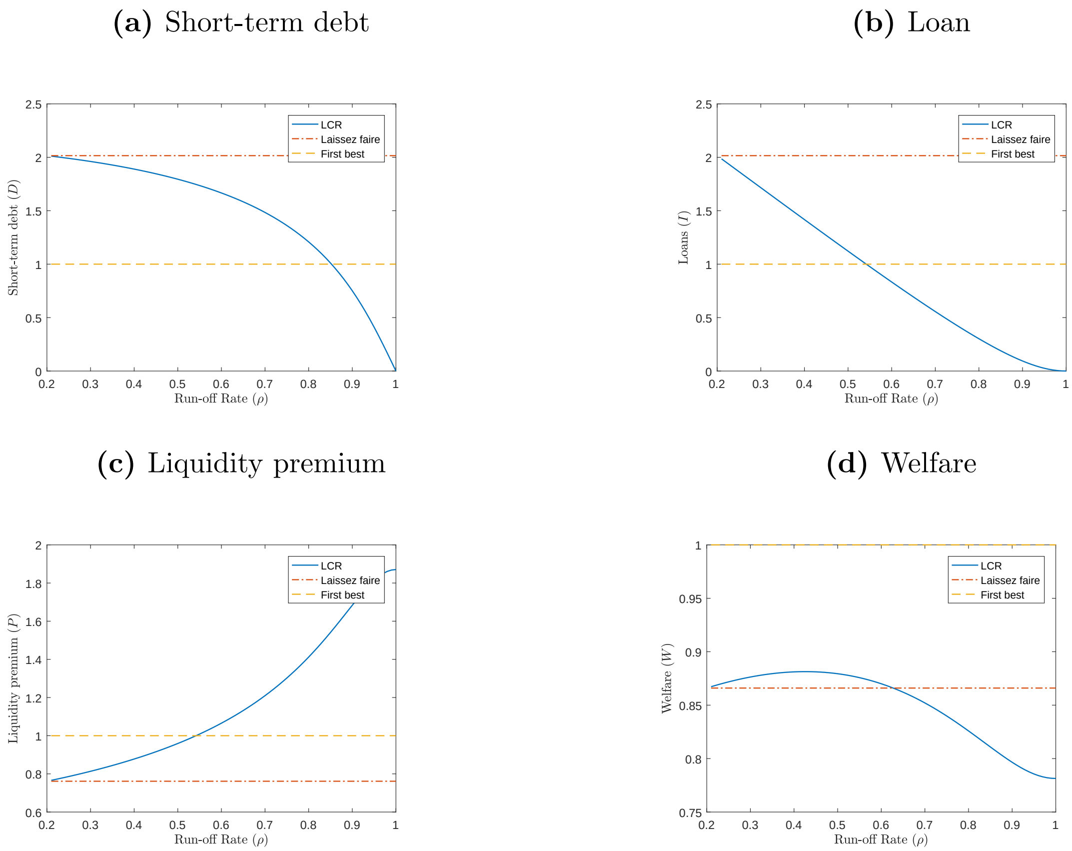

Figure 3: Model Equilibrium with Different Run-off Rates

This figure plots equilibrium prices and quantities for different runoff rates. The fraction of withdraw in good state a is 0.2. The demand for liquidity ξ is fixed at 1. The liquidity demand elasticity σ is 2. The insurance 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.

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(a) Short-term debt

(b) Loan

(c) Liquidity premium

(d) Welfare

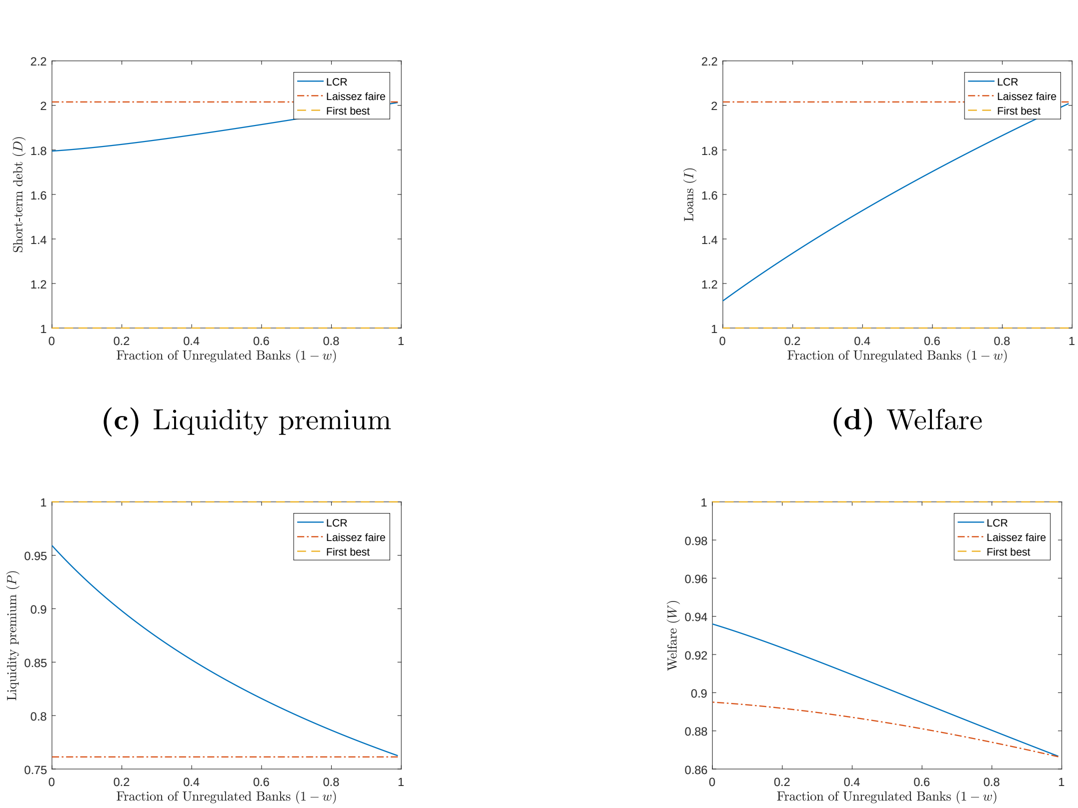

Figure 4: Model Equilibrium with Different Fraction of Unregulated Banks
This figure plots equilibrium prices and quantities for different fraction of unregulated banks, $1 - w$. The runoff rate ρ is fixed at 0.5. The fraction of withdraw in good state a is 0.2. The liquidity demand elasticity σ is 2. The insurance 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.

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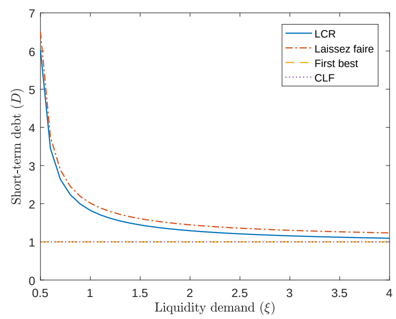
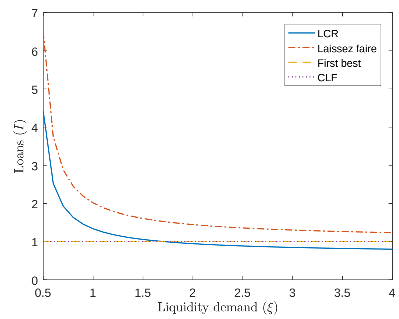
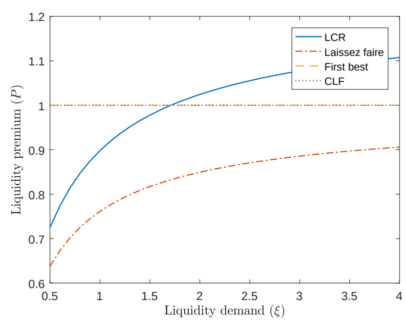
(a) Short-term debt



(b) Loan



(c) Liquidity premium



(d) Welfare

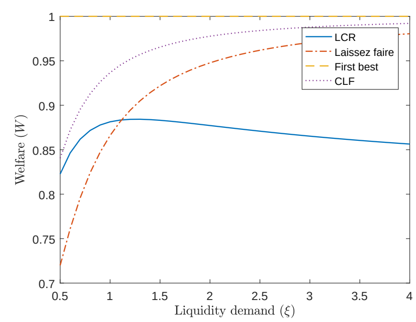


Figure 5: Model Equilibrium with Different Liquidity Demands

This figure plots equilibrium prices and quantities for different liquidity demands, ξ. The runoff rate ρ is fixed at 0.5. The fraction of withdraw in good state a is 0.2. The liquidity demand elasticity σ is 2. The insurance 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.

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Table 1: Summary Statistics of the Bank Balance Sheet Data

Panel A: LCR banks

	mean	sd	p5	p25	p50	p75	p95
Liquidity coverage ratio	0.820	0.455	0.303	0.480	0.740	1.015	1.703
Capital ratio	10.007	2.501	7.210	8.981	9.958	10.940	12.470
Log assets	25.826	1.079	24.621	25.133	25.514	26.240	28.153
HQLA growth	0.109	0.246	-0.206	-0.008	0.040	0.178	0.755
Illiquid asset growth	0.030	0.066	-0.091	-0.002	0.016	0.062	0.184
Deposit growth	0.047	0.055	-0.036	0.000	0.043	0.081	0.160

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	3.476	8.560
Capital ratio	9.986	4.079	6.050	8.550	9.650	10.970	14.410
Log assets	19.149	1.265	17.321	18.310	19.031	19.834	21.435
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

Note: Panels A and B report the summary statistics of the main variables used in the bank-level analysis. The unit of observation is a bank-quarter combination. The sample period is from 2011 to 2017. *Liquidity coverage ratio* is the ratio between high-quality liquid assets and the net cash outflows. *Capital ratio* is the ratio of capital over total assets.

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Table 2: Summary Statistics of the Loan Origination Data

Panel A: LCR banks

	mean	sd	p5	p25	p50	p75	p95
Loan growth	-0.026	0.872	-1.511	-0.577	-0.028	0.487	1.598
LCR-bank share	0.501	0.200	0.166	0.358	0.506	0.646	0.831
Stress-test-bank share	0.645	0.197	0.263	0.515	0.681	0.795	0.919

Panel B: Non-LCR banks

	mean	sd	p5	p25	p50	p75	p95
Loan growth	0.065	0.995	-1.663	-0.598	0.007	0.751	1.780
LCR-bank share	0.503	0.194	0.168	0.359	0.516	0.650	0.798
Stress-test-bank share	0.653	0.187	0.279	0.534	0.696	0.795	0.905

Note: Panels A and B report the loan origination data from CRA for LCR and non-LCR banks, respectively. The unit of observation is a bank-MSA-year combination. *LCR-bank share* is the share of LCR banks in a local market. *Stress-test bank share* is the share of stress-testing banks in a local market.

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Table 3: LCR Banks' Asset Holdings

Panel A: HQLA

	(1) HQLA	(2) HQLA	(3) HQLA
Post * Liquidity ratio gap	0.418**	0.392**	0.458**
	[0.188]	[0.187]	[0.198]
Control	Yes	Yes	Yes
Bank F.E.	Yes	Yes	Yes
Time F.E.	Yes	Yes	No
Category-Time F.E.	No	No	Yes
Observations	588	588	588
Adj. R-squared	0.214	0.244	0.227

Panel B: illiquid assets

	(1) Illiquid assets	(2) Illiquid assets	(3) Illiquid assets
Post * Liquidity ratio gap	-0.036**	-0.034**	-0.036**
	[0.016]	[0.015]	[0.016]
Control	Yes	Yes	Yes
Bank F.E.	Yes	Yes	Yes
Time F.E.	Yes	Yes	No
Category-Time F.E.	No	No	Yes
Observations	588	588	588
Adj. R-squared	0.261	0.378	0.352

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 variables are the growth rates of high-quality liquid assets and illiquid assets for panel A and B, respectively. *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. The control variables include *Log Assets*, *Capital ratio gap*, and the interaction term of *Capital ratio gap* and *Post*. Standard errors shown in parentheses are clustered at the quarter level. ***, **, and * represent 1%, 5%, and 10% significance levels, respectively.

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Table 4: Lending of LCR Banks

	(1) Loans	(2) Loans	(3) Loans
Post * Liquidity ratio gap	-0.147***	-0.158***	-0.157***
	[0.056]	[0.056]	[0.058]
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	28,315	28,313	27,984
Adj. R-squared	0.056	0.057	0.011

Note: This table shows the impact of liquidity regulation on the lending of LCR banks. The sample includes banks with assets above $50 billion from 2011Q1 to 2017Q4. The dependent variable, *Loans*, 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. The control variables include *Log Assets*, *Capital ratio gap*, and the interaction term of *Capital ratio gap* and *Post*. Standard errors shown in parentheses are clustered at the MSA level. ***, **, and * represent 1%, 5%, and 10% significance levels, respectively.

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Table 5: Lending of Non-LCR Banks

	(1) Loans	(2) Loans	(3) Loans
Post * LCR-bank share	0.295***	0.209**	0.172*
	[0.059]	[0.090]	[0.092]
Post * Stress-test-bank share		0.118	0.127
		[0.093]	[0.093]
Unemployment rate			-0.020**
			[0.008]
Constant	-0.052**	-0.078**	0.058
	[0.024]	[0.032]	[0.066]
Bank-Time F.E.	Yes	Yes	Yes
MSA F.E.	Yes	Yes	Yes
Observations	49,281	49,281	49,281
Adj. R-squared	0.099	0.099	0.099

Note: This table shows the spillover effect of liquidity regulation on the loan growth of non-LCR banks. The sample includes banks in the CRA data with assets below $50 billion from 2011Q1 to 2017Q4. The dependent variable, *Loans*, is the growth rates 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. Standard errors shown in parentheses are clustered at the MSA level. ***, **, and * represent 1%, 5%, and 10% significance levels, respectively.

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Table 6: Liquidity Ratio of Non-LCR Banks

	(1) Liquidity ratio	(2) Liquidity ratio	(3) Liquidity ratio
Post * LCR-bank share	-0.579***	-0.503***	-0.548***
	[0.175]	[0.157]	[0.146]
Control	Yes	Yes	Yes
Bank F.E.	Yes	Yes	Yes
Time F.E.	No	No	Yes
Observations	15,466	15,466	15,466
Adj. R-squared	0.802	0.802	0.807

Note: This table 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 effects and time fixed effects are added to the regressions, as shown in the table. Standard errors shown in parentheses are clustered at the quarter level. ***, **, and * represent 1%, 5%, and 10% significance levels, respectively.

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Appendix

A.1 Derivation of the Aggregate Demand for Liquidity

Following Nagel (2016), we assume that households derive utility from holding a stock of liquid assets. The representative household seeks to maximize the objective

$$\mathbb{E}_0 \sum_{t=1}^{\infty} \beta^t u(C_t + \alpha_t v(Q_t)), \tag{38}$$

subject to the budget constraint

$$D_t + N_t + B_t + C_t = D_{t-1}R^d_{t-1} + N_{t-1}R^g_{t-1} + B_{t-1}R_t + \Pi_{t-1} - T_{t-1} + Y_t, \tag{39}$$

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 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, α_t is utility weight on the liquidity services, and v is the utility function from liquidity services. The households' total stock of liquidity is the sum of short-term debt issued by banks D_t and government securities N_t:

$$Q_t = D_t + N_t. \tag{40}$$

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

$$R_t = \frac{1}{\beta}\left\{\mathbb{E}_t\left[\frac{u'_{t+1}}{u'_t}\right]\right\}^{-1}. \tag{41}$$

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

$$u_t'\left(\alpha_t v'(Q_t) - 1\right) = -\beta \mathbb{E}_t\left[u_{t+1}'\right] R_t^d. \tag{42}$$

Plug in the Euler equation to replace $\mathbb{E}_t\left[u_{t+1}'\right]$, we have

$$R_t - R_t^d = R_t \alpha_t v'(Q_t). \tag{43}$$

Define $P_t \equiv R_t - R_t^d$ as the liquidity premium of short-term debt, and $\xi_t \equiv R_t \alpha_t$ as the aggregate liquidity demand shock. we can derive the aggregate demand for short-term debt:

$$P_t = \xi_t v'(Q_t). \tag{44}$$

Because the demand for liquidity is static, we can drop the time subscript, which gives rise to equation (19).

The household first-order condition with respect to the government securities yields the following equation:

$$u_t'\left(\alpha_t v'(Q_t) - 1\right) = -\beta \mathbb{E}_t\left[u_{t+1}'\right] R_t^g. \tag{45}$$

Comparing the above equation with equation (42), we get that the liquidity premium of government securities is the same as the liquidity premium of short-term debt issued by banks:

$$R_t - R_t^g = R_t - R_t^d = P_t. \tag{46}$$

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

$$G_t = G_{t-1} R_{t-1}^g + T_t - \eta(D_t - L_t), \tag{47}$$

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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 2

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:

$$(\rho - a)(P - \mu\phi) = \mu\eta. \tag{48}$$

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:

$$I^{LCR} < I^{FB}. \tag{49}$$

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

$$P^{LCR} > P^{FB}. \tag{50}$$

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

A.3 Proof of Proposition 4

Given $\lambda = \frac{\mu\eta(1-a)}{w(\rho-a)}$, we can always find a large enough ρ such that $\lambda \leq P - \mu\phi$. Consequently, banks use the committed liquidity facility to meet the liquidity requirement. The F.O.C. of the regulated banks is given by

$$P = c'(d_1) + (1-a)\mu\phi + aP + (\rho - a)\lambda. \tag{51}$$

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

$$P = c'(d_0) + (1 - a)\mu\phi + aP. \tag{52}$$

Multiplying the above two equations with the weights of regulated and unregulated intermediaries, w and $1 - w$, and the sum them up, we can obtain the aggregate supply of short-term debt is determined by the following equation:

$$P = c'(D) + (1 - a)\mu\phi + aP + w(\rho - a)\lambda, \tag{53}$$

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. ∎

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Online Appendix

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Table OA.1: The Regulatory Weights of LCR: Assets

Description	**Factor**
Level 1 HQLA	
Cash / Reserve	100%
U.S. Government Securities	
GNMA MBS	100%
Non-GSE Agency Debts	100%
Foreign Sovereign Debt Securities	100%
Level 2a HQLA	
GSE Debts	85%
GSE MBS	85%
Agency CMBS	85%
Level 2b HQLA	
Investment-grade corporate bonds	50%
Russell 1000 equities	50%
Investment-grade municipal bonds	50%
Non-HQLA	
Loans	0%

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Table OA.2: The Regulatory Weights of LCR: Liabilities

Description	Factor
Expected Cash Outflows	
Deposits	
Stable foreign deposits with a remaining maturity of one month or less	5%
Less-stable foreign deposits with a remaining maturity of one month or less	25%
Stable large-time deposits with a remaining maturity of one month or less	20%
Less-stable large-time deposits with a remaining maturity of one month or less	40%
Stable small-time deposits with a remaining maturity of one month or less	3%
Less-stable small-time deposits with a remaining maturity of one month or less	10%
Stable wholesale transaction deposits	5%
Less-stable wholesale transaction deposits	25%
Stable retail transaction deposits	3%
Less-stable retail transaction deposits	10%
Stable wholesale saving deposits	20%
Less-stable wholesale saving deposits	40%
Stable saving deposits	3%
Less-stable retail saving deposits	10%
Wholesale Funding	
Secured by level 1 liquid assets	0%
Secured by level 2A liquid assets	15%
Secured by level 2B liquid assets	50%
Secured by other assets (with sovereigns and GSEs as counterparty)	25%
Secured by other assets (with other counterparty)	100%
Unsecured borrowing	100%
Loan commitment	
Negative fair value of derivatives	100%
Unused commitments for securities underwriting	100%
Unused commitments of commercial real estate	10%
Unused commitments of credit cards	5%
Unused commitments of home equity line of credit	5%
Other unused commitments	5%
Letters of credit	5%
Repo	30%
Repo Offset	30%
Securities Lent	30%
Expected Cash Inflows	
50% of loans with a remaining maturity less than one month	100%
Positive fair value of derivatives	100%
Securities Borrowed	30%
Reverse Repo	30%

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Table OA.3: Effect of LCR on HQLA: Difference-in-Differences

	(1) HQLA	(2) HQLA	(3) HQLA
LCR*Post	0.057**	0.054**	0.052**
	[0.026]	[0.024]	[0.025]
Control	Yes	Yes	Yes
Bank F.E.	No	Yes	Yes
Time F.E.	No	No	Yes
Observations	23,765	23,765	23,765
Adj. R-squared	0.027	0.064	0.087

Note: This table shows the effect of liquidity regulation on high-quality liquid assets held by LCR banks. The sample includes both LCR and non-LCR banks from 2011Q1 to 2017Q4. The dependent variable, $HQLA$, is the growth rate of high-quality liquid assets. *Post* is a dummy variable that equals one if the time is after 2013Q1. *LCR* is a dummy variable that equals one if a bank is subject to the LCR rule. The control variables include *Capital ratio gap* and *Log Assets*. Standard errors shown in parentheses are clustered at the quarter level. ***, **, and * represent 1%, 5%, and 10% significance levels, respectively.

Table OA.4: High-Quality Liquid Assets of LCR Banks: Alternative Dependent Variable

	(1) HQLA share	(2) HQLA share	(3) HQLA share
Post * Liquidity ratio gap	0.077***	0.081***	0.077***
	[0.017]	[0.016]	[0.017]
Control	Yes	Yes	Yes
Bank F.E.	Yes	Yes	Yes
Time F.E.	Yes	Yes	No
Category-Time F.E.	No	No	Yes
Observations	588	588	588
Adj. R-squared	0.947	0.953	0.952

Note: This table shows the effect of liquidity regulation on high-quality liquid assets held by LCR banks. The sample includes banks with assets above $50 billion from 2011Q1 to 2017Q4. The dependent variable, $HQLAshare$, is the share of high-quality liquid assets in total 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. The control variables include *Capital ratio gap* and *Log Assets*. Standard errors shown in parentheses are clustered at the quarter level. ***, **, and * represent 1%, 5%, and 10% significance levels, respectively.

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