A Macroeconomic Model of Liquidity, Wholesale Funding and Banking Regulation

Corinne Dubois* Luisa Lambertini†
EPFL EPFL

Abstract

This paper proposes a theoretical analysis of wholesale funding, liquidity and liquidity regulation in the US banking sector. We develop a dynamic macroeconomic model with regulated banks and a shadow banking sector. The banks raise deposits and get wholesale funding from the shadow bank, but are subject to moral hazard that limits their ability to leverage. In this context we impose liquidity regulation on the banks and study its macroeconomic effect. We find that liquidity regulation does not crowd out lending, but rather increases it. In steady state, liquidity regulation leads to larger banks, higher consumption, output and credit. In a dynamic setting, we find that countercyclical liquidity regulation helps mitigating the macroeconomic effects of shocks. We then test the implication of our model empirically, and provide evidence that banks with a higher liquidity ratio suffer less contraction of wholesale funding and loans during a time of financial stress.

*École Polytechnique Fédérale de Lausanne, E-mail: corinne.dubois@epfl.ch.
†École Polytechnique Fédérale de Lausanne, E-mail: luisa.lambertini@epfl.ch.

1 Introduction

The financial crisis of 2007- 2009 emphasized the central importance of banks in the macroeconomy and how their financial weakness quickly transmits to the real economy. In the pre-crisis context, banks increased leverage and reliance on short-term wholesale funding, while investing in illiquid assets with uncertain valuation. Banks were thus exposed to liquidity risk. During the financial crisis, banks got trapped in an adverse liquidity spiral: assets lost value, banks faced higher margins and haircuts on their short-term borrowing, making it increasingly difficult for them to roll-over their debt, and forcing them to sell their assets, which would then further depress asset prices. Following the financial crisis, Basel III introduced liquidity regulation for banks, aimed at making the banking sector more resilient to liquidity stress. The impact of bank liquidity regulation on aggregate variables such as output, credit, investment, consumption and asset prices, is uncertain. The goal of this paper is to analyze liquidity regulation from a macroeconomic perspective.

We study bank holding company (BHC) balance sheet data from the Federal Reserve Y-9C report (FRY9C) and find that wholesale funding is highly procyclical, whereas deposit and liquidity ratio are highly countercyclical. We then propose a dynamic macroeconomic model with regulated banks and a shadow banking sector. The financial sector is made up of banks and a shadow bank. The banks raise deposits from households and get wholesale funding from the shadow bank; they lend to firms that are subject to idiosyncratic risk. There is a moral hazard problem for the banks: because of limited liability, they have an incentive to invest in a suboptimal and riskier firm. The shadow bank recognizes the moral hazard and limits its lending to the bank to ensure that it invests optimally. The moral hazard increases with the standard deviation of idiosyncratic risk and with bank leverage. An increase in the riskiness of bank assets translates in a forced deleveraging: the bank is unable to roll over its wholesale funding. The forced deleveraging leads to a credit crunch and a fall in investment and output. In this setting we introduce a liquidity regulation that forces the bank to hold a fraction of safe and highly liquid assets and study the effect on the macroeconomy. The regulation changes the steady state of the model: banks hold safe assets, so their portfolio of assets becomes safer. This relieves their moral hazard and enables them to leverage more and lend more to firms. Thus, the steady state with regulation features more credit, higher output, investment and consumption. In a dynamic setting, we find that a countercyclical liquidity regulation that requires banks to hold on to more safe assets when the economy is in a slump helps to mitigate the macroeconomic shocks.

Our model predicts that banks that hold a higher ratio of liquid assets will suffer a smaller contraction of wholesale funding during a time of financial stress. In the second part of this paper, we take the implication of our model to the data and test it empirically. We use the TED spread as a proxy for market liquidity stress, and interact it with the liquidity ratio of the banks. We then run a regression of the growth of wholesale funding on the liquidity ratio and the interaction term of liquidity and TED spread. We find that the coefficient on the interaction term between the liquidity ratio and the TED spread is positive and significant. This implies that when the TED spread is high, banks with a higher liquidity ratio suffer less of a run on their wholesale funding. The empirical evidence lends some support to our theoretical findings.

2 Literature review

An important literature, starting with Diamond and Dybvig (1983) emphasizes the role of banks as liquidity providers. The authors show that bank liquidity provision improves the economic outcome, but can also be subject to harmful bank runs, hence the crucial role of deposit insurance. Diamond and Rajan (2001) and Diamond and Rajan (2000) further show that bank fragility resulting from accepting demand deposit is an essential feature of the bank. Demand deposits are a disciplining mechanism for bankers and makes it possible for them to lend more, which is beneficial to the economy. Angeloni and Faia (2013) introduce banks à la Diamond and Rajan (2001) in an dynamic macroeconomic model. More recently, Gertler and Kiyotaki (2015) develop a macroeconomic model with banks and sunspot bank run equilibria. In all these papers, the main risk for bank is a run by depositors. However, the existence of deposit insurance makes deposits a relatively safe source of funding for the bank. In our model, deposits are safe and the risk for the bank comes from wholesale funding.

A second group of contributions examines the role of financial frictions in the transmission of shocks to the macroeconomy. An early contribution on financial frictions is Bernanke et al. (1999). The financial friction is asymmetric information between borrowers and lenders and a costly state verification. The friction gives rise to a countercyclical external finance premium, leading to an amplification of the business cycle. Gertler and Kiyotaki (2010) and Gertler et al. (2012) develop a dynamic macroeconomic model with financial intermediation. Banks are subject to moral hazard due to their ability to divert a fraction of assets. The friction gives rise to an endogenous balance sheet constraint that will amplify the effects of shocks. He and Krishnamurthy (2013) and Brunnermeier and Sannikov (2014) propose a continuous-time nonlinear macroeconomic model with a financial sector. Brunnermeier and Sannikov (2014) model generates a strong amplification to large shocks that hit the net worth of the financial intermediaries, forcing them to fire-sell their capital. The liquidity risk in Brunnermeier and Sannikov (2014) stems from the lower liquidation price of assets when sold to households. In He and Krishnamurthy (2013) financial experts face an occasionally binding equity capital constraint. The equity constraint relates how much equity a bank can raise to its reputation, which is based in part performance. The equity constraint only binds during systemic crises, so the model features high amplification of shocks during crises. Our approach is different, because we introduce regulation on financial intermediaries.

Our theoretical work is related to Adrian and Shin (2014). The authors provide empirical evidence on investment banks and show that the leverage ratio is procyclical, whereas Value-at-Risk over equity remains relatively stable over the business cycle. Value-at-Risk (VaR) is a quantile measure on the loss distribution defined as the smallest threshold loss L such that the probability that the realized loss turns out to be larger than L is at most α. Their evidence supports the idea that banks actively manage their leverage ratios in order to maintain their equity equal to their VaR. Namely, they let their assets and debt grow during good times and cut them during bad times. If a bank manages its risk by keeping its VaR smaller than its equity, then it ensures that it can absorb losses up to the level of the VaR and it will be solvent with a probability of at least $1 - \alpha$. The authors propose a theoretical model with banks that borrow from a wholesale creditor. Banks have the choice between investing in a productive project, or in an inefficient project that has lower expected payoff and more volatility. Due to limited liability, the bank has an incentive to invest in the inefficient project because it has higher upside risk. The incentive to invest inefficiently increases with the leverage of the bank, so the contracting framework results in an endogenous leverage ratio for the bank. Nuño and Thomas (2013) implement the contract proposed by Adrian and Shin (2014) in a dynamic macroeconomic model. Their model explains bank leverage cycles as the result of risk shocks, namely of exogenous changes in the volatility of idiosyncratic risk. Intuitively, the higher volatility makes it more attractive for banks to invest inefficiently, and so the wholesale creditor reduces lending to induce banks to invest efficiently. Following a risk shock, banks are forced to deleverage, the price of bank assets fall, inducing a decline in investment and output. Our work builds on the work by Adrian and Shin (2014) and by Nuño and Thomas (2013), but we extend it in several important ways. First, our banks are able to chose their liability structure, namely they chose between deposits and wholesale funding. Second, our banks are regulated and subject to deposit insurance by the government.

Several empirical papers emphasize the importance of wholesale funding and liquidity in causing or amplifying the crisis. Raddatz (2010) performs an event study on 662 banks (commercial and investment) from 44 countries , where the liquidity crunch event is the failure of Lehman Brothers on September 15$^{\text{th}}$ 2008. Raddatz (2010) finds that banks that relied more heavily on wholesale funding before the event experienced a significantly larger decline in stock returns following the liquidity crunch. Dagher and Kazimov (2012) provide empirical evidence on the effect of wholesale funding on the supply of lending during the crisis. They use loan-level data from 2005 to 2008 and check whether banks that are more reliant on wholesale funding have a higher rate of rejection of loan applications. After controlling for bank, borrower and regional characteristics, results show that banks that were relying more on wholesale funding experienced a significantly larger contraction in the volume of credit in 2008. Ivashina and Scharfstein (2010) and Cornett et al. (2011) analyze the impact of bank vulnerability to liquidity risk on lending during the financial crisis. liquidity risk is defined as exposure to wholesale funding and drawdown from credit lines. Ivashina and Scharfstein (2010) uses the percentage of credit lines that are co-syndicated with Lehman Brothers to approximate for unexpected drawdowns on credit lines, and find that banks with higher unexpected drawdowns on credit lines and higher wholesale funding cut credit more during the financial crisis. Cornett et al. (2011) use the TED spread as an indicator of liquidity stress and interact it with the deposit, equity and unused commitment ratios. Their regression suggests that banks with higher liquidity risk has a stronger negative effect on lending when the TED spread is high. Our empirical analysis builds upon the identification strategy of Cornett et al. (2011). We analyze the impact of holding liquid assets on the growth of wholesale funding and loans, using the TED spread to proxy for market stress.

3 Basel III Liquidity regulation

The aim of Basel III is to strengthen the global capital and liquidity rules to make the banking sector more resilient to shocks. Basel III requires higher capital ratios compared to previous regulations, and also introduces two liquidity requirements: the liquidity coverage ratio and the net stable funding ratio.

The liquidity coverage ratio is the stock of high quality liquid assets (HQLA) over the total net cash outflow over the next 30 days. Basel III requires this ratio to be at least 100%. The goal is to ensure that the bank has enough liquid assets to withstand a 30-days liquidity stress scenario. In order to qualify as HQLA, assets should be liquid in markets during a time of stress and, in most cases, be eligible for use in central bank operations. Certain types of assets within HQLA are subject to a range of haircuts. There is a cap on total inflows (75%) to avoid that banks rely only on anticipated inflows to meet their liquidity requirements.Total net cash flow over the next 30 days is then calculated as follows:

$$\text{Total net cash flow over the next 30 days} = \text{outflows} - min(\text{inflows}, 75\% \text{ of outflows}). \quad (1)$$

The net stable funding ratio is defined as:

$$\frac{\text{Available amount of stable funding}}{\text{Required amount of stable funding}} \geq 100\% \quad (2)$$

Basel III requires this ratio to be at least 100%. The goal of the net stable funding ratio is to ensure that a certain fraction of long-term assets is funded with stable liabilities and avoid over-reliance on short-term funding when market is buoyant. The available stable funding is the portion of equity and liability expected to be reliable over a one-year time horizon under conditions of extended stress. The required stable funding depends on the liquidity characteristics of the assets. It is calculated as the sum of the value of the assets, multiplied by a specific required stable funding factor assigned to each particular asset type.

4 Stylized facts

We use bank holding company balance sheet data from the Federal Reserve Y-9C consolidated financial statements (FRY9C) to study the evolution and cyclical behavior of liquidity and wholesale funding. Our real GDP series is from Federal Reserve Economic Data (FRED). We use quarterly data from 1994Q1 to 2014Q4.

4.1 Definitions

Following Basel III regulation, we define liquid assets as assets that are liquid in markets during a time of stress, and can be easily and immediately converted into cash at little or no loss of value. We include cash and excess federal funds reserves as well as T-bills. We also include a fraction of securities issued or guaranteed by government sponsored agencies [1] (henceforth agency securities). Following the liquidity coverage ratio in Basel III, we apply a haircut of 15% to agency securities. We also put a cap on the use of agency securities: their share of liquid asset should not exceed 40%. We then adjust liquid assets by subtracting a fraction of the securities sold under agreement to repurchase (repo). The idea is that liquid assets should be unencumbered, and so not part of a repo agreement. We do not have precise information on what securities are part of repos, so we subtract a fraction of repos that corresponds to the fraction of liquid securities over all securities. See Data appendix for detailed calculations.

Wholesale funding is the sources of funding for the banks, other than retail deposits and equity. It can include short-term commercial papers issued by the banks, brokered or foreign deposits, repurchase agreements, interbank loans, or any other type of borrowing. We define short-term wholesale funding as wholesale funding with maturity less than one year.

[1] Government sponsored agencies are the Federal National Mortgage Association (Fannie Mae), the Federal Home Loan Mortgage Corporation (Freddie Mac) and the Government National Mortgage Association (Ginnie Mae)

We also consider a measure that captures liquidity mismatch on bank balance sheet. Following Choi and Zhou (2014), we build a liquidity stress ratio (LSR) for the banks. The LSR is a ratio of liquidity-adjusted liabilities and off-balance-sheet items, and liquidity adjusted assets. Liquidity adjusted assets is a weighted average of bank assets, where more liquid assets have higher weights. Liquidity weighted liabilities and off balance sheet items are also weighted averages where the weights are smaller for items that are more reliable sources of funding. A high value of the LSR indicates that a bank holds relatively more illiquid assets and relatively less stable funding, and so is exposed to liquidity mismatch.

The liquidity, wholesale funding and deposit ratios are calculated by dividing the relevant measure by total assets. We give a detailed description of our time series and calculation in the data appendix.

4.2 Summary statistics

We calculate the average of the bank balance sheet ratios for every quarter, and then average across all time period. The results are in table 1. The first moments of the data will later be used to calibrate our model.

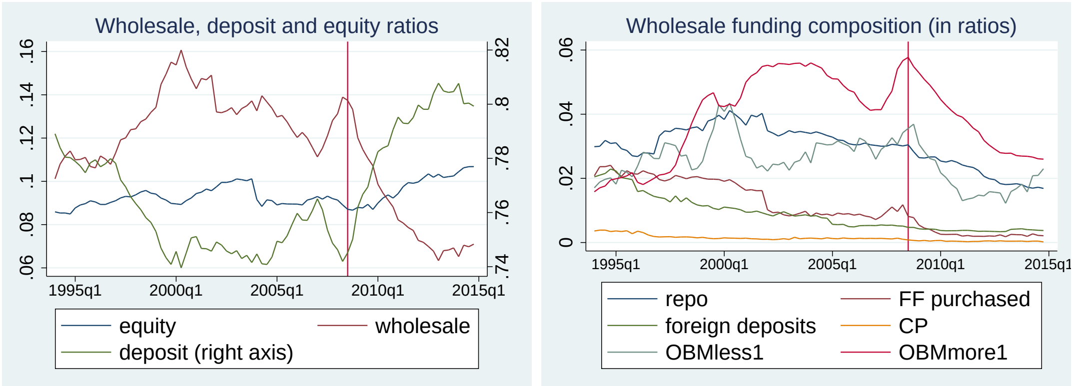
Table 1: Balance sheet ratio average

Deposit ratio	76.72%
Equity ratio	9.38%
Wholesale ratio	11.51%
Short term wholesale ratio	7.60%
Liquid asset ratio	10.52%

4.3 Evolution of average bank balance sheet variables

Figure 1 displays the evolution of wholesale funding ratio, equity ratio and deposit ratio. Note that in all the figures, the vertical red line corresponds to the third quarter of 2008, that is when Lehman Brothers collapsed and is the peak of the financial crisis. Since the mid-90s, banks have decreased their reliance on deposits and increased their reliance on wholesale funding. The advantage of wholesale funding is that it is flexible, which allows banks to increase lending. The main

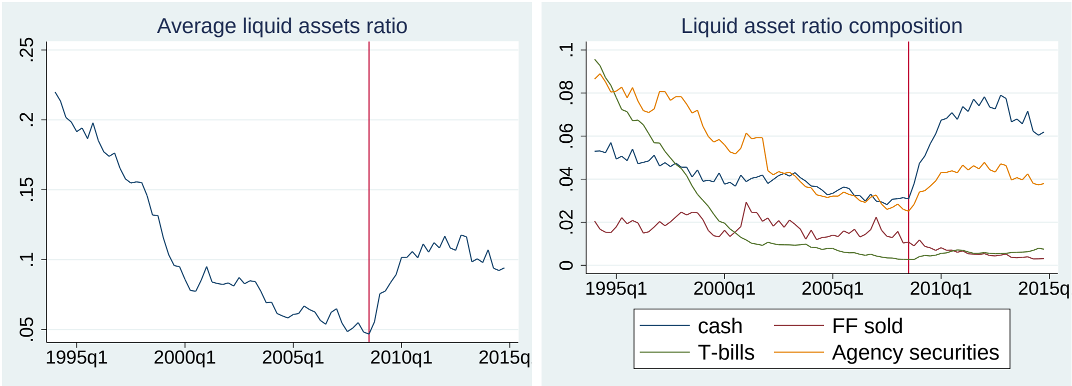
Figure 1: Wholesale funding evolution and composition



drawback is that it exposes the bank to wholesale bank runs. Whereas insured deposits are stable, wholesale lenders are much more concerned about banks' financial health, because their debt is not insured. Wholesale lenders can rapidly curtail funding if financial conditions change. This sudden reversal can be seen clearly in figure 1, the wholesale funding ratio falls dramatically starting in 2008Q4, after the collapse of Lehman Brothers. At the end of 2014, the wholesale funding ratio had not returned to its pre-crisis level, and is back at the level of the early 90s. The picture does not enable us to determine whether the fall in wholesale funding was driven by a fall in demand for wholesale funding by the banks, or by a fall in supply. Gorton and Metrick (2010) suggest that the fall in wholesale funding was due to a run by wholesale investors, and so a supply side reduction. The deposit ratio has increased a lot after the crisis, as well as the equity ratio. Bank turn to safer sources of funding, whether by choice or through the effect of banking regulation.

The second panel of figure 1 shows the break-down of wholesale funding, where OBMless1 is borrowed money with maturity less than one year and OBMmore1 is borrowed money with maturity more than one year. We saw in the previous section that a sizable fraction of wholesale funding was short-term (65% on average). The most important source of short-term borrowing are repurchase agreements. In the years before the financial crisis banks have reduced their use of commercial paper, foreign deposits and borrowing from the federal funds and increasingly turned to repurchase agreements and other short-term borrowing. The financial crisis marks a turning point in the use of wholesale funding, all sources of wholesale funding

Figure 2: Liquidity ratio evolution and composition

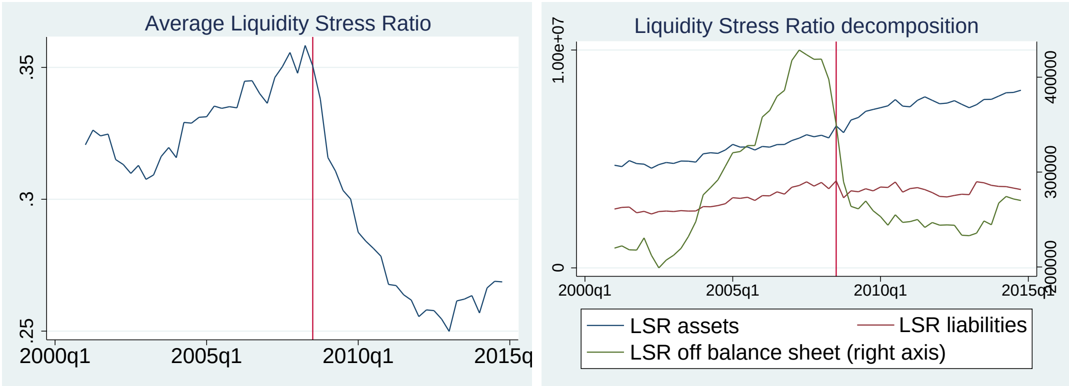


fall after the crisis.

Figure 2 shows the evolution of the average liquidity ratio. The average liquidity ratio decreased persistently since the mid-90s and hit its lowest value before the crisis. Following the financial crisis banks started hoarding liquidity and the liquidity ratio increased sharply. The second panel of figure 2 shows the composition of liquid assets. Before the crisis the main component of liquid assets were (eligible) agency securities. By eligible agency securities we mean those that can be counted as liquid securities so that their share is no more than 40%. Note that for about 80% of our observations, the cap on agency securities is binding, meaning that the banks could not count their entire stock of agency securities as liquid assets. Over the years, banks have reduced their holding of treasury bills and federal funds. Following the crisis, banks have responded by increasing their liquidity mainly by a sharp increase in cash holdings.

Figure 3 displays the evolution of the LSR, that measures liquidity mismatch on bank balance sheet. For consistency reasons, the LSR is only calculated since 2001Q1, as there has been a change in reporting at that date. The LSR peaks right before the financial crisis and then falls dramatically. The figure clearly shows the build-up of liquidity risk on bank balance sheet during the years leading to the financial crisis and the sudden reversal. The second panel of figure 3 shows the break-down of LSR into liquidity adjusted assets, liquidity adjusted liabilities and off balance sheet items. Before the financial crisis, banks were building up liquidity mismatch. Although they were holding more liquidity-adjusted assets, they had at the same time more illiquid liabilities and off balance sheet items. Following the

Figure 3: Liquidity stress ratio



crisis, banks adjust by increasing liquidity adjusted assets and reducing illiquid off balance sheet items.

4.4 Cyclical pattern

We detrend real GDP using a linear trend and calculate its correlation with the time series of average liquidity ratio, wholesale ratio, deposit ratio and LSR. The cyclical pattern of the wholesale ratio, deposit ratio, liquidity ratio and LSR is displayed in table 2. Wholesale ratio strongly correlates with GDP whereas deposit ratio comoves negatively with GDP. This is consistent with the idea that banks turn to wholesale funding when times are good to get flexible funding and make more loans. However bad times mean a sudden reduction in the availability of wholesale funding so that banks rely increasingly on deposits. Liquidity ratio negatively comoves with GDP, so during good times banks hold little liquidity as the level of risk is seemingly low. However there is a run to safety during bad times, and bank seek to increase their liquidity level. We find that the liquidity stress ratio strongly comoves with GDP. This suggests that banks build up liquidity mismatches during good times, which can be a major source of financial instability during recessions, when banks suddenly need to reduce the mismatch.

Table 2: correlation with real GDP

	GDP (detended)
Liquidity ratio	-0.727***
Wholesale ratio	0.643***
Deposit ratio	-0.762***
LSR	0.867***

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

5 Model

Our model builds upon Nuño and Thomas (2013). We extend their model by allowing banks to raise deposits directly from households, and to chose their liability structure optimally. We also introduce deposit insurance and liquidity regulation on the banks.

5.1 Households

There is a representative household that maximizes utility. The household supplies L_t hours of work and receives wage w_t, which can be saved in the form of insured bank deposit (D_t), treasury bills (TB_t^h), and shadow bank equity (M_t).

$$\begin{aligned} &\max_{C_t,D_t,M_t,L_t,TB_t} \sum_{t=0}^{\infty} \beta^t \left[\frac{C_t^{1-\gamma}}{1-\gamma} - \eta \frac{L_t^{1+\varphi}}{1+\varphi}\right] \\ &\text{s.t. } C_t + D_t \left(1 + \frac{\chi_d}{2}\left(D_t - \bar{D}\right)^2\right) + M_t + TB_t^h = \\ &\qquad L_t w_t + R_{D,t-1}^H D_{t-1} + R_{M,t} M_{t-1} + R_{TB,t-1} TB_{t-1} + \Pi_t - T_t \end{aligned} \tag{3}$$

where γ is the intertemporal elasticity of substitution, η is the disutility from labor and φ is the inverse of the Frisch elasticity of labor supply. Π_t are net transfers from the banking sector, and T_t are lump sum taxes. The returns on deposits and treasury bills are perfectly safe and predetermined, whereas the return on the shadow bank equity is state contingent. The household faces quadratic adjustment costs to deposits, meant to capture the deposit stickiness. The idea is that households like to hold a certain amount in deposits ($\bar{D}$), and if their deposits differ too much form that amount, they would invest the money in T-Bills or equity. The stickiness of deposits is documented in Dinger and Craig (2013) and Huang and Ratnovski (2011).

5.2 Firms

Firms are perfectly competitive and produce the final good Y_t^j using capital K_t^j and labor L_t^j. Firms are segmented across a continuum of islands indexed by $j \in [0,1]$ and are subject to idiosyncratic capital quality shocks ω_t^j that changes their effective capital to $\omega_t^j K_t^j$. There is also an aggregate capital quality shock Ω_t. Firms are risk-neutral profit maximizers:

$$\max_{K_t, L_t} \quad Z_t(\Omega_t \omega_t^j K_t^j)^\alpha (L_t^j)^{1-\alpha} - R_t^k \Omega_t \omega_t^j K_t - w_t L_t \tag{4}$$

Firms finance their purchase of new capital through perfectly state-contingent loans A_t^j. They can only borrow from a bank that is situated on the same island. Hence, market clearing for capital implies $K_{t+1}^j = A_t^j$.

On each island there are two types of firms, standard and substandard. The two types only differ in the distribution of the idiosyncratic shock: the standard type has a distribution $F_t(\omega)$ and the substandard has distribution $\tilde{F}_t(\omega)$. The substandard distribution has a lower mean but higher variance than the standard firm. The substandard firms never operate in equilibrium, but they are present in order to create a moral hazard problem for the banks. Like Nuño and Thomas (2013), we assume that the standard deviation of the idiosyncratic shock is known one period in advance. The lognormal distributions for the island-specific capital quality shocks of the standard and the substandard firms are:

$$log(\omega) \overset{iid}{\sim} N\left(\frac{-\sigma_t^2}{2}, \sigma_t\right) \tag{5}$$

$$log(\tilde{\omega}) \overset{iid}{\sim} N\left(\frac{-\upsilon\sigma_t^2 - \vartheta}{2}, \sqrt{\upsilon}\sigma_t\right) \tag{6}$$

The parameter $\vartheta > 0$ captures the difference in the mean and the parameter $\upsilon > 0$ captures the difference in the variance between the substandard and the standard distributions.

5.3 Capital producers

There is one perfectly competitive representative capital producer. The capital producer buys the final good in amount I_t at a price of one, and transforms it into new capital subject to adjustment costs $S(\frac{I_t}{I_{t-1}})$. The new capital is then sold at a price Q_t. The capital producer chooses investment optimally to maximize its expected profits. The maximization problem of the capital producer is:

$$\max_{I_t} \quad E_0 \sum_{t=0}^{\infty} \Lambda_{t,t+1} \left(Q_t(1 - S(\frac{I_t}{I_{t-1}}))I_t - I_t \right) \tag{7}$$

where we assume quadratic adjustment costs of the form:

$$S(\frac{I_t}{I_{t-1}}) = \frac{\chi}{2} \left(\frac{I_t}{I_{t-1}} - 1 \right)^2 \tag{8}$$

The law of motion of capital is therefore:

$$K_{t+1} = \left(1 - S(\frac{I_t}{I_{t-1}}) \right) I_t + (1-\delta)\Omega_t K_t \tag{9}$$

5.4 Banks

Banks are also segmented across islands. They raise deposits from households (D_t^j), get wholesale funding (B_t^j) from the shadow banks, and accumulate net worth (N_t^j). On their asset side, banks make loans to firms that are located on the same island (A_t^j), and they hold a risk-free bond issued by the government (TB_t^j). Wholesale funding is modeled as uncollateralized short-term borrowing: the bank borrows an amount B_t^j at time t and promises to the shadow bank a payment of $\bar{B}_t^j$ the following period. If the bank has enough assets, it repays the full amount. If the bank defaults, depositors are paid off first and the remaining assets are seized and liquidated by the shadow bank. The balance sheet of the bank is:

Table 3: Balance Sheet of bank j

Assets	**Liabilities**
A_t^j	D_t^j
TB_t^j	B_t^j
	N_t^j

The cash inflow at time t of banks is given by

$$R_t^A \omega_t^j A_{t-1}^j + R_{TB,t-1} TB_{t-1}^j \tag{10}$$

where $R_t^A \equiv R_t^k + (1-\delta)$. Therefore, a bank will default if:

$$R_t^A \omega_t^j A_{t-1}^j + R_{TB,t-1} TB_{t-1}^j < R_{D,t-1}^B D_{t-1}^j + \bar{B}_{t-1}^j \tag{11}$$

Thus, we can calculate the default threshold $\bar{\omega}_t^j$:

$$\bar{\omega}_t^j = \frac{R_{D,t-1}^B D_{t-1}^j - R_{TB,t-1} TB_{t-1}^j + \bar{B}_{t-1}^j}{R_t^A A_{t-1}^j} \tag{12}$$

Banks on islands where the realization of ω is above $\bar{\omega}$ will repay the full amount of their debt and deposits whereas banks on islands where the realization of the idiosyncratic shock is below $\bar{\omega}$ will default.

We now define another threshold $\bar{\bar{\omega}}_t^j$. This is the threshold under which the realization of ω is so low that the bank does not have enough assets to pay back depositors. In this case, the shadow bank gets nothing, and the government has to make deposit insurance payment to depositors to compensate for the shortfall. This threshold is calculated as:

$$\bar{\bar{\omega}}_t^j = \frac{R_{D,t-1}^B D_{t-1}^j - R_{TB,t-1} TB_{t-1}^j}{R_t^A A_{t-1}^j} \tag{13}$$

5.4.1 The moral hazard problem of banks

As explained in the previous section, on each island there are two types of firms: the standard and the substandard. The bank can chose to invest in either one or the other. The substandard firm has lower expected return but higher volatility compared to the standard one. When choosing where to invest, the bank faces a trade-off: it prefers an investment with higher expected return, but it also prefers an investment with higher volatility. The bank has limited liability: for very low realizations of the idiosyncratic shock, the bank defaults and the losses are taken by the creditors. However, with large positive realizations of the shock, it is the bank that takes the profits. Thus, the bank prefers volatile investments to take advantage of the upside risk. Note that the bank holds a short position in a defaultable debt. As explained in Adrian and Shin (2014), defaultable debt with face value $\bar{B}_t$ can be replicated by a portfolio with a safe debt $\bar{B}_t$, minus a put option with strike price $\bar{B}_t$. Thus, by being short on the defaultable debt, it is as if the bank owed a non-defaultable amount $\bar{B}_t$, together with a long position in a put option value with strike price $\bar{B}_t$.

To see it more clearly, consider the bank expected profit:

$$\int_{\bar{\omega}_{t+1}^j}^{\infty} \Big(R_{t+1}^A A_t^j \omega + R_{TB,t} TB_t^j - \bar{B}_t^j - R_{D,t}^B D_t^j \Big) dF_t(\omega) \tag{14}$$

Replacing $\bar{B}_t^j$ using the definition of $\bar{\omega}_t^j$, we get:

$$= R_{t+1}^A A_t^j \int_{\bar{\omega}_{t+1}^j}^{\infty} (\omega - \bar{\omega}_{t+1}^j) dF_t(\omega) \tag{15}$$

Rearranging:

$$= R_{t+1}^A A_t^j \Big(E(\omega) - \bar{\omega}_{t+1}^j + \underbrace{\int_0^{\bar{\omega}_{t+1}^j} (\bar{\omega}_{t+1}^j - \omega) dF_t(\omega)}_{\equiv \pi_t(\bar{\omega}_{t+1}^j)} \Big) \tag{16}$$

We have that $\pi_t(\bar{\omega}_{t+1}^j)$ is a put option value with strike price $\bar{\omega}_{t+1}^j$. Under our distributional assumptions, we have that $\tilde{\pi}_t(\bar{\omega}_{t+1}^j) > \pi_t(\bar{\omega}_{t+1}^j)$, but $\tilde{E}(\omega) < E(\omega)$. So when choosing between standard and substandard, the bank trades off higher expected return and lower put option value.

The put option value increases with risk. Therefore, an increase in the riskiness of bank assets makes the moral hazard problem more severe: banks have a higher incentive to invest suboptimally. The put option value also increases with leverage. Other things being equal, higher leverage implies a higher default threshold $\bar{\omega}_t^j$. Therefore, the strike price of the put option is higher, so its value is also higher. It then follows that in order to keep the bank from investing suboptimally, it cannot be too leveraged.

The moral hazard problem of the banks is a key mechanism in this model: an increase in the riskiness of bank assets makes the moral hazard more severe. The shadow bank recognizes this and responds by reducing wholesale funding.

5.4.2 Deposit insurance

The government is providing a deposit insurance scheme. It collect deposit insurance fees from the banks and covers losses to households in case banks default on their deposits. From the households perspective, the deposits are effectively safe. However, banks have to pay a deposit insurance fee on their deposits. We assume a deposit insurance fee (DI_t) that is proportional to the risk of default on deposits.

$$DI_t = (1 + \iota)E_t \left(F_t(\bar{\bar{\omega}}_{t+1})\right) \tag{17}$$

Banks pay an interest rate $R^B_{D,t}$ on their deposits which includes the deposit insurance fee. The equilibrium condition for deposit rates is:

$$R^B_{D,t} = R^H_{D,t}(1 + DI_t) \tag{18}$$

In the United States, the Federal Deposit Insurance Corporation (FDIC) insures deposits up to \$250000 per person, per insured bank. Banks pay quarterly insurance premiums to the FDIC that are calculated as:

$$\text{Premium} = (\text{Assets} - \text{Equity}) \times \text{Assessment rate} \tag{19}$$

The assessment rate depends on the risk taken by banks and how well they are capitalized. So more risky banks pay a higher rate of deposit insurance. In our model, we make the assessment rate increasing with risk by making it dependent on the default on deposits probability.

5.4.3 Liquidity regulation on banks

We introduce a liquidity regulation on the banks in the spirit of the liquidity coverage ratio of Basel III. The liquidity coverage ratio specifies that the bank must hold sufficient liquid assets to withstand a 30-day stress scenario. In the model, the highly liquid asset is the government bond. The stress scenario is a deposit withdrawal of $\xi_{0,t}$ and a run on wholesale funding of $\xi_{1,t}$. The continuing bank j must therefore be able to withstand such a stress scenario at all times by holding sufficient liquid assets. We specify the liquidity Coverage Ratio constraint as follows:

$$TB^j_t \geq \xi_{0,t} D^j_t + \xi_{1,t} B^j_t \tag{20}$$

We first consider flat regulation when ξ_0 and ξ_1 are constant; then we propose a countercylical liquidity regulation, where the coefficient ξ_0 and ξ_1 vary with the business cycle.

$$\xi_{0,t} = \bar{\xi}_0 - \chi_{y,0}(Y_t - \bar{Y}) \tag{21}$$

$$\xi_{1,t} = \bar{\xi}_1 - \chi_{y,1}(Y_t - \bar{Y}) \tag{22}$$

where $\bar{Y}$ is steady-state output.

5.4.4 The maximization problem of banks

In order to avoid that banks accumulate net worth indefinitely, we assume that a fraction $(1-\epsilon)$ of non-defaulting banks close down every period for exogenous reasons, in which case they transfer their accumulated net worth to households. This transfer from the banking sector to the household can be interpreted as dividend payment. The exiting banks are then replaced by new banks that receive a transfer from households.

Banks maximize their value. The maximization problem of a continuing bank j can then be written as a Bellman equation:

$$V_t(N_t^j) = \max_{A_t^j, B_t^j, \bar{B}_t^j, D_t^j, TB_t^j} \quad E_t \Lambda_{t,t+1} \int_{\bar{\omega}_{t+1}^j} \left(\epsilon V_{t+1}(N_{t+1}^j) + (1-\epsilon) N_{t+1}^j \right) dF_t(\omega) \tag{23}$$

subject to five constraints. The first is the balance sheet constraint:

$$A_t^j + TB_t^j = N_t^j + B_t^j + D_t^j \tag{24}$$

The second is the flow of funds constraint:

$$N_{t+1}^j = R_{t+1}^A \omega_{t+1}^j A_t^j + R_{TB,t} TB_t^j - R_{D,t}^B D_t^j - \bar{B}_t^j \tag{25}$$

which specifies the evolution of net worth of non-defaulting bank j.
The third is the liquidity coverage ratio constraint:

$$TB_t^j \geq \xi_{0,t} D_t^j + \xi_{1,t} B_t^j \tag{26}$$

The fourth is the incentive compatibility constraint (ICC):

$$\overbrace{E_t\Lambda_{t,t+1}\int_{\bar{\omega}^j_{t+1}}\left(\epsilon V_{t+1}(N^j_{t+1})+(1-\epsilon)N^j_{t+1}\right)dF_t(\omega)}^{\text{expected value from investing in standard firm}}\geq \underbrace{E_t\Lambda_{t,t+1}\int_{\bar{\omega}^j_{t+1}}\left(\epsilon V_{t+1}(N^j_{t+1})+(1-\epsilon)N^j_{t+1}\right)d\tilde{F}_t(\omega)}_{\text{expected value from investing in substandard firm}} \tag{27}$$

The incentive compatibility constraint states that the value of the bank when investing in the standard firms (distribution $F_t(\omega)$) must exceed the value of the bank when investing in the substandard segment (distribution $\tilde{F}_t(\omega)$) .
The fifth is the participation constraint of the shadow bank (PC):

$$E_t\Lambda_{t,t+1}\Bigg(\overbrace{\bar{B}^j_t(1-F(\bar{\omega}^j_{t+1}))}^{\text{no default}}+\overbrace{R^A_{t+1}A^j_t\int_{\bar{\bar{\omega}}^j_{t+1}}^{\bar{\omega}^j_{t+1}}\omega_{t+1}dF_t(\omega)}^{\text{default}} \tag{28}$$
$$-\underbrace{\left(F(\bar{\omega}^j_{t+1})-F(\bar{\bar{\omega}}^j_{t+1})\right)(R^B_{D,t}D^j_t-R_{TB_t}TB^j_t)}_{\text{default}}\Bigg)\geq E_t\Lambda_{t,t+1}R_{TB,t}B^j_t$$

The shadow bank has an outside option: invest in treasury bills instead of lending to the bank. The participation constraint insures that the shadow bank is willing to lend to the bank. The expected return from lending to the bank must exceed the rate on treasury bills. The return of the shadow bank will be explained in the next section.

5.5 The Shadow Bank

The shadow bank issues equity to households (M_t) and lends to banks in the form of short-term debt (B_t). Shadow bank equity is risky because of the default risk of the banks. The shadow bank is 100% equity funded, its return from lending to a bank j is:

- if $\omega\geq\bar{\omega}$, shadow bank receives full payment $\bar{B}$
- if $\bar{\bar{\omega}}<\omega<\bar{\omega}$, depositors are paid in full and shadow bank seizes the remaining assets of the bank

- if $\omega \leq \bar{\bar{\omega}}$, Shadow bank gets 0

We can write it as:

$$min(\bar{B}_t^j, max(0, R_{t+1}^A \omega_{t+1}^j A_t^j + R_{TB,t} TB_t^j - R_{D,t} D_t^j)) \tag{29}$$

Aggregating across all banks, the gross return to the shadow bank is:

$$\begin{aligned} R_{M,t+1} M_t = \Big(& \overbrace{\bar{B}_t^j (1 - F(\bar{\omega}_{t+1}))}^{\text{no default}} + \overbrace{R_{t+1}^A A_t^j \int_{\bar{\bar{\omega}}_{t+1}}^{\bar{\omega}_{t+1}} \omega_{t+1} dF_t(\omega)}^{\text{default}} \\ & - \underbrace{(F(\bar{\omega}_{t+1}) - F(\bar{\bar{\omega}}_{t+1}))\,(R_{D,t}^B D_t^j - R_{TB_t} TB_t^j)}_{\text{default}} \Big) \end{aligned} \tag{30}$$

5.6 The Government

The government issues the safe asset (TB_t), provides deposit insurance and raises lump-sum taxes T_t. Its budget constraint is as follows:

$$TB_t^{supp} + T_t + Ins_t^{fee} = R_{TB,t-1} TB_{t-1}^{supp} + Ins_t^{pay} \tag{31}$$

Where TB^{supp} is the total supply of treasury bills, which we assume to be fixed. Ins^{fee} are insurance deposit fees collected from banks and Ins^{pay} are deposit insurance payouts to households. We have:

$$Ins_t^{fee} = R_{D,t}^H D_t (1 + \iota) E_t F_t(\bar{\bar{\omega}}_{t+1}) \tag{32}$$

$$Ins_t^{pay} = R_{D,t-1}^H D_{t-1} F_{t-1}(\bar{\bar{\omega}}_t) \tag{33}$$

And the total supply of treasury bills is either held be the households or by the banks:

$$TB_t^{supp} = TB_t^h + TB_t \tag{34}$$

5.7 Solution and aggregation

A solution to the model is an equilibrium where banks, households, firms and capital producers are optimizing and all markets clear. Following Nuño and Thomas

(2013), we guess and verify the existence of a solution where bank balance sheet ratios and default thresholds are equalized across all islands. Banks in different islands are different in terms of size, but they all chose the same leverage ratio, deposit ratio, wholesale funding ratio and safe asset ratio. We can then aggregate the banking sector. Aggregating the flow of funds constraint across all continuing banks we find the evolution of aggregate net worth of continuing banks. It is given by:

$$N_t^{cont} = \epsilon R_t^A Q_{t-1} A_{t-1} \int_{\bar{\omega}_t}^{\infty} (\omega - \bar{\omega}_t) dF_{t-1}(\omega) \tag{35}$$

Banks can exit either because they defaulted or because they were hit by the exogenous probability of closing down $(1-\epsilon)$. Every period, new banks enter to replace those that have exited. The new banks are given a transfer of $\tau(Q_t A_{t-1} + TB_{t-1})$ from households. The transfer corresponds to a fraction τ of total assets in the banking sector at the beginning of the period. We assume that the new banks start with the same balance sheet ratios as the continuing banks. The net worth of new banks is therefore:

$$N_t^{new} = \left[1 - \epsilon\left(1 - F_{t-1}(\bar{\omega}_t)\right)\right] \tau(Q_t A_{t-1} + TB_{t-1}) \tag{36}$$

Net transfers to households are the net worth transfers from exiting banks minus the transfers from households to new banks:

$$\Pi_t = \frac{(1-\epsilon)}{\epsilon} N_t^{cont} - N_t^{new} \tag{37}$$

The first order conditions of all the agents are given in Appendix A. The model can then be reduced to a set of 24 dynamic equations that fully determine it and are given in Appendix B.

6 Quantitative analysis

6.1 Calibration

In the data, we find that the average Equity/Assets ratio of bank holding companies is about 9%, deposit ratio is 77% and wholesale funding ratio is around 11%. Our model economy is calibrated to get steady state values of the bank balance sheet ratios close to the ones we find in the data. Our calibration mainly follows Nuño and Thomas (2013). The standard RBC parameters (α, β, δ, χ, φ, η) are set in line with the macro literature. The value of steady state level of technology $\bar{z}$ is calculated to normalize steady state output to 1. The steady state idiosyncratic volatility $\bar{\sigma}$ is calibrated to match a leverage ratio of 10, and the variance substandard technology υ is set to get a wholesale funding ratio of 10%, broadly consistent with our earlier empirical findings. The share of asset transfer into new banks τ is set to target an investment over output ratio of 20%. The other financial parameters (θ, ϑ, ρ_z , ρ_σ, ρ_κ) are taken directly from Nuño and Thomas (2013). The full calibration is given in table 4. In the regulated version of the model, banks are required to hold 5% of liquid assets against their deposits and wholesale funding. In the version of the model with countercyclical regulation, banks are required to hold an additional 0.5% of liquid assets for every percentage point of GDP below steady state. All the regulatory parameters are set to zero in the unregulated model. The total supply of T-Bills is set at 2. This parameter does not have any impact on the model behavior, but need to be set high enough to make sure than the banks always have access to T-Bills to cover their regulatory requirements.

6.2 Steady-State analysis

We first study the steady-state for the unregulated model. In the unregulated model, banks do not hold safe assets, so the liquidity ratio is always zero. Then we compare the unregulated and regulated models.

The steady-state value of the default threshold $\bar{\omega}$ and default probability are pinned down by the ICC, that simplifies to equation 38. Higher default probability makes the moral hazard more severe, so high value of $\bar{\omega}$ is making the ICC more binding, whereas low $\bar{\omega}$ makes it slack. There is a unique value of $\bar{\omega}$ that makes the ICC hold with equality. The default threshold depends on the parameters of the idiosyncratic distribution of the standard and substandard firms, and it is independent of liquidity regulation.

$$1 - \tilde{E}(\omega) = \tilde{\pi}(\bar{\omega}) - \pi(\bar{\omega}) \tag{38}$$

$\bar{\bar{\omega}}$ has to be such that rate of return on deposits demanded by households equals

Table 4: Calibration

Parameter	**Value**	**Description**
		Standard RBC parameters
β	0.99	discount factor
α	0.36	share of capital in production
δ	0.025	depreciation rate
χ	0.5	adjustment cost on investment
χ_d	0.0001	adjustment cost on deposits
φ	1	inverse elasticity of labor supply
η	1	disutility of labor
$\bar{z}$	0.5080	steady state TFP
ρ_z	0.9297	serial correlation TFP shock
		Financial parameters
$\bar{\sigma}$	0.06988	steady state idiosyncratic volatility
υ	1.126	variance substandard technology
ϑ	0.001	shift in mean of substandard technology
τ	0.05846	share of asset transfer into new banks
θ	0.75	survival probability of banks
ρ_σ	0.9457	serial correlation risk shock
ι	0.0005	deposit insurance fee parameter
ρ_κ	0.3591	serial correlation capital quality shock
		Regulatory parameters
$\bar{\xi}_0$	0.05	steady state regulatory parameter on deposits
$\bar{\xi}_1$	0.05	steady state regulatory parameter on wholesale funding
$\chi_{y,0}$	0.5	cyclical regulatory parameter on deposits
$\chi_{y,0}$	0.5	cyclical regulatory parameter on wholesale funding
$TBsupp$	2	Total supply of treasury bills

the rate of return offered by banks, net of deposit insurance payment. Combining the first order conditions with respect to deposits of banks and households, together with equilibrium condition on deposit rates, pins down $\bar{\bar{\omega}}$ (equation 39). The deposit default threshold is related to the modeling of deposit insurance. In our baseline calibration, with $\xi_0 = \xi_1$, the default on deposit threshold in steady state depends only on ι, the deposit insurance parameter, and is independent of liquidity regulation. However if we have $\xi_1 \neq \xi_1$ the equilibrium default on deposit probability is decreasing in ξ_1

$$F(\bar{\omega}) = 1 - \frac{1}{1+\iota} \times \frac{1-\xi_0}{1-\xi_1} \tag{39}$$

An important aspect of the model is how banks chose between deposits and wholesale funding. Deposits are cheaper than wholesale funding, because the interest rate on wholesale funding (henceforth WS rate) is higher than the deposit rate, so banks have an incentive to raise deposits. However, a higher deposit ratio means higher probability of default on deposits, and so higher deposit insurance payment for the bank. Moreover, the WS rate is also increasing in the deposit ratio. The reason is that a high deposit ratio implies a lower liquidation value for the shadow bank when there is default. Since the shadow bank recuperates less after default, it requires a higher rate of return when there is no default, hence a higher WS rate. Banks face a trade-off: they would prefer to use deposits that are less costly, but the cost of both deposit and wholesale funding is increasing in the deposit ratio. Banks then chose an allocation of deposits and wholesale funding that minimizes their cost of funding.

The steady-state values of the key variables of the model are given in table 5. The regulation requires the bank to hold safe assets that cover 5% of their deposits and wholesale funding. The portfolio of assets held by the regulated bank is safer, since it holds a fraction of it in safe assets. We have seen that a reduction of risk of the bank assets implies a reduction in the moral hazard, which means the bank can leverage more. The key point is that holding of safe assets does not crowd out credit to firms, but rather expands it. The reason is that the bank is able to leverage more while keeping the same probability of default, because its portfolio of assets is safer.

More regulation incites banks to borrow more: they increase both deposits and wholesale funding. However they increase deposits by more than wholesale funding, so that the deposit ratio increases with regulation. Since the regulated bank is holding more safe assets, it is able to increase deposits while maintaining an identical probability of default on deposits. The regulation reduces the steady-state value of the liquidity stress ratio. Banks are more leveraged, but at the same time they carry less liquidity mismatch on their balance sheet.

The regulation has some real effects too. An increase in regulations results

Table 5: Steady state

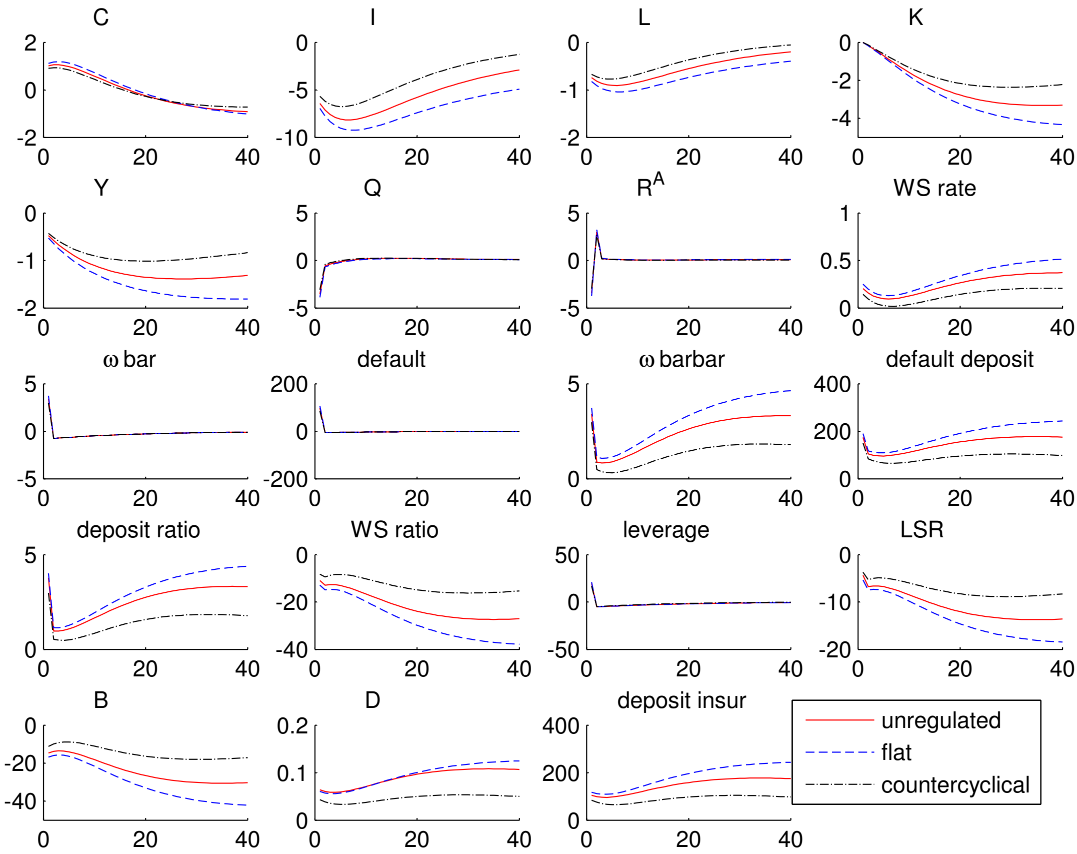
	Unregulated	**Regulated**
Consumption	0.8000	0.8064
Labor	0.8944	0.8965
Capital	8.0000	8.2510
Output	1.0000	1.0127
R^A	1.0200	1.0192
Liquidity ratio	0.0000	0.0452
Deposit ratio	0.8000	0.8084
Total deposits	6.4000	6.9859
Leverage ratio	10.000	10.3996
Wholesale ratio	0.1000	0.0954
Total Wholesale funding	0.8000	0.8247
WS rate	1.0251	1.0251
Liquidity Stress Ratio	0.6000	0.5315
$\bar{\omega}$	0.8932	0.8932
Default probability	0.0568	0.0568
$\bar{\bar{\omega}}$	0.7926	0.7926
Default on deposit probability	0.0005	0.0005
Welfare	-0.6231	-0.6170

in more loans by banks. Thus, firms can have more investment and more capital. More capital implies the marginal productivity of labor goes up, so that labor goes up as well. Output increases, as well as consumption. Lower marginal product of capital implies lower interest rate on the loans. Welfare is higher in the regulated model.

6.3 Dynamic analysis

We now turn our attention to the dynamic behavior of the model. We consider three different shocks: risk shock, total factor productivity (TFP) shock and capital quality shock. In each case, we compare the behavior of the unregulated model, where there is no liquidity requirement, with the model with a flat liquidity requirement and that with a cyclical liquidity requirement.

Figure 4: The effect of liquidity regulation, risk shock



6.3.1 Response to a risk shock

A risk shock is an increase in the cross-sectional volatility of the idiosyncratic capital quality shock. Since the distribution is known one period in advance, the risk shock acts as a news shock: at time t the agents learn that at $t+1$ their assets will become more risky. The impulse responses are in figure 4

Banks learn that next period their assets are going to be more volatile. An increase in asset riskiness makes the moral hazard problem faced by the banks more severe, it affects the ICC. In a dynamic setting, the ICC boils down to 40. The expected default threshold at $t+1$ ($\bar{\omega}_{t+1}$) is pinned down by the ICC. We saw that an increase in σ makes the value of the put option $\tilde{\pi}(\bar{\omega_{t+1}})$ relatively higher. It must then be the case that $\bar{\omega}_{t+1}$ is lower than steady state. In other words, the bank will have to adjust their balance sheet at time t so that the expected default threshold at $t+1$ is the one implied by the ICC.

$$1 - \tilde{E}(\omega) = \tilde{\pi}(\bar{\omega_{t+1}}) - \pi(\bar{\omega_{t+1}}) \tag{40}$$

We now go through a more intuitive explanation of the dynamic behavior of the model. Following the risk shock and the increase in moral hazard, the only way to prevent the banks from investing in the substandard technology it to make sure that they become less leveraged. The shadow bank recognizes that the bank has additional incentives to invest suboptimally, and responds by cutting its lending to the bank. The total amount of wholesale funding B falls by about 15% on impact, and banks are forced to deleverage. At the same time, banks slightly increase their deposits. Since deposits are sticky, they only depart very little from their steady state value, banks cannot make up for the loss of wholesale funding by increasing deposits. However, since banks lost a sizable portion of their wholesale funding, they end up with a higher deposit ratio. The probability of default on deposit remains persistently higher and so are deposit insurance payments. This is an extra cost for the bank. Moreover, a higher value of $\bar{\bar{\omega}}$ means a lower recuperation value by the shadow bank when there is default. This implies that the shadow bank imposes a higher WS rate. Thus, the banks find themselves in a situation where they have to pay more on both their deposits and their wholesale funding. The LSR falls after the shock, driven by the sharp fall in wholesale funding.

The deleveraging implies that banks need to curtail credit to firms, and so the risk shock also has real effects. Firms get fewer loans from banks, they need to cut investment and the price of capital falls. Marginal productivity of labor also falls (since capital is lower), so that labor is lower. Output therefore falls as well. The fall in Q has an immediate impact on the return on loans at time t. R_t^A falls on impact, which in turn affects the current values of $\bar{\omega}_t$ and $\bar{\bar{\omega}}_t$. Following a risk shock, investment falls more than output, so that consumption actually goes up.

Note that the model predicts that the wholesale funding ratio is pro-cyclical, the deposit ratio is counter-cyclical and the liquidity stress ratio is pro-cyclical. This is consistent with our stylized facts.

We saw in the last section that liquidity regulation has steady state effects, but how does it affect the economy in a dynamic setting? First let us compare the unregulated model with the model with a flat liquidity regulation. The flat liquidity regulation implies that the banks need to keep 5% of liquid assets against deposits and wholesale funding at all time. It is interesting to note that while a flat liquidity regulation yields a steady state with higher consumption and output, it actually amplifies the fluctuations after the shock. The shadow bank cuts B more, which means a more severe deleveraging for the bank. The fall in output, investment and capital is also higher on impact, and takes longer to converge back. The reason is primarily that the regulated and unregulated model start from different steady states. The effect of the risk shock is somewhat amplified, due to the initially higher leverage in the regulated model.

What happens if instead of a flat liquidity regulation we consider a countercyclical liquidity regulation? The idea is that when output goes below the steady state, banks are required to hold more liquid assets, and so to become safer. Note that the flat and cyclical liquidity regulation start from the same steady state, so the difference between the two is only due to the cyclical component of the regulation. First, note that $\bar{\omega}_{t+1}$ are rigorously identical for all three models. So default probabilities at $t+1$ and onwards are the same for all models, they are not affected by regulation. After the risk shock, banks are required to hold more safe assets, because output goes below steady-state. Banks that hold more T-bills have a safer portfolio of assets after the crisis. Since the regulated banks are relatively safer, the shadow bank does not cut its lending to the banks as much. Wholesale funding is more stable when the countercyclical regulation is in place. The deposit ratio of the banks increases by less, and so their deposit insurance payment also increases less. Overall, the banks pay a lower WS rate and a lower rate on deposits. The LSR is still pro-cyclical, but the regulation mitigates the procyclicality. On the asset side, banks do not need to cut loans as much as in the flat regulation case. Since banks do not curtail credit as much, the real variables are also less negatively affected. In a nutshell, regulation reduces the negative effect of forced deleveraging resulting from the shocks.

It may seem counterintuitive to require banks to hold on to more liquid assets during a recession. However it is important to take into account the way in which banks manage their risk. Adrian and Shin (2014) argue that banks manage their risk by aiming at a stable Value-at-risk, and our model builds upon that assumption. In this case, the way to avoid cyclical expansions and contractions in credit due to macroeconomic shocks is to require the banks to adjust their assets in a way that they become relatively less risky during recessions.

6.3.2 Response to a TFP shock

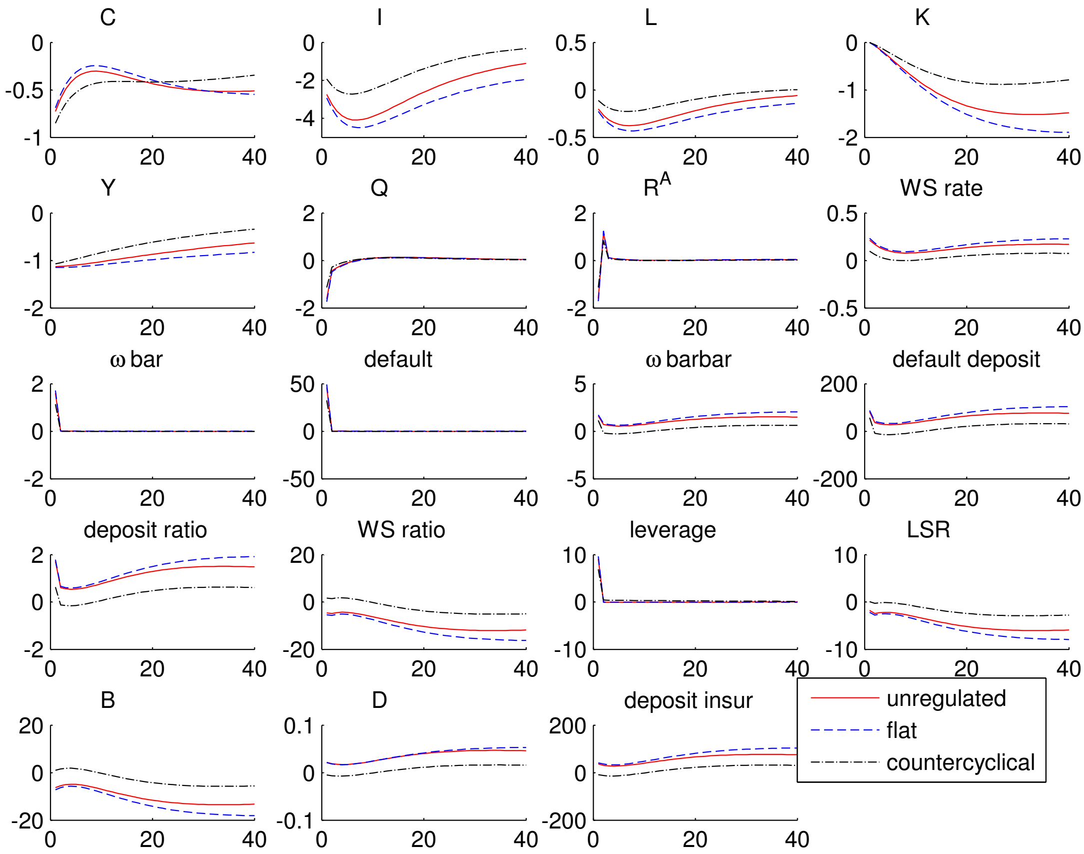
The impulse response functions following a TFP shock are in figure 5. figure A TFP shock reduces the marginal productivity of capital, and therefore the return on capital. On impact, banks get a lower return on their assets, R_t^A goes down which drives up the default probability at time t. Unlike the risk shock, a TFP shock does not affect the distribution of ω and the severity of moral hazard faced by the banks. Thus, the default threshold $\bar{\omega}_{t+1}$ returns to its steady-state value from $t+1$ onwards. In other words, since the moral hazard of the banks has not increased, banks have no need to reduce the probability of default.

However, the TFP shock affects the return on assets, so banks need to make adjustments to their balance sheet at time t so that $\bar{\omega}_{t+1}$ is back to steady state value. If the banks did not change anything to their balance sheet structure, $\bar{\omega}_{t+1}$ and default would remain higher than steady-state. So the TFP shock requires banks to shrink their balance sheet in order to keep a constant probability of default. Again, it is the shadow banks that understand that following the TFP shock the banks are less profitable, and so more likely to default if nothing is done. They respond by reducing their lending to the banks B. This in turn forces banks to reduce their own credit to firms K. The deposit ratio is higher since deposits are sticky. The probability of default on deposit and insurance payment also remain persistently higher. The recuperation value for the shadow bank in case of default is lower, and so the shadow bank imposes a higher WS rate.

The TFP shock reduces output and the marginal productivity of labor and capital. Thus, we have that labor, capital and consumption fall. The TFP shock also has an indirect effect on the real economy through the financial sector. Banks deleveraging implies that firms get fewer loans, and need to further reduce investment.

How does liquidity regulation affect the outcome? As in the case of a risk shock, a flat liquidity regulation slightly amplifies the response of the model to a TFP shock. The main reason is again the different steady state that we are starting

Figure 5: The effect of liquidity regulation, TFP shock

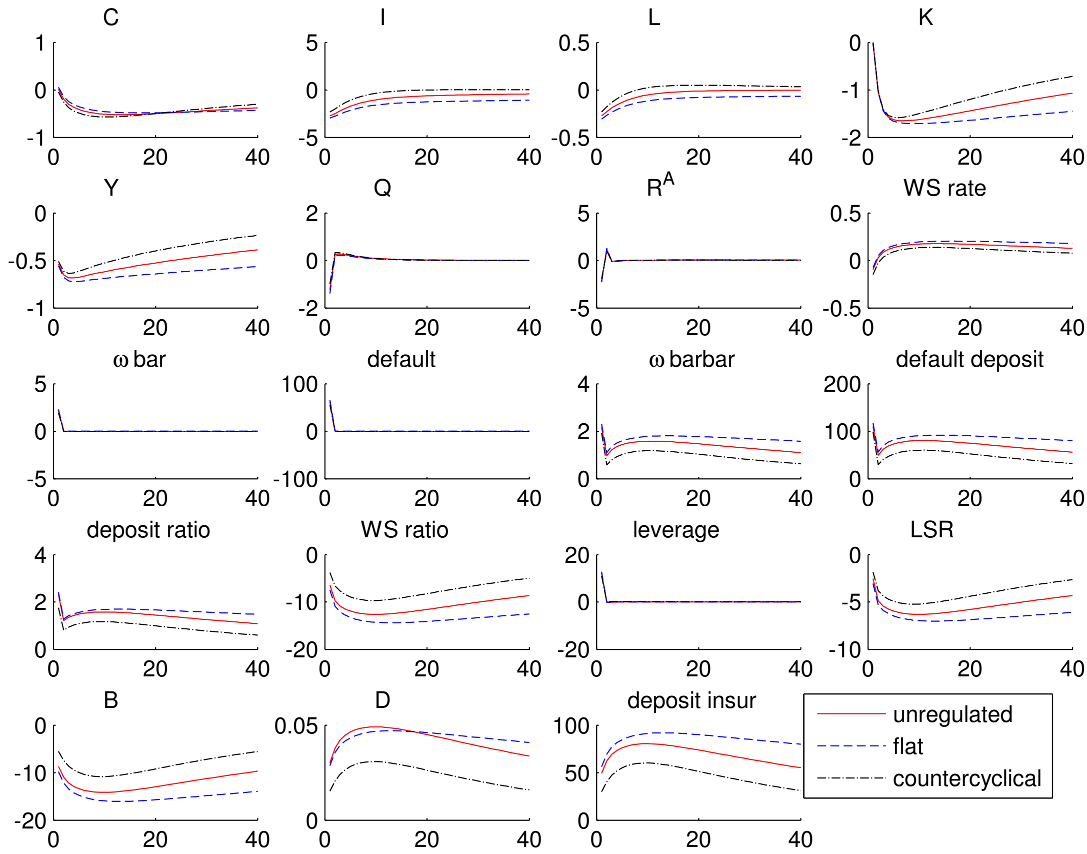


from. On the other hand, a countercyclical regulation mitigates the shock. As banks are forced to become safer when output falls, we have that the shadow bank does not cut its lending to the bank as much, and so the banks themselves do not curtail credit as much. Hence a de-amplified effect on the real variables.

6.3.3 Response to an aggregate capital quality shock

The impulse response functions of an aggregate capital quality shock are in figure 6. An aggregate capital quality shock reduces the value of capital on all islands. Output and the return on capital fall sharply. Thus, R_t^A falls on impact, leading to a sharp increase of the current value of the default thresholds $\bar{\omega}_t$ and $\bar{\bar{\omega}}_t$.

Figure 6: The effect of liquidity regulation, capital quality shock



As in the case of TFP, the distribution of ω and the moral hazard faced by the banks are not affected by the capital quality shock. This implies that the value of the default threshold $\bar{\omega}$ is back to steady state from $t+1$ onwards. However, bringing $\bar{\omega}$ back to steady-state requires some adjustments on the balance sheet of the banks. If banks did not change their balance sheet, the return on assets would be lower and so $\bar{\omega}$ would be too high. Banks suffer a run on their wholesale funding, so they make fewer loans. The real economy is affected by the capital quality shock directly, output falls on impact. As in the case of TFP, there is also an indirect effect through banks deleveraging and a fall in credit.

The effect of liquidity regulation is similar to the other shocks. A countercyclical liquidity regulation mitigates a capital quality shock by making wholesale funding more stable, which limits the impact of the shock on credit and the real economy.

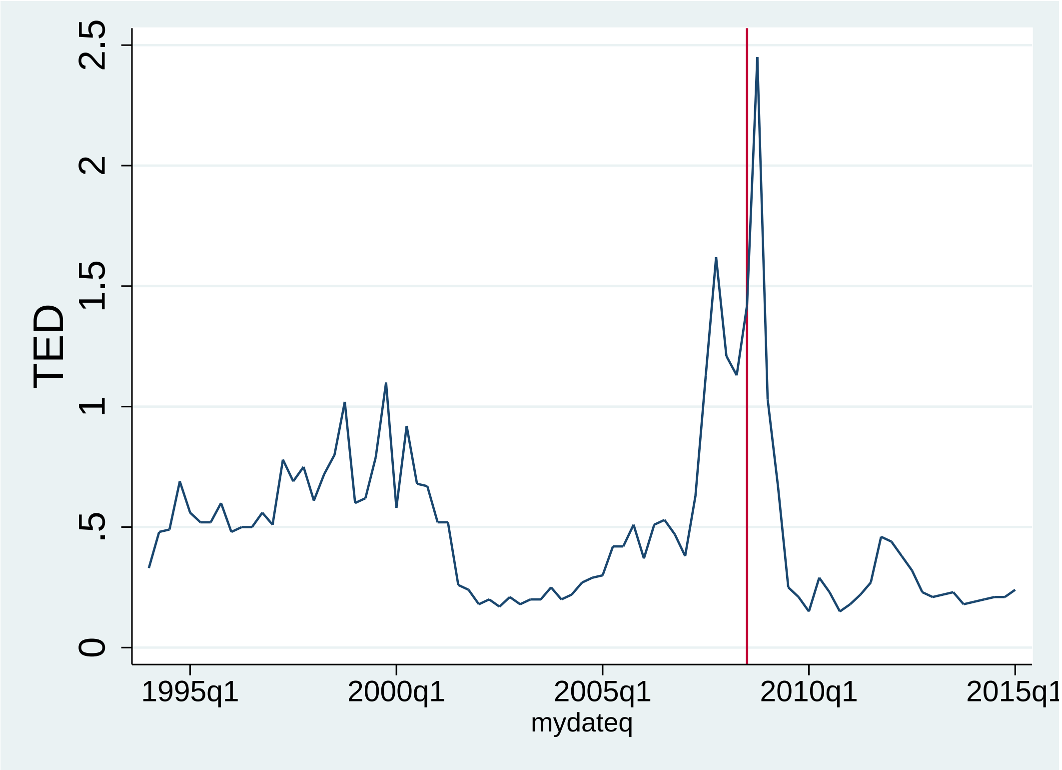
7 Empirical analysis

Our theoretical model has strong implications about the role of liquidity regulation. Requiring banks to hold a larger fraction of liquid assets helps making their funding more stable. In particular, banks that are required to hold more liquid assets do not suffer as much fall in their wholesale funding during a time of stress, and therefore they also do not need to cut credit as much. Since credit is not reduced as much, investment and output are not as negatively affected. It is through that channel that bank liquidity regulation helps stabilize the macroeconomy. In this section, we want to test empirically this key mechanism that drives the results in the theoretical model. Our empirical specification builds upon the work of Cornett et al. (2011). We capture stress in the market by the TED spread. The TED spread is the difference between the 3-moth London Interbank Offered Rate (LIBOR) and the 3-month treasury bills rate. The TED spread is a good proxy for perceived credit risk in the market. Treasury bills are considered risk-free whereas the LIBOR reflects the risk that banks face when they lend to each other. The TED spread therefore is low when banks believe they can lend to each other without much risk, and it increases dramatically when banks start worrying about counterparty default. The evolution of the TED spread is given in figure 7. In the years before the collapse of the US housing bubble, the TED spread was very low, around 20 basis points, so banks had access to cheap liquidity through the interbank loans. The TED spread spiked to a historical height in the 3^{rd} and 4^{th} quarters of 2008, following the collapse of Lehman brothers. The TED spread remained high all through the financial crisis and the great recession, regaining its pre-crisis values only in the second half of 2009.

7.1 Data

We build a quarterly panel data set, using bank holding company balance sheet data from the Federal Reserve Y-9C consolidated financial statements (FRY9C)

Figure 7: TED spread



Real GDP, inflation, Federal funds rate and the TED spread are from Federal Reserve Economic Data (FRED). We define wholesale funding as the sum of repurchase agreements, federal funds purchased, foreign deposits, commercial paper and other borrowed money. The liquid assets are cash, federal funds sold, treasury bills and agency securities, subject to a haircut of 15% and a 40% cap. Detailed calculations can be found in the Data Appendix. To neutralize the effects of very large outliers, we drop observations for which wholesale growth is more than 500% in one year, this results in a loss of 833 observations. We use quarterly data from 1994Q1 to 2014Q4. Our sample includes 1732 bank holding companies and 52846 observations.

7.2 Empirical specification

We regress wholesale funding growth on lagged liquidity, as well as the interaction term between liquidity and the TED spread. Our hypothesis is that banks with higher liquidity should suffer less fall in their wholesale funding during a time of stress. This means we expect a positive coefficient on he interaction term between liquidity and TED. Our baseline empirical model is as follows:

$$\frac{Wholesale_t - Wholesale_{t-4}}{Wholesale_{t-4}} = B_i + \beta_1 LiquidityRatio_{t-4} \\ +\beta_2 LiquidityRatio_{t-4} * TED_t + \beta_3 X_{t-4} \quad (41)$$

We use a panel data fixed effect model, to account for heterogeneity at the bank level. We cluster the error term at the bank level to estimate standard errors that are robust to serial correlation at the bank level. The growth rate of wholesale funding is annual, so we calculate it with respect to the wholesale funding in the same quarter of the previous year. The reason is that quarter on quarter data is more noisy and is subject to seasonality. Note however that our results are robust to using either quarter on quarter or annualized data. Our measure of liquidity ratio is lagged by four quarters to avoid potential endogeneity issues. The variable X is a set of macroeconomic variables meant to control for the state of the economy, lagged by 4 quarters again to avoid potential endogeneity. Our macroeconomic controls are annualized GDP growth, unemployment, inflation (measured as one year percent change in GDP deflator) and federal funds rate.

7.3 Regression results

Our baseline regression is given in table 6. The regression results show that the coefficient on the liquidity ratio is not significant, but the coefficient on the interaction term between liquidity and TED is positive. In normal times (when TED is low) liquidity does not appear to have any significant effect on the growth of wholesale funding. However, and this is the key point, when the TED spread is high and the market is under stress, a higher liquidity ratio translate in a higher wholesale growth (or a smaller fall in wholesale). So banks that kept a higher buffer of liquidity suffered less of a wholesale bank run during the crisis. We further note that GDP growth enters positively, which confirms that wholesale funding is procyclical. Unemployment and inflation enter negatively. We then run our regression on a restricted sample that excludes the financial crisis (1994Q1 to 2007Q4). We find that the interaction term between liquidity ratio and the TED still enters positively and significantly. The effect that we are capturing is then not only due to the turmoil during the financial crisis.

Table 6: Baseline regression

	Whole sample	Pre-crisis
Liquidity ratio	-0.131	-0.255
	(0.0975)	(0.160)
Liquidity*TED	0.728***	0.739***
	(0.128)	(0.176)
GDP growth	2.227***	0.129
	(0.222)	(0.546)
Unemployment	-0.0690***	0.0288
	(0.00480)	(0.0194)
FF rate	0.00908**	0.0218***
	(0.00418)	(0.00727)
inflation	-7.208***	-13.68***
	(0.779)	(1.120)
Constant	0.628***	0.298**
	(0.0456)	(0.124)
Observations	44341	22756
F	174.3	34.89

Standard errors in parentheses

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

In a second experiment, we divide banks in quartiles according to their liquidity ratios. In every quarter, banks that have a liquidity ratio that is higher than the 75^{th} percentile go in the first quartile (liquid) and similarly for the second, third and fourth quartile (illiquid). We run our baseline regression on the four groups of banks, the results are in tables 7. For all liquidity quartiles, we find that the coefficient on the interaction term is positive and significant. We further observe that the size of the coefficient term is low for the very liquid banks but is increasing when we look at less liquid banks. This means that banks that are already in a

Table 7: Regression by liquidity quartiles

	1st Quartile (liquid)	2nd Quartile	3rd Quartile	4th Quartile (illiquid)
Liquidity ratio	-0.141	0.0276	0.141	1.257***
	(0.135)	(0.186)	(0.228)	(0.376)
Liquidity*TED	0.310**	1.494***	2.522***	2.002***
	(0.143)	(0.264)	(0.356)	(0.510)
GDP growth	0.731	0.999**	1.694***	2.576***
	(0.465)	(0.438)	(0.389)	(0.393)
Unemployment	-0.0349***	-0.0766***	-0.0997***	-0.0734***
	(0.0101)	(0.00927)	(0.00899)	(0.00835)
FF rate	0.0299***	-0.00802	-0.0250***	-0.00454
	(0.00936)	(0.00806)	(0.00753)	(0.00814)
inflation	-4.720***	-5.362***	-6.027***	-7.946***
	(1.724)	(1.428)	(1.377)	(1.308)
Constant	0.292***	0.617***	0.804***	0.655***
	(0.0975)	(0.0857)	(0.0836)	(0.0822)
Observations	9131	10451	12024	12735
F	20.87	42.85	73.12	70.89

Standard errors in parentheses

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

high liquidity group are not as affected by variation in liquidity when the TED is high. For bank that are in lower liquidity quartiles, additional liquidity however plays an important role in avoiding wholesale funding contraction when the TED is high. We interpret this result as evidence that the lack of liquidity played a major role in the wholesale bank run during the last financial crisis. If banks had started with higher liquidity ratios, the contraction in wholesale funding may have been reduced significantly, leading to less contraction in credit and instability. Our results also show that banks that are in lower liquidity quartile have wholesale

Table 8: Loan regression

	Whole sample	Pre-crisis
Liquidity ratio	0.125***	0.0685
	(0.0305)	(0.0526)
Liquidity*TED	0.0631*	0.100***
	(0.0375)	(0.0382)
GDP growth	1.236***	1.809***
	(0.0768)	(0.171)
Unemployment	-0.0281***	0.0207***
	(0.00178)	(0.00678)
FF rate	-0.00586***	0.00402
	(0.00149)	(0.00264)
inflation	-0.650**	-1.525***
	(0.257)	(0.385)
Constant	0.252***	-0.0226
	(0.0162)	(0.0425)
Observations	44341	22756
F	157.9	31.98

Standard errors in parentheses

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

growth that is more procyclical, as the coefficient on GDP growth is higher.

Finally, we keep our baseline regression but use loan growth instead of wholesale growth, to try and determine how liquidity affects the supply of credit when TED is high. The results are given in table 8. We find that, looking only at the years before the financial crisis, a higher level of liquidity does not have a significant effect on the growth of wholesale funding. However when the TED is high, we see that those banks with higher liquidity do not contract their credit as much. This is also consistent with the finding of our model, that a higher liquidity helps stabilize credit during market stress. When we consider the whole sample, liquidity is associated with higher loan growth.

7.4 Robustness checks

In this section, we carry out a robustness check of our empirical results. All the tables are in appendix C.

In table 11 we carry our empirical specification using different definitions of wholesale funding. The first column is our baseline scenario. In the second column, we define wholesale funding as all the liabilities of the bank except equity and domestic deposits, so it is a wider definition of wholesale funding. In the third column, we consider only short-term wholesale funding, so wholesale funding with a maturity of less than one year. We find that the results are qualitatively similar.

In table 12 we carry our empirical specification using different definitions of liquidity ratio. In the baseline we include agency-backed securities in the liquid assets but with a haircut of 15% and a cap of 40%. We test the robustness of our result to the inclusion of those agency securities. Again, the first column is our baseline regression. The second column uses a stricter definition of liquid assets that does not include any agency securities. The third uses a wider definition of liquidity, where we include the entire stock of agency securities. The results are broadly similar using the three specifications.

In the following experiment, we replace the TED by a dummy that takes value one when the TED is above its 75^{th} percentile and zero otherwise. We construct the interaction term between liquidity ratio and the TED dummy and run our regression using that interaction term. The results are in table 13 and are consistent with our baseline scenario.

Finally, we analyze whether the effect of liquidity on wholesale funding differs for banks of different size. To do that, we group banks in quartiles based on their total asset size. The top 25% banks are in the first quartile and so forth. We run our regression on the different quartiles separately, results are reported in table 14. We find that the coefficient on the interaction term of liquidity ratio and TED is positive and significant for all size groups. We observe that the effect of the interaction term between liquidity and TED is smaller for the top quartile of banks. These banks suffer less of the lack of liquidity when TED is high, maybe because of the implicit bailout of the government. However, procyclicality of wholesale funding increases with bank size.

8 Conclusion

This paper develops a DSGE model with a financial sector and studies the effect of liquidity, wholesale funding and liquidity regulation on the macroeconomy. We find that a risk shock, a TFP shock or a capital quality shock is followed by a sharp fall in wholesale funding, a reduction in credit and a recession. Countercyclical liquidity regulation can improve on that outcome by making banks safer after the shock, which then limits the reduction in credit. We also found that liquidity regulation leads to a steady state with safer banks, higher output, consumption and credit. We then test empirically the implications of our model and find that banks that have a higher liquidity ratio face a lower reduction in wholesale funding and credit when the market is stressed. The empirical evidence supports the findings of our model.

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Data appendix

Variable definitions

Our data comes from the Bank Holding Company Federal Reserve Y-9C report, from 1994Q1 to 2014Q4. Since 2006Q1, only BHCs with consolidated assets more than 500 millions have to fill in the FRY9C. In order to have a consistent sample of banks, we then consider only those BHCs that are above the 2006Q1 reporting threshold. We remove entities that are subsidiaries of a parent company that also files a FRY9C report to avoid double counting (remove observation with bhck9802=2). Savings and Loan companies only started reporting in 2001Q1, for consistency we eliminate them from our sample (rssd9198=1).

Tables 9 and 10 gives the mapping from the FRY9C variables to the variables we refer to in the paper.

Note that every time we mention a ratio, we mean that we have divided the variable by total assets.

Liquid asset

Liquid assets should be liquid in markets during a time of stress, and can be easily and immediately converted into cash at little or no loss of value. We include cash, treasury bills, federal funds bought and a fraction of agency securities. Following Basel 3, we consider agency securities as level 2 liquid assets. They can be counted as liquid assets, but with a haircut of 15% and subject to a cap of 40%. This means that agency securities cannot be more than 40% of total liquid assets. We define

[2] The estimated fraction of Federal funds sold is calculated by taking the average of bhck0276/bhck1350 in 1996Q4 and bhckb987/bhck1350 in 2002Q1

[3] The estimated fraction of reverse repo is calculated by taking the average of bhck0277/bhck1350 in 1996Q4 and bhckb989/bhck1350 in 2002Q1

[4] The estimated fraction of agency MBS is calculated as (bhckk143+ bhckk145+ bhckk151+ bhckk153)/(bhckk143+ bhckk145+ bhckk151+ bhckk153+ bhckk147+ bhckk149+ bhckk155+ bhckk157) from 2011 to 2014

[5] The estimated fraction of other MBS is (1-estimated fraction of agency MBS)

[6] The estimated fraction of Federal funds purchased is calculated by taking the average of bhck0278/bhck2800 in 1996Q4 and bhckb993/bhck2800 in 2002Q1

[7] The estimated fraction of repo is calculated by taking the average of bhck0279/bhck2800 in 1996Q4 and bhckb995/bhck2800 in 2002Q1

Table 9: Mapping from FRY9C to our variables

Variable	FRY9C
Total assets	bhck2170
Cash	bhck0081+bhck0395+bhck0397
Federal funds sold	**until 1996Q4**: bhck0276 **1997Q1 to 2001Q4**: bhck1350 × estimated fraction of federal funds sold[2] **from 2002Q1**: bhckb987
Reverse repo	**until 1996Q4**: bhck0277 **1997Q1 to 2001Q4**: bhck1350 × estimated fraction of reverse repo[3] **from 2002Q1**: bhckb989
Tbills	bhck0213 + bhck1287
State securities	bhck8497 + bhck8499
Agency MBS	**until 2009Q1**: bhck1699+bhck1702+bhck1705+ bhck1707+bhck1715+bhck1717+bhck1719+bhck1732 **2009Q2 to 2010Q4**: bhckg301+bhckg303 +bhckg305 +bhckg307+bhckg313+bhckg315+bhckg317+bhckg319 +estimated fraction of agency MBS[4] × (bhckg325+bhckg327+bhckg329+bhckg331) **from 2011Q1**: bhckg301+bhckg303+bhckg305+bhckg307+bhckk143+bhckk145 +bhckg313+bhckg315+bhckg317+bhckg319+bhckk151+bhckk153
Agency other securities	bhck1290+bhck1293+bhck1295+bhck1298
agency securities	agency MBS + agency other securities
Other MBS	**until 2009Q1**: bhck1710+bhck1713+bhck1734+bhck1736 **2009Q2 to 2010Q4**:bhckg309+bhckg311+bhckg321+bhckg323 +estimated fraction of other MBS[5] × (bhckg325+bhckg327+bhckg329+bhckg331) **from 2011Q1**: bhckg309+bhckg311+bhckg321 +bhckg323+bhckk147+bhckk149+bhckk155+bhckk157
Other securities	bhck1771+bhck1773 − (Tbills + State securities + agency securities + other MBS)
loans	bhck5369+bhckb529

Table 10: Mapping from FRY9C to our variables

Deposits	bhdm6631+bhdm6636
Foreign deposits	bhfn6631+bhfn6636
Federal funds purchased	**until 1996Q4**: bhck0278 **1997Q1 to 2001Q4**: bhck1280 × estimated fraction of federal funds purchased[6] **from 2002Q1**: bhckb993
Repo	**until 1996Q4**: bhck0279 **1997Q1 to 2001Q4**: bhck2800 × estimated fraction of repo[7] **from 2002Q1**: bhckb995
CP	bhck2309
OBMless1	bhck2332
OBMmore1	bhck2333
subordinated debt	bhck4062
trading liabilities	bhck3548
unused commission	bhck3814+bhck3816+bhck6560
standby letters of credit	bhck6566+bhck6570+bhck3411
securities underwriting	bhck3817
securities lent	bhck3433

eligible agency securities as follows:

If $0.85 \times$ agency securities $< 0.4 \times$ liquid assets, then:
eligible agency securities = agency securities.

If $0.85 \times$ agency securities $> 0.4 \times$ liquid assets, then:
eligible agency securities $= 0.4 \times$ liquid assets.

Moreover, liquid assets should be unencumbered, so not a part of a repo agreement. This means that treasury bills and agency securities should only be counted towards liquid assets if they are not pledged or sold in a repo agreement. We do not have exact information on what securities are sold in repos, so we adjust liquid assets by subtracting a fraction of repos. The fraction of repo to be subtracted is calculated by taking the fraction of t-bills and agency securities over all securities.

Finally, our Liquid assets are calculated as:

$$\begin{aligned}\text{Liquid assets} = \text{cash} + \text{federal funds bought} + \text{Tbills} + 0.85 \times \text{eligible agency securities} \\ - \text{fraction of liquid securities} \times \text{repo}\end{aligned} \tag{42}$$

In the empirical section, we use liquid assets that are not adjusted for repos. The reason is that for running a regression of wholesale funding on liquidity, we cannot have the repos accounted both in wholesale funding and negatively in liquid assets. Our Liquid assets are then defined as:

$$\text{Unadjusted liquid assets} = \text{cash} + \text{federal funds sold} + \text{Tbills} + 0.85 \times \text{eligible agency securities} \tag{43}$$

Wholesale funding

We define wholesale funding as follows:

$$\begin{aligned}\text{Wholesale funding} = \text{foreign deposits} + \text{federal funds purchased} + \text{repos} \\ + \text{OBMless1} + \text{OBMmore1}\end{aligned} \tag{44}$$

And short term wholesale funding is:

$$\begin{aligned}\text{Short-term Wholesale funding} = \text{foreign deposits} + \text{federal funds purchased} \\ + \text{repos} + \text{OBMless1}\end{aligned} \tag{45}$$

Liquidity stress ratio

We follow the description of the liquidity stress ratio in Choi(2014). The weights for calculating the LSR is given in the online appendix of Choi(2014).

Liquidity adjusted assets: assets have liquidity weights that are higher the more liquid the asset is.

$$\begin{aligned}\text{Liquidity adjusted assets} &= \text{cash} + \text{federal funds sold} + \text{reverse repo} \\ &+0.85 \times \text{agency securities} + 0.85 \times \text{state securities} + 0.75 \times \text{other MBS} \\ &+0.5 \times \text{other securities} + 0.3 \times \text{loans}\end{aligned} \tag{46}$$

Liabilites and off balance sheet items have weights that are lower the more reliable a source of funding the item is.

$$\begin{aligned}\text{Liquidity adjusted liabilities} &= \text{federal funds purchased} + \text{repo} + 0.5 \times \text{trading liabilites} \\ &+0.5 \times \text{cp} + 0.4 \times \text{OBMless1} + 0.1 \times \text{subordinated debt} \\ &+0.1 \times \text{deposits} + 0.15 \times \text{foreign deposits}\end{aligned} \tag{47}$$

$$\begin{aligned}\text{Liquidity adjusted off balance sheet} &= 0.1 \times \text{unused commitments} + 0.1 \times \text{securities lent} \\ &+0.1 \times \text{standby letters of credit} + 0.3 \times \text{securities underwriting}\end{aligned} \tag{48}$$

$$LSR = \frac{\text{Liquidity adjusted liabilities} + \text{Liquidity adjusted off balance sheet}}{\text{Liquidity adjusted assets}} \tag{49}$$

Appendix A: the full model

Households

$$\max_{C_t,D_t,M_t,L_t,TB_t} \sum_{t=0}^{\infty} \beta^t \left[\frac{C_t^{1-\gamma}}{1-\gamma} - \eta \frac{L_t^{1+\varphi}}{1+\varphi}\right]$$
$$\text{s.t. } C_t + D_t\left(1 + \frac{\chi_d}{2}\left(D_t - \bar{D}\right)^2\right) + M_t + TB_t =$$
$$L_t w_t + R^H_{D,t-1} D_{t-1} + R_{M,t} M_{t-1} + R_{TB,t-1} TB_{t-1} + \Pi_t - T_t \tag{50}$$

First Order Conditions:

$$C_t^{-\gamma} = \lambda_t^{BC} \tag{51}$$

$$\eta L_t^{\varphi} = \lambda_t^{BC} w_t \tag{52}$$

$$\lambda_t^{BC}\left(1 + \frac{\chi_d}{2}(D_t - \bar{D})^2 + D_t \chi_d (D_t - \bar{D})\right) = \beta \lambda_{t+1}^{BC} R_{D,t} \tag{53}$$

$$\lambda_t^{BC} = \beta R_{TB,t} E_t(\lambda_{t+1}^{BC}) \tag{54}$$

$$\lambda_t^{BC} = \beta E_t(\lambda_{t+1}^{BC} R_{M,t+1}) \tag{55}$$

Firms

$$\max_{K_t,L_t} \quad Z_t(\Omega_t \omega_t^j K_t^j)^{\alpha}(L_t^j)^{1-\alpha} - R_t^k \Omega_t \omega_t^j K_t - w_t L_t \tag{56}$$

First Order Conditions:

$$w_t = (1-\alpha) Z_t \left(\frac{\Omega_t \omega_t^j K_t^j}{L_t^j}\right)^{\alpha} \tag{57}$$

$$R_t^k = \alpha Z_t \left(\frac{L_t^j}{\Omega_t \omega_t^j K_t^j}\right)^{(1-\alpha)} \tag{58}$$

Capital producers

$$\max_{I_t} \quad E_0 \sum_{t=0}^{\infty} \Lambda_{t,t+1} \left(Q_t (1 - S(\frac{I_t}{I_{t-1}})) I_t - I_t \right) \tag{59}$$

FOC I_t

$$1 = Q_t \left(1 - S(\frac{I_t}{I_{t-1}}) - S'(\frac{I_t}{I_{t-1}}) \frac{I_t}{I_{t-1}} \right) + E_t \Lambda_{t,t+1} \left(Q_{t+1} S'(\frac{I_{t+1}}{I_t})(\frac{I_{t+1}}{I_t})^2 \right) \tag{60}$$

Using quadratic adjustment costs:

$$S(\frac{I_t}{I_{t-1}}) = \frac{\chi}{2} \left(\frac{I_t}{I_{t-1}} - 1 \right)^2 \tag{61}$$

The maximization problem of continuing bank j

Redefining variables: $b_t^j = B_t^j/(Q_t A_t^j)$, $\bar{b}_t^j = \bar{B}_t^j/(Q_t A_t^j)$, $d_t^j = D_t^j/(Q_t A_t^j)$, $tb_t^j = TB_t^j/(Q_t A_t^j)$.

Defining the default thresholds:

Default on shadow bank debt:

$$\bar{\omega}_{t+1}^j = \frac{R_{D,t}^B}{R_{t+1}^A} d_t^j - \frac{R_{TB,t}}{R_{t+1}^A} tb_t^j + \frac{1}{R_{t+1}^A} \bar{b}_t^j \tag{62}$$

Default on deposit:

$$\bar{\bar{\omega}}_{t+1}^j = \frac{R_{D,t}^B}{R_{t+1}^A} d_t^j - \frac{R_{TB,t}}{R_{t+1}^A} tb_t^j \tag{63}$$

Maximization problem is:

$$V_t(N_t^j) = \max_{A_t^j, b_t^j, \bar{b}_t^j, d_t^j, tb_t^j} \quad E_t \Lambda_{t,t+1} \int_{\bar{\omega}_{t+1}^j} \left(\epsilon V_{t+1}(N_{t+1}^j) + (1-\epsilon) N_{t+1}^j \right) f_t(\omega) d\omega \tag{64}$$

Subject to

Balance Sheet Constraint:

$$Q_t A_t^j + Q_t A_t^j tb_t^j = N_t^j + Q_t A_t^j b_t^j + Q_t A_t^j d_t^j \tag{65}$$

Flow of Funds Constraint:

$$N_{t+1}^j = R_{t+1}^A \omega_{t+1}^j Q_t A_t^j + R_{TB,t} Q_t A_t^j tb_t^j - R_{D,t}^B Q_t A_t^j d_t^j - Q_t A_t^j \bar{b}_t^j = R_{t+1}^A Q_t A_t^j (\omega_{t+1}^j - \bar{\omega}_{t+1}^j) \tag{66}$$

Liquidity Coverage Ratio constraint:

$$Q_t A_t^j tb_t^j \geq \xi_{0,t} Q_t A_t^j d_t^j + \xi_{1,t} Q_t A_t^j b_t^j \tag{67}$$

Participation constraint of the creditor:

$$\begin{aligned} E_t \Lambda_{t,t+1} Q_t A_t^j \Big(\bar{b}_t^j (1 - F_t(\bar{\omega}_{t+1}^j)) + R_{t+1}^A \int_{\bar{\bar{\omega}}_{t+1}^j}^{\bar{\omega}_{t+1}^j} \omega f_t(\omega) d\omega \\ - \left(F_t(\bar{\omega}_{t+1}^j) - F_t(\bar{\bar{\omega}}_{t+1}^j) \right) \left(R_{D,t}^B d_t^j - R_{TB,t} tb_t^j \right) \Big) \geq Q_t A_t^j b_t^j \end{aligned} \tag{68}$$

Incentive compatibility constraint:

$$\begin{aligned} E_t \Lambda_{t,t+1} \int_{\bar{\omega}_{t+1}^j} \left(\epsilon V_{t+1}(N_{t+1}^j) + (1-\epsilon) N_{t+1}^j \right) f_t(\omega) d\omega \geq \\ E_t \Lambda_{t,t+1} \int_{\bar{\omega}_{t+1}^j} \left(\epsilon V_{t+1}(N_{t+1}^j) + (1-\epsilon) N_{t+1}^j \right) \tilde{f}_t(\omega) d\omega \end{aligned} \tag{69}$$

First order Conditions:

FOC d_t^j

$$\begin{aligned} -R_{D,t}^B E_t \Lambda_{t,t+1} \int_{\bar{\omega}_{t+1}^j} \left(\epsilon V'_{t+1}(N_{t+1}^j) + (1-\epsilon) \right) f_t(\omega) d\omega \\ -\lambda_t^{PC} \Big(E_t \Lambda_{t,t+1} R_{D,t}^B \Big(\left(F_t(\bar{\omega}_{t+1}^j) - F_t(\bar{\bar{\omega}}_{t+1}^j) \right) \Big) - 1 \Big) \\ -R_{D,t}^B \lambda_t^{ICC} \Big(E_t \Lambda_{t,t+1} \Big(\int_{\bar{\omega}_{t+1}^j} \left(\epsilon V'_{t+1}(N_{t+1}^j) + (1-\epsilon) \right) f_t(\omega) d\omega \\ - \int_{\bar{\omega}_{t+1}^j} \left(\epsilon V'_{t+1}(N_{t+1}^j) + (1-\epsilon) \right) \tilde{f}_t(\omega) d\omega \Big) \Big) \\ +\lambda_t^{LCR} \Big(-\xi_{0,t} + \xi_{1,t} \Big) = 0 \end{aligned} \tag{70}$$

FOC tb_t^j

$$
\begin{aligned}
R_{TB,t}E_t\Lambda_{t,t+1}\int_{\bar{\omega}_{t+1}^j}\big(\epsilon V'_{t+1}(N_{t+1}^j)+(1-\epsilon)\big)\,f_t(\omega)d\omega(\omega)\\
+\lambda_t^{PC}\Bigg(E_t\Lambda_{t,t+1}R_{TB,t}\Big(\,\big(F_t(\bar{\omega}_{t+1}^j)-F_t(\bar{\bar{\omega}}_{t+1}^j)\big)\,\Big)-1\Bigg)\\
+R_{TB,t}\lambda_t^{ICC}\Bigg(E_t\Lambda_{t,t+1}\Big(\int_{\bar{\omega}_{t+1}^j}\big(\epsilon V'_{t+1}(N_{t+1}^j)+(1-\epsilon)\big)\,f_t(\omega)d\omega\\
-\int_{\bar{\omega}_{t+1}^j}\big(\epsilon V'_{t+1}(N_{t+1}^j)+(1-\epsilon)\big)\,\tilde{f}_t(\omega)d\omega\Big)\Bigg)\\
+\lambda_t^{LCR}\Bigg(1-\xi_{1,t}\Bigg)=0
\end{aligned}
\tag{71}
$$

FOC $\bar{b}_t^j$

$$
\begin{aligned}
-E_t\Lambda_{t,t+1}\int_{\bar{\omega}_{t+1}^j}\big(\epsilon V'_{t+1}(N_{t+1}^j)+(1-\epsilon)\big)\,f_t(\omega)d\omega\\
+\lambda_t^{PC}\Bigg(E_t\Lambda_{t,t+1}\Big(1-F_t(\bar{\omega}_{t+1}^j)\Big)\Bigg)\\
-\lambda_t^{ICC}\Bigg(E_t\Lambda_{t,t+1}\Big(\int_{\bar{\omega}_{t+1}^j}\big(\epsilon V'_{t+1}(N_{t+1}^j)+(1-\epsilon)\big)\,f_t(\omega)d\omega\\
-\int_{\bar{\omega}_{t+1}^j}\big(\epsilon V'_{t+1}(N_{t+1}^j)+(1-\epsilon)\big)\,\tilde{f}_t(\omega)d\omega\Big)\Bigg)=0
\end{aligned}
\tag{72}
$$

FOC A_t^j

$$
\begin{aligned}
&E_t\Lambda_{t,t+1}R^A_{t+1}\int_{\bar{\omega}^j_{t+1}}\left(\epsilon V'_{t+1}(N^j_{t+1})+(1-\epsilon)\right)(\omega-\bar{\omega}^j_{t+1})f_t(\omega)d\omega\\
&+\lambda_t^{PC}\Bigg(E_t\Lambda_{t,t+1}R^A_{t+1}\Big((\bar{\omega}^j_{t+1}(1-F_t(\bar{\omega}^j_{t+1}))-\bar{\bar{\omega}}^j_{t+1}(1-F_t(\bar{\bar{\omega}}^j_{t+1}))\\
&\qquad+\int_{\bar{\bar{\omega}}^j_{t+1}}^{\bar{\omega}^j_{t+1}}\omega f_t(\omega)d\omega\Big)-1-tb^j_t+d^j_t\Bigg)\\
&+\lambda_t^{ICC}\Bigg(E_t\Lambda_{t,t+1}R^A_{t+1}\Big(\int_{\bar{\omega}^j_{t+1}}\left(\epsilon V'_{t+1}(N^j_{t+1})+(1-\epsilon)\right)(\omega-\bar{\omega}^j_{t+1})f_t(\omega)d\omega\\
&\qquad-\int_{\bar{\omega}^j_{t+1}}\left(\epsilon V'_{t+1}(N^j_{t+1})+(1-\epsilon)\right)(\omega-\bar{\omega}^j_{t+1})\tilde{f}_t(\omega)d\omega\Big)\Bigg)\\
&+\lambda_t^{LCR}\Bigg(tb^j_t-\xi_{0,t}d^j_t-\xi_{1,t}(1+tb^j_t-d^j_t)\Bigg)=0
\end{aligned}
\tag{73}
$$

Envelope condition on N_t^j:

$$V'(N_t^j)=\lambda_t^{PC}+\lambda_t^{LCR}\xi_{1,t} \tag{74}$$

Appendix B: the full model in reduced form

Our model can be reduced to a set of 24 dynamic equations that jointly determine 24 endogenous variables: C_t,L_t,K_t,I_t,Y_t,R_t^A,$R_{TB,t}$,$R_{D,t}^B$,N_t,ϕ_t (leverage ratio $N_t/(A_t+TB_t)$), θ_t (deposit ratio $D_t/(A_t+TB_t)$), ψ_t (safe asset ratio $TB_t/(A_t+TB_t)$), $\bar{\omega}_t$, $\bar{\bar{\omega}}_t$, $\bar{b}_t$, λ_t^{PC}, λ_t^{LCR}, λ_t^{BC}. λ_t^{ICC},Q_t, $R_{D,t}^H$, DI_t, $\xi_{0,t}$, $\xi_{1,t}$.

FOC C_t Households

$$C_t^{-\gamma} = \lambda_t^{BC} \tag{75}$$

FOC labor household and market clearing

$$\frac{\eta L_t^{\varphi}}{\lambda_t^{BC}} = (1-\alpha)\frac{Y_t}{L_t} \tag{76}$$

FOC D_t household

$$\lambda_t^{BC}\left(1+\frac{\chi_d}{2}(D_t-\bar{D})^2 + D_t\chi_d(D_t-\bar{D})\right) = \beta\lambda_{t+1}^{BC}R_{D,t} \tag{77}$$

FOC TB_t household

$$\lambda_t^{BC} = \beta R_{TB,t}E_t(\lambda_{t+1}^{BC}) \tag{78}$$

FOC M_t household and participation constraint:

$$\lambda_t^{BC} = \beta E_t\lambda_{t+1}^{BC}\left(R_{t+1}^A\frac{1-\psi_t}{1-\phi_t-\theta_t}[\bar{\omega}_{t+1}-\bar{\bar{\omega}}_{t+1}-\pi_t(\bar{\omega}_{t+1})+\pi_t(\bar{\bar{\omega}}_{t+1})]\right) \tag{79}$$

Aggregate production

$$Y_t = Z_t L_t^{1-\alpha}(\Omega_t K_t)^{\alpha} \tag{80}$$

Law of motion of capital

$$K_{t+1} = \left(1-S(\frac{I_t}{I_{t-1}})\right)I_t + (1-\delta)\Omega_t K_t \tag{81}$$

Aggregate output

$$Y_t = C_t + I_t \tag{82}$$

Return on bank asset

$$R_t^A = \Omega_t\frac{(1-\delta)Q_t+\alpha\frac{Y_t}{\Omega_t K_t}}{Q_{t-1}} \tag{83}$$

definition default threshold on SB debt

$$\bar{\omega}_t = \frac{R^B_{D,t-1}}{R^A_t}\frac{\theta_{t-1}}{1-\psi_{t-1}} - \frac{R_{TB,t-1}}{R^A_t}\frac{\psi_{t-1}}{1-\psi_{t-1}} + \frac{1}{R^A_t}\bar{b}_{t-1} \tag{84}$$

definition default threshold on deposits

$$\bar{\bar{\omega}}_t = \frac{R^B_{D,t-1}}{R^A_t}\frac{\theta_{t-1}}{1-\psi_{t-1}} - \frac{R_{TB,t-1}}{R^A_t}\frac{\psi_{t-1}}{1-\psi_{t-1}} \tag{85}$$

Incentive compatibility constraint holding with equality

$$1-\tilde{E}(\omega) = \frac{E_t\lambda^{BC}_{t+1}R^A_{t+1}\left[(\epsilon\lambda^{PC}_{t+1} + \epsilon\xi_{1,t+1}\lambda^{LCR}_{t+1} + 1 - \epsilon)(\tilde{\pi}_t(\bar{\omega}_{t+1}) - \pi_t(\bar{\omega}_{t+1}))\right]}{E_t\lambda^{BC}_{t+1}R^A_{t+1}(\epsilon\lambda^{PC}_{t+1} + \epsilon\xi_{1,t+1}\lambda^{LCR}_{t+1} + 1 - \epsilon)} \tag{86}$$

Aggregate net worth banks

$$N_t = \epsilon R^A_t Q_{t-1}K_t[1-\bar{\omega}_t + \pi_{t-1}(\bar{\omega}_t)] + [1-\epsilon(1-F_{t-1}(\bar{\omega}_t))]\left(Q_t + \frac{\psi_{t-1}}{1-\psi_{t-1}}Q_{t-1}\right)\tau K_t \tag{87}$$

Liquidity coverage ratio constraint holding with equality

$$\psi_t = \xi_{0,t}\theta_t + \xi_{1,t}(1-\phi_t-\theta_t) \tag{88}$$

Balance Sheet ratio:

$$Q_tK_{t+1} = \frac{1-\psi_t}{\phi_t}N_t \tag{89}$$

FOC A_t banks

$$\begin{aligned} E_t\beta\frac{\lambda^{BC}_{t+1}}{\lambda^{BC}_t}R^A_{t+1}\Bigg([\epsilon\lambda^{PC}_{t+1} + \epsilon\xi_{1,t+1}\lambda^{LCR}_{t+1} + 1 - \epsilon][1-\bar{\omega}_{t+1} + \pi_t(\bar{\omega}_{t+1})]\Bigg) \\ = \lambda^{PC}_t\frac{\phi}{1-\psi_t} - \lambda^{LCR}_t\left(\frac{\psi - \xi_{0,t}\theta - \xi_{1,t}(1-\theta)}{1-\psi}\right) \end{aligned} \tag{90}$$

FOC b_t banks

$$\begin{aligned} \lambda^{ICC}_t = & \frac{\lambda^{PC}_t E_t\lambda^{BC}_{t+1}(1-F_t(\bar{\omega}_{t+1}))}{E_t\lambda^{BC}_{t+1}(\epsilon\lambda^{PC}_{t+1} + \epsilon\xi_{1,t+1}\lambda^{LCR}_{t+1} + 1 - \epsilon)(\tilde{F}_t(\bar{\omega}_{t+1}) - F_t(\bar{\omega}_{t+1}))} \\ & - \frac{E_t\lambda^{BC}_{t+1}(\epsilon\lambda^{PC}_{t+1} + \epsilon\xi_{1,t+1}\lambda^{LCR}_{t+1} + 1 - \epsilon)(1-F_t(\bar{\omega}_{t+1}))}{E_t\lambda^{BC}_{t+1}(\epsilon\lambda^{PC}_{t+1} + \epsilon\xi_{1,t+1}\lambda^{LCR}_{t+1} + 1 - \epsilon)(\tilde{F}_t(\bar{\omega}_{t+1}) - F_t(\bar{\omega}_{t+1}))} \end{aligned} \tag{91}$$

FOC d_t banks

$$R^B_{D,t} E_t \beta \frac{\lambda^{BC}_{t+1}}{\lambda^{BC}_t} \left(\lambda^{PC}_t [1 - F_t(\bar{\bar{\omega}}_{t+1})] \right) = \lambda^{PC}_t - \xi_{0,t} \lambda^{LCR}_t + \xi_{1,t} \lambda^{LCR}_t \tag{92}$$

FOC tb_t banks

$$R_{TB,t} E_t \beta \frac{\lambda^{BC}_{t+1}}{\lambda^{BC}_t} \left(\lambda^{PC}_t [1 - F_t(\bar{\bar{\omega}}_{t+1})] \right) = \lambda^{PC}_t - \lambda^{LCR}_t + \xi_{1,t} \lambda^{LCR}_t \tag{93}$$

FOC Capital producers

$$1 = Q_t \left(1 - S(\frac{I_t}{I_{t-1}}) - S'(\frac{I_t}{I_{t-1}}) \frac{I_t}{I_{t-1}} \right) + E_t \Lambda_{t,t+1} \left(Q_{t+1} S'(\frac{I_{t+1}}{I_t}) (\frac{I_{t+1}}{I_t})^2 \right) \tag{94}$$

Deposit insurance:

$$DI_t = (1 + \iota) E_t \left(F_t(\bar{\bar{\omega}}_{t+1}) \right) \tag{95}$$

Equilibrium condition deposit rates:

$$R^B_{D,t} = R^H_{D,t} (1 + DI_t) \tag{96}$$

Time-varying $\xi_{0,t}$ and $\xi_{1,t}$:

$$\xi_{0,t} = \bar{\xi}_0 - \chi_{y,0} (Y_t - \bar{Y}) \tag{97}$$

$$\xi_{1,t} = \bar{\xi}_1 - \chi_{y,1} (Y_t - \bar{Y}) \tag{98}$$

Appendix C: Additional tables

Table 11: Regression with different definitions of wholesale funding

	Baseline	Wholesale, wide	Wholesale, short-term
Liquidity ratio	-0.131	0.0766	0.0562
	(0.0975)	(0.0716)	(0.112)
Liquidity*TED	0.728***	0.273***	0.700***
	(0.128)	(0.0837)	(0.139)
GDP growth	2.227***	2.282***	2.580***
	(0.222)	(0.164)	(0.297)
Unemployment	-0.0690***	-0.0634***	-0.0723***
	(0.00480)	(0.00375)	(0.00647)
FF rate	0.00908**	0.000117	-0.0199***
	(0.00418)	(0.00331)	(0.00528)
inflation	-7.208***	-5.945***	-3.696***
	(0.779)	(0.580)	(0.978)
Constant	0.628***	0.574***	0.671***
	(0.0456)	(0.0353)	(0.0623)
Observations	44341	44328	41299
F	174.3	208.9	89.53

Standard errors in parentheses

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

Table 12: Regression with different definitions of liquidity

	Baseline	No Agency	All agency
Liquidity ratio	-0.131		
	(0.0975)		
Liquidity*TED	0.728***		
	(0.128)		
GDP growth	2.227***	2.278***	2.222***
	(0.222)	(0.220)	(0.222)
Unemployment	-0.0690***	-0.0681***	-0.0691***
	(0.00480)	(0.00480)	(0.00480)
FF rate	0.00908**	0.0109***	0.00892**
	(0.00418)	(0.00414)	(0.00418)
inflation	-7.208***	-7.314***	-7.198***
	(0.779)	(0.778)	(0.780)
Liquidity ratio, strict		-0.238*	
		(0.130)	
strict liquidity*TED		0.956***	
		(0.177)	
Liquidity ratio, wide			-0.120
			(0.0930)
wide liquidity*TED			0.695***
			(0.122)
Constant	0.628***	0.627***	0.628***
	(0.0456)	(0.0455)	(0.0456)
Observations	44341	44341	44341
F	174.3	175.1	174.3

Standard errors in parentheses

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

Table 13: Regression using TED dummy

Liquidity ratio	0.144*
	(0.0843)
Liquidity*TED dummy	0.195**
	(0.0818)
GDP growth	2.254***
	(0.222)
Unemployment	-0.0670***
	(0.00478)
FF rate	0.0163***
	(0.00400)
inflation	-6.932***
	(0.784)
Constant	0.594***
	(0.0452)
Observations	44341
F	177.1

Standard errors in parentheses

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

Table 14: Regression by size quartiles

	1st Quartile (big)	2nd Quartile	3rd Quartile	4th Quartile (small)
Liquidity ratio	0.130	-0.417**	-0.0313	0.0548
	(0.139)	(0.206)	(0.244)	(0.308)
Liquidity*TED	0.595***	0.766***	0.786**	1.280**
	(0.181)	(0.243)	(0.311)	(0.543)
GDP growth	2.921***	1.277***	0.817*	2.751***
	(0.340)	(0.446)	(0.486)	(0.724)
Unemployment	-0.0552***	-0.0502***	-0.0330***	-0.0684***
	(0.00778)	(0.00951)	(0.0115)	(0.0204)
FF rate	0.0103*	0.0328***	0.0612***	0.0467**
	(0.00573)	(0.00982)	(0.0127)	(0.0221)
inflation	-7.758***	-4.436***	-6.043***	-13.17***
	(1.133)	(1.447)	(1.802)	(3.033)
Constant	0.533***	0.433***	0.261**	0.560***
	(0.0710)	(0.0925)	(0.114)	(0.198)
Observations	21663	11821	7509	3348
F	70.76	49.69	25.35	16.48

Standard errors in parentheses

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