

# A Macroeconomic Model of Liquidity, Wholesale Funding and Banking Regulation\*

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## Abstract

We develop a model with regulated banks and a hedge fund to analyze the behavior of wholesale funding and the macroeconomic consequences of liquidity regulation. Banks raise deposits and subordinated wholesale funding from the hedge fund. Wholesale funding amplifies shocks: it is curtailed in economic downturns to avoid leveraging up and risk-taking by banks, further depressing credit and economic activity. By making banks safer, liquidity regulation increases wholesale funding at the steady state. Flat liquidity regulation, as in Basel III, increases volatility while cyclically adjusted regulation is stabilizing and welfare-improving.

*Keywords:* Banking; DSGE model; Liquidity; Financial Crisis; Financial Stability; Banking regulation.

*JEL Classification:* E44, E58, G21, G23

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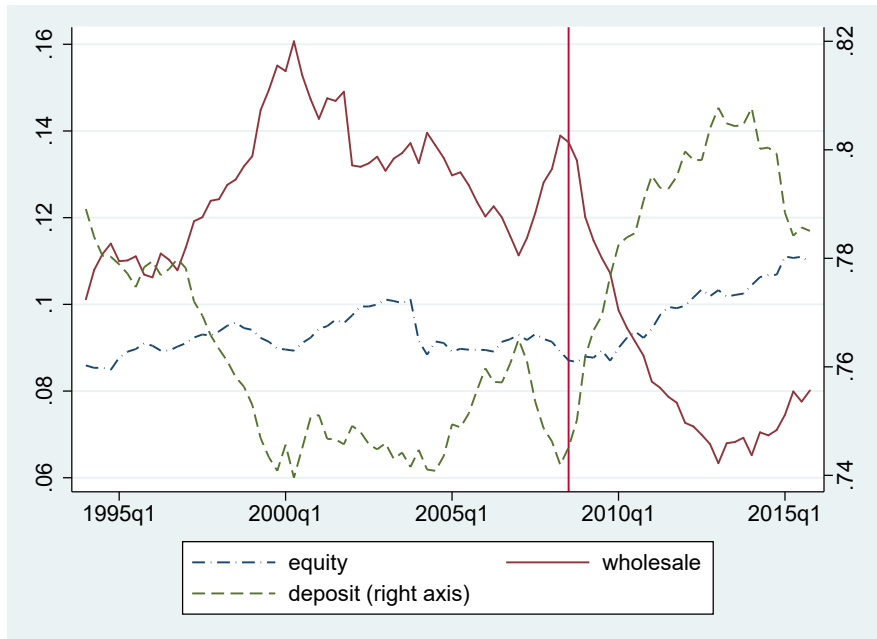
# 1 Introduction

In the five years prior to the financial crisis of 2007-10, the growth of U.S. commercial bank assets outpaced that of deposits (77 versus 53 percent). Strong asset growth was driven by a booming housing market and widespread securitization, as described in Gorton and Metrick (2010) and Brunnermeier (2009), among others. Retail deposits, on the other hand, continued to expand along their long-run trend. To achieve the desired expansion in assets, U.S. commercial banks tapped into wholesale funding. Figure 1 displays the evolution of deposits, equity and wholesale funding relative to assets; the data is quarterly bank holding company (BHC) balance sheet data from the FR Y-9C from 1994Q1 to 2015Q4 and, for every period, we report the average across all banks. Wholesale funding is calculated as funding other than retail deposits and equity and it includes short-term commercial papers, brokered or foreign deposits, repurchase agreements (repos), interbank loans, and any other type of borrowing. Banks' reliance on deposits fell until the peak of the financial crisis in the third quarter of 2008, when Lehman Brothers collapsed, which corresponds to the vertical line in our graphs. Up to the financial crisis, equity remained stable as a fraction of assets and the wholesale ratio is the mirror image of the deposit ratio.

The advantage of wholesale funding is that it is flexible, which allows banks to easily expand lending during good times. Dinger and Craig (2013) argue that retail deposits are sluggish and document that more volatile loan demand leads to a larger wholesale funding share. The flexibility of wholesale funding, however, becomes a drawback during periods of stress, as such funding can quickly evaporate and force banks into fire sales of assets. The wholesale ratio indeed fell dramatically after the collapse of Lehman Brothers and, by the end of 2014, it was still less than half its pre-crisis level, as shown in Figure 1. Gorton and Metrick (2012) trace the core of the financial crisis to a run on repos. Depositors in repo contracts with banks worried about selling the collateral in a tumbling market and either raised haircuts or curtailed lending altogether. Other components of wholesale funding, however, fell even more than repos in the crisis, as shown in Figure 2. Deposits and repos are senior to these debts in case of bank default; when the risk that banks might fail went up, non-repos sources of wholesale funds quickly evaporated.

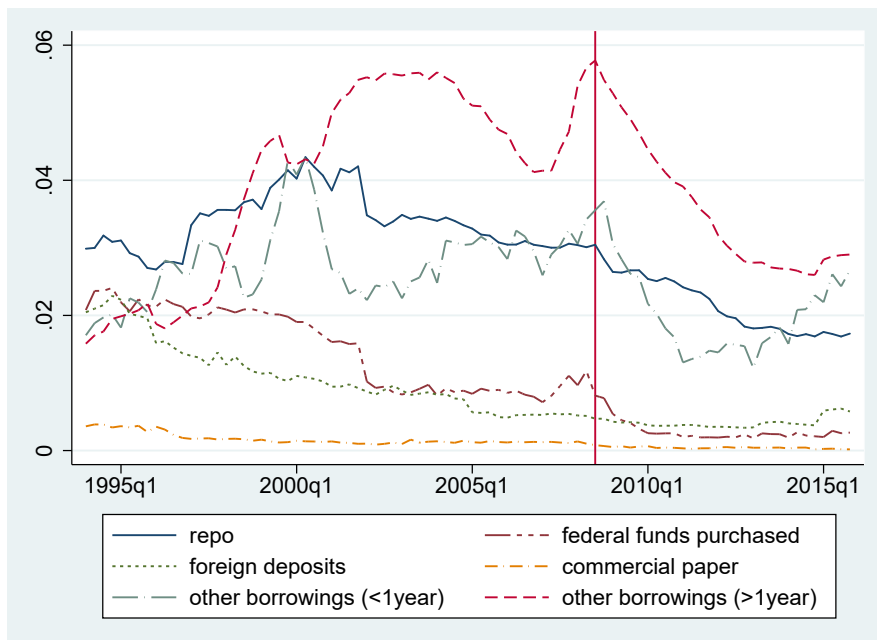
While increasingly relying on wholesale funds, banks steadily reduced their holdings of liquid assets in the period leading to the financial crisis. Figure 3 reports the

Figure 1: Wholesale, deposit and equity ratios



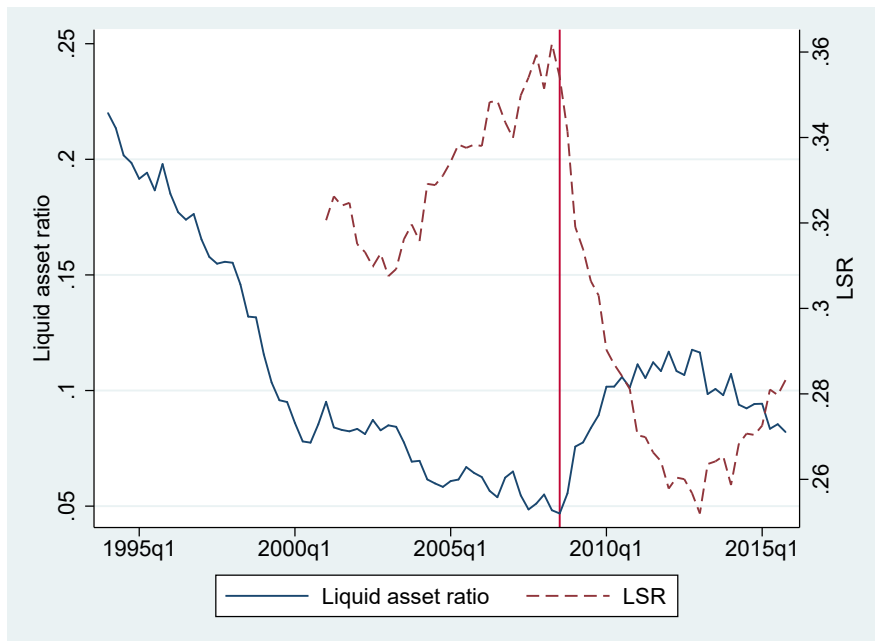
Source: FRY-9C

Figure 2: Wholesale funding components (ratios)



Source: FRY-9C

Figure 3: Liquidity ratio



Source: FRY-9C

evolution of the average BHC’s liquidity ratio, i.e. liquid over total assets.<sup>1</sup> The liquidity ratio decreased persistently since the mid-90s and reached its trough at the onset of the financial crisis; the reduction was substantial – from 23 to 5 percent of total assets. When the crisis unfolded, unprecedented low levels of liquidity exacerbated the run by wholesale investors; the interbank market froze up and widespread default was avoided by massive injections of liquidity by central banks.

As argued above, banks raised short-term wholesale debt and reduced liquid holdings in the pre-crisis period. At the same time, banks invested in illiquid assets with uncertain valuation. Following Choi and Zhou (2014), we build a Liquidity Stress Ratio (LSR) for the banks.<sup>2</sup> The LSR is the ratio of liquidity-adjusted liabilities and off-balance-sheet items to liquidity-adjusted assets. Liquidity-adjusted assets is the 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 more stable sources of funding. A higher value of the

<sup>1</sup>We define liquid assets in Appendix A.

<sup>2</sup>For an alternative measurements of liquidity mismatch, see Berger and Bouwman (2009), Brunnermeier et al. (2014) and Bai et al. (2017).

LSR indicates that a bank holds relatively more illiquid assets and less stable funding and it is therefore more exposed to liquidity mismatch. Further details on how we construct the LSR are provided in Appendix A. Figure 3 displays the evolution of the LSR.<sup>3</sup> The LSR peaks right before the financial crisis and then falls rapidly, bringing evidence of the build-up of liquidity risk during the years leading to the financial crisis.

Given the low levels of liquidity held by banks before the financial crisis, the Basel Committee on Banking Supervision introduced liquidity regulation requiring banks to hold at all times a minimum stock of liquid assets. The impact of liquidity regulation on macroeconomic variables is unknown. Banking sector advocates argue that higher liquidity holdings will crowd out productive loans, thereby leading to lower levels of economic activity. This is the partial equilibrium view: given liabilities, one dollar increase in liquid assets implies one dollar decrease in other loans. In general equilibrium, however, a bank's ability to borrow depends on its asset composition and liquidity holdings.

This paper proposes a general equilibrium dynamic macroeconomic model with banks and wholesale funding. Commercial banks (banks henceforth) raise external funds via deposits from households and wholesale debt from a wholesale lender that we refer to as the hedge fund; banks also raise internal funds via retained earnings. Each bank makes loans with an uncertain rate of return and, if the realized return is low, it goes bankrupt. In case of bank default, there is limited liability and deposits are senior to wholesale debt. Deposit insurance renders deposits safe from the perspective of the households, who have neither incentive to run on deposits nor to monitor the bank's activities. The hedge fund, on the other hand, is the junior creditor and its wholesale lending terms: a) ensure that the bank does not take excessive risk; b) are consistent with the expected rate of default and return that guarantees participation by the hedge fund. When bank loans become more risky, wholesale funding is reduced.

As long as loans to firms dominate liquid assets in terms of expected return, banks choose to hold zero liquidity if free to do so. In this setting, regulation forcing banks to hold some liquid assets has two effects. First, it cuts into banks' revenues and profits; second, it makes banks' asset portfolios safer. The former effect explains why liquidity regulation always binds in our model. The latter effect leads to an expansion of wholesale funding, bank leverage and lending to firms. In line with evidence in Dubois and Lambertini (2018), our analysis suggests that the volatility of wholesale

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<sup>3</sup>The LSR is calculated since 2001Q1 because of a change in reporting of its components at that date.

funding is reduced when banks hold liquid assets.

Our benchmark regulation is inspired by the Liquidity Coverage Ratio (LCR) of Basel III and it requires banks to hold a constant fraction of deposits and wholesale funds in the form of liquid assets. In our model benchmark (flat hereafter) liquidity regulation raises steady-state welfare because it expands credit and economic activity at the steady state. When we consider shocks, however, the welfare implications of flat liquidity regulation are ambiguous. Intuitively, a shock that reduces wholesale funding also reduces bank required liquid holdings, which in turn leads to a further decrease in wholesale funding stemming from the increase in riskiness of banks' assets. As a result, wholesale debt is more volatile with flat regulation than without liquidity regulation altogether. A counter-cyclical liquidity regulation, i.e. with the same steady state as the flat regulation but requiring banks to hold a higher share of liquid assets during downturns, unambiguously improves welfare both in conditional and unconditional terms.

The rest of the paper is organized as follows. In Section 2 we review the papers connected to our work. Section 3 presents the model; the calibration and quantitative analysis are in Section 4. The welfare implications of liquidity regulation are relegated to Section 5 and Section 6 concludes.

## 2 Literature review

Starting with Diamond and Dybvig (1983), the literature emphasizes the role of banks as liquidity providers. These authors show that bank liquidity provision improves economic outcomes but banks may be subject to harmful runs. Diamond and Rajan (2000, 2001) further show that bank fragility resulting from 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. Angeloni and Faia (2013) introduce banks à la Diamond and Rajan (2001) in a 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 the 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 there are no bank runs initiated by depositors because deposits are guaranteed by deposit insurance; the risk for the bank comes from wholesale funding.

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 amplifies the effects of shocks. He and Krishnamurthy (2014) and Brunnermeier and Sannikov (2014) propose a continuous-time nonlinear macroeconomic model with a financial sector. Both models feature strong amplification of shocks during systemic crises. Our approach is different because we introduce regulation on financial intermediaries.

Calomiris and Kahn (1991) build a model with demandable-debt, short-term wholesale debt falling into this category. In this environment, the banker has an informational advantage over demandable-debt depositors and he can divert realized returns for his own purposes. Early withdrawals and sequential service for depositors make demandable debt the optimal contract, as depositors have an incentive to monitor the banker, who can therefore pre-commit to higher payoffs. Huang and Ratnovski (2011) add a costless, noisy public signal as well as passive retail depositors to this setting. If demandable-debt depositors replace costly monitoring with the noisy public signal, early liquidations may exceed the optimal level; seniority of demandable-debt depositors may also be suboptimal. In our model retail deposits are insured and senior to demandable debt; information is symmetric. There is moral hazard for banks and demandable-debt depositors curtail loans to limit risk-taking by banks.

Our theoretical work is related to Adrian and Shin (2014). The authors propose a theoretical model where financial institutions have the incentive to invest in risky, sub-optimal projects; due to limited liability, this incentive becomes stronger with leverage. In equilibrium creditors withhold debt to reduce the leverage of financial institutions and induce them to invest only in safe projects. Nuño and Thomas (2017) 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. Our work builds on Adrian and Shin (2014) and Nuño and Thomas (2017), which we extend in several important ways. First, our banks choose their liability structure, namely they choose between deposits and wholesale funding, and they can default on depositors. Second, our banks are subject to liquidity regulation and deposit insurance.

### 3 Model

The economy consists of several actors. Households can save using insured deposits, risk-less bonds and shares in the hedge fund. The hedge fund is a financial intermediary that raises funds from households to finance banks. Banks raise deposits from households, subordinated wholesale funding from the hedge fund and accumulate retained earnings. Banks lend to firms subject to idiosyncratic risk and can default when their asset value is low. There is a continuum of firms subject to idiosyncratic risk; each firm receiving a loan from the local bank. Capital producers transform consumption goods into capital subject to adjustment costs. The government runs the deposit insurance scheme and provides the liquid asset. We now describe each agent in detail.

#### 3.1 Households

We look at a representative household that maximizes utility. The household chooses how much to consume ( $C_t$ ) and how many hours  $L_t$  to work at the wage  $w_t$ . Household can save using insured bank deposit ( $D_t$ ), treasury bills ( $TB_t^h$ ) and hedge fund equity ( $M_t$ ). The maximization problem of the household can be written as follows:

$$\max_{C_t, D_t, M_t, L_t, TB_t} \sum_{t=0}^{\infty} \beta^t \left[ \frac{C_t^{1-\gamma}}{1-\gamma} - \eta \frac{L_t^{1+\varphi}}{1+\varphi} \right] \quad (1)$$

$$\text{s.t.} \quad C_t + D_t \left( 1 + \frac{\chi_d}{2} (D_t - \bar{D})^2 \right) + M_t + TB_t^h = \\ L_t w_t + R_{D,t-1}^H D_{t-1} + R_{M,t} M_{t-1} + R_{TB,t-1} TB_{t-1}^h + \Pi_t - T_t, \quad (2)$$

where  $\gamma$  is the intertemporal elasticity of substitution,  $\eta$  is the disutility from labor and  $\varphi$  is the inverse of the Frisch elasticity of labor supply.  $\Pi_t$  are net transfers from the banks and the capital producers and  $T_t$  are lump-sum taxes.

The rate of return on deposits ( $R_{D,t-1}^H$ ) and treasury bills ( $R_{TB,t-1}$ ) are perfectly safe and predetermined, which is why we index them by  $t - 1$ . Shadow bank equity is “risky” in the sense that the return on the hedge fund equity ( $R_{M,t}$ ) is state contingent, so it is indexed by  $t$ .<sup>4</sup> The household faces quadratic adjustment costs to deposits; these costs capture the fact that deposits are relatively inflexible, as documented by XXXXXX Flannery 1982, Song and Thakor 2008XXXXXXXXXXXXXXXXXXXX. The idea is that households hold deposits ( $\bar{D}$ ) in steady state and changing the allocation implies

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<sup>4</sup>In the deterministic steady state of the model, the rate of returns on all assets are equal. However, the results would not change qualitatively if households were to be paid an equity premium.



costs  $\chi_d$  that can be interpreted as fees stemming from low balances or from opening an additional account, etc. The first order conditions of the households are in Appendix B.

### 3.2 Firms

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

$$\max_{L_t} Z_t (\Omega_t \omega_t^j K_t^j)^\alpha (L_t^j)^{1-\alpha} - w_t L_t^j - R_t^k \Omega_t \omega_t^j K_t^j. \quad (3)$$

At time  $t - 1$ , firms purchase capital  $K_t^j$  at price  $Q_{t-1}$  from the capital producer. They finance their purchase of capital using loans from banks. They can only borrow from the bank situated on the same island; hence, their balance sheet constraint is given by  $K_t^j = A_{t-1}^j$ . Hence, banks in our model will also be subject to non-diversifiable risk. After production takes place in period  $t$ , firms pay labor, sell back depreciated capital to the capital producer and repay loans from banks. Bank loans pay a state-contingent rate of return and perfect competition ensures zero profit for firms. The first order conditions of the firms are in Appendix B.

On each island there are two types of firms: standard and substandard. The two types of firms differ only in the distribution of idiosyncratic risk, which at time  $t$  is  $F_{t-1}(\omega)$  for the standard firm and  $\tilde{F}_{t-1}(\omega)$  for the substandard firm. We follow Nuño and Thomas (2017) and assume that the distribution of the idiosyncratic shocks is known one period in advance. The substandard distribution has lower mean but higher variance than the standard one. Substandard firms never operate in equilibrium but create a moral hazard problem for the banks. The distribution of the standard and the substandard firms at time  $t + 1$  are:

$$\begin{aligned} \log(\omega) &\stackrel{iid}{\sim} N\left(\frac{-\sigma_t^2}{2}, \sigma_t\right), \\ \log(\tilde{\omega}) &\stackrel{iid}{\sim} N\left(\frac{-v\sigma_t^2 - \vartheta}{2}, \sqrt{v}\sigma_t\right). \end{aligned} \quad (4)$$

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

### 3.3 Capital producer

There is a representative capital producer. The capital producer buys the final good in amount  $I_t$  at the (real) 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 the price  $Q_t$ . The capital producer chooses investment optimally to maximize its expected profits. The maximization problem of the capital producer is:

$$\max_{I_t} E_0 \sum_{t=0}^{\infty} \Lambda_{t,t+1} \left( Q_t (1 - S(\frac{I_t}{I_{t-1}})) I_t - I_t \right), \quad (5)$$

Profits of the capital producer ( $\Pi_t^{cap}$ ) are transferred to the households in a lump-sum fashion. The first order condition of the capital producer is given in Appendix B.

### 3.4 Banks

Banks are segmented across a continuum of islands indexed by  $j \in [0, 1]$ . Each bank raises external funds in the form of deposits from households and wholesale funding from a hedge fund; it also accumulates net worth by retaining earnings. Bank funds are either lent to the firm located on the same island or invested in the risk-free bond issued by the government. The balance sheet constraint of bank  $j$  in  $t$  is:

$$Q_t A_t^j + T B_t^j = N_t^j + B_t^j + D_t^j, \quad (6)$$

where  $D_t^j$  are deposits,  $B_t^j$  is wholesale debt,  $N_t^j$  is net worth and  $Q_t A_t^j$  is the loan to the local firm.

In our model banks finance capital purchases. Firm  $j$  borrows  $Q_t A_t^j$  in period  $t$  from the local bank to purchase capital  $K_{t+1}^j$  at price  $Q_t$ ; in period  $t+1$  it pays the realized gross rate of return  $\omega_{t+1}^j Q_t A_t^j R_{t+1}^A$ , where  $R_{t+1}^A$  is the aggregate return and it is equal to

$$R_{t+1}^A \equiv \frac{\alpha Z_{t+1} \Omega_{t+1} (L_{t+1} / (\Omega_{t+1} K_{t+1}))^{1-\alpha} + (1-\delta) \Omega_{t+1} Q_{t+1}}{Q_t}.$$

Hence, bank loans are state-contingent securities subject to idiosyncratic risk.<sup>5</sup> The risk-free bond, on the other hand, pays the pre-determined rate  $R_{TB,t}$ . On the liability

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<sup>5</sup>In this economy there is a strong case for pooling all bank loans into a single security paying the aggregate return to capital, which we assume not to be feasible.

side, the bank borrows  $B_t^j$  from the hedge fund under the promise to repay  $\bar{B}_t^j$  in the following period. Barring default, the net worth of bank  $j$  in period  $t + 1$  is given by

$$N_{t+1}^j = \omega_{t+1}^j R_{t+1}^A Q_t A_t^j + R_{TB,t} T B_t^j - R_{D,t}^B D_t^j - \bar{B}_t^j, \quad (7)$$

where  $R_{D,t}^B$  is the gross cost per unit of deposit that we explain in detail below.

Banks retain all earnings so as to overcome their financial constraint, which we explain below. To keep them relying on external funding, we assume banks exit with exogenous probability  $1 - \epsilon$ , at which point their accumulated earnings are paid out as dividends to households. In our model banks exit also due to default, in which case retained earnings are used to repay depositors and the hedge fund. We assume limited liability, i.e. banks are responsible only up to their assets in case of default. Default happens when bank asset returns are not sufficient to cover liabilities. We define  $\bar{\omega}_{t+1}^j$  to be the threshold of idiosyncratic risk such that

$$R_{t+1}^A \bar{\omega}_{t+1}^j Q_t A_t^j + R_{TB,t} T B_t^j = R_{D,t}^B D_t^j + \bar{B}_t^j. \quad (8)$$

Banks experiencing realizations of idiosyncratic risk below  $\bar{\omega}_{t+1}^j$  are unable to repay deposits and wholesale debt and declare bankruptcy.

We assume that wholesale debt is uncollateralized<sup>6</sup> and junior to deposits in the event of bank default. This means that, in case of default, bank assets are liquidated to pay depositors first and then (partially) the hedge fund. Defaulting banks are replaced by new ones. Seniority among bank creditors leads to a second threshold  $\bar{\bar{\omega}}_{t+1} < \bar{\omega}_{t+1}$  such that:

$$R_{t+1}^A \bar{\bar{\omega}}_{t+1}^j Q_t A_t^j = R_{D,t}^B D_t^j - R_{TB,t} T B_t^j. \quad (9)$$

For idiosyncratic realizations between  $\bar{\bar{\omega}}_{t+1}$  and  $\bar{\omega}_{t+1}$  depositors are fully repaid and the hedge fund is the residual, partial claimant of remaining assets. For realizations below  $\bar{\bar{\omega}}_{t+1}$ , however, bank assets are not even sufficient to cover deposits.

The government provides deposit insurance. Fees are collected from all banks and channeled to the government who covers losses to households in case of bank default on deposits. In our model deposit insurance premia have two features. First, they increase with the expected probability of default  $E_t F_t(\bar{\bar{\omega}}_{t+1})$ . In the United States, Federal Deposit Insurance Corporation (FDIC) fees are indeed based on banks' overall conditions as measured by the Camels rating system, with riskier and less-capitalized

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<sup>6</sup>Dubois (2017) analyzes liquidity regulation when wholesale funding is collateralized and senior to deposits.

banks paying higher premia. Second, deposit insurance premia rise when default is expected to be above average. FDIC fees have indeed been counter-cyclical, since they are raised during recessions, when the deposit insurance fund is drawn down, and vice versa during expansions. Formally, our deposit insurance fee is given by

$$DI_t = \left( 1 + \iota + \frac{E_t(\omega_{t+1}^{\bar{\omega}}) - \bar{\omega}^{ss}}{\bar{\omega}^{ss}} \right) E_t(F_t(\bar{\omega}_{t+1})), \quad (10)$$

where  $\iota$  is a positive constant and  $\bar{\omega}^{ss}$  is the steady-state value of  $\bar{\omega}$ . The unit cost of deposit is therefore equal to

$$R_{D,t}^B = R_{D,t}^H(1 + DI_t). \quad (11)$$

We follow Adrian and Shin (2014) and assume that banks can finance standard or substandard firms, as argued in Section 3.2. Limited liability causes moral hazard: the bank prefers to invest in the substandard firm because it offers higher upside risk relative to the standard firm. Since households are atomistic and perceive deposits as safe, they have no incentive to monitor the bank. This is not the case for the hedge fund. The wholesale rate is pre-determined and it reflects the probability of default, which depends on the bank's lending choice. The hedge fund sets the wholesale rate *conditional* on the standard firm being financed and then it chooses wholesale debt to ensure the bank is indeed better off by doing so. As explained in Section 3.2, the distributions of the idiosyncratic shocks are known one period in advance. When lending to the banks, the hedge fund then knows how risky their assets will be under either the standard or substandard distributions and can ensure they invest optimally. As in principal-agent models à la Holmstrom and Tirole (1997), the hedge fund sets  $\bar{B}_t^j$  to limit the option value of limited liability:<sup>7</sup>

$$\begin{aligned} E_t \Lambda_{t,t+1} \int_{\bar{\omega}_{t+1}^j} (\epsilon V_{t+1}(N_{t+1}^j) + (1 - \epsilon) N_{t+1}^j) dF_t(\omega) &\geq \\ E_t \Lambda_{t,t+1} \int_{\bar{\omega}_{t+1}^j} (\epsilon V_{t+1}(N_{t+1}^j) + (1 - \epsilon) N_{t+1}^j) d\tilde{F}_t(\omega). & \end{aligned} \quad (12)$$

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<sup>7</sup>The bank expected profit can be written as:

$$R_{t+1}^A Q_t A_t^j \left( E(\omega) - \bar{\omega}_{t+1}^j + \underbrace{\int_0^{\bar{\omega}_{t+1}^j} (\bar{\omega}_{t+1}^j - \omega) dF_t(\omega)}_{\equiv \pi_t(\bar{\omega}_{t+1}^j)} \right),$$

where  $\pi_t(\bar{\omega}_{t+1}^j)$  is the value of a put option with strike price  $\bar{\omega}_{t+1}^j$ . Under our distributional assumptions,  $\tilde{\pi}_t(\bar{\omega}_{t+1}^j) > \pi_t(\bar{\omega}_{t+1}^j)$  so the option value of limited liability is greater under the substandard technology.

Equation (12) is the incentive-compatibility constraint ensuring that the bank is better off lending to the standard firm relative to the nonstandard one. The expected return to wholesale funding must be at or above  $R_{TB,t}$  since the hedge fund has the option to invest in risk-free government bonds. Hence the hedge fund chooses  $B_t^j$  to satisfy its participation constraint.

$$E_t \Lambda_{t,t+1} \left\{ \bar{B}_t^j (1 - F(\bar{\omega}_{t+1}^j)) + R_{t+1}^A Q_t A_t^j \int_{\bar{\omega}_{t+1}^j}^{\bar{\omega}_{t+1}^j} \omega_{t+1} dF_t(\omega) - (F(\bar{\omega}_{t+1}^j) - F(\bar{\omega}_{t+1}^j)) (R_{D,t}^B D_t^j - R_{TB,t} T B_t^j) \right\} \geq E_t \{ \Lambda_{t,t+1} R_{TB,t} B_t^j \}. \quad (13)$$

In our benchmark model without liquidity regulation, the objective of continuing bank  $j$  at the end of period  $t$  can be written as:

$$V_t(N_t^j) = \max_{A_t^j, B_t^j, \bar{B}_t^j, D_t^j, T B_t^j} E_t \Lambda_{t,t+1} \int_{\bar{\omega}_{t+1}^j} (\epsilon V_{t+1}(N_{t+1}^j) + (1 - \epsilon) N_{t+1}^j) dF_t(\omega), \quad (14)$$

where  $V(N_t^j)$  is the value of the bank at  $t$ . The bank maximizes its value, namely the expected discounted value of its final dividend payment subject to the bank balance sheet constraint (6), the evolution of net worth (7), the incentive-compatibility constraint (12) and the participation constraint (13).

### 3.4.1 Liquidity regulation

The Basel Committee on Banking Supervision introduced the Liquidity Coverage Ratio (LCR) in 2013 to promote short-term resilience of banks to liquidity stress. The LCR 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. Expected cash outflows are calculated by multiplying the outstanding balances of various types of liabilities and off-balance sheet commitments by the rates at which they are expected to run off or be drawn down under a stress scenario. In the United States, Federal Banking Regulators issued the final version of the LCR in September 2014; the main difference relative to Basel III's LCR standard is in the shorter implementation period requiring U.S. banks to be fully compliant by January 2017.

We introduce liquidity regulation on banks in the spirit of the LCR of Basel III. In our model, the high-quality liquid asset is the government bond; the stress scenario is a withdrawal rate on deposits and wholesale funding equal to  $\xi_t$ . Formally the LCR constraint is

$$TB_t^j \geq \xi_t(D_t^j + B_t^j). \quad (15)$$

We first consider a LCR-type regulation, which we refer to as flat, where  $\xi$  is constant; then we go beyond the LCR and propose a counter-cyclical liquidity regulation where the coefficient  $\xi_t$  vary with the business cycle as follows:

$$\xi_t = \bar{\xi} - \chi_y(Y_t - \bar{Y}), \quad (16)$$

where  $\bar{Y}$  is steady-state output and  $\chi_y$  is a positive constant. Intuitively, the stress scenario envisions higher withdrawal rates of deposits and wholesale funding during economic downturns.<sup>8</sup>

In the economy with liquidity regulation, continuing bank  $j$  maximizes (14) subject to (6), (7), (12), (13) and the LCR constraint (15). The problem and the relevant first-order conditions can be found in Appendix B.

### 3.5 The Hedge Fund

The hedge fund is an institution that issues equity ( $M_t$ ) to households and lends to banks in the form of uncollateralized debt ( $B_t$ ). Hedge fund equity is risky, it pays a state-contingent rate of return ( $R_{M,t+1}$ ). The payoff of the hedge fund from lending to bank  $j$  can therefore be written as:

$$\min(\bar{B}_t^j, \max(0, R_{t+1}^A \omega_{t+1}^j Q_t A_t^j + R_{TB,t} TB_t^j - R_{D,t} D_t^j)). \quad (17)$$

Since the hedge fund lends to all banks, it is exposed to aggregate but not to idiosyncratic risk. Aggregating across all banks, the gross return to the hedge fund is:

$$\begin{aligned} R_{M,t+1} M_t = & \bar{B}_t^j (1 - F(\bar{\omega}_{t+1})) + R_{t+1}^A Q_t A_t^j \int_{\bar{\omega}_{t+1}}^{\bar{\omega}_{t+1}} \omega_{t+1} dF_t(\omega) \\ & - (F(\bar{\omega}_{t+1}) - F(\bar{\omega}_{t+1})) (R_{D,t}^B D_t^j - R_{TB,t} TB_t^j). \end{aligned} \quad (18)$$

Bank liquidity  $TB_t^j$  has a positive impact on the gross return to the hedge fund because it increases the liquidation value in case of default. Deposits, on the other hand, have

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<sup>8</sup>Bai et al. (2017) argue it is important to account for the macroeconomic conditions when calculating bank liquidity shortfall.

a negative impact on the gross return to the hedge fund. Since deposits are paid first in case of default, more deposits reduce the resources available to the hedge fund to cover its losses.

### 3.6 The Government

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

$$TB^{supp} + T_t + Ins_t^{fee} = R_{TB,t-1}TB^{supp} + Ins_t^{pay}, \quad (19)$$

$Ins^{fee}$  are insurance deposit fees collected from banks and  $Ins^{pay}$  are deposit insurance payout to households. The two are not necessarily equal, so the difference is collected or redistributed to households via lump sum taxes. The government must balance its budget every period.  $Ins^{fee}$  and  $Ins^{pay}$  are given by:

$$Ins_t^{fee} = R_{D,t-1}^H D_{t-1} DI_{t-1} (1 - F_{t-1}(\bar{\omega}_t)), \quad (20)$$

$$Ins_t^{pay} = R_{D,t-1}^H D_{t-1} F_{t-1}(\bar{\omega}_t). \quad (21)$$

Treasury bills are either held by the households or by the banks. The bank holding of treasury bills is determined by liquidity regulation while households hold the residual supply.

$$TB_t^{supp} = TB_t^h + TB_t. \quad (22)$$

### 3.7 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 (2017), 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 choose the same leverage, deposit, wholesale funding and safe asset ratios; hence, we can aggregate the banking sector. Aggregating the flow of funds constraint across all continuing banks we find that the evolution of aggregate net worth of continuing non-defaulting banks is given by:

$$N_t^{cont} = \epsilon R_t^A Q_{t-1} A_{t-1} \int_{\bar{\omega}_t}^{\infty} (\omega - \bar{\omega}_t) dF_{t-1}(\omega). \quad (23)$$

Every period, new banks enter to replace exiting ones. Each new bank receives a transfer  $\tau(Q_t A_{t-1} + TB_{t-1})$  from households. The transfer corresponds to the fraction  $\tau$  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 total net worth of new banks is:

$$N_t^{new} = [1 - \epsilon(1 - F_{t-1}(\bar{\omega}_t))] \tau(Q_t A_{t-1} + TB_{t-1}). \quad (24)$$

The net transfer from banks to households ( $\Pi_t^{banks}$ ) is equal to the net worth of exiting non-defaulting banks minus the transfer to new banks:

$$\Pi_t^{banks} = \frac{(1 - \epsilon)}{\epsilon} N_t^{cont} - N_t^{new}. \quad (25)$$

Total transfers to households are given by the profit from the capital producers and the transfer from the banks:  $\Pi_t = \Pi_t^{banks} + \Pi_t^{cap}$ . The model can be reduced to a set of 28 equations that are given in Appendix B.

## 4 Quantitative analysis

### 4.1 Calibration

The standard RBC parameters ( $\alpha, \beta, \gamma, \delta, \chi, \varphi, \eta$ ) are set in line with the macro literature. The steady-state level of technology  $\bar{z}$  is chosen to normalize steady-state output to 1. The fraction of total assets transferred to new banks  $\tau$  is set to target an investment-output ratio of 20%.

Our model economy is calibrated to obtain steady-state values of the bank balance sheet ratios in the unregulated model in line with average pre-regulation values in the data. Table 1 shows summary statistics for the leverage, wholesale funding and deposit ratios as well as the LSR. The empirical moments are calculated using quarterly BHC balance sheet data from the FR Y-9C from 1994Q1 to 2012Q4. The liquidity, wholesale funding and deposit ratios are calculated by dividing the relevant measure by total assets. Leverage ratio is total assets divided by equity. The LCR regulation started being phased in 2015, but banks were likely anticipating it and adjusting in advance. Hence, we exclude data later than 2012Q4 to ensure data is not affected by regulation.<sup>9</sup>

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<sup>9</sup>We also tried cutting the sample in 2011Q4 and 2010Q4, the summary statistics are very comparable



Table 1: Balance sheet ratio moments

	<b>mean</b>		<b>standard deviation</b>	
	Data	Model	Data	Model
Deposit ratio	0.763	0.80	0.024	0.024
Leverage ratio	10.82	10	0.048	0.033
Wholesale ratio	0.12	0.10	0.2	0.2
Liquidity Stress Ratio	0.315	0.36	0.099	0.1

Sample: 1994Q1 to 2012Q4

Empirical mean and standard deviation are calculated by first taking the average across all banks for every quarter, and then taking respectively the average and the standard deviation for all quarters.

Model and empirical standard deviations are calculated on logged variables.

The steady-state idiosyncratic volatility  $\bar{\sigma}$  is calibrated to target a leverage ratio of 10 and the variance of the substandard technology  $v$  is chosen to generate a wholesale funding ratio of 10%. Consistent with Adrian and Shin (2014) and Nuño and Thomas (2017), we find that the leverage is procyclical. The correlation with output is 0.21 in the data, and 0.31 in the model. The variable  $\vartheta$  is set large enough to ensure it is never optimal for the economy to let the banks invest in the substandard technology to avoid the cost related to moral hazard (see Appendix E).

Table 1 shows that deposits were considerably less volatile than wholesale funding; this evidence points towards stickiness of deposits, as argued in Section 3.1, which is a feature that helps us calibrate the model. The scaling factor of shocks  $\varsigma$  and the parameter for deposit stickiness  $\chi_d$  are chosen to match the volatilities of output and deposit ratio, respectively. The volatility of output is 0.012 in the data and the model.<sup>10</sup> The parameters  $(\theta, \rho_z, \sigma_z, \rho_\sigma, \sigma_\sigma)$  follow Nuño and Thomas (2013) and  $(\rho_\kappa, \sigma_\kappa)$  follow Nuño and Thomas (2017).

The model LSR is calculated as:

$$LSR_t = \frac{B_t + 0.1 \times D_t}{0.5 \times Q_t A_t + TB_t}. \quad (26)$$

The weights on deposits, treasury bills and wholesale funding follow directly from our empirical measure of LSR.<sup>11</sup> We calibrate the weight on loans so that our model

<sup>10</sup> The real GDP and population data comes from the Federal Reserve Bank of St Louis Economic Data (FRED); We calculate the log of real GDP per capita and hp-filter it.

<sup>11</sup>The weight of one on  $B_t$  mirrors the empirical weight on the most illiquid type of wholesale funding. See Appendix A for the data calculations.

steady-state LSR matches the average of empirical LSR.

Basel III specifies a 5% run-off rate on deposits under stress scenario; we use this number for our liquidity regulation. In the model with regulation, banks are required to hold 5% of liquid assets against their deposits and wholesale funding ( $\bar{\xi}=0.05$ ). 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 ( $\chi_y = 0.5$ ). All the regulatory parameters are set to zero in the unregulated model. The total supply of treasury bills is set at 2, i.e. 200% of GDP. This parameter does not have any impact on the model behavior but it needs to be high enough to ensure that banks have access to treasury bills to cover their regulatory requirements. The full calibration is given in Table 2.

Table 2: Calibration

Parameter	Value	Description
Standard RBC parameters		
$\beta$	0.99	discount factor
$\alpha$	0.36	share of capital in production
$\delta$	0.025	depreciation rate
$\chi$	0.5	adjustment cost on investment
$\chi_d$	0.00008	adjustment cost on deposits
$\varphi$	1	inverse elasticity of labor supply
$\gamma$	1	intertemporal elasticity of substitution
$\eta$	1	disutility of labor
$\bar{z}$	0.5080	steady-state TFP
$\rho_z$	0.9297	serial correlation TFP shock
$\sigma_z$	0.0067	standard deviation TFP shock
Financial parameters		
$\bar{\sigma}$	0.06988	steady-state idiosyncratic volatility
$v$	4.2899	variance substandard technology
$\vartheta$	0.04	shift in mean of substandard technology
$\tau$	0.05846	share of asset transfer into new banks
$\theta$	0.75	survival probability of banks
$\rho_\sigma$	0.9457	serial correlation risk shock
$\sigma_\sigma$	0.0465	standard deviation risk shock
$\iota$	0.0005	deposit insurance fee parameter
$\rho_\kappa$	0.3591	serial correlation capital quality shock
$\sigma_\kappa$	0.0081	standard deviation capital quality shock
$\varsigma$	0.115	scaling parameter for all shocks
Regulatory parameters		
$\bar{\xi}$	0.05	steady-state regulatory parameter
$\chi_y$	0.5	cyclical regulatory parameter
$TB_{supp}$	2	total supply of treasury bills

## 4.2 Steady-state analysis

The steady-state values of the key variables of the model are given in Table 3. Regulation requires banks to hold safe assets to cover 5% of their deposits and wholesale funding. In the unregulated model, banks do not hold safe assets and the liquidity

Table 3: Steady state

	<b>Unregulated</b>	<b>Regulated</b>
Bank balance sheet ratios		
Deposit ratio	0.8000	0.8084
Wholesale ratio	0.1000	0.0954
Liquidity ratio	0.0000	0.0452
Leverage ratio	10.000	10.3996
Liquidity Stress Ratio	0.3600	0.3373
Bank balance sheet items (levels)		
Total deposits	6.4000	6.9859
Total Wholesale funding	0.8000	0.8247
Net worth	0.8000	0.8309
rates of return and default probabilities		
$R^A$	1.0200	1.0192
wholesale rate	1.0251	1.0251
Default probability	0.0568	0.0568
Default on deposit probability	0.0005	0.0005
Real variables		
Consumption	0.8000	0.8064
Labor	0.8944	0.8965
Capital	8.0000	8.2510
Output	1.0000	1.0127

ratio is zero. Indeed, since the return on treasury bills is lower than the return on loans, banks choose not to hold any treasury bill in the absence of liquidity regulation. Thus, liquidity regulation is always binding in our model and it implies an increase in the liquidity ratio.

The default probabilities and default thresholds  $\bar{\omega}$  and  $\bar{\bar{\omega}}$  are independent from liquidity regulation.  $\bar{\omega}$  is pinned down by the ICC, Equation (12), which at the steady state simplifies to:

$$E(\omega) - \tilde{E}(\omega) = \tilde{\pi}(\bar{\omega}) - \pi(\bar{\omega}). \quad (27)$$

Intuitively, the ICC is satisfied (with equality) when the higher expected return from standard firm is exactly compensated by the lower put option value relative to non-standard firm. Equation (27) depends only on the distribution of returns and there is a unique value of  $\bar{\omega}$  that solves this equation.  $\bar{\bar{\omega}}$  is pinned down by deposit demand of

households and deposit supply of banks, which simplify as follows:

$$F(\bar{\omega}) = 1 - \frac{1}{1 + \iota}. \quad (28)$$

The steady-state probability of default on deposits depends only on  $\iota$ . In steady state, bank payment to deposit insurance must cover payment to depositors of failed institutions ( $Ins_t^{fee} = Ins_t^{pay}$ ). The higher  $\iota$ , the more resources there are to cover failed institutions, and banks can raise more deposits and default on them. Hence, the probability of default on deposits is an increasing function of the insurance fee.

The portfolio of assets held by the regulated bank is safer relative to the portfolio held by unregulated banks because a positive fraction is invested in the safe asset. As emphasized earlier, if bank assets are safer, the moral hazard problem is reduced and banks can increase their leverage. This is to say that holding safe assets does not crowd out credit to firms but rather crowds it in: total loans (Capital) is higher in the regulated model relative to the unregulated one. The reason is that the bank is able to leverage up while keeping the same probability of default because its portfolio of assets is safer. Regulated banks borrow more; both deposits and wholesale funding increase, although deposits go up more than wholesale funding, so that the deposit ratio increases with regulation. Since regulated banks hold more safe assets, they are able to increase deposits while maintaining an identical probability of default on them. Liquidity regulation reduces the steady-state value of the LSR: banks are more leveraged but, at the same time, they carry less liquidity mismatch on their balance sheet.

Since liquidity regulation allows the bank to expand its assets and to leverage up, one may wonder why the bank chooses not to hold liquidity in the absence of regulation. The reason is that the bank is less profitable when it holds liquid, low-return assets and its expected value is therefore lower under liquidity regulation. The value function of the bank in steady state can be written as:

$$V(N) = \frac{\beta(1 - \epsilon)\Phi R^A(1 - \bar{\omega} + \pi(\bar{\omega}))}{1 - \beta\epsilon\Phi R^A(1 - \bar{\omega} + \pi(\bar{\omega}))}N \quad (29)$$

where  $\Phi \equiv K/N$  (see Appendix C for proof). We know that  $\bar{\omega}$  is not affected by the regulation, so the term  $(1 - \bar{\omega} + \pi(\bar{\omega}))$  is unaffected. However, the higher level of capital in the economy makes  $R^A$  smaller. Moreover  $\Phi$  is 10 in the unregulated and 9.93 in the regulated. This means that out of each unit of net worth, less risky loans are given out. The lower values in  $R^A$  and  $\Phi$  capture the reduced profitability of the banks.

Although the banks are bigger and have higher net worth in the regulated case, their value function is lower because each unit of net worth is valued less.  $V(N)$  is 1.219 in the unregulated and 1.211 in the regulated model. Even though regulation expands financial intermediation and thereby output and consumption, the bank is atomistic and it does not internalize the effect of liquidity holding on aggregate consumption level.

The banks must choose between deposits and wholesale funding. Deposits are cheaper than wholesale funding, because the wholesale rate  $\bar{B}/B$  is higher than the deposit rate. However, a higher deposit ratio implies a higher probability of default on deposits and thereby a higher deposit insurance payment for the bank. Moreover, the wholesale rate increases with the deposit ratio. This is due to the fact that a higher deposit ratio implies a lower liquidation value for the hedge fund in case of default. Since the hedge fund recuperates less after default, it demands a higher rate of return when there is no default, hence a higher wholesale rate. Banks face a trade-off: they would prefer to use deposits, which are cheaper, but the cost of both deposit and wholesale funding goes up with the deposit ratio. Banks choose the liability structure that minimizes their cost of external funding.

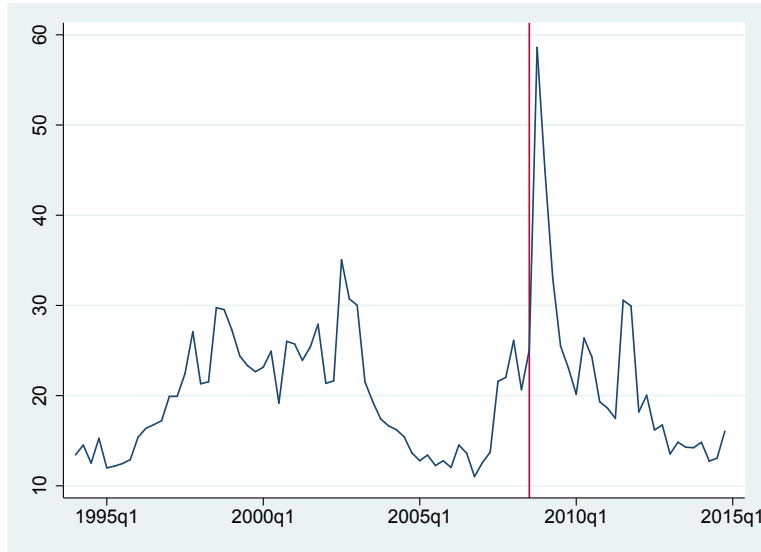
Liquidity regulation affects the real economy in our model. Liquidity regulation generates an increase in loans, i.e. in capital. More capital implies higher marginal productivity of labor, so that labor goes up as well. Output as well as consumption increase. A lower marginal product of capital implies a lower interest rate on the loans.

### 4.3 Response to a risk shock

The financial crisis was characterized by a sharp increase in the riskiness of bank assets. Figure 4 reports the evolution of the VIX index. The VIX is an index of volatility in the stock market, a weighted average of prices of a range of options on the S&P 500. It captures expectations of volatility in the market over the next 30 days. The unprecedented increase in the VIX marks the peak of the financial crisis.

We analyze the dynamics of the model under a risk shock, which 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 reported in Figure 5 and are in percent deviation from steady state. We compare the behavior of the model without regulation and with liquidity regulation, flat and countercyclical.

Figure 4: VIX

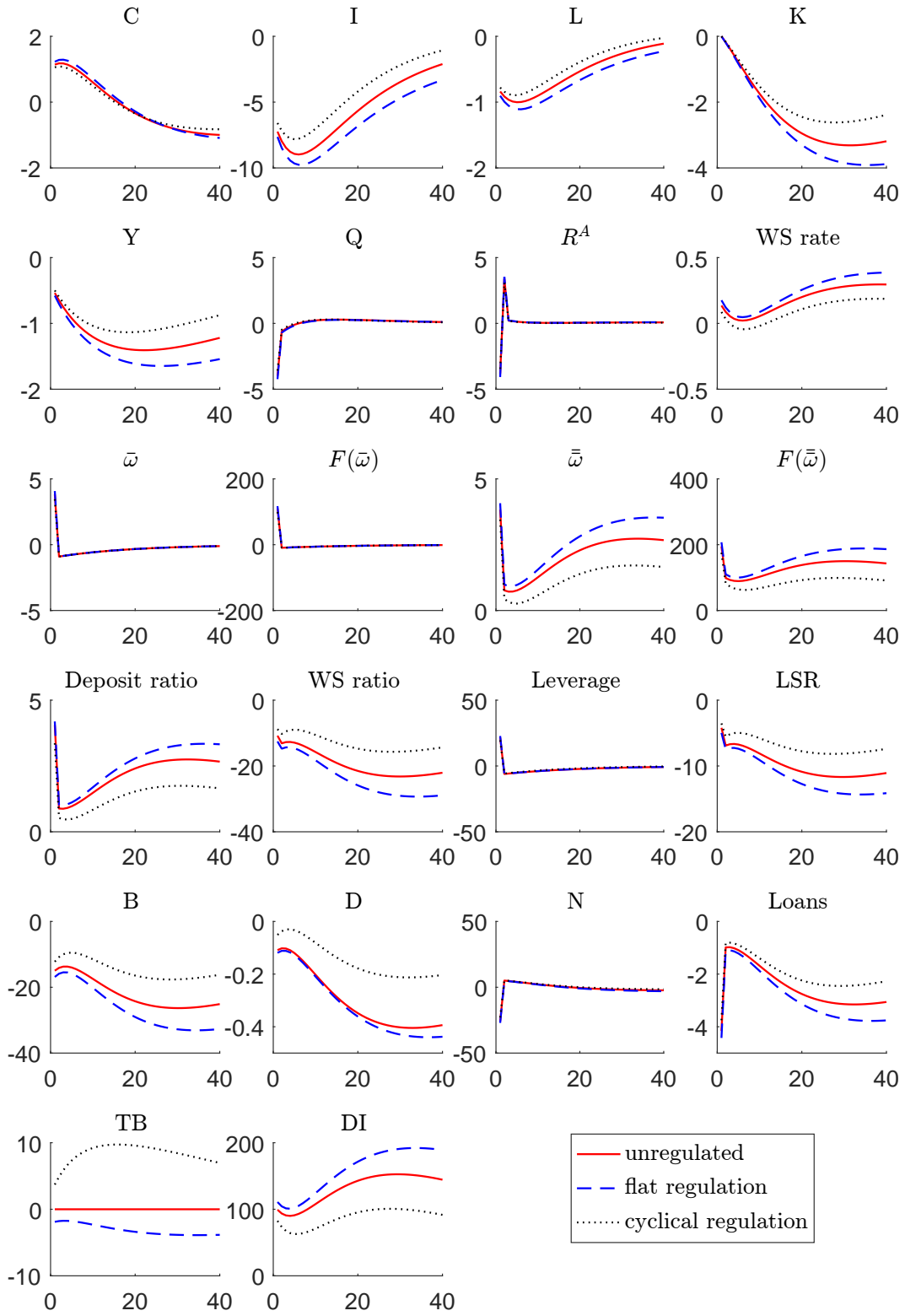


Source: FRED

Banks learn that next period the return to their assets is going to be more volatile. An increase in asset riskiness makes the moral hazard problem of banks more severe. The hedge fund cuts wholesale lending to banks recognizing their stronger incentives to invest in the suboptimal firm. The total amount of wholesale funding  $B$  falls by about 13% on impact and banks are forced to deleverage. The default threshold  $\bar{\omega}$  remains below steady state from  $t + 1$  onwards. With a sizable portion of wholesale funding gone, banks end up with a higher deposit ratio. The probability of default on deposit remains persistently higher and so are deposit insurance payments, thereby raising costs for banks. An increase in the deposit ratio means a reduction in the recuperation value by the hedge fund in case of default. As a result the hedge fund imposes a higher wholesale rate. Thus, banks pay more for both their deposits and their wholesale funding. The LSR falls after the shock, driven by the sharp fall in wholesale funding.

The risk shock has real effects because deleveraging leads to a reduction in credit to firms. Fewer loans from banks lead to lower investment and a reduction in the price of capital. The marginal productivity of labor falls since capital is lower, so that hours worked are also reduced. Output therefore falls as well. The fall in asset prices has an immediate impact on the return on loans:  $R_t^A$  falls on impact, which in turn raises  $\bar{\omega}_t$  and  $\bar{\bar{\omega}}_t$ . In other words, banks are less profitable and the rates of default on wholesale funding and depositors go up on impact. Following a risk shock, investment falls more

Figure 5: Risk shock





than output, so that consumption actually goes up.

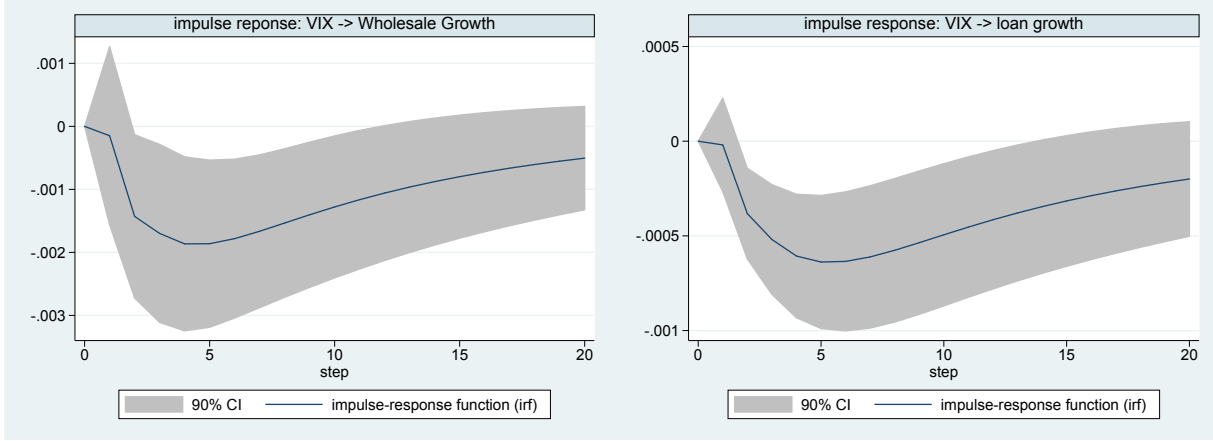
We now turn to the analysis of the dynamic implications of liquidity regulation. The LCR-type flat liquidity regulation requires banks to keep at least 5% of liquid assets against deposits and wholesale funding at all times. While flat liquidity regulation leads to higher steady-state consumption and output, it amplifies fluctuations after shocks – we report and discuss the standard deviation of several variables of our model in Section 5. The reduction in wholesale lending  $B$  is more pronounced in the economy with flat liquidity regulation relative to the unregulated one, which in turn leads to a more severe and persistent deleveraging and fall in output, investment and capital. Flat liquidity regulation ties the behavior of liquid assets, deposits and wholesale funding, which makes the dynamics of bank ratios more persistent. Since wholesale funding and deposits are lower after the shock, flat liquidity regulation allows banks to reduce their safe asset holdings, which intensifies moral hazard and its adverse effect on the economy.

Countercyclical liquidity regulation requires banks to hold a larger fraction of liquid assets when output is below steady state. It may seem counterintuitive at first to require banks to hold on to more safe assets during a recession, but this regulation has a stabilizing effect on the economy. After a risk shock banks are forced to become safer, which relaxes their moral hazard problem. Since banks have less incentive to invest in the suboptimal firm, the hedge fund cuts wholesale funding less. In other words, countercyclical liquidity regulation makes wholesale funding more stable over the business cycle by reducing moral hazard exactly at the time when it is most acute. Banks do not need to rely as heavily on deposits (the deposit ratio goes up less), so the deposit insurance fee increases less. Banks pay lower wholesale and deposit rates relative to flat regulation. The LSR is still procyclical but less so. Banks do not curtail credit as much, so the transmission of a risk shock to the real economy is mitigated.

The result is not specific to risk shocks. We analyze the impulse response of the economy with and without regulation under TFP and capital quality shocks (see Appendix F). The effects of flat and countercyclical liquidity regulations are similar to those under the risk shock.

The model predicts that a risk shock leads to a wholesale funding run and a credit crunch. We analyze how wholesale funding and loans react to an increase in risk using vector autoregression (VAR), where the risk shock is captured by an increase in the VIX. Our structural VAR comprises three variables: VIX, wholesale growth and loan growth, and includes a constant term. Wholesale growth and loan growth are quarter-

Figure 6: Impulse response, one-unit shock to VIX



on-quarter and averaged across all banks. We winsorize wholesale growth at 1% to get rid of outliers. Since wholesale and loan growth display seasonal pattern, they are deseasonalized by taking residuals from a regression on quarterly dummies. The ordering of the variables is based on our model: the risk shock is ordered first, then wholesale funding growth and last loan growth. Based on selection criteria, we choose a VAR model with two lags. The impulse responses and confidence intervals are plotted in Figure 6. We find that an increase in risk leads to a decline in wholesale growth and loan growth. This evidence supports our theoretical findings: an increase in risk makes wholesale funding provider less willing to lend to banks. Banks find it harder to access wholesale funding, which in turn forces them to curtail lending.

## 5 Welfare

Flat and cyclical regulation generate different dynamic responses to shocks. Table 4 reports the volatility of macroeconomic and financial variables in the economy without regulation, with flat regulation and with cyclical regulation. Flat regulation makes macroeconomic and financial variables more volatile, whereas countercyclical reduces their volatility. We consider welfare conditional on the initial state of the economy being the deterministic steady state; we also consider unconditional welfare (detailed calculations in Appendix D). Welfare results are reported in Table 5.

In steady state, either flat or cyclical liquidity regulation improve welfare by 0.614% in consumption-equivalent terms, driven by the increase in steady-state consumption (as explained in Section 4.2). Flat regulation entails an improvement in deterministic

Table 4: Standard deviations (in %)

	<b>Unregulated</b>	<b>Flat</b>	<b>Cyclical</b>
Output	1.21	1.55	0.90
Consumption	0.96	1.16	0.77
Investment	4.37	5.20	3.45
Deposit ratio	2.41	3.19	1.44
Wholesale ratio	19.95	27.68	12.58
Leverage ratio	3.31	3.42	2.96
Liquidity Stress Ratio	10.03	13.53	6.53
Total bank assets	2.75	3.60	2.00
Total bank equity	3.98	4.59	3.34

steady-state welfare but a worsening of volatility. The overall welfare implications of the flat liquidity regulation are ambiguous. Flat regulation implies an improvement of conditional welfare but a worsening of unconditional welfare. In the conditional welfare case, the steady-state effect dominates the volatility effect and overall conditional welfare improves. High persistency in the model implies that the macroeconomic variables remain away from steady state for a prolonged period following shocks; unconditional welfare predicts that the volatility effect dominates and unconditional welfare worsens. Countercyclical liquidity regulation has the same positive effect on steady-state welfare but it also reduces volatility in the macroeconomic variables. This implies an unambiguous improvement in welfare, of 0.748% conditionally, and 1.117% unconditionally.

Table 5: Welfare benefits

	<b>unregulated to flat</b>	<b>unregulated to cyclical</b>
Steady-state welfare	0.614	0.614
Conditional welfare	0.354	0.748
Unconditional welfare	-0.780	1.117

## 6 Conclusions

This paper develops a DSGE model with depository institutions (banks) and a hedge fund and analyzes the macroeconomic implications of imposing liquidity requirements

on banks. Due to limited liability, banks prefer high-return, high-risk investments. The hedge fund provides wholesale funding to banks that is junior to deposits in the event of bank default. Since the hedge fund is the residual claimant when bankruptcy arises, it uses wholesale funding to control bank leverage and risk-taking. Regulation requiring banks to hold a fraction of their deposits and risky assets in the form of liquid assets has real consequences for the economy. By making bank portfolios safer, liquidity regulation leads to an increase in wholesale funding and credit supply.

We analyze two types of liquidity regulation: flat, which does not depend on the business cycle, and counter-cyclical, which requires banks to hold a higher fraction of liquid assets during economic downturns. Flat liquidity regulation raises credit supply and consumption at the steady state but it also increases macroeconomic volatility; hence its welfare effects are ambiguous. On the other hand, counter-cyclical regulation improves welfare unambiguously because it mitigates the transmission of shocks to the real economy in addition to retaining expansionary steady-state effects. Following an adverse risk shock, the contraction in wholesale funding and thereby in leverage is less severe.

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# A Data

## 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 of more than 500 million have to fill in the FR Y-9C. 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 FR Y-9C 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`).

Table 6 gives the mapping from the FR Y-9C 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 Assets

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, treasuries, 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 eligible agency securities as follows:

1. If  $0.85 \times \text{agency securities} < 0.4 \times \text{liquid assets}$ , then eligible agency securities = agency securities
2. If  $0.85 \times \text{agency securities} > 0.4 \times \text{liquid assets}$ , then eligible agency securities =  $0.4 \times \text{liquid assets}$

Moreover, liquid assets should be unencumbered, so not a part of a repo agreement. This means that treasuries 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

Table 6: Mapping from FR Y-9C to model variables

Variable	FR Y-9C
Total assets	bhck2170
Cash	bhck0081+bhck0395+bhck0397
Federal funds sold	<b>until 1996Q4:</b> bhck0276 <b>1997Q1 to 2001Q4:</b> bhck1350 $\times$ estimated fraction of federal funds sold <sup>1</sup> <b>from 2002Q1:</b> bhckb987
Reverse repo	<b>until 1996Q4:</b> bhck0277 <b>1997Q1 to 2001Q4:</b> bhck1350 $\times$ estimated fraction of reverse repo <sup>2</sup> <b>from 2002Q1:</b> bhckb989
Treasuries	bhck0213 + bhck1287
State securities	bhck8497 + bhck8499
Agency MBS	<b>until 2009Q1:</b> bhck1699+bhck1702+bhck1705+ bhck1707+bhck1715+bhck1717+bhck1719+bhck1732 <b>2009Q2 to 2010Q4:</b> bhckg301+bhckg303 +bhckg305 +bhckg307+bhckg313+bhckg315+bhckg317+bhckg319 +estimated fraction of agency MBS <sup>3</sup> $\times$ (bhckg325+bhckg327+bhckg329+bhckg331) <b>from 2011Q1:</b> 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	<b>until 2009Q1:</b> bhck1710+bhck1713+bhck1734+bhck1736 <b>2009Q2 to 2010Q4:</b> bhckg309+bhckg311+bhckg321+bhckg323 +estimated fraction of other MBS <sup>4</sup> $\times$ (bhckg325+bhckg327+bhckg329+bhckg331) <b>from 2011Q1:</b> bhckg309+bhckg311+bhckg321 +bhckg323+bhckk147+bhckk149+bhckk155+bhckk157

<sup>1</sup> The estimated fraction of Federal funds sold is calculated by taking the average of bhck0276/bhck1350 in 1996Q4 and bhckb987/bhck1350 in 2002Q1

<sup>2</sup> The estimated fraction of reverse repo is calculated by taking the average of bhck0277/bhck1350 in 1996Q4 and bhckb989/bhck1350 in 2002Q1

<sup>3</sup> 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



Other securities	bhck1771+bhck1773 – (treasuries + state securities + agency securities + other MBS)
Loans	bhck5369+bhckb529
Deposits	bhdm6631+bhdm6636
Foreign deposits	bhfn6631+bhfn6636
Federal funds purchased	<b>until 1996Q4:</b> bhck0278 <b>1997Q1 to 2001Q4:</b> bhck1280 × estimated fraction of federal funds purchased <sup>5</sup> <b>from 2002Q1:</b> bhckb993
Repo	<b>until 1996Q4:</b> bhck0279 <b>1997Q1 to 2001Q4:</b> bhck2800 × estimated fraction of repo <sup>6</sup> <b>from 2002Q1:</b> 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

<sup>4</sup> The estimated fraction of other MBS is (1-estimated fraction of agency MBS)

<sup>5</sup> The estimated fraction of Federal funds purchased is calculated by taking the average of bhck0278/bhck2800 in 1996Q4 and bhckb993/bhck2800 in 2002Q1

<sup>6</sup> The estimated fraction of repo is calculated by taking the average of bhck0279/bhck2800 in 1996Q4 and bhckb995/bhck2800 in 2002Q1

fraction of treasuries and agency securities over all securities. Finally, our liquid assets are calculated as:

$$\begin{aligned} \text{Liquid assets} = & \text{cash} + \text{federal funds bought} + \text{treasuries} + 0.85 \times \text{eligible} \\ & \text{agency securities} - \text{fraction of liquid securities} \times \text{repo} \end{aligned} \quad (30)$$

## Wholesale funding

Wholesale funding is funding for the banks other than retail deposits and equity. We include short-term commercial papers issued by the banks, brokered or foreign deposits, repos, interbank loans, and any other type of borrowing.

$$\begin{aligned} \text{Wholesale funding} = & \text{foreign deposits} + \text{federal funds purchased} + \text{repos} \\ & + \text{OBMless1} + \text{OBMmore1} \end{aligned} \quad (31)$$

## Liquidity stress ratio

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

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

$$\begin{aligned} \text{Liquidity-adjusted assets} = & \text{cash} + \text{federal funds sold} + \text{reverse repo} \\ & + 0.85 \times \text{agency securities} + 0.85 \times \text{state securities} + 0.75 \times \text{other MBS} \\ & + 0.5 \times \text{other securities} + 0.3 \times \text{loans} \end{aligned} \quad (32)$$

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

$$\begin{aligned} \text{Liquidity-adjusted liabilities} = & \text{federal funds purchased} + \text{repo} \\ & + 0.5 \times \text{trading liabilities} + 0.5 \times \text{CP} + 0.4 \times \text{OBMless1} + 0.1 \times \text{subordinated debt} \\ & + 0.1 \times \text{deposits} + 0.15 \times \text{foreign deposits} \end{aligned} \quad (33)$$

$$\begin{aligned} \text{Liquidity-adjusted off-balance sheet} = & 0.1 \times \text{unused commitments} \\ & + 0.1 \times \text{securities lent} + 0.1 \times \text{standby letters of credit} \\ & + 0.3 \times \text{securities underwriting} \end{aligned} \quad (34)$$

$$LSR = \frac{\text{Liquidity-adjusted liabilities} + \text{Liquidity-adjusted off-balance sheet}}{\text{Liquidity-adjusted assets}} \quad (35)$$

## B The Full Model

Equations (36) to (63) jointly determine 28 endogenous variables:  $C_t, L_t, K_t, I_t, Y_t, R_t^A, R_{TB,t}, R_{D,t}^B, N_t, D_t, \phi_t$  (inverse of leverage ratio  $N_t/(Q_t A_t + TB_t)$ ),  $\theta_t$  (deposit ratio  $D_t/(Q_t A_t + TB_t)$ ),  $\psi_t$  (safe asset ratio  $TB_t/(Q_t A_t + TB_t)$ ),  $\bar{w}_t, \bar{\omega}_t$  (that is  $\bar{\omega}_t/(Q_t A_t)$ ),  $\bar{b}_t, \lambda_t^{PC}, \lambda_t^{LCR}, \lambda_t^{BC}, \lambda_t^{ICC}, Q_t, R_{D,t}^H, DI_t, \xi_t, w_t, R_t^K, R_t^M, V(N_t)$ .

### B.1 Households

Households maximize (1) subject to (2), where  $\lambda_t^{BC}$  is the lagrangian on the budget constraint. The first order conditions are:

$$C_t^{-\gamma} = \lambda_t^{BC} \quad (36)$$

$$\frac{\eta L_t^\varphi}{\lambda_t^{BC}} = w_t \quad (37)$$

$$\lambda_t^{BC} \left( 1 + \frac{\chi_d}{2} (D_t - \bar{D})^2 + D_t \chi_d (D_t - \bar{D}) \right) = \beta \lambda_{t+1}^{BC} R_{D,t}^H \quad (38)$$

$$\lambda_t^{BC} = \beta R_{TB,t} E_t(\lambda_{t+1}^{BC}) \quad (39)$$

$$\lambda_t^{BC} = \beta E_t \lambda_{t+1}^{BC} R_{t+1}^M \quad (40)$$

### B.2 Firms

Firms maximize (3). The first order conditions, aggregated for all firms are:

$$w_t = (1 - \alpha) \frac{Y_t}{L_t} \quad (41)$$

$$R_t^K = \alpha \frac{Y_t}{\Omega_t K_t} \quad (42)$$

Aggregate production is given by

$$Y_t = Z_t L_t^{1-\alpha} (\Omega_t K_t)^\alpha \quad (43)$$

The rate of return paid by firms on their bank loans is given by the rate of capital and the proceeds from the sale of capital to capital producers:

$$R_t^A = \Omega_t \frac{R_t^k + (1 - \delta) Q_t}{Q_{t-1}} \quad (44)$$

### B.3 Capital producer

The Capital producer maximizes (5), the first order condition is:

$$1 = Q_t \left( 1 - S\left(\frac{I_t}{I_{t-1}}\right) - S'\left(\frac{I_t}{I_{t-1}}\right)\frac{I_t}{I_{t-1}} \right) + E_t \Lambda_{t,t+1} \left( Q_{t+1} S'\left(\frac{I_{t+1}}{I_t}\right) \left(\frac{I_{t+1}}{I_t}\right)^2 \right) \quad (45)$$

where we assume quadratic adjustment costs of the form:

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

The law of motion of capital is therefore:

$$K_{t+1} = \left( 1 - S\left(\frac{I_t}{I_{t-1}}\right) \right) I_t + (1 - \delta)\Omega_t K_t. \quad (46)$$

### B.4 Banks

Banks maximize (14) subject to the balance sheet constraint (6), flow of funds constraint (7), the ICC (12), the PC (13) and the LCR constraint (15). The lagrangians on the ICC, PC and LCR are respectively  $\lambda_t^{ICC}$ ,  $\lambda_t^{PC}$  and  $\lambda_t^{LCR}$ . The first order conditions are:

$$E_t \beta \frac{\lambda_{t+1}^{BC}}{\lambda_t^{BC}} R_{t+1}^A \left( [\epsilon \lambda_{t+1}^{PC} + \epsilon \xi_{t+1} \lambda_{t+1}^{LCR} + 1 - \epsilon][1 - \bar{\omega}_{t+1} + \pi_t(\bar{\omega}_{t+1})] \right) = \lambda_t^{PC} \frac{\phi}{1 - \psi_t} - \lambda_t^{LCR} \left( \frac{\psi - \xi_t}{1 - \psi} \right) \quad (47)$$

$$\lambda_t^{ICC} = \frac{\lambda_t^{PC} E_t \lambda_{t+1}^{BC} (1 - F_t(\bar{\omega}_{t+1}))}{E_t \lambda_{t+1}^{BC} (\epsilon \lambda_{t+1}^{PC} + \epsilon \xi_{t+1} \lambda_{t+1}^{LCR} + 1 - \epsilon) (\tilde{F}_t(\bar{\omega}_{t+1}) - F_t(\bar{\omega}_{t+1}))} - \frac{E_t \lambda_{t+1}^{BC} (\epsilon \lambda_{t+1}^{PC} + \epsilon \xi_{t+1} \lambda_{t+1}^{LCR} + 1 - \epsilon) (1 - F_t(\bar{\omega}_{t+1}))}{E_t \lambda_{t+1}^{BC} (\epsilon \lambda_{t+1}^{PC} + \epsilon \xi_{t+1} \lambda_{t+1}^{LCR} + 1 - \epsilon) (\tilde{F}_t(\bar{\omega}_{t+1}) - F_t(\bar{\omega}_{t+1}))} \quad (48)$$

$$R_{D,t}^B E_t \beta \frac{\lambda_{t+1}^{BC}}{\lambda_t^{BC}} \left( \lambda_t^{PC} [1 - F_t(\bar{\omega}_{t+1})] \right) = \lambda_t^{PC} \quad (49)$$

$$R_{TB,t} E_t \beta \frac{\lambda_{t+1}^{BC}}{\lambda_t^{BC}} \left( \lambda_t^{PC} [1 - F_t(\bar{\omega}_{t+1})] \right) = \lambda_t^{PC} - \lambda_t^{LCR} + \xi_t \lambda_t^{LCR} \quad (50)$$

And the value function of the bank:<sup>12</sup>

$$V(N_t) = (\lambda_t^{PC} + \lambda_t^{LCR} \xi_t) N_t \quad (51)$$

We can rewrite the constraints of the banks as:

$$R_{t+1}^M = \left( R_{t+1}^A \frac{1 - \psi_t}{1 - \phi_t - \theta_t} [\bar{\omega}_{t+1} - \bar{\omega}_{t+1} - \pi_t(\bar{\omega}_{t+1}) + \pi_t(\bar{\omega}_{t+1})] \right) \quad (52)$$

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<sup>12</sup>see proof in Appendix C

$$1 - \tilde{E}(\omega) = \frac{E_t \lambda_{t+1}^{BC} R_{t+1}^A [(\epsilon \lambda_{t+1}^{PC} + \epsilon \xi_{t+1} \lambda_{t+1}^{LCR} + 1 - \epsilon)(\tilde{\pi}_t(\bar{\omega}_{t+1}) - \pi_t(\bar{\omega}_{t+1}))]}{E_t \lambda_{t+1}^{BC} R_{t+1}^A (\epsilon \lambda_{t+1}^{PC} + \epsilon \xi_{t+1} \lambda_{t+1}^{LCR} + 1 - \epsilon)} \quad (53)$$

$$N_t = \epsilon R_t^A Q_{t-1} K_t [1 - \bar{\omega}_t + \pi_{t-1}(\bar{\omega}_t)] + [1 - \epsilon(1 - F_{t-1}(\bar{\omega}_t))] \left( Q_t + \frac{\psi_{t-1}}{1 - \psi_{t-1}} Q_{t-1} \right) \tau K_t \quad (54)$$

$$\psi_t = \xi_t (1 - \phi_t) \quad (55)$$

$$\xi_t = \bar{\xi} - \chi_y (Y_t - \bar{Y}) \quad (56)$$

Deposit insurance equations:

$$DI_t = \left( 1 + \iota + \frac{E_t(\omega_{t+1}^{\bar{\omega}}) - \bar{\omega}^{ss}}{\bar{\omega}^{ss}} \right) E_t(F_t(\bar{\omega}_{t+1})), \quad (57)$$

$$R_{D,t}^B = R_{D,t}^H (1 + DI_t) \quad (58)$$

The other equations relative to the banks are:

$$\bar{\omega}_t = \frac{R_{D,t-1}^B}{R_t^A} \frac{\theta_{t-1}}{1 - \psi_{t-1}} - \frac{R_{TB,t-1}}{R_t^A} \frac{\psi_{t-1}}{1 - \psi_{t-1}} + \frac{1}{R_t^A} \bar{b}_{t-1} \quad (59)$$

$$\bar{\omega}_t = \frac{R_{D,t-1}^B}{R_t^A} \frac{\theta_{t-1}}{1 - \psi_{t-1}} - \frac{R_{TB,t-1}}{R_t^A} \frac{\psi_{t-1}}{1 - \psi_{t-1}} \quad (60)$$

$$Q_t K_{t+1} = \frac{1 - \psi_t}{\phi_t} N_t \quad (61)$$

$$D_t = \frac{\theta_t}{1 - \psi_t} Q_t K_{t+1} \quad (62)$$

## B.5 Resource constraint of the economy

$$Y_t = C_t + I_t \quad (63)$$

## C The bank value function

The value function of the bank is:

$$V_t(N_t^j) = E_t \Lambda_{t,t+1} \int_{\bar{\omega}_{t+1}^j}^{\infty} \left( \epsilon V_{t+1}(N_{t+1}^j) + (1 - \epsilon) N_{t+1}^j \right) f(\omega) d\omega \quad (64)$$

Iterating forward, we can also write the value function as an infinite sum of discounted future  $N^j$ s:

$$\begin{aligned} V_t(N_t^j) &= (1 - \epsilon) E_t \Lambda_{t,t+1} \int_{\bar{\omega}_{t+1}^j}^{\infty} N_{t+1}^j f(\omega) d\omega \\ &+ \epsilon (1 - \epsilon) E_t \Lambda_{t,t+2} \int_{\bar{\omega}_{t+1}^j}^{\infty} \int_{\bar{\omega}_{t+2}^j}^{\infty} N_{t+2}^j f(\omega)^2 d\omega^2 \\ &+ \epsilon^2 (1 - \epsilon) E_t \Lambda_{t,t+3} \int_{\bar{\omega}_{t+1}^j}^{\infty} \int_{\bar{\omega}_{t+2}^j}^{\infty} \int_{\bar{\omega}_{t+3}^j}^{\infty} N_{t+3}^j f(\omega)^3 d\omega^3 \\ &+ \dots \end{aligned} \quad (65)$$

For a continuing bank, we can write future values of  $N^j$  as a function of the current  $N_j$  (where we define  $\Phi_t = Q_t K_t^j / N_t^j$ ):

$$N_{t+1}^j = \Phi_t R_{t+1}^A (\omega_{t+1}^j - \bar{\omega}_{t+1}) N_t^j \quad (66)$$

$$\begin{aligned} N_{t+2}^j &= \Phi_{t+1} R_{t+2}^A (\omega_{t+2}^j - \bar{\omega}_{t+2}) N_{t+1}^j \\ &= \Phi_t \Phi_{t+1} R_{t+1}^A R_{t+2}^A (\omega_{t+1}^j - \bar{\omega}_{t+1}) (\omega_{t+2}^j - \bar{\omega}_{t+2}) N_t^j \end{aligned} \quad (67)$$

And so on for all future values of  $N_t^j$ .

Using this we can write the value function:

$$\begin{aligned} V_t(N_t^j) &= (1 - \epsilon) \Phi_t E_t \Lambda_{t,t+1} R_{t+1}^A (1 - \bar{\omega}_{t+1} + \pi(\bar{\omega}_{t+1})) N_t^j \\ &+ \epsilon (1 - \epsilon) E_t \Lambda_{t,t+2} \Phi_t \Phi_{t+1} R_{t+1}^A R_{t+2}^A (1 - \bar{\omega}_{t+1} + \pi(\bar{\omega}_{t+1})) (1 - \bar{\omega}_{t+2} + \pi(\bar{\omega}_{t+2})) N_t^j \\ &+ \epsilon^2 (1 - \epsilon) E_t \Lambda_{t,t+3} \Phi_t \Phi_{t+1} \Phi_{t+2} R_{t+1}^A R_{t+2}^A R_{t+3}^A (1 - \bar{\omega}_{t+1} + \pi(\bar{\omega}_{t+1})) \\ &\quad (1 - \bar{\omega}_{t+2} + \pi(\bar{\omega}_{t+2})) (1 - \bar{\omega}_{t+3} + \pi(\bar{\omega}_{t+3})) N_t^j \\ &+ \dots \end{aligned} \quad (68)$$

Let us define the discounting factors  $Z_{t+1,t+2}$

$$Z_{t+1,t+2} = \epsilon \Lambda_{t+1,t+2} \Phi_{t+1} R_{t+2}^A (1 - \bar{\omega}_{t+2} + \pi(\bar{\omega}_{t+2})) \quad (69)$$

We can rewrite  $V_t(N_t^j)$  as :

$$V_t(N_t^j) = (1 - \epsilon)\Phi_t E_t \Lambda_{t,t+1} R_{t+1}^A (1 - \bar{\omega}_{t+1} + \pi(\bar{\omega}_{t+1})) \left( 1 + Z_{t+1,t+2} + Z_{t+1,t+2} Z_{t+2,t+3} + \dots \right) N_t^j \quad (70)$$

In steady-state this boils down to:

$$V(N) = \frac{\beta(1 - \epsilon)\Phi R^A (1 - \bar{\omega} + \pi(\bar{\omega}))}{1 - \beta\epsilon\Phi R^A (1 - \bar{\omega} + \pi(\bar{\omega}))} N \quad (71)$$

We can now prove that our conjecture for the value function is right:

$$V(N) = (\lambda^{PC} + \xi_1^{LCR}) N \quad (72)$$

Using Equations (47) and 55):

$$E_t \beta \frac{\lambda_{t+1}^{BC}}{\lambda_t^{BC}} R_{t+1}^A \left( [\epsilon \lambda_{t+1}^{PC} + \epsilon \xi_{t+1} \lambda_{t+1}^{LCR} + 1 - \epsilon][1 - \bar{\omega}_{t+1} + \pi_t(\bar{\omega}_{t+1})] \right) = \frac{1}{\Phi_t} (\lambda_t^{PC} + \xi_t \lambda_t^{LCR}) \quad (73)$$

In steady-state:

$$\beta \Phi R^A \left( [\epsilon \lambda^{PC} + \epsilon \xi \lambda^{LCR} + 1 - \epsilon][1 - \bar{\omega} + \pi(\bar{\omega})] \right) = (\lambda^{PC} + \xi \lambda^{LCR}) \quad (74)$$

Hence:

$$\lambda^{PC} + \xi \lambda^{LCR} = \frac{(1 - \epsilon)\beta\Phi R^A [1 - \bar{\omega} + \pi(\bar{\omega})]}{1 - \epsilon\beta\Phi R^A [1 - \bar{\omega} + \pi(\bar{\omega})]} \quad (75)$$

Thus, using (71) and (75), it is clear that our guess  $V(N) = (\lambda^{PC} + \xi \lambda^{LCR}) N$  is verified.

## D Welfare

To estimate the welfare effect of regulation, we take a second order approximation of the model. We denote conditional welfare in the unregulated, flat- and countercyclical-regulated economy respectively as  $V_{cond}^u$ ,  $V_{cond}^f$ ,  $V_{cond}^c$ . Conditional welfare is given by:

$$V_{cond}^s = E_0 \sum_{t=0}^{\infty} \beta^t \left[ \frac{C_t^{1-\gamma}}{1-\gamma} - \eta \frac{L_t^{1+\varphi}}{1+\varphi} \right], \quad s = \{u, f, c\}. \quad (76)$$

The second-order approximation of the welfare function around the deterministic steady state yields:

$$V_{cond}^s = V_{ss}^s + \frac{1}{2} \times V_{\zeta\zeta}^s \times \zeta^2, \quad s = \{u, f, c\}. \quad (77)$$

where  $V_{ss}^s$  is the steady-state value of welfare and  $V_{\zeta\zeta}^s$  is the second derivative of welfare. Conditional welfare benefits of moving from unregulated to flat regulation in consumption-equivalent terms are given by:

$$\text{Welfare benefits } u \text{ to } f = \left[ \exp \left( (1 - \beta) \times (V_{cond}^f - V_{cond}^u) \right) - 1 \right] \times 100, \quad (78)$$

Unconditional welfare is based on the long-run expectation of welfare in the presence of shocks. Welfare benefits are then calculated in the same way.



Table 7: Steady-state comparison

	Baseline	First best	No ICC
$C$	0.8	0.8868	0.667
$L$	0.8944	0.9277	0.9505
$K$	8	12.2319	6.1953
$I$	0.2	0.3058	0.2745
$Y$	1	1.1926	0.9414
$R^A$	1.02	1.0101	1.0308
default	0.0568		0.2818
Ws rate	1.0251		1.089
Welfare gain		7.5402	-20.8312

## E Steady state and financial frictions

The steady state of the model in the absence of financial frictions is reported in the second column of Table 7. This steady state can be solved by taking Equations (37),(41),(43),(46),(63), (42) and 44 together with the first best version of (52), which is:

$$\lambda_t^{BC} = \beta E_t \lambda_{t+1}^{BC} R_{t+1}^A \quad (79)$$

This is the first best outcome, households hold capital directly and the return on capital is equal to  $1/\beta$ . In this equilibrium, capital and investment are higher, and so the economy is larger. Consumption is bigger, which drives large welfare benefits relative to our baseline model. Welfare gains are calculated in percent consumption equivalent terms improvement relative to our baseline model. In our model, the financial friction in the banking sector prevents banks from lending to firms up to the point where  $R^A = 1/\beta$ . There is a wedge between the rate of return on loans and the marginal rate of substitution which enables banks to make profits. The wedge can easily be seen by comparing Equations (52) and (79).

In our model, the hedge fund monitors the banks required them to invest in the optimal firm. The hedge fund lends to banks knowing they will invest in the good firm and will curtail its lending when the moral hazard tightens. The role of the ICC is exactly to ensure that banks invest only in the good firms. What would happen if instead the hedge fund did not require banks to invest optimally but instead let them choose to invest in the bad firm? The hedge fund could still lend to the bank but impose a different rate since the return on bank assets is different. Column 3 of Table 7 shows that case. Banks choose the suboptimal technology, they give less loans and earn higher return on their loans since the marginal productivity is higher. Note the marginal productivity is higher despite the fact that we

are in the suboptimal firm, just because the total capital is lower. The hedge fund realizes this and imposes a high rate on wholesale funding. Overall, the economy is much smaller given banks give out less loans. They have a much higher default probability. Output and consumption are lower, and hence welfare is lower as well.

Hence, under our calibration, the economy is better off when there is the ICC. For calibrations where the suboptimal is too close to the optimal technology, it could also be the case that it is optimal to let banks invest in the bad firms just to avoid the cost of the ICC constraint.

## F Impulse responses to a TFP and capital shock

The impulse response functions to a negative TFP shock are reported in Figure 7. A negative TFP shock reduces the marginal productivity of capital and thereby the return on capital. On impact, banks' 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  $\omega$  and the ICC. Thus, the default threshold  $\bar{\omega}_{t+1}$  returns to its steady-state value from  $t + 1$  onwards. However, the TFP shock affects the profitability of the banks. The hedge fund recognizes that banks are less profitable and responds by reducing wholesale lending by about 5% on impact. The TFP shock and the wholesale run force banks to curtail credit and keep a constant probability of default from  $t + 1$  onwards. The deposit ratio increases; the probability of default on deposit and the deposit insurance payment also remain persistently above steady state. Since the recuperation value for the hedge fund in case of bank default falls, the wholesale rate goes up. The TFP shock reduces output and the marginal productivity of both labor and capital. Thus, labor, capital and consumption fall. The TFP shock also affects the real economy indirectly through the financial sector. The reduction in wholesale lending implies a reduction in credit to firms and in investment.

As in the case of a risk shock, the flat liquidity regulation slightly amplifies the effects of a TFP shock relative to the case of no liquidity regulation. On the other hand, the countercyclical regulation mitigates the effects of the shock relative to both flat and no liquidity regulation.

The impulse response functions to an aggregate capital quality shock are shown in Figure 8. An aggregate capital quality shock reduces the value of capital on all islands. Output and the return on capital fall sharply, causing the net worth of banks to fall. As a result, the default thresholds  $\bar{\omega}_t$  and  $\bar{\bar{\omega}}_t$  increase sharply. As in the case of a TFP shock, the distribution of  $\omega$  and the ICC are not affected by the capital quality shock. This implies that the value of the default threshold  $\bar{\omega}$  must go back to its steady-state value from  $t + 1$  onwards, which in turn requires a reduction in wholesale funding. The real economy is affected by the capital quality shock directly and indirectly via the credit crunch stemming from the reduction in wholesale funding. The effects of liquidity regulation following a capital quality shock are similar to the other shocks.

Figure 7: TFP shock

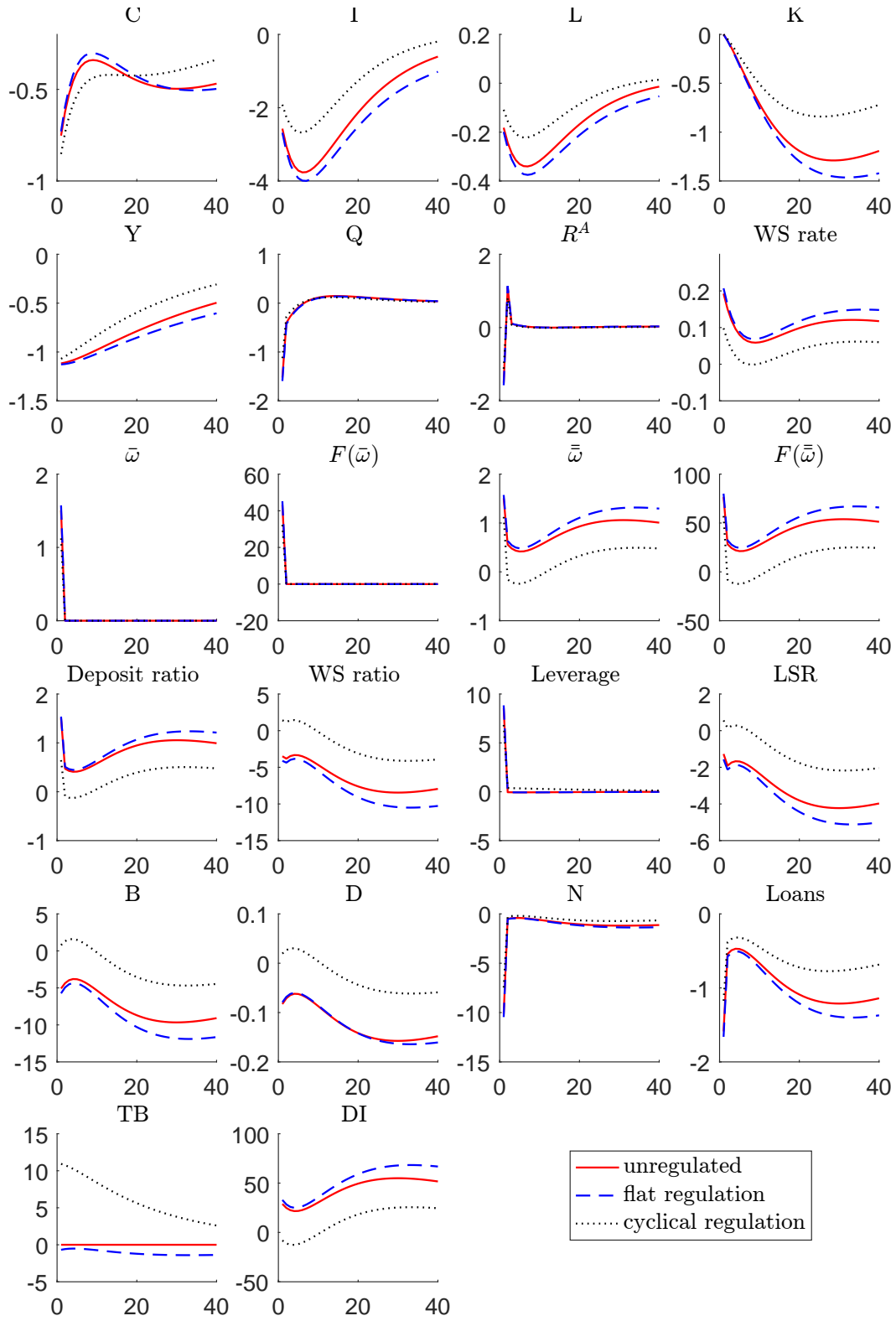


Figure 8: Capital Quality shock

