Risk Sharing, Creditor Diversity, and Bank Regulation*

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Abstract

Can creditor diversity mitigate bank fragility such as asset diversification? We argue that a capitalized bank, which has enough liquidation value to issue safe securities, is unlikely to experience financial fragility if it is funded by creditors with diverse attitudes toward risk. In the presence of such diversity, the bank matches the riskiness of securities to the risk tolerance of creditors in order to reduce financing costs, making it financially stable. Indeed, our theory and evidence suggest capital regulation can eliminate the potential for financial fragility, conditional on the presence of creditors with heterogeneous attitudes toward risk.

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1 Introduction

Diversifying creditors is often cited as one of the key concerns in recent bank mergers and acquisitions. For instance, in the recent merger between CoBiz Financial and BOK Financial in 2018, Steven G. Bradshaw, president and CEO of BOK Financial, said, "The merger ... provides further geographic diversity for both banks' loan and deposit portfolio."[1] Similarly, in another high-profile M&A deal between CIT Group and OneWest Bank in 2015, John Thain, ex-chairman and CEO of CIT Group, said that OneWest's retail deposits gave CIT a more diverse and lower-cost source of funds for lending.[2] CIT recently suggested the improvement in its credit ratings benefited from such diversification strategy.[3] These claims make us wonder whether and how creditor diversity can contribute to reducing the risk of a bank.

One plausible merit of creditor diversity is that it enhances the risk-sharing function of a bank. To see how, suppose a bank generates value by issuing safe securities to risk-averse creditors and investing in risky assets. Then a bank also sells risky securities, because it has to back up its securities with risky assets. The issuance of risky securities can cause a self-fulfilling prophecy, because the buyers of risky securities demand high spreads when they anticipate high risk, which threatens bank solvency. However, if a bank is funded by creditors with diverse risk attitudes toward risk, it seems able to match the riskiness of securities to the risk tolerance of creditors, thereby reducing financing costs. Thus, creditor diversity seems to mitigate bank fragility.

To investigate this possibility, we develop a parsimonious model of financial intermediation that endogenizes a bank's financial choice to issue safe securities. In our model, a bank has a

[1] See http://investor.bokf.com/file/Index?KeyFile=393916332.

[2] See http://www.latimes.com/business/la-fi-onewest-cit-20150804-story.html.

[3] See https://www.businesswire.com/news/home/20160323005355/en/CIT-Update-Strategic-Plan-%E2%80%93-Creating-Leading.

chance to save on financing costs by issuing safe securities, because risk-averse creditors demand less interest when they purchase safe securities. Our model assesses the financial stability of a bank in which the bank generates value through this channel.

We depart from the previous literature by paying particular attention to the diversity of risk attitudes among bank creditors.[4] Because a bank backs up its securities with risky assets, it has to simultaneously issue risky securities when it issues safe ones. In the presence of both securities, more risk-averse bank creditors tend to buy safe ones, whereas less risk-averse creditors tend to buy risky ones. This "matching" mechanism should help a bank reduce financing costs to some extent because the buyers of safe securities never require a risk premium, regardless of their risk aversion, whereas the buyers of risky securities require less of a risk premium. This mechanism therefore plays a significant role in improving the solvency of a bank. Our model addresses the matching of bank creditors with heterogeneous risk preference to bank-issued securities with different risk levels.

Our model also accounts for the effect of bank regulation on financial stability. In particular, bank capital, which is junior to other bank-issued securities, tends to increase the liquidation value per creditor at default, and thus raises the capacity to issue safe securities. Because a bank makes money by issuing safe securities, bank capital also plays an important role in improving the solvency of a bank. We therefore address how capital regulation is connected to a bank's capacity to share risks with bank creditors.

With these elements in mind, we assess the financial stability of the banking sector by cap-

[4]Goetz et al. (2016) empirically estimate the causal impact of geographic diversification on bank risk. We differentiate our work by focusing on how the diversity in creditors' risk attitudes mitigates bank fragility. In this respect, we attempt to narrow down the source of creditor diversity that is important for bank stability.

turing two potential causes of financial crises: excessive risk taking[5] and a sunspot crisis.[6] More specifically, we simultaneously endogenize a bank's investment and financial decisions under limited liability and limited commitment to bank creditors, based on Leland (1998) and Hortaçsu et al. (2011). Then our model predicts a risk-shifting problem because a bank can waive liability when it defaults; it does not incur the downside of return on risky assets. Moreover, our model reveals a bank's asset and default risk can increase even if the bank's fundamentals are left intact. For example, suppose bank creditors suddenly anticipate higher bank risk and raise credit spreads due to their lack of confidence in the bank's solvency. Then the bank has lower continuation value and weaker incentives to continue in business. A bank that is reluctant to continue has a stronger risk-shifting incentive, increasing its asset risk and default probability. Consequently, a self-fulfilling prophecy takes place. In other words, the banking system is subject to multiple equilibria: Both the high-risk equilibrium with high risky assets and default risk and the safe equilibrium with low risky assets and default risk can occur. As in Diamond and Dybvig (1983), we assess the financial stability of the banking sector while taking into account the potential existence of the high-risk equilibrium.

Our numerical example shows the high-risk equilibrium can vanish if a bank is moderately capitalized and funded by creditors with heterogeneous risk preference, because the bank's continuation value (the opportunity cost of default) can be large enough to prevent the bank from defaulting and risk shifting even when creditors anticipate high bank risk. On the other hand,

[5]For example, in the US Savings and Loan Crisis during the 1980s, failed thrifts had disproportionately high concentrations of commercial mortgages, real estate loans, and direct equity investments (Barth et al., 1990). In the Japanese Banking Crisis during the 1990s, Japanese banks passively ran excessive risk by continuing to lend to their most troubled borrowers (e.g., Peek and Rosengren (2005) and Caballero et al. (2008)). In accordance with these observations, researchers suspect that excessive risk taking is associated with recent crises in the US and Europe (e.g., Boyd and Hakenes (2014) and Drechsler et al. (2016)).

[6]See, for example, Hertzberg et al. (2010) and the survey by Goldstein (2012).

the high-risk equilibrium is likely to remain if either one of the two conditions is unmet. This is because a bank is unlikely to have sufficient liquidation value for issuing safe deposits to all the stringently risk-averse depositors in the absence of bank capital, and it cannot utilize the matching mechanism to reduce financing costs in the absence of creditors' diverse attitudes toward risk. This result suggests that bank creditors' risk aversion heterogeneity seems necessary for achieving financial stability and that capital requirement's effectiveness is likely to depend on the presence of such diversity.[7]

Our model predictions are also consistent with empirical evidence. In particular, we find a bank's interest expense rate is lower in the joint presence of risk-weighted capital and creditors' heterogeneous attitudes toward risk, using the U.S. bank holding companies (BHC) data. Because a bank's interest expense rate increases in the bank's asset and default risk and decreases in the bank's safe deposits, this finding is consistent with the hypothesis that the safe equilibrium, in which the bank issues more safe deposits and experiences lower asset and default risk, is more likely to occur in the joint presence of bank capital and risk aversion heterogeneity among creditors. Overall, our theory and evidence suggest capital regulation seems effective, conditional on the presence of risk aversion heterogeneity among creditors.

2 Relation to the literature

Our work is first related to the current discussion on the role of financial intermediaries. The banking literature has proposed three theories on the role of financial intermediaries: risk sharing, delegated monitoring, and liquidity provision. The first theory posits that a bank transfers invest-

[7] We also assess the effect of liquidity regulation in the appendix.

ment risk from risk-averse households to itself by issuing safe deposits – optimal risk sharing is facilitated by this transfer (e.g., Allen and Gale (1997)). The second theory suggests the role of a financial intermediary is to monitor investments on behalf of households, save on investment costs, and increase the credit supply (e.g., Diamond (1984); Martinez-Miera and Repullo (2017)). The third theory explores the synergy between a bank's lending via credit lines and issuing deposits. Kashyap et al. (2002) argue the cost of holding liquid assets is lower when one institution specializes in both functions than when two separate institutions specialize in only one of the two functions; the two activities can "share" the burden of holding liquid assets, so that a bank that offers both deposits and loan commitments can reduce the volume of liquid assets. In this case, a bank is considered an institution that specializes in providing liquidity to the rest of the economy. Empirically, the discussion has not reached a consensus. For instance, Berger and Bouwman (2009) use a large sample of U.S. banks to construct four liquidity-creation measures, and they find bank liquidity creation is positively related to bank value. Their finding supports the third theory on banks' liquidity-provision role. By contrast, Egan et al. (2017b) test the three theories and find the risk-sharing role is dominant because safe deposit productivity explains most of the variation in bank value. Our work contributes to the literature by showing that the strength of a bank's risk-sharing role depends on the extent of risk aversion heterogeneity among creditors.

Our study next contributes to the literature on the role of creditor heterogeneity in the banking system. For example, our work complements Gorton and Pennacchi (1990), who study the joint presence of informed and uninformed creditors, by instead focusing on the diversity of creditors' risk attitudes. [8] Our work also presents an explicit channel through which geographic diversifica-

[8] We note that some previous research focuses on the risk preference of bank managers and owners instead of creditors (e.g., Sealey (1980); Ho and Saunders (1981)).

tion may help a bank reduce risk. We complement empirical papers that show the mitigating effect of geographical diversification on bank risk (e.g., Akhigbe and Whyte (2003); Deng and Elyasiani (2008); Goetz et al. (2016)) by identifying the source of heterogeneity that is likely to contribute to the reduction of bank risk.

Another insight our analysis offers concerns the efficiency of capital regulation. Discussion on this topic has lasted a few decades but has not reached a consensus. Most studies find capital regulation is, at best, suboptimal. Capital regulations are proposed to mitigate excessive bank risk in the presence of limited liability and deposit insurance, as discussed in Merton (1977) and Sharpe (1978). However, they are often criticized for their reduction of liquidity provision (Diamond and Rajan, 2000), bank lending (Thakor, 1996), and the crowding out of deposits (Gorton and Winton, 2017). Moreover, recent studies suggest banks might bypass capital regulations (e.g., Kisin and Manela (2016)). If regulatory arbitrage is possible, capital regulations might encourage banks to shift their risky lending practices into shadow banking (Plantin, 2014) or simply shift investments into risky projects within the same asset class (Duchin and Sosyura, 2014). Nevertheless, some studies suggest the necessity of capital regulation. For example, Morrison and White (2005) find capital regulation is an efficient tool enabling regulators to combat moral hazard and enhance screening outcomes. Mehran and Thakor (2011) show both theoretically and empirically that bank values are positively correlated with equity capital. The empirical findings about the effects of capital requirements are also mixed. Opponents of capital regulation argue it is costly for banks and society (e.g., Baker and Wurgler (2015); Kisin and Manela (2016); Van den Heuvel (2008)), reduces bank lending (Aiyar et al., 2014), and fails to reduce risk (Rime, 2001). Others find the effects of capital requirements are conditional. Berger and Bouwman (2009) test the relationship between capital and liquidity creation and find it tends to be positive for large banks and negative for small ones. Others find the effects of capital regulations depend on ownership structure (Laeven and Levine, 2009) or economic condition (Demirguc-Kunt et al., 2013). We contribute to the ongoing discussion on the effects of capital regulation by showing they depend on the presence or absence of risk aversion heterogeneity among bank creditors.

Our study is also related to the literature on the differential behavior of heterogeneous investors toward a bank's financial fragility. For example, Schmidt et al. (2016) suggest informed investors are more prone to run than uninformed investors, observing the differential withdrawals from the U.S. money market by investors with different monitoring abilities during the Global Financial Crisis (GFC). Moreover, many studies show depositors deeply connected to banks are less prone to run, regardless of the banks' fragility (e.g., Brown et al. (2013); Iyer et al. (2016); Iyer and Puri (2012)). Overall, these studies suggest heterogeneity in depositors' characteristics substantially explains the diversity in their "ex-post" actions in the face of financial fragility (i.e., propensity to run). We complement those studies by instead focusing on their "ex-ante" actions – we analyze the selection of depositors with heterogeneous risk aversion into bank-issued securities with various risk levels.

Finally, our study is related to a growing body of literature on the role of risk aversion heterogeneity in finance. Empirical researchers have observed cross-sectional differences in risk tolerance (e.g., Barsky et al. (1997)). Many attribute such diversity to genetic variation (e.g., Barnea et al. (2010); Cronqvist and Siegel (2015)). On the other hand, Calvet and Sodini (2014), using data on Swedish twins to control for genetic differences, find environmental factors such as financial wealth, human capital, internal habits, and expenditure commitment can also affect risk preference. Risk aversion heterogeneity has been increasingly examined to explain various issues in asset pricing (e.g., Gârleanu and Panageas (2015)), investor decisions (e.g., Barnea et al.

(2010); Cesarini et al. (2010); Cronqvist and Siegel (2015)), and wealth inequality (e.g., Gomez (2016)). We instead explore how bank creditors' heterogeneous risk aversion affects their choices of bank-issued securities and the financial (in)stability of a bank.

3 Model

3.1 Overview

We consider banks that are spatially or segmentally separated and hence do not compete for deposits. Treating the bank as monopolist simplifies the analysis by allowing us to side-step some complications that arise from having to model the deposit market equilibrium (Diamond and Kashyap, 2016). Alternatively, the model can be interpreted as a description of the whole banking sector.

A monopolistic risk-neutral bank raises funds from both a continuum of creditors and itself to invest in risky or safe assets. We denote the fraction of risky assets by q ($0 < q < 1$). Without loss of generality, we set the book value of the bank's assets to 1. Specifically, the bank issues safe and risky securities to raise $1 - e(q)$ and self-funds $e(q)$ to meet the exogenous capital requirement ($0 \leq e(q) < 1$), where $e(.)$ is a differentiable function of q.[9] For convenience, we use "demand deposits" as a generic term for safe securities, and "time deposits" as a generic term for risky securities.[10]

We assume that the demand deposits can be withdrawn in the middle of the year, whereas the

[9]As seen later, q is defined as the fraction of risky assets of the bank's total assets, which can be considered the bank's risk-weighted assets (RWA). We consider the capital requirement can be sensitive to RWA.

[10]Depending on the context, the demand deposits can be considered as insured deposits for which the banking sector self-reserves liquid assets. Correspondingly, we can consider the time deposits as generic short-term debts uninsured by the banking sector.

time deposits reach maturity at the end of the year. A fraction y of the deposits are the demand deposits ($0 \leq y \leq 1$). Some of the demand deposits are withdrawn in the middle of the year when the bank survives. All of the demand deposits are withdrawn in the middle of the year when the bank defaults. The demand depositors rush into the bank to receive their claims before the time depositors receive their claims at the end of the year. Thus, the demand deposits are safe and senior, whereas the time deposits are risky and junior.

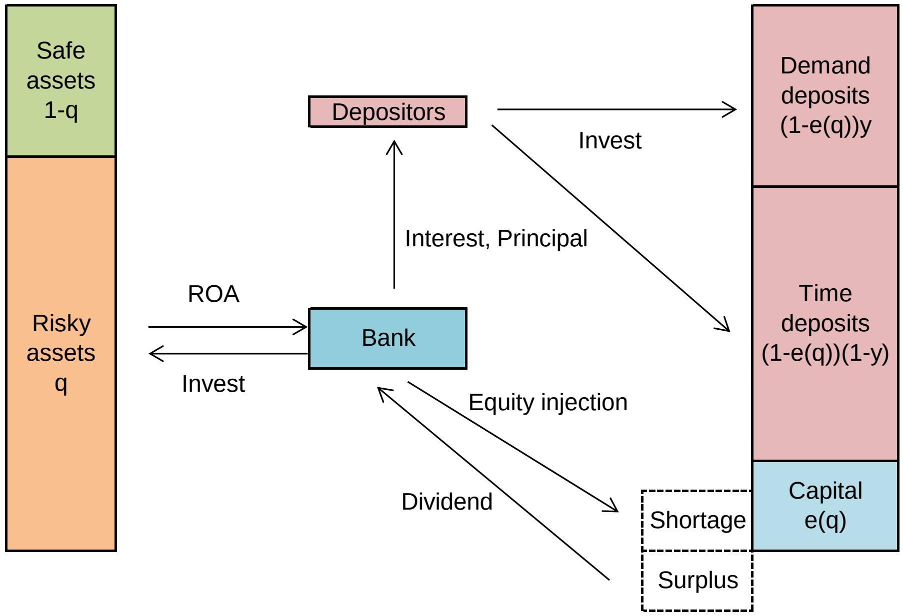
After the bank's risky assets reach maturity at the end of the year, the bank consumes any positive residual claim as dividends after retaining some cash to recover its capital. Then, the bank continues business. Otherwise, the bank can inject equity to pay the net cash outflow and recover its capital to continue business, or it can default voluntarily if it finds the amount of equity injection is greater than its charter value. Because of this possibility, the bank is subject to default risk. At default, the bank loses its capital because all the liquidation value is considered to be claimed by the depositors. We assume equity injection is possible only at the end of the year. Figure 1 describes the bank's balance sheet and the actions of the bank's stakeholders.

3.2 Timing

We develop an infinite-horizon model of banking. We consider the same series of events occurs in each year. These events are recursive for a surviving bank. We summarize these events occurring in each year as follows.

1. **Liability side**: Each depositor receives a unit endowment. The bank issues the demand and time deposits and posts the deposit rates. The depositors make investment decisions, and the bank finances itself to meet the capital requirement.

Figure 1: Bank Balance Sheet



Asset side: The bank invests in risky or safe assets.

2. **Liability side**: Some of the depositors receive private preference shocks. Observing the return to the bank's risky assets, the bank makes a default decision.

    - *Default*: All the demand depositors withdraw their accounts.
    - *Survival*: The demand depositors who receive shocks withdraw their accounts.

    Asset side: The return on the bank's risky assets is revealed to the bank.

    - *Default*: The bank liquidates all its risky assets to pay the principal of the deposits.
    - *Survival*: The bank uses the safe assets to cover the interim withdrawal of the demand deposits.

3. **Liability side**: The time deposits reach maturity. At survival, the bank receives dividends or injects equity.

- *Default*: The bank does not incur any further cash outflow due to limited liability, but it loses its capital and pays the cost of capital. Then, the new business starts from Step 1.

- *Survival*: If the net cash outflow is negative or the bank loses some capital, the bank injects equity. Otherwise, the bank retains some of the net cash inflow to meet the capital requirement in the next period and consumes the rest as dividends. Then the business restarts from Step 1.

Asset side: At survival, the bank's risky assets reach maturity.

- *Default*: The time depositors claim all the residual liquidation value. Then, the new business starts from Step 1.

- *Survival*: The bank uses the return to its risky assets and the residual safe assets to pay interest and principal to the time depositors, principal to the remaining demand depositors, and the cost of capital. Then, the business restarts from Step 1.

Figure 2 describes the life cycle of a bank in our model.

3.3 Key frictions

3.3.1 Limited commitment and multiple equilibria

We assume the bank cannot commit to its risk choice to the depositors. This assumption is relevant to the financial contract between the bank and the depositors, who can observe the bank's risk but need to incur a large cost to verify it.[11] In the presence of this friction, the bank cannot control the

[11] We assume the bank commits to its investment decision to the government that imposes capital requirement, because the government seems able to incur the cost to verify the bank's asset risk.

Figure 2: Bank Life Cycle

…	Year -2	Year -1	Year 1	Year 2	…	Year X-1	Year X	Year X+1	Year X+2	…
…	Continue	Default	Start	Continue	…	Continue	Default	Start	Continue	…
…	Step 1	Step 1	Step 1	Step 1	…	Step 1	Step 1	Step 1	Step 1	…
…	Step 2	Step 2	Step 2	Step 2	…	Step 2	Step 2	Step 2	Step 2	…
…	Step 3	Step 3	Step 3	Step 3	…	Step 3	Step 3	Step 3	Step 3	…

depositors' beliefs about its risk. Consequently, the bank's asset and default risk can jump up or down even if the bank's fundamentals are left intact.

For example, suppose the depositors suddenly anticipate higher asset and default risk and raise credit spreads. Then the bank loses continuation value and has a reduced incentive to continue in business. When a bank is reluctant to continue in business, it has an increased risk-shifting incentive, raising both its asset and default risk. This closed feedback is a self-fulling prophecy mechanism that can cause financial instability. In other words, the banking system is subject to multiple equilibria: Both high-risk equilibrium with high risky assets and default risk and safe equilibrium with low risky assets and default risk can occur.

3.3.2 Liquidation value constraint

We also consider the bank's liquidation value perceived by the depositors has to be no lower than the amount of demand deposits. Owing to this constraint, the demand deposits become safe from credit risks.

3.3.3 Liquidity constraint

In addition, we consider the bank is subject to a liquidity constraint. Because the bank can inject equity or receive investment returns from its risky assets only at the end of the year, it must have safe assets in amounts no lower than the size of the demand deposit withdrawal in the middle of the year to avoid liquidation before knowing the return to assets. Because the bank can at worst lose its capital and pay the cost of capital after knowing the return to assets, whereas it inevitably does so when it chooses liquidation before knowing the return to the assets, it is always willing to avoid liquidation before knowing the return to assets. Therefore, the bank has an incentive to comply with this constraint. Alternatively, this constraint can be artificially imposed by a regulator as a liquidity requirement. In this case, the constraint may require a safe asset amount higher than the amount of the deposit withdrawal in the middle of the year.

3.3.4 Bank charter

Finally, we consider bank regulators screen and monitor the bank's worthiness before the bank starts. Then the bank needs to guarantee the worthiness of its charter value beyond a certain level, c. The FDIC's early intervention approach is one of the examples for this constraint. In this case, the valuation of the bank has to exceed c when the bank starts business.

3.4 The bank's risk choice

To find equilibria, we characterize each player's action. We start with a bank's risk choice, in which the bank determines (1) the asset risk through its investment decision in Step 1 and (2) the default risk through its default decision in Step 2.

For (1), we allow the bank to invest in either risky or safe assets. Recall that q is the exposure to risky loans. Then they invest $1-q$ of the bank assets into safe assets, which does not yield any return. The return on risky assets is assumed to follow a normal distribution, $\mu+\sigma\tilde{z}\sim N[\mu,\sigma^2]$ ($\sigma>0$), where $\tilde{z}$ follows the standard normal distribution i.i.d. across years. Then the bank's return on assets, $\tilde{R}$, is represented by $\tilde{R}=q(\mu+\sigma\tilde{z})$. Throughout the paper, we use $\Phi(.)$ and $\phi(.)$ to denote the CDF and PDF of a standard normal distribution, respectively. Also, we denote $\phi(.)/(1-\Phi(.))$ by $\lambda(.)$.

Regarding (2), Hortaçsu et al. (2011) show a firm plans the reservation rate of ROA to make an optimal default decision. Let the reservation rate be $R=q(\mu+\sigma z)$, such that the bank continues to operate if $\tilde{R}\geq R$; otherwise, it liquidates its risky assets. Then, this strategy is equivalent to the strategy such that the bank continues as long as $\tilde{z}\geq z$. We represent the default decision of the bank by z because it sufficiently represents the probability of default ($\Phi(z)$). In this way, the bank optimizes both the asset risk q (investment decision) and default risk z (default decision). We denote the strategy of the bank by s, where s $=(q,z)$.

3.5 The depositors' investment choice and the bank's pricing strategy

Next, we characterize the depositors' investment choice and the bank's pricing strategy in Step 1. We consider every depositor has access to the financial market, where the depositor can invest in storage, which is safe and liquid, and riskless bond, which is safe but illiquid, in Step 1. Depositors who invest in storage can withdraw the funds in the middle of the year. No investment return to storage occurs, even if the depositor waits until the end of the year. On the other hand, depositors who invest in riskless bonds cannot withdraw the funds in the middle of the year. Instead, they receive a liquidity premium, r, in addition to the principal at the end of the year ($r \geq 0$), so that they are indifferent between these two securities in Step 1. Because they do not perceive their private preference shocks in Step 1, r is independent of whether they receive preference shocks in Step 2.

These two securities are considered the depositors' outside options. Then the supply of each type of deposits is perfectly elastic at the deposit rate that yields the same expected surplus as the corresponding outside option. If the depositor is not worse off by investing in the deposits than by taking the outside option with the corresponding maturity, the depositor is incentive-compatible with investing in any amount of the deposits. The bank sets the optimal deposit rates that maximize its value while fulfilling the depositor's incentive to fund the bank.

We consider depositors have two risk-aversion levels. We call the more risk-averse ones "type h depositors" and the less risk-averse ones "type l depositors." We denote the fraction of type h depositors as p ($0 \leq p \leq 1$). To simplify our analysis, we assume the bank wants to acquire funds from all types of depositors.[12] We also assume a fraction, x, of the depositors receives private preference shocks in Step 2 independently of their type or the bank's asset return ($0 \leq x$).[13] Hence, the aggregate withdrawal demand in Step 2 is predetermined.

For the rest of the section, we characterize the optimal deposit rates. We note that the optimal demand deposit rate is zero because every depositor is willing to invest in the demand deposit as long as it is as beneficial as storage. Because the demand deposit is safe, the depositor is incentive-

[12] For example, the bank may not want to reduce the asset size for fear of losing systemic importance. By being systemically important, the bank becomes fully capable of injecting equity thanks to financial support from the government, which has an incentive to save systemically important banks.

[13] For a positive analysis, x should be smaller than 1. For a normative analysis, as conducted later, this parameter can exceed 1. For example, if the regulator requires the bank to have safe assets equivalent to twice the amount of the demand deposits, x can be considered 2.

compatible with investing in it even if its rate is zero regardless of risk-aversion type or whether the depositor receives preference shocks in Step 2.

Because the time deposit is risky while the demand deposit is safe, the deposits issued by the bank attract investors with different risk-aversion levels. Although both depositors accept the bank's offer of non-negative demand deposit rates, type l depositors are more likely than type h depositors to accept the offer of the same time deposit rate. If the issued demand deposits, y, are equal to or greater than the fraction of type h depositors, p, the bank makes only type l depositors invest in the time deposits by setting the time deposit rate to the level at which type l depositors are indifferent between time deposits and outside options. In this way, the bank saves on the relatively high risk premium it would pay if type h depositors (instead of type l depositors) invested in the time deposits.[14] Correspondingly, the "marginal" time depositor type, $f(y)$, becomes l. On the other hand, if y is below p, type h depositors also invest in the time deposits. Then, $f(y)$ becomes h because type h depositors require a higher risk premium than type l depositors do. In this case, the bank sets the time deposit rate to the level at which type h depositors are indifferent between time deposits and outside options.[15] Thus, the optimal time deposit rate set by the bank depends on the type of "marginal" time depositors, $f(y)$.

Because the time deposit is risky and the bank's risk is not verifiable for the depositors, the optimal time deposit rate also depends on the depositors' common belief about the bank's strategy,

[14] If demand deposit rates are set to the level at which each of depositor is indifferent between demand deposits and outside options, whereas time deposit rates are set to the level at which type l depositors are indifferent between time deposits and outside options, type h depositors are indifferent between demand deposits and outside options and prefer demand deposits to time deposits, whereas type l depositors are indifferent between time deposits, demand deposits, and outside options. Then, type l depositors can be matched to both deposits, whereas type h depositors can be matched to only demand deposits.

[15] If demand deposit rates are set to the level at which each depositor is indifferent between demand deposits and outside options, whereas time deposit rates are set to the level at which type h depositors are indifferent between time deposits and outside options, type l depositors prefer time deposits to demand deposits and outside options, whereas type h depositors are indifferent between time deposits, demand deposits, and outside options. Then type l depositors are matched to time deposits, whereas type h depositors can be matched to both deposits.

denoted $\mathbf{s^d}$ ($\mathbf{s^d} = (q^d, z^d)$), where q^d is the belief about q and z^d is the belief about z.[16] We also denote the belief about the bank's capital $e(q^d)$, which is a function of the belief about the bank's risk weighted assets (q^d). We consider that the optimal time deposit rate depends on q^d as well as z^d, because the asset quality matters to the liquidation value of the bank. We assume that the bank cannot sell its risky assets at book value, because the buyer has to incur the cost of default, probably, due to the difficulty of re-deploying the relationship lender.[17] Consequently, the liquidation value of the bank's risky assets is impaired. We denote the loss given default (LGD) of the bank's risky assets as d, whereas the LGD of the bank's safe assets is zero.

The time depositors compare the expected utility (EU) of investing in the time deposits with the EU of investing in riskless bonds, which have the same maturity as the time deposits in Step 1. The optimal time deposit rate, $i(y, \mathbf{s^d})$, is set to the level at which the marginal time depositors are indifferent between investing in the time deposits and riskless bond. Considering that the time depositors' wealth in Step 3 is the payoff from their investment, $i(y, \mathbf{s^d})$ solves:

$$\begin{aligned} & i(y, \mathbf{s^d}) \\ = \; & \min \left\{ i \middle| \underbrace{(1-\Phi(z^d))U_{f(y)}(1+i) + \Phi(z^d)U_{f(y)}\left(\frac{1-dq^d-(1-e(q^d))y}{(1-e(q^d))(1-y)}\right)}_{\text{EU from the time deposits}} \geq \underbrace{U_{f(y)}(1+r)}_{\text{EU from riskless bond}} \right\}, \end{aligned}$$

where $U_{f(y)}(.)$ is the utility function for the marginal time depositor's type, $f(y)$.

[16] y is determined before the bank sets the deposit rates, so its decision is committable to the depositors by nature.

[17] Alternatively, the bank may not be able to find a third-party bidder who can manage the assets as efficiently as it can in a short time.

3.6 The bank's issuance of demand deposits

Finally, we note that the bank chooses the level of demand deposits y, subject to the liquidation value constraint in Step 1.

3.7 Equilibrium

From the previous section, we can characterize the bank's financing cost as

$$c(y, \mathbf{s}, \mathbf{s^d}) = (1 - e(q))(1 - y)i(y, \mathbf{s^d}),$$

where $(1 - y)i(y, \mathbf{s^d})$ is the bank's interest expense rate.

We consider the bank incurs the quadratic cost of risk taking, $\frac{k}{2}q^2$ $(k > 0)$. The quadratic cost can be explained as the monitoring cost associated with risk-taking behavior. We also denote the cost of capital by γ $(\gamma \geq 0)$. Its continuation value, $V(y, \mathbf{s}, \mathbf{s^d})$, immediately after raising the deposits and the capital is then described by

$$V(y, \mathbf{s}, \mathbf{s^d}) = \frac{\overbrace{1 - \Phi(z)}^{\text{survival probability}}}{1 + r} \left(\underbrace{\overbrace{q(\mu + \sigma\lambda(z))}^{\text{expected asset return at survival}} - c(y, \mathbf{s}, \mathbf{s^d}) - \frac{k}{2}q^2}_{\text{expected residual claim at survival}} + \underbrace{V(y, \mathbf{s}, \mathbf{s^d})}_{\text{continuation value}} \right)$$
$$- \frac{\overbrace{\Phi(z)}^{\text{default probability}}}{1 + r} \underbrace{e(q)}_{\text{capital loss at default}} - \underbrace{\frac{\gamma}{1 + r} e(q)}_{\text{capital cost}}.$$

We focus on the stationary Nash equilibrium in which the bank chooses the same strategy every year to maximize the continuation value, whereas the depositors rationally expect a stationary strategy from the bank. We denote the risk space of the bank by $\mathbf{\Sigma}$, where $\mathbf{\Sigma} = (0,1) \times \mathbb{R}$.[18] Then we define the equilibrium as follows:

Definition 1. Bank risk $\mathbf{s}^*$ is the equilibrium if $(y^*, \mathbf{s}^*) \in \arg\max_{(y,\mathbf{s}) \in [0,1] \times \mathbf{\Sigma}} V(y, \mathbf{s}, \mathbf{s}^*)$,

s.t.

$$\underbrace{1 - dq^* \geq (1 - e(q^*))y,}_{\text{liquidation value} \geq \text{the amount of the demand deposits, perceived by the depositors}}$$

$$\underbrace{1 - q \geq x(1 - e(q))y,}_{\text{safe assets} \geq \text{the withdrawal of the demand deposits in Step 2}}$$

$$\underbrace{V(y^*, \mathbf{s}^*, \mathbf{s}^*) \geq c.}_{\text{bank value} \geq \text{minimum charter value}}$$

The first constraint captures the liquidation value constraint, whereas the second constraint captures the liquidity constraint. The last constraint reflects the regulation related to bank charter.

Then we can characterize the equilibrium as follows:

[18] We choose an open interval for the space of asset risk to focus on an interior solution in which q does not hit the corner of the interval. This approach enables us to simplify the computation of an equilibrium.

Proposition 1. If s^* is the equilibrium, it satisfies either[19]

$$\underbrace{\frac{1-\Phi(z^*)}{r+\Phi(z^*)}\left(\mu + \overbrace{\sigma\lambda(z^*)}^{\text{gain from limited liability}} + \overbrace{e'(q^*)\left((1-y^*)i(y^*,\mathbf{s}^*) - \frac{\Phi(z^*)}{1-\Phi(z^*)} - \frac{\gamma}{1-\Phi(z^*)}\right)}^{\text{gain from rising capital}}\right)}_{\text{marginal value of risk taking}}$$

$$= \underbrace{\frac{1-\Phi(z^*)}{r+\Phi(z^*)}kq^*}_{\text{marginal operating cost of risk taking}},$$

$$\underbrace{\overbrace{\frac{q^*\sigma\left(1-\Phi(z^*)\right)\left(\lambda(z^*)-z^*\right)}{1+r}}^{\text{saved equity injection}} - \overbrace{\frac{(1+\gamma)e(q^*)}{1+r}}^{\text{capital loss}}}_{\text{value of default}} = \underbrace{V(y^*,\mathbf{s}^*,\mathbf{s}^*)}_{\text{opportunity cost of default}},$$

$$y^* \in \arg\min_{y\in[0,1]} (1-y)i(y,\mathbf{s}^*) \text{ s.t. } 1-dq^* \geq (1-e(q^*))y,$$

or

$$q^* = Q(y^*),$$

$$\underbrace{\overbrace{\frac{q^*\sigma\left(1-\Phi(z^*)\right)\left(\lambda(z^*)-z^*\right)}{1+r}}^{\text{saved equity injection}} - \overbrace{\frac{(1+\gamma)e(q^*)}{1+r}}^{\text{capital loss}}}_{\text{value of default}} = \underbrace{V(y^*,\mathbf{s}^*,\mathbf{s}^*)}_{\text{opportunity cost of default}},$$

$$y^* \in \arg\max_{y\in[0,1]} V(y,(Q(y),z^*),\mathbf{s}^*) \text{ s.t. } 1-dq^* \geq (1-e(q^*))y,$$

where $1-Q(y) = x(1-e(Q(y)))y$.

Proof. See the appendix. □

This proposition suggests the bank chooses the asset risk such that the marginal net gain from risk taking through increases in expected asset returns, risk-shifting benefits, and capital is equal

[19]Although this condition is necessary, it is not sufficient. In practice, numerically checking the optimality of the bank's control variables is required to verify the second order condition. Indeed, we numerically verify the optimality of the bank to find equilibria in our numerical examples.

to the marginal cost from increases in operating expenses at equilibrium. It also optimally trades off charter value with the burden of injecting equity when setting the default threshold at equilibrium. However, when the liquidity constraint binds, the bank cannot freely determine asset risk. Therefore, the liquidity constraint may limit the bank's endogenous choice of asset risk.

3.8 Efficiency

We propose "social return," $\Pi(\mathbf{s}^*)$, as the measure of efficiency. We define $\Pi(\mathbf{s}^*)$ as

$$
\begin{aligned}
\Pi(\mathbf{s}^*) = \quad & \underbrace{(1-\Phi(z^*))\left(q^*(\mu+\lambda(z^*)) - c(y^*,\mathbf{s}^*,\mathbf{s}^*) - \frac{k}{2}q^{*2}\right) - (\gamma+\Phi(z^*))e(q^*)}_{\text{net return to shareholders}} \\
& + \underbrace{(1-e(q^*))\left((1-\Phi(z^*))(1+i(y^*,\mathbf{s}^*)) + \Phi(z^*)\frac{(1-q^*)+q^*(1-d)}{1-e(q^*)} - 1\right)}_{\text{net return to depositors}} \\
& - \underbrace{\Phi(z^*)\left(q^*\left(\frac{\phi(z^*)}{\Phi(z^*)} - \mu\right) + \frac{k}{2}q^{*2}\right)}_{\text{other costs incurred by society}} \\
& + \underbrace{\gamma e(q^*)}_{\text{net return to capital providers}} \\
= \quad & \underbrace{q^*\mu - \frac{k}{2}q^{*2}}_{\text{value of risk taking}} - \underbrace{\Phi(z^*)dq^*}_{\text{bankruptcy cost}} .
\end{aligned}
$$

We note that this measure does not depend on the capital structure of the bank, given the bank's risk profile. The bank's capital structure therefore affects social return only through the bank's choices of asset and default risks.

We compare the socially optimal asset risk with the equilibrium asset risk in the absence of regulation in order to measure excessive risk taking in a laissez-faire economy. Let $q^0(z^*)$ be the socially optimal level of asset risk given z^*, and let $q^e(z^*)$ be the equilibrium asset risk given z^* in the absence of regulation. We denote the extent of excessive risk taking or risk shifting by $\Delta(z^*)$, where $\Delta(z^*) = q^e(z^*) - q^0(z^*)$. Then the following proposition holds:

Proposition 2. $\Delta(z^*)$ strictly increases in z^*. Therefore, excessive risk taking in the absence of regulation is larger if the equilibrium default risk is larger.

Proof. See the appendix. □

This finding implies the regulatory benefit of restricting asset risk is larger when a bank is closer to default. Therefore, the favorable effect of restricting asset risk is stronger in the high-risk equilibrium than in the safe equilibrium.

4 Numerical examples

4.1 Parameters used for the benchmark case

In the benchmark case, we consider depositors have a uniform risk preference. Specifically, both depositors have a CRRA (constant relative risk aversion) utility function with an RRA (relative risk aversion) of 1.9. We choose this value, considering that commonly accepted measures of the coefficient of RRA lie between 1 and 3 (Gandelman and Hernandez-Murillo, 2015). Table 1 lists the parameters used for our benchmark simulation.

4.2 Financial regulations

Our model is useful for simulating financial regulations recently proposed by the Basel Committee. In 2010, the Basel Committee issued the Basel III rules text. The major changes introduced under Basel III include increasing capital requirements and introducing liquidity requirements. Although

Table 1: Parameters for Simulation

Parameter	Notation	Value	Note
Risk free rate	r	0.020	U.S. 1-year TB rate as of March 2018
Cost of capital	γ	0.030	U.S. long-term TB rate as of March 2018
Mean risky asset ret.	μ	0.085	Matched to mean ROA in Egan et al. (2017a) at the safe equilibrium
Risky asset ret. vol.	σ	0.25	Matched to standard deviation of ROA in Egan et al. (2017a) at the safe equilibrium
LGD for risky assets	d	0.45	Recover rate of 0.55 for risky assets[a]
Operating cost coeff.	k	0.12	Matched to 0.7 (0.3) for the fraction of risky (safe) assets at the safe equilibrium[b]

[a]See Schuermann (2004) for the typical range of recovery rates for bank loans.
[b]Liquid assets/total assets ranged from 23 % to 31 % in the U.S. between 2003 and 2013 (Buehler et al., 2013).

capital requirements have been set by the Basel Committee for some time, the new rule raises the minimum capital requirement (as a percentage of risk-weighted assets) by 0.625 percentage points per year (from 8% in 2015, the minimum level specified in Basel II, to 10.5% in 2019). Because our measure of asset risk, q, can be considered a risk-weighted asset, we can directly simulate the effect of the risk-sensitive capital requirement by setting $e(q) = bq$, where b is the capital ratio. In the benchmark case, we consider the no-requirement case ($b = 0$). Moreover, liquidity regulations were introduced for the first time by Basel III, which imposes a minimum net stable funding ratio (NSFR) and minimum liquidity coverage ratio (LCR). Our liquidity constraint captures these requirements by setting x higher than the actual withdrawal. We consider 20% of the demand deposits are withdrawn in the middle of the year. Therefore, in the benchmark case, we set $x = 0.2$. Lastly, we set $c = 0.3$. Thus, the value of the bank has to exceed 0.3 in order for the bank to operate.

4.3 Results

4.3.1 Benchmark case

In the benchmark case, our analysis suggests the presence of multiple equilibria. In the safe equilibrium, a bank invests 70.8% of its assets in risky ones and almost never defaults. In the high-risk equilibrium, the bank invests 77.4% of its assets in risky ones, and its default probability is 1.2%. The social return is higher in the safe equilibrium (3.0%) than in the high-risk equilibrium (2.6%). These results show the bank's limited commitment can cause the self-fulfilling prophecy and generate financial instability without involving changes in the bank's fundamentals. This observation is consistent with the other models, such as Gertler and Kiyotaki (2015) and Egan et al. (2017a).

We also find that the bank sells 68.0% of the total deposits to the demand depositors in the safe equilibrium, but it sells only 39.3% in the high-risk equilibrium. The issuance of safe demand deposits is crucial for the bank's risk-sharing function, because it enables risk-averse depositors to invest in the bank without demanding high spreads. This risk-sharing role improves the bank's solvency, reduces its asset and default risks, and increases social return. Indeed, the bank issues more demand deposits in the safe equilibrium than in the high-risk equilibrium.

The existence of the high-risk equilibrium indicates the bank cannot costlessly increase demand deposits. Time depositors demand more spreads in accordance with the increase in demand deposits, anticipating the lower liquidation value they can seize at default. In particular, when they anticipate an asset risk above a certain threshold, the bank cannot raise any more demand deposits without violating the liquidation value constraint. In the high-risk equilibrium, the bank is severely restricted in the issuance of demand deposits because time depositors anticipate a high asset risk. Because the bank's sharing of risks with bank creditors is restricted, the high-risk equilibrium emerges.

4.3.2 Eliminating financial fragility

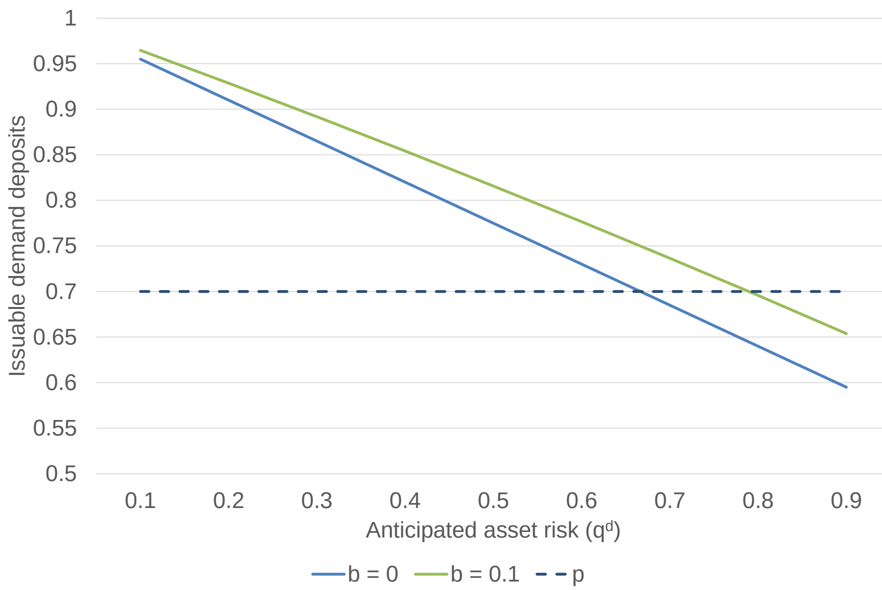
Next, we assess whether the capital requirement and heterogeneity in risk aversion among depositors can mitigate the above concern. When we analyze risk-aversion heterogeneity, we consider that type h depositors have a CRRA utility function with an RRA of 2.4, whereas type l depositors have a CRRA utility function with an RRA of 0.6. The fraction of type h depositors, p, is assumed to be 0.7. Our choice of parameters is set to satisfy the condition that the average RRA in the presence of risk-aversion heterogeneity is equal to the benchmark RRA, 1.9. In addition, we consider a capital ratio of 10% when we analyze the effect of the capital requirement ($b = 0.1$).[20]

We start by presenting in figure 3 how the issuable amount of demand deposits is affected by the capital requirement. The figure shows the issuable amount of demand deposits is higher when the capital requirement is present ($b = 0.1$) than when it is absent ($b = 0$). It also shows the issuable amount of demand deposits is decreasing in the anticipated level of the bank's asset risk. For example, the bank cannot sell 70% of total deposits to demand depositors when depositors anticipate that 75% of the bank's assets are risky at $b = 0$, but selling 70% of total deposits to demand depositors is feasible at $b = 0.1$. Thus, a risk-sensitive capital requirement relaxes the liquidation value constraint, particularly when depositors anticipate a high asset risk.

Still assuming a capital ratio of 10%, we next compute the optimal level of demand deposits and interest expense rate as well as the opportunity cost and value of default for different levels of default probability (and corresponding asset risk) that are rationally anticipated by depositors. Figure 4 presents the results from this analysis. The left panels show the case in which depositors

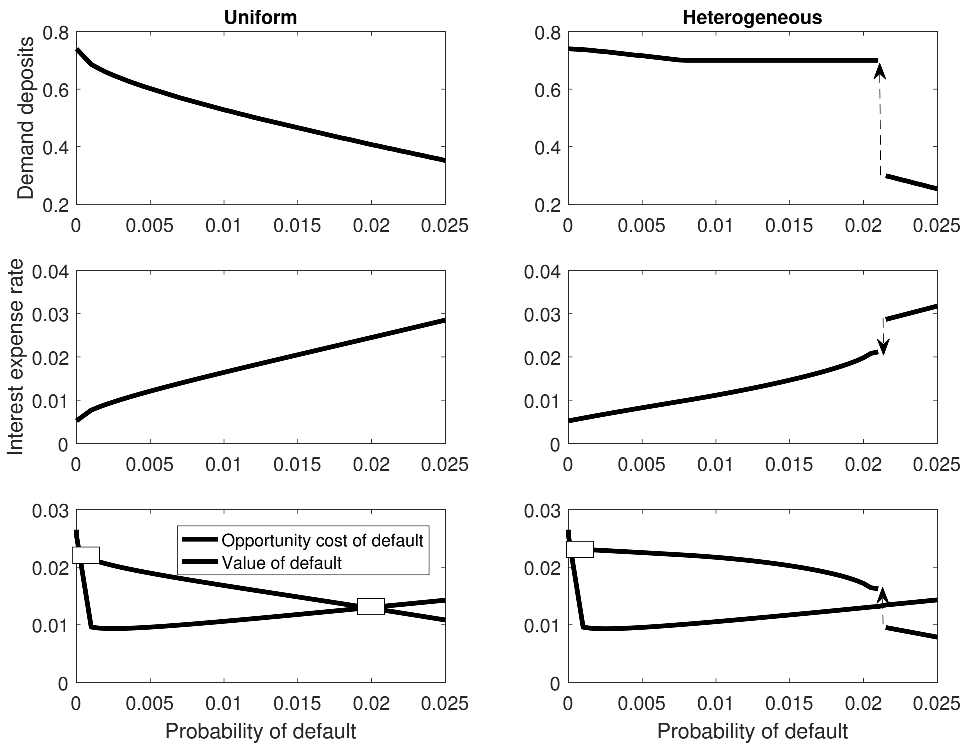
[20] We also analyze continuous distribution of relative risk aversion in the appendix.

Figure 3: Issuable Demand Deposits



have a uniform risk preference, whereas the right panels present the case in which they have a heterogeneous preference. The top left panel shows demand deposits issued by the bank sharply decrease in the bank's risk when depositors have a uniform risk preference. The middle left panel shows the interest expense rate rises sharply in accordance with the decrease in the bank's demand deposits. Consequently, as shown in the bottom left panel, the opportunity cost of default sharply decreases with the bank's risk and intersects with the value of default. Because the equilibrium emerges at the intersection of the two curves, the high-risk equilibrium occurs when depositors have a uniform risk preference. On the other hand, the top right panel shows that demand deposits issued by the bank do not decrease with the bank's risk as much when depositors have a heterogeneous risk preference, because marginal time depositors are less risk-averse, demanding lower compensation for losses through default, so the bank can keep issuing demand deposits until

Figure 4: Bank's Strategies and Equilibria

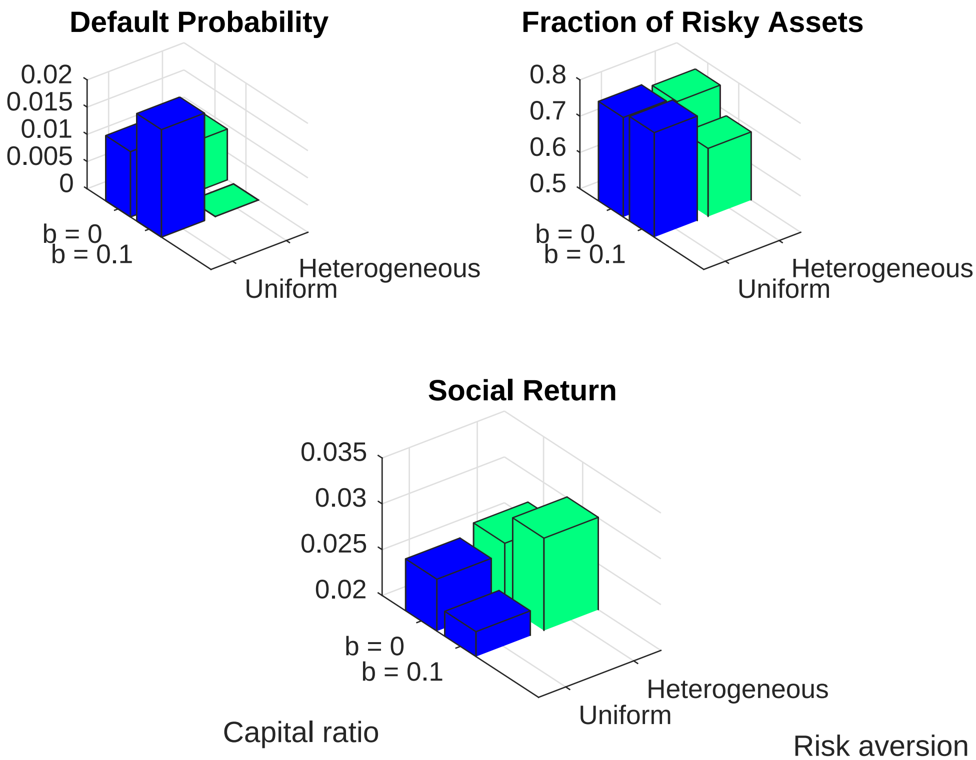


Note: The figure presents the optimal level of demand deposits and interest expense rate as well as the opportunity cost and value of default for different levels of default probability (and corresponding asset risks) depositors rationally anticipate. The opportunity cost and value of default are converted into corresponding flow items. We consider a 10% capital ratio ($b = 0.1$). The white rectangles represent equilibria in the bottom panels.

the liquidation constraint is binding. The middle right panel shows the interest expense rate shifts downward in accordance with the increase in the bank's demand deposits. Consequently, as shown in the bottom right panel, the opportunity cost of default shifts upward without intersecting with the value of default at high default probability. This outcome is also attributable to the presence of the capital requirement, which relaxes the liquidation value constraint when depositors anticipate high default probability (and corresponding high asset risk) and enables the bank to utilize the matching mechanism explained above. Thus, the potential for the high-risk equilibrium is eliminated jointly by depositors' risk aversion heterogeneity and the capital requirement.

To assess the effects of risk-aversion heterogeneity and capital requirement on the financial

Figure 5: Bank's Financial Stability



Note: The figure presents the equilibrium risk and social return at the "worst" equilibrium. In the presence of multiple equilibria, we choose the one with the largest default probability, highest asset risk, and lowest social return.

stability of the banking sector, we also simulate the bank's "worst" equilibrium outcome.[21] Figure 5 reports the simulation outcome. In the presence of risk aversion heterogeneity and the capital requirement, the high-risk equilibrium is eliminated, as described in the previous paragraph. Therefore, the bank's potential risk is lowest, whereas the social return never becomes too low. However, for the other cases in which the high-risk equilibrium occurs, the bank's potential risk remains relatively high, and the social return could be relatively low.

This analysis reveals that capital requirement is necessary, but not sufficient for achieving financial stability. Although it relaxes the liquidation value constraint, depositors need to have a

[21] In the presence of multiple equilibria, we report the equilibrium outcome with the highest default probability. If no multiple equilibria exist, we report the outcome of the unique equilibrium.

heterogeneous risk preference for a bank to utilize the matching mechanism and eliminate the potential for financial fragility.

4.3.3 Liquidity regulation

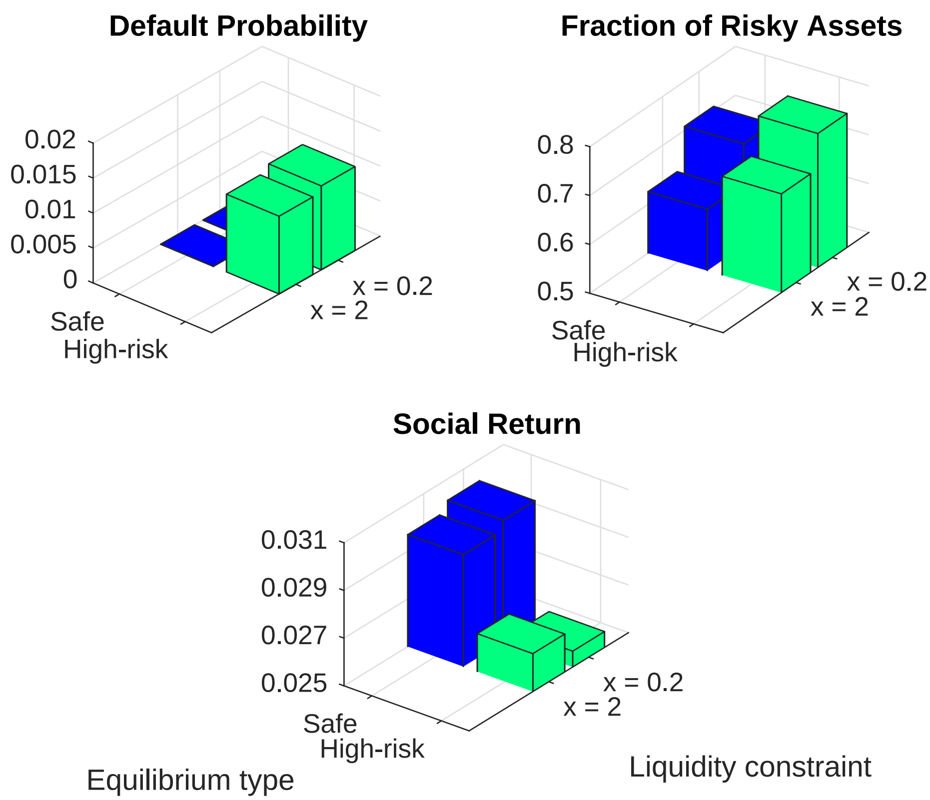
Lastly, we look into the effectiveness of the liquidity regulation. The first observation we made is that the liquidity constraint does not bind in the benchmark case. Whenever a bank increases its risk, it simultaneously increases its share of time deposits. This action reduces the demand for liquidity and makes the liquidity constraint hard to bind even when the asset risk is relatively high.

Because the liquidity constraint is hard to bind without regulation, there is room for policy intervention. In particular, we focus on the case with no risk-aversion heterogeneity; the capital requirement cannot eliminate the potential for the high-risk equilibrium. To assess the usefulness of the liquidity requirement, we compute the equilibria of a bank funded by depositors with uniform risk preference while setting $x = 2$, thus artificially forcing a bank to invest at least twice the amount of demand deposits in safe assets.

Figure 6 illustrates the safe and high-risk equilibria for different levels of liquidity requirements in the absence of a capital requirement and risk-aversion heterogeneity among creditors. For the high-risk equilibrium, when the liquidity requirement tightens, a bank tends to hold fewer risky assets. Social return consequently improves due to the mitigation of excessive risk taking.[22] On the other hand, a tight liquidity requirement can force a bank to reduce asset risk excessively in the safe equilibrium. Because a bank rarely defaults, it already chooses an asset risk close to the socially optimal level even in the absence of a liquidity requirement at the safe equilibrium. As

[22] Although a liquidity requirement may weaken the risk sharing mechanism (making it difficult to issue demand deposits), this unfavorable effect is limited in the high-risk equilibrium, because the laissez-faire level of demand deposits is already low in this type of equilibrium.

Figure 6: Effect of Liquidity Requirement



Note: The figure presents the risk and social return for each equilibrium in the absence of risk aversion heterogeneity. We set $b = 0$.

a result, a liquidity requirement can reduce social return due to underinvestment. In accordance with Proposition 2, the regulatory benefit of a liquidity requirement is greater in the high-risk equilibrium than in the safe equilibrium.

This analysis reveals that imposing a liquidity requirement can be welfare-enhancing in the high-risk equilibrium, but can reduce efficiency in the safe equilibrium. Considering the opposing effects of a liquidity requirement on safe and high-risk equilibria, the use of liquidity regulations may be justified as a tradeoff strategy.

5 Empirical evidence

We seek further evidence for a joint effect of risk-weighted capital requirement and creditor heterogeneity in risk attitudes on the financial stability of a bank. For this purpose, we investigate how a bank's interest expense rate, which increases in the bank's default risk and decreases in the bank's safe deposits, is associated with bank risk-weighted capital and creditor heterogeneity in risk attitudes. Our theory predicts that a bank's interest expense rate is lower in the joint presence of them, because the safe equilibrium, in which the bank issues more safe deposits and experiences lower asset and default risk than in the high-risk equilibrium, is more likely to occur.

5.1 Data

5.1.1 Bank Holding Company (BHC) data

To capture a BHC's interest expense rate and risk-weighted capital, we used yearly Reports of Condition and Income (Call Reports) for the period between 2010 and 2015.[23] We also used the Summary of Deposits Survey (SOD) conducted yearly by the FDIC.[24] Using this data set, we measured each BHC's deposits at the branch level every year. Then, for each BHC-year, we aggregated deposits at the county level. We denote BHC i's deposits in county c as of BHC i's total deposits in year t by $D_{i,c,t}$. This variable is defined as

$$D_{i,c,t} = \frac{\sum_{b \in B^i_{c,t}} Deposits_{i,b,t}}{\sum_{c \in C_t} \sum_{b \in B^i_{c,t}} Deposits_{i,b,t}},$$

[23]This report is called FR Y-9 for BHCs, which contains financial statements data in a consolidated basis.
[24]This survey is a requirement for all insured deposit-taking institutions.

where b is a generic indicator for branch. $B^i_{c,t}$ is the set of BHC i's branches in county c in year t, and C_t is the set of U.S. counties for which we do not miss county-level variables in year t. We use this variable as a weight to calculate the weighted averages of county-level variables when generating BHC-level variables.

5.1.2 Regulatory and market environment

Since the GFC, an emerging pool of literature has begun to explore the issue of too-big-to-fail (TBTF) and to argue the weakness of safety net regulation such as the moral hazard problem in systemically important banks and government bailouts. To account for the impact of systemic importance on a bank's risk-taking behavior and interest rate, we control for the dummy variable Global Systemically Important Banks (GSIB). Starting in 2011, the Financial Stability Board (FSB) has published a list for globally systematically important banks on an annual basis. We consider all banks that have ever been included in the list from 2011 to 2017 to be GSIB.

In addition, market conditions may drive a bank's risk-taking behavior through both supply and demand sides. To address this concern, we first observe the local macroeconomic environment (unemployment rates and income growth rates) for each county. Then we observe the extent of deposit competition for each county. In particular, we calculate the county-level Herfindahl-Hirschman Index (HHI) to capture the level of local deposit competition.[25] At the BHC level, we measure each bank's overall exposure to market conditions by calculating the weighted averages of county-level

[25]For example, if there are two banks (bank A and bank B) in the county and bank A's deposit is 50 whereas bank B's deposit is 50, the HHI for the county is $(\frac{50}{50+50})^2 + (\frac{50}{50+50})^2 = 0.5$.

variables across counties in which the bank has branches. Specifically, it is calculated as:

$$AZ_{i,t} = \sum_{c \in C_t} D_{i,c,t} Z_{c,t},$$

where $Z_{c,t}$ is the county-level variable for the market environment (unemployment rates, income growth rates, and HHI).

5.1.3 Risk preference index

To measure creditor heterogeneity in risk attitudes, we collected county-level demographic variables from the County Health Rankings & Roadmaps program. The program is conducted by the Robert Wood Johnson Foundation and the University of Wisconsin Population Health Institute. The data span from 2010 to 2016. Among the available variables, we chose the rate of the uninsured, the adult smoking rate, the teen birth rate, and the chlamydia infection rate as proxies for risk preference. Each variable is considered a relevant proxy for risk preference, given that the previous research supports the association of these variables with risk appetite. We explain the relevance of each variable in the following paragraph.

- *Uninsurance*: Insurance is a financial product used to hedge risks for individuals. Barseghyan et al. (2013) infer risk preference from insurance choices. Moreover, Barsky et al. (1997) find correlation between being uninsured and the indicators for financial risk taking. We therefore consider the uninsured population a proxy for risk preference.

- *Adult smoking*: Numerous health studies have established the fact that smoking is the leading risk factor for various diseases and for death from cancer (e.g., Lim et al. (2012)).Therefore, a smoker who is aware of this fact can be considered less risk averse. However, distinguishing misinformation from risk taking is difficult. For instance, young people may smoke due to misinformed risk (Leventhal et al., 1987). To address this concern, we chose the adult smoking rate as our proxy for risk preference in health choice.

- *Teen birth*: Schmidt (2008) suggests females with greater tolerance for risk experience tend to experience earlier births and less effective contraception. Therefore, we chose teen birth as our proxy for risk preference.

- *Chlamydia infection*: Baeten et al. (2001) find consistent condom use can significantly reduce the risk of sexually transmitted infections, including chlamydia. On the other hand, the use of condoms is also considered a key indicator of sexual risk taking (Tapert et al., 2001). As a result, we chose the chlamydia infection rate as another proxy for risk preference in sexual behavior.

Although different factors might affect health-related and financial risk taking, Barsky et al. (1997) find their unique measure of risk tolerance predicts a wide range of risky behaviors, including smoking, drinking, failing to have insurance, and holding stocks rather than Treasury bills. Moreover, Calvet and Sodini (2014) reveal the proportion of the liquid financial portfolio invested in risky assets is positively linked to health risk-taking factors such as alcohol consumption.

Because each variable may capture a behavioral factor that is irrelevant to risk preference, we performed a principle component analysis (PCA) to reduce noise.[26] The first component has an eigenvalue of 2.02 and is the only component that has an eigenvalue higher than 1. It alone explains 51% of the variations in the data. The following equation describes the structure of the

[26] We used standardized proxies to perform PCA.

risk preference index for county c in year t:

$$RPI_{c,t} = 0.4780 Uninsured_{c,t} + 0.4140 Smoking_{c,t} + 0.6345 TeenBirth_{c,t} + 0.4444 Chlamydia_{c,t}.$$

The factor loading of each proxy is positive, which captures the positive relationship between our proxies and underlying risk preference. We find the correlation between the index that we construct from PCA and the probability of being uninsured, the proxy most directly related to financial risk taking, is 0.6799. The strong correlation between them suggests the index is a relevant measure of financial risk preference.

After constructing the county-year level risk preference index, $RPI_{c,t}$, we calculated the average and weighted standard deviation of each county's risk preference index per bank-year, considering the bank's deposits located in each county, $D_{i,c,t}$, as the weight. Specifically, the average risk preference index, $ARPI_{i,t}$, is calculated as

$$ARPI_{i,t} = \sum_{c \in C_t} D_{i,c,t} RPI_{c,t}.$$

Then, we generated the risk preference heterogeneity, $RPH_{i,t}$, by the following:

$$RPH_{i,t} = \sqrt{\sum_{c \in C_t} \left(D_{i,c,t} \left(RPI_{c,t} - ARPI_{i,t} \right)^2 \right)}.$$

The risk preference heterogeneity, $RPH_{i,t}$, captures the bank creditors' risk preference heterogeneity. Table 2 reports the summary statistics of the merged data. In the merged data, we have 1,058 banks and 4,790 observations.

Table 2: Summary Statistics

Variables	N	Mean	Sd
Interest expense rate (%)	4,790	0.814	0.516
Risk preference heterogeneity	4,790	0.607	0.414
Lagged risk weighted equity ratio	4,790	0.143	0 .070
Average risk preference	4,790	-0.261	1.149
Lagged log total assets (log thousands of dollars)	4,790	14.249	1.307
Bank age (years)	4,790	22.954	13.515
Average HHI	4,790	0.213	0.092
Average unemployment rate (%)	4,790	7.361	2.188
Average income growth (%)	4,790	1.523	2.860
Global systemically important banks	4,790	0.010	0.099

Note: The sample period of the merged data ranges from 2010 to 2015.

5.2 Empirical analysis

To estimate the effect of risk-weighted capital and creditor diversity in risk attitudes on a bank's interest expense rate, we estimate the ordinary least squares (OLS) regression by the following equation:

$$IR_{i,t} = \alpha + \beta RPH_{i,t} \times RWE_{i,t} + \theta RPH_{i,t} + \delta RWE_{i,t} + \Gamma * X_{i,t} + \varepsilon_{i,t}, \tag{1}$$

where $IR_{i,t}$ represents bank i's interest expense rate paid to creditors in year t, $RPH_{i,t}$ is the bank's exposure to creditor diversity in risk attitudes, and $RWE_{i,t}$ characterizes the one-year lagged risk-weighted equity ratio of the bank. Specifically, we measure $IR_{i,t}$ by dividing interest expenses over total liabilities and $RWE_{i,t}$ by taking the ratio of total equity to risk weighted assets in the previous year. $X_{i,t}$ is the set of control variables, including $AZ_{i,t}$ and $ARPI_{i,t}$.[27] To detrend variables, we also include year dummies in $X_{i,t}$.

In this specification, the explanatory variable of interest is the interaction term $RPH_{i,t} \times$

[27] We do not include endogenous variables, such as profitability, because our dependent variable, interest rate, directly affects a bank's profits.

$RWE_{i,t}$. The coefficient on this term, β, captures the joint effect of risk-weighted capital and creditor diversity in risk attitudes on a bank's interest expense rate. Note that we include bank size and age in the set of control variables, which can potentially explain some of the variations in interest expense rates.

Column (1) in table 3 reports the outcome of this regression. We find β is estimated to be negative and statistically significant at the 5% level. This result suggests capitalized banks exposed to higher levels of creditor diversity experience, on average, lower interest expense rates. In other words, a bank's risk tends to be lower in the joint presence of capital adequacy and creditor diversity in risk attitudes. On the other hand, our estimates for θ and δ are statistically insignificant. This result implies neither risk-weighted capital nor creditor diversity in risk attitudes is likely to reduce a bank's risk by itself. Overall, our finding is consistent with our simulation outcome; that is, the high-risk equilibrium vanishes only in the joint presence of risk-weighted capital and risk aversion heterogeneity among creditors.

We note that the coefficients reported in column (1) are estimated using both time-series and cross-sectional variations in our data. Because we detrend variables by including year dummies, time-series variations are somewhat suppressed though not perfectly eliminated. Given that our theoretical predictions are based on differences in risk-weighted capital ratios and exposure to creditor diversity *across* banks, a more appropriate test of our predictions would involve estimating β by relying entirely on cross-sectional variations in our data.

To perform a more appropriate test, we re-estimate β using the between-group estimator. Specifically, we estimate the following model:

$$\overline{IR_i} = \alpha + \beta\overline{RPH_i \times RWE_i} + \theta\overline{RPH_i} + \delta\overline{RWE_i} + \Gamma * \overline{X_i} + \overline{\varepsilon_i}, \quad (2)$$

where each variable is averaged over time at the bank level.

We report our estimates based on this alternative specification in column (2). In this case, the coefficient on the interaction term is negative and statistically significant at the 1% level, whose magnitude is similar to the result in column (1). This result further supports the consistency of our simulation outcome with our empirical evidence.

Lastly, we perform multiple robustness checks in the appendix. Overall, we obtain estimation results similar to our benchmark estimates.

6 Discussion

Our finding that risk aversion heterogeneity across depositors and moderate capital requirements jointly eliminate the potential for a sunspot crisis has a direct policy implication concerning the appropriate level of capital ratio, which has been widely debated among both academics and practitioners.[28] We contribute to this debate by arguing that the appropriate capital ratio level depends on the diversity of creditors' risk attitudes. We find a capital ratio of 10% is sufficient for eliminating financial fragility in the presence of risk aversion heterogeneity among creditors, but not in the absence of such heterogeneity. Thus, this result shows the efficiency of capital regulation is contingent on the heterogeneity of risk aversion among depositors.

In addition, our finding suggests an alternative perspective on the antitrust policy in banking. The previous literature indicates market competition in the banking sector can both enhance welfare and detract from efficiency. Although Allen and Gale (2004) suggest the increased charter value due to market concentration reduces the frequency of bank failure, Boyd and De Nicoló

[28]For example, Begenau (2016) argues the optimal capital ratio is around 15%, whereas Van den Heuvel (2008) suggests a capital ratio of 10% imposes a welfare cost of between 0.1 and 1.0% of consumption.

Table 3: Regression Results

	(1)	(2)
Risk preference heterogeneity × Lagged risk weighted equity ratio	-0.969**	-0.948***
	(0.477)	(0.322)
Risk preference heterogeneity	0.0657	0.0784
	(0.0718)	(0.0537)
Lagged risk weighted equity ratio	0.111	0.00709
	(0.484)	(0.209)
Average risk preference	-0.0187*	-0.0171
	(0.0104)	(0.0110)
Lagged log total assets	-0.659***	-0.563***
	(0.214)	(0.158)
Lagged log total assets squared	0.0217***	0.0183***
	(0.00738)	(0.00515)
Bank age	-0.00377	-0.00480***
	(0.00235)	(0.000949)
Average HHI	0.154	-0.00255
	(0.161)	(0.133)
Average unemployment rate	-0.00561	-0.00676
	(0.00738)	(0.00734)
Average income growth	-0.00202	-0.0191**
	(0.00200)	(0.00956)
Global systemically important banks	-0.741**	-0.543***
	(0.337)	(0.202)
Year dummies	X	X
Observations	4,790	4,790
R^2	0.420	0.320

Note: In column (2), we report between-R^2. Standard errors are in parentheses and clustered at bank level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

(2005) argue that market concentration encourages risk shifting by entrepreneurs. Martinez-Miera and Repullo (2010) claim, meanwhile, that both effects are present. We propose another factor affecting the welfare of a bank merger: The merger synergy depends on how similar the merged banks' creditors' risk preference are.

Although our model endogenizes a variety of a bank's strategies, including investment and default decisions, liability structure choice, and deposit pricing under the condition of limited commitment, it leaves several issues open. For example, we have not modeled state evolution over time. Because our model focuses on stationary equilibria, it does not capture time-series variations within a bank, and best fits to explain cross-sectional variations across local monopolistic banks.[29] Another issue is that our model assumes depositors' liquidity preference shocks are independent of realized asset returns. If they were correlated, a bank would not be able to fully predict the amount of deposit withdrawal ex ante. Then the bank could default from forced liquidation due to the large withdrawal of demand deposits before the maturity of asset. The bank's investment choice would directly affect its default probability in this case. Lastly, we have not captured the crowding-out effect of bank capital. We, however, note that the discontinuous gain from capital regulation (eliminating the high-risk equilibrium) seems to outweigh its unfavorable effect due to the reduction in liquidity provision, which is rather continuous in the level of capital ratio. We recommend addressing these issues in future research.

[29]For example, our model does not predict how a bank's liability size and structure evolves over time.

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A.1 Proofs

A.1.1 Proof for Proposition 1

The closed form of $V(y, \mathrm{s}, \mathrm{s}^{\mathbf{d}})$ is derived by

$$\begin{aligned}
V(y,\mathbf{s},\mathbf{s^d}) &= \frac{1-\Phi(z)}{1+r}\left(q(\mu+\sigma\lambda(z)) - c(y,\mathbf{s},\mathbf{s^d}) - \frac{k}{2}q^2 + V(y,\mathbf{s},\mathbf{s^d})\right) - \frac{(\Phi(z)+\gamma)e(q)}{1+r} \\
\frac{r+\Phi(z)}{1+r}V(y,\mathbf{s},\mathbf{s^d}) &= \frac{1-\Phi(z)}{1+r}\left(q(\mu+\sigma\lambda(z)) - c(y,\mathbf{s},\mathbf{s^d}) - \frac{k}{2}q^2\right) - \frac{(\Phi(z)+\gamma)e(q)}{1+r} \\
V(y,\mathbf{s},\mathbf{s^d}) &= \frac{1+r}{r+\Phi(z)}\frac{1-\Phi(z)}{1+r}\left(q(\mu+\sigma\lambda(z)) - c(y,\mathbf{s},\mathbf{s^d}) - \frac{k}{2}q^2\right) - \frac{(\Phi(z)+\gamma)e(q)}{r+\Phi(z)} \\
V(y,\mathbf{s},\mathbf{s^d}) &= \frac{1-\Phi(z)}{r+\Phi(z)}\left(q(\mu+\sigma\lambda(z)) - c(y,\mathbf{s},\mathbf{s^d}) - \frac{k}{2}q^2\right) - \frac{(\Phi(z)+\gamma)e(q)}{r+\Phi(z)}.
\end{aligned}$$

First, I consider the case in which the liquidity constraint does not bind. Because we focus on the interior solution s^*, the solution has to satisfy the first order conditions with respect to asset risk q and tail risk z, respectively. Also, rational expectation requires that $\mathrm{s}^{\mathbf{d}} = \mathrm{s}^*$. The partial derivative of the value function with respect to q at the optimized y, y^*, is

$$\frac{\partial V(y^*,\mathbf{s}^*,\mathbf{s}^*)}{\partial q} \propto \qquad \mu+\sigma\lambda(z^*)-kq^*+e'(q^*)\left((1-y^*)i(y^*,\mathbf{s}^*)-\frac{\Phi(z^*)+\gamma}{1-\Phi(z^*)}\right).$$

Since $\mathbf{s}^*$ satisfies $\frac{\partial V(y^*,\mathbf{s}^*,\mathbf{s}^*)}{\partial q} = 0$, $\mathbf{s}^*$ also satisfies $\mu + \sigma\lambda(z^*) - kq^* + e'(q^*)\left((1-y^*)i(y^*,\mathbf{s}^*)-\frac{\Phi(z^*)+\gamma}{1-\Phi(z^*)}\right) = 0$. Thus, $\mathbf{s}^*$ satisfies:

$$\begin{aligned}
\mu+\sigma\lambda(z^*)+e'(q^*)\left((1-y^*)i(y^*,\mathbf{s}^*)-\frac{\Phi(z^*)+\gamma}{1-\Phi(z^*)}\right) &= \qquad kq^* \\
\frac{1-\Phi(z^*)}{r+\Phi(z^*)}\left(\mu+\sigma\lambda(z^*)+e'(q^*)\left((1-y^*)i(y^*,\mathbf{s}^*)-\frac{\Phi(z^*)+\gamma}{1-\Phi(z^*)}\right)\right) &= \frac{1-\Phi(z^*)}{r+\Phi(z^*)}kq^*.
\end{aligned}$$

In addition, I can characterize the partial derivative of the value function with respect to z as follows:

$$\begin{aligned}
\frac{\partial V(y^*,\mathbf{s}^*,\mathbf{s}^*)}{\partial z} &= \frac{-\phi(z^*)(r+\Phi(z^*))-(1-\Phi(z^*))\phi(z^*)}{(r+\Phi(z^*))^2}\pi(y^*,\mathbf{s}^*,\mathbf{s}^*)+\frac{1-\Phi(z^*)}{r+\Phi(z^*)}q^*\sigma\lambda'(z^*) \\
&\quad -\frac{r\phi(z^*)e(q^*)}{(r+\Phi(z^*))^2}+\frac{\gamma\phi(z^*)e(q^*)}{(r+\Phi(z^*))^2} \\
&= \frac{-\phi(z^*)(1+r)}{(r+\Phi(z^*))^2}\pi(y^*,\mathbf{s}^*,\mathbf{s}^*)+\frac{1-\Phi(z^*)}{r+\Phi(z^*)}q^*\sigma\lambda(z^*)(\lambda(z^*)-z^*) \\
&\quad -\frac{r\phi(z^*)e(q^*)}{(r+\Phi(z^*))^2}+\frac{\gamma\phi(z^*)e(q^*)}{(r+\Phi(z^*))^2} \\
&= \frac{\phi(z^*)(1+r)}{r+\Phi(z^*)}\frac{-\pi(y^*,\mathbf{s}^*,\mathbf{s}^*)}{r+\Phi(z^*)}+\frac{1-\Phi(z^*)}{r+\Phi(z^*)}\frac{\phi(z^*)}{1-\Phi(z^*)}q^*\sigma(\lambda(z^*)-z^*) \\
&\quad -\frac{r\phi(z^*)e(q^*)}{(r+\Phi(z^*))^2}+\frac{\gamma\phi(z^*)e(q^*)}{(r+\Phi(z^*))^2} \\
&\propto -\frac{\pi(y^*,\mathbf{s}^*,\mathbf{s}^*)}{r+\Phi(z^*)}+\frac{1}{1+r}q^*\sigma(\lambda(z^*)-z^*)-\frac{r-\gamma}{1+r}\frac{e(q^*)}{r+\Phi(z^*)},
\end{aligned}$$

where $\pi(y,\mathbf{s},\mathbf{s^d}) = q(\mu+\sigma\lambda(z)) - c(y,\mathbf{s},\mathbf{s^d}) - \frac{k}{2}q^2$. Because $\mathbf{s}^*$ satisfies $\frac{\partial V(y^*,\mathbf{s}^*,\mathbf{s}^*)}{\partial z} = 0$, $\mathbf{s}^*$ also satisfies $-\frac{\pi(y^*,\mathbf{s}^*,\mathbf{s}^*)}{r+\Phi(z^*)}+\frac{1}{1+r}q^*\sigma(\lambda(z^*)-z^*)-\frac{r-\gamma}{1+r}\frac{e(q^*)}{r+\Phi(z^*)}=0$. Thus, $\mathbf{s}^*$ satisfies:

$$-\frac{\pi(y^*,\mathbf{s}^*,\mathbf{s}^*)}{r+\Phi(z^*)}+\frac{1}{1+r}q^*\sigma(\lambda(z^*)-z^*)-\frac{r-\gamma}{1+r}\frac{e(q^*)}{r+\Phi(z^*)}=0$$
$$\frac{(\gamma+\Phi(z^*))e(q^*)}{r+\Phi(z^*)}-\frac{(1-\Phi(z^*))\pi(y^*,\mathbf{s}^*,\mathbf{s}^*)}{r+\Phi(z^*)}+\frac{1-\Phi(z^*)}{1+r}q^*\sigma(\lambda(z^*)-z^*)-\frac{(1+\gamma)e(q^*)}{1+r}=0$$
$$\frac{q^*\sigma(1-\Phi(z^*))(\lambda(z^*)-z^*)}{1+r}-\frac{(1+\gamma)e(q^*)}{1+r}=V(y^*,\mathbf{s}^*,\mathbf{s}^*).$$

Next, we consider the case in which the liquidity constraint binds. Because $V(y,\mathbf{s},\mathbf{s^d})$ is not differentiable with respect to y, we cannot use the Lagrange multipliers method. Instead, we use the substitution method. We thus have

$$(y^*,z^*)\in\arg\max_{(y,z)\in[0,1]\times\mathbb{R}}V(y,(Q(y),z),\mathbf{s}^*)\text{ s.t. }1-dq^*\geq(1-e(q^*))y.$$

Our goal is to further characterize the optimality condition. Because V is differentiable in the z-direction for fixed y anywhere, the partial derivative of V with respect to z has to be zero at z^*, which is located in the interior of an open interval due to the equilibrium definition. Therefore, $\frac{\partial V(y^*,\mathbf{s}^*,\mathbf{s}^*)}{\partial z}=0$ has to be satisfied. Then y^* satisfies

$$y^*\in\arg\max_{y\in[0,1]}V(y,(Q(y),z^*),\mathbf{s}^*)\text{ s.t. }1-dq^*\geq(1-e(q^*))y.$$

A.1.2 Proof for Proposition 2

Consider no regulation so that $e(q) = x = 0$. From Proposition 1,

$$q^e(z^*) = \frac{\mu + \sigma\lambda(z^*)}{k}$$

In addition, $\frac{\partial \Pi(q^0(z^*), z^*)}{\partial q^*} = 0$ implies

$$q^0(z^*) = \frac{\mu - \Phi(z^*)d}{k}.$$

Then, the excessive asset risk can be characterized by

$$\Delta(z^*) = \frac{\mu + \sigma\lambda(z^*)}{k} - \frac{\mu - \Phi(z^*)d}{k} = \frac{\sigma\lambda(z^*) + \Phi(z^*)d}{k}.$$

Therefore, we can show

$$\frac{\partial \Delta(z^*)}{\partial z^*} = \frac{1}{k}\frac{\partial\left(\sigma\lambda(z^*) + \Phi(z^*)d\right)}{\partial z^*} > 0,$$

because the hazard function of the normal distribution is a strictly increasing function.

A.2 Continuous distribution of relative risk aversion

In this section, we assume depositors' relative risk aversion (RRA) η follows a gamma distribution $G(\alpha, \beta)$, where α is the shape parameter and β is the scale parameter. The cumulative distribution function (CDF) of the distribution is $F(\eta) = \frac{1}{\Gamma(\alpha)}\gamma(\alpha, \frac{\eta}{\beta})$. As in the discrete case, if a bank sets the same time deposit rate to every depositor, less risk-averse depositors would self-select into time deposits and more risk-averse depositors would self-select into demand deposits. In particular, when the bank issues y fraction of total deposits as demand deposits, any depositor with RRA $\eta > \eta^*(y)$ would choose demand deposits, and those with RRA $\eta \leq \eta^*(y)$ would choose time deposits. The cut-off risk aversion $\eta^*(y)$ satisfies the following relationship:

$$\eta^*(y) = F^{-1}(1-y).$$

With regard to the pricing of time deposits, the time deposit rate $i(y, \mathbf{s^d})$ depends on the RRA of the marginal depositor $\eta^*(y)$ and satisfies the following relationship:

$$\begin{aligned} & i(y, \mathbf{s^d}) \\ = \quad & \min \left\{ i | \underbrace{(1-\Phi(z^d))U_{\eta^*(y)}(1+i) + \Phi(z^d)U_{\eta^*(y)}\left(\frac{1-dq^d-(1-e(q^d))y}{(1-e(q^d))(1-y)}\right)}_{\text{EU from the time deposits}} \geq \underbrace{U_{\eta^*(y)}(1+r)}_{\text{EU from riskless bond}} \right\}, \end{aligned}$$

where $U_{\eta^*(y)}(.)$ is the utility function with RRA of $\eta^*(y)$. The time deposit rate $i(y, \mathbf{s^d})$ is determined when the equality holds.

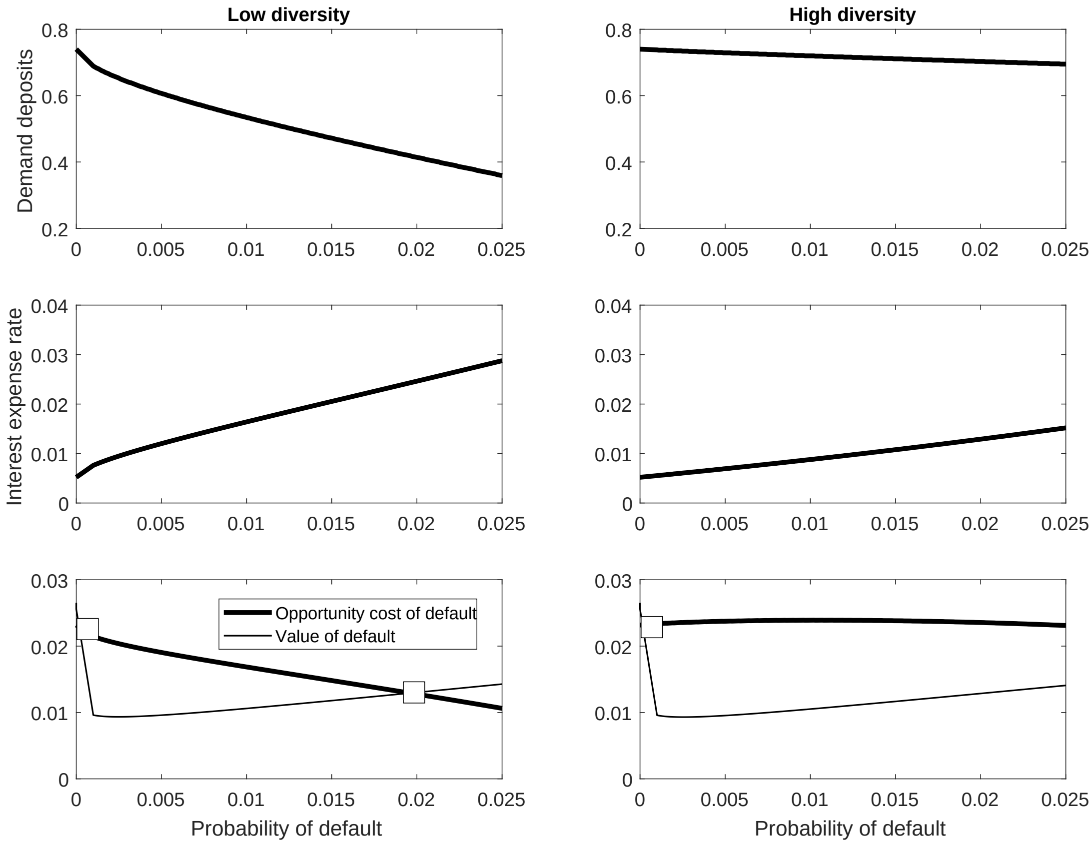
In general, depositors who are more risk-averse than the marginal depositor would demand a higher risk premium from a risky product (i.e., time deposits). Because the time deposit rate $i(y, \mathbf{s^d})$ is the minimum rate such that the marginal depositor weakly prefers time deposits to riskless bond, any depositor with higher η would find the rate generates a lower expected utility than the utility from riskless bond. Therefore, such a depositor would find time deposits unattractive and choose demand deposits that are as attractive as riskless bond to them. Vice versa, depositors who are less risk-averse than the marginal depositor would always find time deposits at least as attractive as riskless bond and demand deposits that are as attractive as riskless bond to them. Thus, depositors with RRA of $\eta > \eta^*(y)$ would choose demand deposits, whereas depositors with RRA of $\eta \leq \eta^*(y)$ would choose time deposits.

For numerical analysis, we compare two scenarios: "Low diversity" and "High diversity" in correspondence with "Uniform" and "Heterogeneous" scenarios in the previous numerical example under which the distribution of RRA is discrete.[30] Both scenarios of the current analysis assume the mean RRA of 1.9, which is identical to the scenarios in the previous numerical example. In the low-diversity scenario, the distribution of RRA has a variance of 0.01. In the high-diversity scenario, the distribution of RRA has a variance of 10. Except for the distribution of RRA, we keep using the same set of parameters that we use for the previous numerical example.

Figures A.1 and A.2 present the results that correspond to figures 4 and 5 in the previous numerical example. Figure A.1 suggests the high-risk equilibrium vanishes in the presence of moderate capital requirement only in the high-diversity scenario. Correspondingly, Figure A.2 shows the social return becomes substantially large in the presence of moderate capital requirement only in the high-diversity scenario. Figure A.1 also reveals the amount of demand deposits is constantly high and smooth in the high-diversity scenario, whereas it is discontinuously shifted up in the corresponding scenario of the previous numerical example. Although the high-risk equilibrium is eliminated due to relatively high demand deposits in the high-diversity scenario and the corresponding scenario in the previous numerical example, the distributional form of RRA alters the

[30] We note the definition and solution of equilibrium as well as the measure of efficiency is not structurally altered by the distributional form of RRA. Therefore, we can still use Definition 1, the measure of social return, and Propositions 1 and 2.

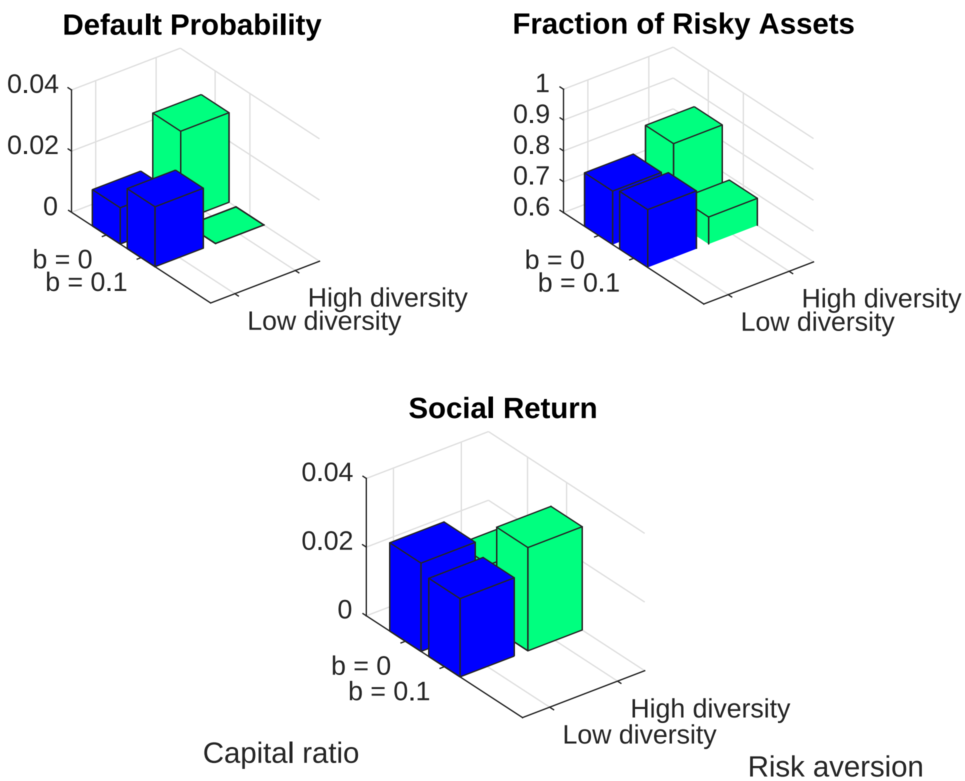
Figure A.1: Bank's Strategies and Equilibria (Continuous RRA Distribution)



Note: The figure presents the optimal level of demand deposits and interest expense rate as well as the opportunity cost and value of default for different levels of default probability (and corresponding asset risks) that depositors rationally anticipate. The opportunity cost and value of default are converted into corresponding flow items. We consider a 10% capital ratio ($b = 0.1$). The white rectangles represent equilibria in the bottom panels.

schedule for the opportunity cost of default through this difference. Overall, the result from this analysis is qualitatively similar to the corresponding result from the previous numerical example despite the difference in detail.

Figure A.2: Bank's Financial Stability (Continuous RRA Distribution)



Note: The figure presents the equilibrium risk and social return at the "worst" equilibrium. In the presence of multiple equilibria, we choose the one with the largest default probability, highest asset risk, and lowest social return.

A.3 Robustness

In this section, we performed multiple robustness checks for our empirical analysis.

One concern is that our proxies for risk preference may capture county characteristics that are not directly related to risk preference. In this case, our measure of risk preference heterogeneity may not be relevant for our study. For example, a depositor's educational attainment, which is likely to capture the availability of information about bank risk for a depositor, can be correlated with the risk preference of a depositor. Because a bank can improve its solvency by matching the riskiness of its securities to its depositors' insensitivity to bank risk, the heterogeneity in educa-

Table A.1: County Demographics

Variables
Percentage of population ages below 18
Percentage of population ages 65 and over
Percentage of African Americans
Percentage of American Indians/ Alaskan Natives
Percentage of Asians
Percentage of Native Hawaiians/ Other Pacific Islanders
Percentage of Hispanics
Percentage of population not proficient in English
Percentage of females
Percentage of rural population
Median household income
Percentage of children eligible for free lunch
Percentage of population ages 16 and older unemployed but seeking work
Percentage of children under age 18 in poverty
Averaged freshman graduation rate
Percentage of single-parent households

tional attainment, instead of risk preference heterogeneity, may cause our results. To address this potential issue, we first regressed each of our proxies on a comprehensive set of county demographics, which are listed in table A.1, and then used regression residuals as the components that generate risk preference indices. This process guarantees risk preference indices are orthogonal to any other county characteristic that could potentially co-move with risk preference.

After this process, we re-ran the benchmark regression model based on these *residual* risk preference indices. We report regression results in table A.2, in which column numbers correspond to equation numbers. In both columns, the coefficients on the interaction term, β, are still negative and as statistically significant as those reported in table 3. Moreover, the coefficients' magnitudes are similar to the corresponding estimates in table 3 for both columns. This result suggests our benchmark estimates stay robust to the control of county-level demographics that may co-move with risk preference index.

Another concern is that the estimated joint effect of risk-weighted bank capital and creditor heterogeneity in risk attitudes may reflect the heterogeneous effect of bank capital on bank risk.

Table A.2: Regression Results (Residual Risk Preference Index)

	(1)	(2)
Residual risk preference heterogeneity × Lagged risk weighted equity ratio	-0.793**	-1.079**
	(0.400)	(0.428)
Residual risk preference heterogeneity	0.0545	0.0903
	(0.0742)	(0.0767)
Lagged risk weighted equity ratio	0.0113	-0.0329
	(0.340)	(0.211)
Average residual risk preference	-0.0413***	-0.0380***
	(0.0143)	(0.0132)
Lagged log total assets	-0.645***	-0.484***
	(0.190)	(0.151)
Lagged log total assets squared	0.0214***	0.0161***
	(0.00656)	(0.00490)
Bank age	-0.00363*	-0.00429***
	(0.00220)	(0.000900)
Average HHI	0.132	0.0238
	(0.159)	(0.130)
Average unemployment rate	-0.0100	-0.0127*
	(0.00674)	(0.00693)
Average income growth	-0.00191	-0.0136
	(0.00175)	(0.00857)
Global systemically important banks	-0.699**	-0.500***
	(0.306)	(0.190)
Year dummies	X	X
Observations	3,927	3,927
R^2	0.275	0.163

Note: Socio-economic variables are observable only since 2011. The sample period is between 2011 and 2015. In column (2), we report between-R^2. Standard errors are in parentheses and clustered at bank level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

For example, if bank capital is negatively associated with bank risk for a larger bank, but not for a smaller bank, the estimated β can be negative, even if it is not driven by creditor heterogeneity in risk attitudes. To tease out this possibility, we re-ran the benchmark regression model while controlling for the interaction of bank size and risk-weighted equity ratio. We report regression results in table A.3. We find the estimate of β is similar to the benchmark estimate.

Overall, we obtain the regression results similar to our benchmark estimates.

Table A.3: Regression Results (Heterogeneous Impact of Bank Capital by Bank Size)

	(1)	(2)
Risk preference heterogeneity × Lagged risk weighted equity ratio	-0.991**	-0.922***
	(0.465)	(0.320)
Lagged log total assets × Lagged risk weighted equity ratio	0.475***	0.547***
	(0.169)	(0.143)
Risk preference heterogeneity	0.0723	0.0804
	(0.0692)	(0.0533)
Lagged risk weighted equity ratio	-6.718***	-7.851***
	(2.525)	(2.069)
Average risk preference	-0.0190*	-0.0170
	(0.0103)	(0.0109)
Lagged log total assets	-0.794***	-0.707***
	(0.220)	(0.162)
Lagged log total assets squared	0.0238***	0.0203***
	(0.00748)	(0.00515)
Bank age	-0.00357	-0.00454***
	(0.00237)	(0.000945)
Average HHI	0.163	0.0111
	(0.160)	(0.133)
Average unemployment rate	-0.00523	-0.00616
	(0.00733)	(0.00729)
Average income growth	-0.00199	-0.0174*
	(0.00199)	(0.00951)
Global systemically important banks	-0.912**	-0.732***
	(0.363)	(0.207)
Year dummies	X	X
Observations	4,790	4,790
R^2	0.425	0.329

Note: In column (2), we report between-R^2. Standard errors are in parentheses and clustered at bank level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.