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Liquidity Crises, Banking, and the Great Recession

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Flight-to-Liquidity and the Great Recession*

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Abstract

This paper argues that counter-cyclical liquidity hoarding by financial intermediaries may strongly amplify business cycles. It develops a dynamic stochastic general equilibrium model in which banks operate subject to financial frictions and idiosyncratic funding liquidity risk in their intermediation activity. Importantly, the amount of liquidity reserves held in the financial sector is determined endogenously: Balance sheet constraints force banks to trade off insurance against funding outflows with loan scale. The model shows that an aggregate shock to the collateral value of bank assets triggers a flight to liquidity, which amplifies the initial shock and induces credit crunch dynamics sharing key features with the Great Recession. The paper thus develops a new balance sheet channel of shock transmission that works through the composition of banks' asset portfolios rather than fluctuations in borrower net worth as in the financial accelerator literature.

Keywords: real business cycles; financial frictions; liquidity hoarding; bank capital channel; credit crunch.

JEL classification: E22; E32; E44.

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1 Introduction

The financial crisis of 2007-09 and the ensuing Great Recession have moved the role of frictions on financial markets in explaining business cycle fluctuations into the limelight of macroeconomic research. Previous studies have identified high levels of leverage achieved in the financial sector during the run-up to the crisis as a major risk factor (Figure 2). In contrast, this paper focuses on flight-to-liquidity by financial intermediaries as a key amplification mechanism of distress on financial markets. This research is motivated by the observation that banks started hoarding liquid assets to cover short-term liquidity needs as interbank-intermediation effectively broke down. In particular, unsecured lending stagnated due to opaque counter-party risk, while secured lending was impaired by a strong decline in the collateral value of financial assets. With financial institutions investing more heavily into liquid assets, less liquid investments were crowded out. This may have eventually disrupted the flow of credit into the economy.

The key argument of this paper is that counter-cyclical liquidity hoarding by financial intermediaries may strongly amplify financial-sector specific shocks.[1] More specifically, this paper presents a model in which banks operate subject to financial frictions and idiosyncratic funding liquidity risk in their intermediation activity. Funding liquidity risk arises from a maturity mismatch between banks' assets and liabilities. Optimal liquidity reserves trade off insurance against idiosyncratic liquidity risk with the amount of funds available for risky investment financing. The amount of liquidity reserves held in the financial sector is, thus, endogenously determined. The paper shows that an aggregate shock to the collateral value of bank assets triggers a flight to liquidity, which amplifies the initial shock and induces credit crunch dynamics sharing key features with the Great Recession. This amplification mechanism is absent in a frictionless economy. The paper thus develops a new balance sheet channel of shock transmission that works through the composition of banks' asset portfolios rather than fluctuations in borrower net worth as in the financial accelerator literature. Unconventional policy in the form of equity injections into stressed banks can attenuate this channel.

The availability of credit as a source of external funding is the pivotal link between the real and the financial sector. This link was disrupted during the Great Recession due to a liquidity crisis on financial markets. Many financial institutions faced liquidity needs as structured investment vehicles

[1] Following the convention in macroeconomics, cyclicality is defined with respect to the cycle of GDP throughout the paper. Labelling a variable as pro-cyclical thus indicates co-movement with GDP.

called on explicit or implicit guarantees by their parent companies to provide liquidity injections.[2] However, several markets, which in normal times provided institutional refinancing, broke down during the crisis: The market for asset-backed commercial paper started collapsing in late 2007, followed by a freeze in the unsecured interbank-market after the demise of Lehman Brothers epitomized by a surge in the TED spread (Brunnermeier, 2009; Heider et al., 2009). The market for repurchase agreements (repos), another pillar of short-term institutional finance, also became distressed with sharply rising haircuts on underlying collateral assets (Gorton and Metrick, 2010; Duffie, 2010; International Monetary Fund, 2008). Overall, the capacity of financial markets to intermediate liquidity between institutions broke down. The impact of these market freezes was exacerbated by the dominantly short-term funding structure among financial institutions, which concentrated funding needs at short horizons.

To insure against such risks, financial institutions took to hoarding liquidity. In the US, the flight-to-liquidity episode started in late 2007, manifested in a rising share of liquid assets in total balance sheet size as shown in Figure 4. In fact, liquidity shares were strongly counter-cyclical at least during the past decade both for traditional banks – with a contemporaneous cross-correlation of -0.46 –, and for shadow banks – with a contemporaneous cross-correlation of -0.40.[3] The hoarding of liquid reserves locked up funds otherwise available for investment into riskier assets thereby curtailing the lending capacity of the financial sector.[4]

I develop a theoretical framework to study the business cycle effects of flight to liquidity. To this end, the canonical Real Business Cycle model is extended to include agency costs in financial intermediation as well as liquidity risk. The setup follows the literature on delegated monitoring in that

[2]This was particularly the case for market-based financial intermediaries or shadow banks. This sector had outperformed growth in the traditional banking sector prior to the crisis, especially through the use of securitisation (Adrian and Shin, 2009, 2010). See Figure 3.

[3]In the US, the liquidity share of shadow banks seems to lead GDP with the highest cross-correlation of -0.50 at lag 2, while the share of traditional banks lags GDP with a maximum cross-correlation of -0.55 at lag 2 using quarterly data.

[4]I define liquid assets as the sum of checkable deposits and currency, cash and reserves at the Federal Reserve, Treasury securities as well as agency- and GSE-backed securities. Of course, if these are truly liquid assets from a macroeconomic viewpoint, they are expected to retain their value during a downturn, while riskier assets' prices would fall. Thus, the value of liquid assets relative to total balance sheet size would mechanically increase. However, the fact that liquidity buffers were not adjusted downwards in line with other asset prices suggests that a flight to liquidity occurred and banks' willingness to lend declined.

banks are introduced as efficient monitors that channel funds from investors to investment projects. Since monitoring is assumed to be privately costly, bank capital is needed to reduce the agency problem between banks and their outside investors. Fluctuations in bank capital affect the financial sector's capacity of financing loans and thus propagate shocks in the economy (bank capital channel of shock transmission).

In addition, banks are assumed to face idiosyncratic liquidity shocks. These are modelled as non-diversifiable withdrawals of external funds during the lifetime of loan projects. Economically, they amount to rollover risk arising from a maturity mismatch between bank-assets and bank-funding. The desire to insure against such shocks provides an incentive for banks to hold liquid reserves, which can be thought of as contingent credit lines from a mutual fund or uncommitted resources on banks' own balance sheets. These endogenously chosen liquidity reserves trade off two effects: On the one hand, they increase the probability that banks can accommodate funding outflows and investment projects survive idiosyncratic shocks. On the other, putting liquidity reserves aside locks up resources that cannot be used to increase the scale of bank-lending when investment decisions are taken. Moreover, they increase expected costs of monitoring, since only surviving projects need monitoring by assumption. Thus, intermediaries will only hold liquidity reserves up to some optimal threshold where the associated marginal benefit and costs are equal. Funding outflows over and above this threshold lead to the termination and inefficient liquidation of investment projects by the outside financiers.

Following evidence on rising haircuts in repo transactions for secured short-term finance, I introduce a shock to the liquidation - or collateral - value of bank assets as a novel type of aggregate risk.[5] This financial-sector-specific shock is intended to capture the effects of a revaluation of financial assets after the bursting of an asset price bubble, for instance, in an *ad hoc* fashion. Intermediaries react to such a shock by strengthening their liquidity cushions. This flight to liquidity unleashes a powerful amplification mechanism as liquidity buffers crowd out funds for bank lending (bank lending channel). These dynamics stand in sharp contrast to a frictionless economy where such crowding-out would not occur.

The model set-up is then used to evaluate the unconventional policy response adopted by the US and several Eurozone governments to contain the financial crisis. These consisted to a large extent in bail-out and recapi-

[5]The liquidation value of an investment project measures the extent to which it is reversible. This corresponds to the concept of *technological liquidity* as defined in Brunnermeier et al. (2012).

talization programs aimed at relieving the funding constraints of distressed financial institutions. In the model, such measures amount to wealth transfers from unconstrained households to credit constrained bankers, that are shown to cushion the impact of the aggregate liquidity shock.

In another extension, I investigate the interaction of nominal with financial frictions and liquidity hoarding. The model demonstrates how nominal rigidities may exacerbate the recessionary impact of a liquidity crisis.

1.1 Related Literature

This paper contributes to the growing body of literature on macro-financial linkages. It builds on two distinct strands of literature. The first strand analyses financial frictions as the source of business cycle fluctuations. At the heart of this research is the balance sheet channel as surveyed by Bernanke and Gertler (1995), i.e. the amplification and propagation of business cycles due to a financial accelerator mechanism arising from the feedback between borrowing constraints and asset fire-sales. Early research in this area focuses mainly on agency frictions between borrowers in the productive sector and their financiers. Townsend (1979) provides the microfoundations for a costly-state-verification problem between lenders and borrowers. Carlstrom and Fuerst (1997), Bernanke and Gertler (1989) and Bernanke et al. (1999) incorporate Townsend's framework into business cycle models to study the dynamic impact of such agency costs. Another, more recent, line of literature including Gertler and Karadi (2011), Gertler and Kiyotaki (2011) and Christiano et al. (2010) picks up on this agency cost framework in order to explicitly study financial frictions between investors and financial intermediaries. An alternative framework to motivate a role for banks follows Holmström and Tirole (1997). In their model, equity capital is required to overcome moral hazard problems in the funding of both firms and intermediaries. The business cycle implications of this bank capital channel are analyzed by Meh and Moran (2010), which is closely related to this paper.

However, the literature discussed so far cannot accommodate the notion of an endogenous choice between liquid and illiquid assets. I introduce this feature following a second strand of literature initiated by Holmström and Tirole (1998) and Kato (2006). The former develop a finite-horizon framework to motivate a demand for corporate liquidity reserves. The latter extends this structure to an infinite horizon environment to analyse the business cycle dynamics that result from liquidity risk at the corporate level. The model is able to replicate the counter-cyclical dependence on external finance by firms and the hump-shaped response of output to shocks observed in US data. Covas and Fujita (2010) expand this analysis by adding regulatory

capital requirements in the banking sector.

The present paper merges the literature on the role of bank capital in the business cycle with the model of liquidity demand due to Holmström and Tirole (1998). However, I depart from this previous research in a number of ways. First, liquidity risk is introduced at the bank level. Second, liquidty risk is modelled as funding risk rather than uncertain reinvestment needs as in the previous literature. Third, the collateral value of liquidated investment projects for banks' financiers is assumed to be non-zero. This allows shocks to the collateral value of bank assets to be introduced as a new source of aggregate risk.

Such financial-sector specific shocks have received considerable attention following the 2007-09 financial crisis. Meh and Moran (2010), for instance, investigate the business cycle properties of an exogenous shock to bank capital. They find the recessionary impact of such a shock to be fairly limited. In a related study, Gertler and Karadi (2011) model a shock to capital quality, which depresses the value of bank assets and triggers fire-sales due to a leverage constraint imposed on banks. The resulting credit crunch drives the economic downturn. Del Negro et al. (2011), on the other hand, explicitly consider a liquidity shock arising from a resaleability constraint on private paper.

A shock to the collateral value of bank assets has the benefit of being a very parsimonious approach towards capturing a financial-sector specific shock. Unlike Meh and Moran (2010), the shock does not operate directly on banks' equity capital, but rather exploits their balance sheet constraints. Unlike Gertler and Karadi (2011), it only assumes that the value of assets to *outsiders* declines, but not so to *insiders*.

The contribution of the paper is threefold: First, it introduces idiosyncratic funding liquidity risk arising from a maturity mismatch between financial assets and external finance into a dynamic stochastic general equilibrium framework. Second, it theoretically demonstrates that counter-cyclical liquidity hoarding acts as a powerful amplification mechanism of financial-sector specific shocks. This adds to the literature on the balance sheet channel of shock transmission. In contrast to earlier work, however, amplification works through the endogenous composition of balance sheets, i.e. the choice between liquid and illiquid assets, rather than fluctuations in the net worth of borrowers. The model can explain the flight-to-liquidity phenomenon as well as pro-cyclical lending and leverage observed during times of distress, such as the Great Recession. Third, the paper adds to the growing literature on unconventional policy in response to financial crises and shows how recessions can be mitigated by wealth transfers to borrowing constrained financial institutions.

The remainder of this paper is organized as follows. Section 2 develops the model. Section 3 presents the baseline calibration of the model as well as the aggregate shocks. Simulation results and their relation to previous work on the balance sheet channel and credit crunch scenarios are discussed in Section 4. This section also offers insights into unconventional credit policy and the role of nominal in addition to financial frictions. Section 5 concludes and suggests avenues for future research.

2 The Model

2.1 The environment

Consider an economy populated by four types of agents. There is a continuum of agents with unit mass comprised of a large fraction, η^h, of consumers (households) and a small fraction, $\eta^b = 1 - \eta^h$, of bankers. In addition, there is a continuum of capital good and final good producers, respectively.

There are two goods in the economy. Final or consumption goods are produced in a competitive market unafflicted with frictions. Capital goods are produced by entrepreneurs who possess a technology to convert final goods into capital goods. This technology is affected by idiosyncratic risk of failure.

Moreover, the financing of capital production is affected by a moral hazard. Capital producers can reduce the probability of failure by exerting unobservable effort at some private cost. Monitoring of investment projects by banks eliminates the option of shirking and induces effort, thereby alleviating the moral hazard problem between capital producing firms and their financiers. However, monitoring is assumed to be privately costly for the monitors. This gives rise to a second moral hazard problem between banks and their investors, i.e. depositors. These investors lack the ability to monitor and therefore deposit funds at banks and delegate the monitoring activity. Without sufficient bank capital financing loans to capital producers, the risk associated with loan portfolios would be mainly borne by investors and hence banks would not be compelled to conduct monitoring effectively. As a result, depositors require banks to put up sufficient own funds in the financing of capital goods.

Besides the financing constraint arising from moral hazard in capital production, banks operate subject to a second type of financial friction. Idiosyncratic liquidity shocks hit banks during the life-time of loan contracts in the form of non-diversifiable withdrawals of external funds. The desire to insure against such shocks provides an incentive for banks to hold liquid reserves.

2.2 Capital Good Producers

Capital good producers manage investment projects in order to produce new capital goods. They have access to a stochastic constant-returns-to-scale technology converting i_t units of consumption goods into Ri_t units of capital, if successful. This technology is subject to idiosyncratic risk: Projects are successful with probability π, yielding Ri_t, and fail with probability $1 - \pi$, yielding zero.

Additionally, the relationship between capital producing firms and their financiers is afflicted with moral hazard. Capital Producers can choose between projects with identical public unit return R when successful, but different probabilities of success and private benefits. Specifically, two types of projects are available:

	effort	shirking
probability of success	π_H	π_L
public return	R	R
private return	0	b

where $\pi_H > \pi_L$ and $b > 0$. Thus, shirking firms would enjoy a private benefit (in terms of capital goods) proportional to the project scale, i.e. bi_t, while reducing the probability of success to π_L. Absent monitoring, capital producers would have to be compensated for foregoing private benefits in order to exert effort.

However, when seeking external finance for their investment projects, entrepreneurs enter a close relationship with their lending banks. In this relationship, banks are assumed to have the capacity to detect shirking via some monitoring technology. Thus, a monitored firm is prevented from shirking which eliminates the moral hazard problem for capital producers. Capital production as such thus becomes frictionless, such that all returns from investment projects can be pledged to outside investors. Absent agency frictions, investments can be financed exclusively with external funds. Hence, capital good producers invest the funds they receive from banks, produce subject to idiosyncratic risk and return the entire proceeds to banks.

2.3 Bankers

While banks eliminate the agency friction in the capital production process, monitoring is taken to be privately costly so that a financial friction emerges in the intermediation of funds. In particular, the relationship between banks and their financiers is affected by moral hazard, since banks must earn a

minimum return in order to cover the private cost of monitoring. Therefore, they need to hold a stake in the monitored project financed by bank capital a_t.[6]

At the same time, banks engaged in financing and monitoring projects may be hit by idiosyncratic liquidity shocks. In contrast to Holmström and Tirole (1998), such shocks are modelled as random outflows of external funds that occur only after banks' resources have been committed in loan contracts. They may, thus, be thought of as rollover risk arising from a maturity mismatch between bank-assets and bank-funding. Assuming such idiosyncratic shocks at the bank-level serves as a short-cut for modelling heterogeneity in banks' funding structures.

Loan projects suffering from liquidity shocks in excess of reserves will be abandoned by banks and liquidated by outside investors. This motivates banks' demand for sufficient liquidity buffers to withstand such shocks. Liquidity reserves can be thought of either as liquid assets on banks' balance sheets such as idle consumption goods, stakes in a market portfolio or contingent credit lines from a mutual fund, which is introduced below. In any case, the liquidity buffer decreases the amount of available funds invested into illiquid assets.

To finance their investment into entrepreneurial projects, banks supplement their equity capital by raising funds from households through deposits. In order to achieve insurance for depositors against idiosyncratic risks, funds are not deposited with banks directly, however, but rather channelled through a mutual fund. The mutual fund makes use of the law large numbers by investing into the pool of all banks. By so pooling the idiosyncratic liquidity risks associated with capital good production, the fund can offer a riskless rate of return on deposits. Eliminating intra-period idiosyncratic risks completely thus ensures risk neutrality of households with respect to deposits.

2.3.1 Intra-period Financial Contract

The timing of events is as follows: Every period is divided into four subperiods (Figure 1). In the first subperiod, aggregate shocks are realized and production of final goods takes place. Capital goods production extends over the last three subperiods. In the second subperiod, financial contracts are negotiated between banks and investors. Since monitoring eliminates financing frictions between banks and capital producers, the latter are not part of these contracts. After successful negotiation, entrepreneurs finance their initial investments entirely through outside funding in the form of bank loans,

[6]The terms equity, capital and net worth will be used interchangeably throughout the paper.

i.e. $i_t = l_t$.[7]

In the third subperiod, liquidity shocks, i.e. random withdrawals of deposits occur. For computational convenience, these are assumed to be proportional to project size, rather than the amount of external finance. Accordingly, they take the form ωl_t, where the random variable $\omega \in [-\alpha, \alpha]$, $\alpha \in [0, 1)$ is distributed symmetrically around zero according to the cumulative distribution function $F(\omega)$ and density $f(\omega)$. Note that these distributional assumptions imply that there is no aggregate outflow of funds from the financial sector. Rather, the population of intermediaries will be split equally into liquidity-deficit banks experiencing funding outflows ($\omega \in [0, \alpha]$) and liquidity-surplus banks experiencing inflows of corresponding size ($\omega \in [-\alpha, 0]$) as shown in Figure 5.

Since at this stage investment projects have already been financed and are being executed, liquidity surpluses can only be stored in order to be paid out to depositors at the end of the period along with the proceeds from successful projects. Here, the crucial friction is that idiosyncratic liquidity risk cannot be traded away on interbank markets. This assumption may seem to staggeringly overstate the under-performance of interbank markets during normal times. However, liquidity risk in the model should be thought as the non-diversifiable part of liquidity risk, that induces financial institutions to hold liquidity reserves in their portfolios even during tranquil times. Accordingly, I will calibrate the model to match the long-term average of liquidity reserves in the U.S. financial sector.

Banks choose the optimal maximum amout of liquidity reserves $\bar{\omega}$ *ex ante* as part of the financial contract. Projects with funding outflows in excess of $\bar{\omega}$ are liquidated by the outside investor, i.e. the mutual fund, who can salvage a fraction ξ of the initial loan scale for depositors. Surviving projects are then implemented and entrepreneurs produce with effort under monitoring. Only at this stage banks need to monitor, incurring the cost μl_t in terms of final goods.[8] At the end of the fourth period, the remaining idiosyncratic risk is resolved and successful projects generate their return in new capital goods. All parties are payed according to their contracts.

To finance a loan of size $l_t > a_t$, a bank needs to raise $l_t - a_t$ plus monitoring costs and liquidity reserves through external financing. Banks raise this amount by combing their capital a_t with deposits d_t^b. I focus on equilibria where effort is induced for all bankers. The optimal financial contract then is a set $\{l_t, d_t^b, R_t^b, R_t^h, \bar{\omega}_t\}$ designed to maximise the expected return to banks.

[7] Due to the lack of entrepreneurial capital, bank loans effectively amount to outside equity stakes in entrepreneurial projects.

[8] In contrast to Townsend (1979), all surviving projects need to be monitored and not only those which are declared insolvent.

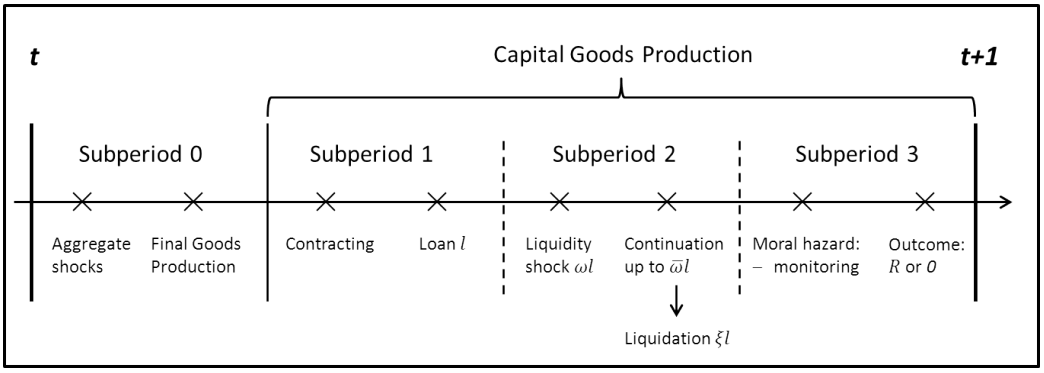

Figure 1: Timing

It specifies the level of loans l_t, the amount of deposits d_t^b, the distribution of total project return R to banks, R_t^b, and households, R_t^h, as well as the threshold level of the liquidity shock, $\bar{\omega}_t$, which banks can accommodate by tapping into their liquidity buffer. Liquidity shocks which exceed the liquidity buffer, i.e. $\omega_t > \bar{\omega}_t$, lead to the termination of the associated investment project. The *ex ante* probability of survival of an investment project is thus $\int_{-\alpha}^{\bar{\omega}} f(\omega)\,\mathrm{d}\omega = F(\bar{\omega})$ (Figure 5).

General equilibrium effects have an impact on the financial contract through the beginning-of-period relative price of capital q_t as well as the previously accumulated net worth of banks a_t. At the time of contracting, these are, however, exogenous. Since the contracting problem is entirely intra-period, I will omit the time subscript in the description of the optimal contract.

Formally, the contract maximises banks' expected return from loans to entrepreneurs subject to incentive compatibility, participation, and feasibility constraints:

$$\max_{\{l,d^b,R^b,R^h,\bar{\omega}\}} qF(\bar{\omega})\pi_H R^b l$$

s.t.

$$qF(\bar{\omega})\pi_H R^b l - F(\bar{\omega})\mu l \geq qF(\bar{\omega})\pi_L R^b l \tag{1}$$

$$q\left\{F(\bar{\omega})\pi_H R^h + (1-F(\bar{\omega}))\xi + F(0)\left[\int_0^{\bar{\omega}} \omega f(\omega)\,\mathrm{d}\omega - \int_{-\alpha}^{0} \omega f(\omega)\,\mathrm{d}\omega\right]\right\} l \geq d^b \tag{2}$$

$$d^b + a \geq \left(1 + F(\bar{\omega})\mu + q\int_0^{\bar{\omega}} \omega f(\omega)\,\mathrm{d}\omega\right) l \tag{3}$$

$$R = R^b + R^h \tag{4}$$

The objective function accounts for the fact that the probability of success-

fully executing a project of scale l is $F(\bar{\omega})\pi_H$, since the ex ante probability of a non-excessive liquidity shock is $F(\bar{\omega})$, and the probability of yielding non-zero output is π_H.[9] As indicated by their incentive compatibility constraint (1), bankers need to be compensated with $R^b \geq \frac{\mu}{q(\pi_H - \pi_L)}$ in order to monitor entrepreneurs. Equation (2) is the participation constraint of households. It requires that the share of the expected return to intermediation activity accruing to households be sufficient to pay back the intra-period deposits lent to the financial sector at the beginning of the period. This return comprises three parts: First, the expected return to households of successful loan projects $qF(\bar{\omega})\pi_H R^h l$; second, the expected liquidation value of loan projects terminated due to illiquidity $q(1-F(\bar{\omega}))\xi l$; third, the expected amount of unused liquidity. This consists of the sum of liquidity buffers $q\left(\int_0^{\bar{\omega}} \omega f(\omega)\,\mathrm{d}\omega\right) l$ and liquidity inflows $q\left(-\int_{-\alpha}^{0} \omega f(\omega)\,\mathrm{d}\omega\right) l$ at liquidity-surplus bank, times the probability of becoming a surplus-bank $F(0)$. The balance sheet constraint (3) ensures that banks' internal and external funds cover their expected expenses consisting of loans inclusive of monitoring costs related to surviving projects, $(1 + F(\bar{\omega})\mu)l$, as well as the buffer set aside to accommodate anticipated funding outflows $q\left(\int_0^{\bar{\omega}} \omega f(\omega)\,\mathrm{d}\omega\right) l$. This buffer decreases the amounts of funds available for loans.[10]

Finally, (4) states that the returns to individual agents from a successful project add up to the total return.

In equilibrium, all constraints hold with equality. Solving constraints (1)

[9] Correspondingly, the law of large numbers implies that out of L units of final goods invested in the aggregate, only a fraction $\pi_H F(\bar{\omega})$ of projects are expected to be successful because of the two types of idiosyncratic risk.

[10] Note that $(F(\bar{\omega}) - F(0))\mathbb{E}(\omega|0 \leq \omega \leq \bar{\omega}) = \int_0^{\bar{\omega}} \omega f(\omega)\,\mathrm{d}\omega$, i.e. an individual bank does not hold liquidity reserves amounting to $\bar{\omega}$ per unit of loan, but rather an amount equal to the expectation of ω truncated at zero from below and at the liquidity threshold $\bar{\omega}$ from above. Due to the idiosyncratic character of liquidity risk, this ensures that aggregate liquidity reserves will suffice to cover aggregate liquidity demand by deficit banks. However, a risk-pooling scheme is required to redistribute liquidity among banks, i.e. from institutions with shocks *short* of expected liquidity needs to those with *excessive* shocks. I assume that the mutual fund can provide contingent liquidity backstops to intermediaries and thus possesses the required risk-pooling capacity. Alternatively, liquidity could be reshuffled between intermediaries via a stock market. To that end, intermediaries would issue equity in subperiod 1, the proceeds of which they could use to finance their loans and to purchase a stake in the market portfolio. In subperiod 2 they would sell off their stock holdings to consumers. Banks with high shock realizations could use the proceeds to cover their liquidity gap, while intermediaries with excess liquidity would pay out dividends. As shown in Holmström and Tirole (2011) this scheme also efficiently redistributes liquidity.

- (3) for l gives the loan function

$$\begin{aligned} l &= \frac{a + d^b}{1 + F(\bar{\omega})\mu + q\int_0^{\bar{\omega}} \omega f(\omega)\,\mathrm{d}\omega} \\ &= \frac{a}{1 + F(\bar{\omega})\mu + q\int_0^{\bar{\omega}} \omega f(\omega)\,\mathrm{d}\omega - J(\bar{\omega})} \\ &\equiv \frac{a}{H(\bar{\omega})} \end{aligned} \tag{5}$$

where $J(\bar{\omega}) \equiv q\left\{F(\bar{\omega})\pi_H R^h + (1 - F(\bar{\omega}))\xi + F(0)\left[\int_0^{\bar{\omega}} \omega f(\omega)\,\mathrm{d}\omega - \int_{-\alpha}^{0} \omega f(\omega)\,\mathrm{d}\omega\right]\right\}$.

Banks' loan scale is thus linear in outside and inside financing. In particular, it is linear in banks' net worth with a leverage ratio of $H(\bar{\omega})^{-1} > 1$. Plugging the investment function back into the objective and maximizing over $\bar{\omega}$ yields the first order condition

$$1 = q\left\{(1 - F(0))\int_0^{\bar{\omega}} F(\omega)\,\mathrm{d}\omega + \xi - F(0)\int_{-\alpha}^{0} \omega f(\omega)\,\mathrm{d}\omega\right\} \equiv Q(\bar{\omega}) \tag{6}$$

Which trade-off pins down the optimal threshold for banks' liquidity demand and ensures an interior solution for $\bar{\omega}$? Increasing the liquidity buffer raises the marginal profitability of an investment from the point of view of the bank, since it will survive larger liquidity shocks, $\frac{\partial F(\bar{\omega})}{\partial \bar{\omega}} > 0$. This comes at the cost of tightening the funding constraint (3) for two reasons: On the one hand, the amount of funds committed to liquidity reserves increases. On the other, more resources will likely have to be spent on monitoring as the probability of survival increases. Both effects bind external funds and hence decrease the amount of financing available for genuine loans, i.e. $\frac{\partial l}{\partial \bar{\omega}} < 0$ as can be gleaned from the stylized balance sheet:

bank balance sheet	
l	a
$\mu F(\bar{\omega})l$	d^b
$q\int_0^{\bar{\omega}} \omega f(\omega)\,\mathrm{d}\omega\, l$	

The trade-off between the (internal) marginal and the (external) level effect is also illustrated in Figure 6. As shown in the lower panel, the expected return to banks clearly achieves a maximum at $\bar{\omega}$.

Note that in the presence of the agency conflict between banks and depositors there are projects with liquidity shocks beyond $\bar{\omega}$ that carry *positive* net present value and are still liquidated. With complete financial markets, i.e. in the absence of agency costs associated with monitoring, funding for such

projects would be readily available. Banks could pledge the returns from investment projects fully to outside investors. Projects would then be refinanced as long as the liquidity shock did not exceed the expected investment return (since initial investments are sunk at this point). The "first-best" refinancing cut-off in the absence of financial frictions due to moral hazard would thus be $\omega_1 = \min(\alpha, \pi_H R)$ (Holmström and Tirole, 1998; Kato, 2006). However, given the agency problem between depositors and banks, the latter can only pledge a fraction of the expected project return and become credit constrained. More specifically, the amount that can be pledged to depositors after the liquidity shock is $\omega_0 = \pi_H R^h = \pi_H(R - R^b) \leq \omega_1$. For shocks that exceed the pledgeable return outside funding is unavailable.[11] Hence, choosing $\bar{\omega} > \omega_0$ in order to increase the marginal profitability of investment to the bank involves a trade-off: With given funds on the liability side of banks' balance sheets, any increase in liquidity reserves comes at the expense of lower initial investment scale as no further resources are available to increase the asset side. Due to these inefficiencies, the refinancing threshold under agency costs is clearly smaller than in the absence of financial frictions, $\bar{\omega} < \omega_1$ (Figure 6).

2.3.2 Evolution of Bank Capital

The economy is inhabited by a continuum of risk-neutral bankers of constant mass η^b. $1 - \tau^b$ bankers exit every period and are replaced with assetless bankers. At the beginning of each period, bankers rent out their accumulated capital stock k_t^b and supply one unit of labour inelastically to final good producers. After final goods production is completed, they earn the respective factor rents. Labour income provides small positive start-up funds even to assetless new bankers.

Bank net worth at this stage is composed of the depreciated capital stock, capital gains and factor rents, i.e.

$$a_t = (q_t(1 - \delta) + r_t)k_t^b + w_t^b \tag{7}$$

The banker invests his entire capital into a loan project yielding $R_t^b l_t$ if successful and zero if unsuccessful as described above. The proceeds can either

[11] This feature makes outsiders' beginning-of-period funding decisions time-consistent. They do not have any incentive to renegotiate and provide further resources to the bank after liquidity shocks exceeding ω_0 have been realized, since these projects have negative net present value for outsiders.

be saved or consumed. The inter-temporal flow of funds is thus

$$\begin{aligned} c_t^b + q_t k_{t+1}^b &= (1 + r_t^a) a_t \\ &= q_t F(\bar{\omega}_t) \pi_H R_t^b l_t \end{aligned}$$

Saving the entire proceeds from investment-funding in end-of-period capital goods represents the optimal consumption-savings-decision for successful surviving bankers due to the high internal return on loans. Unsuccessful agents lose all their net worth and, accordingly, neither save nor consume. Exiting bankers consume their entire assets.

The ad hoc assumption of a stochastic survival probability for bankers ensures the stationarity of aggregate bank capital. In other words, if bankers did not exit the economy to consume their assets they would eventually accumulate enough wealth to finance investments exclusively with internal funds.

2.4 Final Good Producers

Final good producers operate on a competitive, frictionless market. They use capital (K_t) rented from households or bankers and labour from households (H_t^h) as well as bankers (H_t^b) as inputs into production and operate a technology which is subject to stochastic total factor productivity ($\exp(z_t)$).

$$Y_t = \exp(z_t) F(K_t, H_t^h, H_t^b) \tag{8}$$

Factors earn their marginal product, such that the interest rate on capital is $r_t = \exp(z_t) F_K(K_t, H_t^h, H_t^b)$ and wages are given by $w_t^i = \exp(z_t) F_{H^i}(K_t, H_t^h, H_t^b)$ for $i \in \{b, h\}$.

2.5 Households

There exists a continuum of households of mass η^h. Households are risk-averse and maximise utility over consumption c_t^h and labour h_t^h subject to their individual budget constraints. The sequence of events is as follows: At the beginning of each period, households lend previously accumulated capital k_t^h to final goods producers and supply labour to the same sector. Both factors are remunerated with their respective rents. Likewise, last period's bonds pay a gross riskless return $1 + r_t^b$. Capital depreciates at rate δ.

Then households make their consumption-savings decision. Since riskless bonds are in zero net surply, savings (in terms of consumption goods) are entirely channelled to banks. After these have performed their intermediation activity and investment projects generate returns, q_t units of new capital

goods are transferred to households for every unit of savings input. The optimization problem thus takes the form

$$\begin{aligned}\max_{\{c_t^h, k_{t+1}^h, b_{t+1}^h, h_t^h\}} & E_0 \sum_{t=0}^{\infty} \beta^t u(c_t^h, h_t^h) \\ & s.t. \\ & c_t^h + q_t k_{t+1}^h + b_{t+1}^h = (1 + r_t^b) b_t^h + (q_t(1-\delta) + r_t) k_t^h + w_t^h h_t^h \end{aligned} \tag{9}$$

The corresponding first order conditions for consumption, capital stock, bonds and labour supply read

$$u_{c,t} = \lambda_t \tag{10}$$

$$\lambda_t = \beta E_t \left[\lambda_{t+1} \frac{q_{t+1}(1-\delta) + r_{t+1}}{q_t} \right] \tag{11}$$

$$\lambda_t = \beta E_t \left[\lambda_{t+1} (1 + r_{t+1}^b) \right] \tag{12}$$

$$u_{h,t} = -\lambda_t w_t^h \tag{13}$$

where (11) and (12) are the Euler equations with respect to capital and bonds, respectively.

2.6 Aggregation

Due to linearities in the financing and production of capital goods, aggregation turns out to be straightforward. In particular, the production technology for new capital goods and monitoring costs are linear in loans. The distribution of bank capital, therefore, has no effect on aggregate loans L_t and investment $I_t = L_t$, which are simply the sum of individual loans:

$$\begin{aligned} L_t &= \eta^b l_t \\ &= \frac{\eta^b a_t}{H(\bar{\omega}_t)} \\ &= \frac{A_t}{H(\bar{\omega}_t)} \end{aligned} \tag{14}$$

The second step derives from the individual loan function (5).

The economy-wide equivalent to depositors' participation constraint (2)

pins down aggregate deposits.

$$\eta^b d_t = q_t \left\{ F(\bar{\omega}_t)\pi_H R_t^h + (1 - F(\bar{\omega}_t))\xi + F(0) \left[\int_0^{\bar{\omega}_t} \omega f(\omega)\, \mathrm{d}\omega - \int_{-\alpha}^{0} \omega f(\omega)\, \mathrm{d}\omega \right] \right\} L_t \tag{15}$$

Aggregate stocks of capital holdings are the sum of individual stocks.

$$K_t^b = \eta^b k_t^b, \quad K_t^h = \eta^h k_t^h \tag{16}$$

The elasticity of labour supply differs across agents. Bankers individually supply one unit of labour inelastically, while households' supply is elastic.

$$H_t^b = \eta^b, \quad H_t^h = \eta^h h_t^h \tag{17}$$

Individual positions add up to aggregate bank net worth.

$$A_t = (q_t(1 - \delta) + r_t)K_t^b + H_t^b w_t^b \tag{18}$$

Surviving bankers invest all their funds into new capital goods due to risk-neutral preferences and the high internal return. The average internal return on loans for these agents is $F(\bar{\omega})\pi_H R^b l_t$. Since only a fraction τ^b survives, next period's capital holdings by the banking sector will be

$$K_{t+1}^b = \tau^b F(\bar{\omega}_t)\pi_H R_t^b L_t \tag{19}$$

Exiting bankers consume their wealth and aggregate household consumption amounts to the sum of individual households' consumption.

$$C_t^b = (1 - \tau^b) q_t F(\bar{\omega}_t)\pi_H R_t^b L_t \tag{20}$$

$$C_t^h = \eta^h c_t^h \tag{21}$$

2.7 Market Clearing Conditions and Competitive Equilibrium

In equilibrium, markets clear. The corresponding conditions are given by

$$K_t = K_t^b + K_t^h \tag{22}$$

$$H_t = H_t^b + H_t^h \tag{23}$$

$$q_t L_t = q_t I_t \tag{24}$$

$$K_{t+1} = (1-\delta)K_t + F(\bar{\omega}_t)\pi_H R I_t \tag{25}$$

$$B_t = 0 \tag{26}$$

$$\begin{aligned} Y_t &= C_t^h + C_t^b + (1 + F(\bar{\omega}_t)\mu)\, I_t \\ &+ q_t \left(\int_0^{\bar{\omega}} \omega f(\omega)\, \mathrm{d}\omega - (1 - F(\bar{\omega}))\xi - F(0) \left[\int_0^{\bar{\omega}} \omega f(\omega)\, \mathrm{d}\omega - \int_{-\alpha}^{0} \omega f(\omega)\, \mathrm{d}\omega \right] \right) I_t \end{aligned} \tag{27}$$

Equation (22) defines the aggregate capital stock as the sum of capital held by households and bankers. Likewise, aggregate labour is the sum of labour supplied by the two different agents (23). Investment projects are entirely financed through banks, such that aggregate gross investment equals the aggregate loan volume (24). (25) is the law of motion of aggregate capital equating capital supply and demand. Net aggregate investment $F(\bar{\omega}_t)\pi_H R I_t$ reflects the fact that only a fraction $F(\bar{\omega}_t)\pi_H$ of projects survive the different shocks and turn out to be productive. Bonds are in zero net surply ((26)). Finally, the aggregate resource constraint (27) states that available resources are spent on aggregate consumption, gross aggregate investment, monitoring costs, liquidity buffers less the liquidation value of illiquid projects and unused liquidity reserves.

A competitive equilibrium of the economy is a collection of (i) decision rules for $c_t^h, k_t^h, b_{t+1}^h, h_t^h$ that solve the maximization problem of households; (ii) decision rules for K_t, H_t^b, H_t^h that solve the maximization problem of final good producers; (iii) decision rules for $l_t, d_t^b, R_t^b, R_t^h, \bar{\omega}_t$ that solve the maximization problem of banks associated with the financial contract; (iv) consumption c_t^b and saving k_{t+1}^b rules for banks, and the above market clearing conditions.

3 Calibration and Functional Forms

Period-utility - defined over consumption and hours worked - takes the following functional form:

$$u(c_t^h, h_t^h) = \frac{c_t^{h^{1-\theta}}}{1-\theta} + \nu \ln(1 - h_t^h) \tag{28}$$

The parameter θ governs the degree of relative risk aversion or - equivalently - the elasticity of intertemporal substitution of consumption. It is set to a standard value of 1.5 following Kato (2006). The weight on leisure, $\nu = 2.713$, is chosen to match a fraction of working time of 30%. Additionally, households' discount factor assumes a standard value of 0.99, which yields a riskless quarterly interest rate of 1%.

Final goods are produced with a standard Cobb-Douglas technology

$$F(K_t, H_t^h, H_t^b) = K_t^{\alpha^k} H_t^{h^{\alpha^h}} H_t^{b^{\alpha^b}} \tag{29}$$

where $\alpha^k + \alpha^h + \alpha^b = 1$. I follow Meh and Moran (2010) in setting the capital share of output to 0.36 and the share of labour provided by bankers to a very small number (5×10^{-5}), such that its effect on the dynamics is negligible.

Capital production is characterized by two parameters. A quarterly depreciation rate of capital of $\delta = 0.025$ is in line with many RBC studies of the US Economy including King and Rebelo (1999), Kato (2006) and Covas and Fujita (2010).

There is less precedent for the second parameter choice, R - the return to investment in capital production. I calibrate this parameter such that the total expected return to investment is one with full buffering of liquidity shocks, i.e. $\pi_H R = 1$. As elaborated on in section 2.3.1, absent banks' funding frictions all positive net present value projects would be refinanced after the realization of the liquidity shock. In this case, the continuation threshold for investment projects would be equal to the upper bound of the distribution of ω, since $\omega_1 = \min(\alpha, \pi_H R) = \min(\alpha, 1) = \alpha$. Given insurance up to the first-best threshold, the return to investment *before* the realization of the liquidity shock would then be $F(\omega_1)\pi_H R = F(\alpha)\pi_H R = 1$.

Financial intermediation and the associated frictions are characterized by the set of parameters $\{\mu, \xi, \pi_H, \pi_L, \sigma^2(\omega)\}$. The subset $\{\mu = 0.348, \xi = 0.2, \sigma^2(\omega) = 0.65\}$ is jointly determined to match (i) a bank-leverage ratio, defined as the ratio of debt to equity, of 13.44. This corresponds to the average leverage ratio of the US financial sector composed of bank- and market-based financial institution over the past 30 years (Figure 2).[12] (ii) the

[12]Note that no data on leverage ratios was available for ABS issuers, which make up an

liquidation value to outsiders of a project that has failed due to an excessive liquidity shock. Based on Covas and Fujita (2010), I calibrate this parameter to match an average loss given default (LGD) on bank loans of roughly 40%. In the model, the LGD corresponds to

$$LGD = 1 - \frac{q\xi I}{I - A}$$

(iii) the share of liquid assets in banks' balance sheets. In the model, these are defined as the uncommitted resources, i.e. the liquidity buffer, relative to total balance sheet size

$$\kappa = \frac{q_t \int_0^{\bar{\omega}} \omega f(\omega)\, \mathrm{d}\omega\, L_t}{A_t + D_t} \tag{30}$$

As the empirical counter-part I use the sum of cash, central bank reserves as well as all government-backed assets relative to balance sheet size. The evolution of this liquidity share for banks and market-based intermediaries is shown in Figure 4. While the ratio varied widely - between 13% to 30% for banks and 2% to 23% for shadow banks - over the past three decades, the model targets the average empirical liquidity share of about 19%. The underlying distribution of idiosyncratic liquidity shocks is truncated normal on the interval $[-0.4, 0.4]$.

The parameters π_H and π_L capture the idiosyncratic failure risk of entrepreneurs under effort and shirking. Following Meh and Moran (2010), I set $\pi_H = 0.9903$, which translates into a quarterly failure rate of entrepreneurs of 0.97%, as in Carlstrom and Fuerst (1997), and $\pi_L = 0.75$.

The key matched moments and their model-equivalents are summarized in Table 2. The full set of calibrated parameters including the remaining population parameters is listed in Table 1.

3.1 Aggregate shocks

I consider two types of aggregate risk in the economy. The first is a standard technology shock that follows the process $z_t = \rho z_{t-1} + e_t$. I set $\rho = 0.9$ and the standard deviation of the normally distributed white noise process e_t to $\sigma = 0.007$, as is common in the business cycle literature (see, for instance, King and Rebelo (1999), Kato (2006)).

important fraction of the market-based intermediation sector as demonstrated in Figure 3. Since market-based intermediaries' leverage tends to exceed that of traditional banks, the average leverage of 13.44 computed for the financial sector without ABS issuers is downward-biased in Figure 2. Hence, the target is certainly not exaggerated.

The second source of aggregate risk is a collateral shock. I model this shock as a collapse in the liquidation value of bank loans to outside investors, i.e. a negative shock to ξ. This liquidation value can be interpreted as the collateral value of bank assets. Gorton and Metrick (2010) investigate the development of the collateral value of bank assets during the Great Recession by looking at the most important market for short-term refinancing among market-based financial intermediaries, the repo market. They argue that haircuts on the underlying assets in repo transactions amount to a decrease in the collateral values of these assets. During the financial crisis, and particularly in the wake of the Lehman crash in September 2008, haircuts applied to subprime-related securities surged, as even non-subprime-related assets suffered haircuts of up to 20% (see Figure 2 in Gorton and Metrick, 2010). This evidence is supported by a study of funding conditions for hedge funds on repo markets, which indicates increases in haircuts across all asset classes (see Box 1.5 in International Monetary Fund, 2008). This run in the repo market was a key amplification and propagation mechanism of financial risk that triggered the gridlock in the financial sector. Accordingly, I use the evidence on the decline in collateral values of non-subprime-related structured products of 20% as my calibration target for the standard deviation of the aggregate liquidity shock. The shock is modelled as $\xi^* = \xi + z_t^{\xi}$ where $z_t^{\xi} = \rho_{\xi} z_{t-1}^{\xi} + e_t^{\xi}$ and $e_t^{\xi} \sim \mathcal{N}(0, \sigma_{\xi} = 0.06)$[13]. This amounts to a far more conservative crisis scenario than found in Del Negro et al. (2011), who rather calibrate the standard deviation of their liquidity shock on the much larger haircut on subprime-related securities.

4 Results

In this section I present my main findings regarding business cycle dynamics in the presence of idiosyncratic liquidity risk and a balance sheet channel of shock transmission working through banks. The model is solved using a first-order approximation to the policy functions around the non-stochastic steady state.

[13]Due to the proprietary nature of data on haircuts in repo-markets, there is no obvious calibration target for the persistence of the collateral shock. I somewhat arbitrarily set it to the same value as the persistence of the technology shock, i.e. $\rho_{\xi} = 0.9$, and perform a sensitivity analysis with respect to this parameter (chapter 4.5).

4.1 Aggregate Technology Shock

The impulse response functions of key aggregate variables to a one-standard deviation technology shock are shown in Figure 7. For comparison, the impulses of the frictionless benchmark model without agency costs, but identical technological constraints are presented in the appropriate panels. Recall from the discussion in section 2.3.1 that in the absence of agency costs the first-best refinancing threshold is constant at $\omega_1 = \min(\alpha, \pi_H R)$. Since propagation effects due to financial frictions are shut off in this environment, real variables follow the AR(1) structure of the productivity shock. Thus, the key difference between the two models is the slightly hump-shaped and more sluggish response of output and investment in the agency-cost framework. This contrast is driven by the behaviour of bank capital as explained in detail below.

The technology shock depresses productivity in the final goods sector which reduces factor rents. Households react to lower expected rental income from holding capital by reducing their demand for new capital goods. This, in turn, puts downward pressure on the price of capital, q_t. The fall in the capital price reduces the share of loan returns accruing to households as can be seen from the aggregate analogue to households' participation constraint, equation (15). As a consequence, the share of deposits in financing investment projects of size L_t needs to decline. Conversely, the share of bank capital has to rise. However, since bank capital is - to the largest extent - accumulated from retained earnings, its immediate reaction to the shock is limited.

The drop in deposits implies that the liability-side of banks' balance sheets contracts. With bank capital being sluggish, intermediaries are forced to deleverage by curtailing lending in order to shorten their asset side. Therefore, bank lending drops on impact by as much as 4.7%. The model, thus, exhibits pro-cyclical bank lending and leverage. Due to the one-to-one relationship between bank lending L_t and gross investment I_t, the latter drops on impact, too, and recovers sluggishly. The response of net investment output, $F(\bar{\omega}_t)\pi_H R I_t$, is driven by that of gross investment.

The depressed value of investment projects as well as the decrease in aggregate investment eat into banks' earnings and reduce their future net worth. This triggers second-round effects and thus propagates the initial shock over time (capital channel of shock propagation). Bank capital plummets by about 4.8% three quarters after the shock and then slowly reverts back to the steady state. As a result of the sluggishness of equity capital, the response of output to technology shocks becomes slightly hump-shaped with its trough at -1.5%.

In addition to the dynamics of bank capital and lending, the response of liquidity buffers is a key aspect of the model. As the first order condition (6) for the liquidity threshold, $\bar{\omega}$, suggests, the marginal liquidity buffer is negatively correlated with the relative price of capital.[14] Intuitively, a fall in the price of capital reduces the marginal profitability of loans. To compensate this loss, bankers raise their marginal liquidity buffers. Hence, $\bar{\omega}$ increases slightly (0.5%). Total liquidity demand

$$L_t^D = q_t \int_0^{\bar{\omega}} \omega f(\omega)\, \mathrm{d}\omega\, L_t \tag{31}$$

falls nonetheless, since the increase of marginal reserves is outweighed by the drop in the price of capital and the scale of lending. However, it falls less than in the frictionless environment where marginal reserves stay constant. The share of liquid assets in banks' balance sheets κ_t increases, on the other hand. Overall, these effects are rather small and do not amplify the technology shock.

4.2 Aggregate Collateral Shock and the Great Recession

Consider now a shock to the collateral value of bank assets. As mentioned in chapter 1.1, this shock operates on the balance sheet constraints of financial intermediaries. In particular, a drop in the collateral value tightens the participation constraint of households (2). As explained below, banks react to this by increasing their liquidity buffers. The financial shock will, thus, unfold its adverse effects through its impact on liquidity hoarding. These dynamics can be traced in the impulse responses shown in Figure 8.

In order to disentangle the effect of agency problems and liquidity hoarding from the impact of the collateral shock as such, consider first the frictionless benchmark version of the model. As described in sections 2.3.1 and 4.1, the first-best liquidity threshold equals the expected return from investment projects $\omega_1 = min(\alpha, \pi_H R) = \alpha$. In other words, in the absence of agency problems between investors and banks liquidity shocks are fully insured, such that liquidation does not occur, i.e. the probability of surviving

[14] By the Implicit Function Theorem (IFT)

$$\frac{\partial \bar{\omega}}{\partial q} = -\frac{\partial Q/\partial q}{\partial Q/\partial \bar{\omega}}$$
$$= -\left\{(1-F(0))F(\bar{\omega})\left[(1-F(0))\int_0^{\bar{\omega}} F(\omega)\,\mathrm{d}\omega + \xi - F(0)\int_{-\alpha}^{0} \omega f(\omega)\,\mathrm{d}\omega\right]\right\}^{-1} \leq 0$$

a future liquidity shock is $F(\omega_1) = F(\alpha) = 1$. As a consequence, the drop in the collateral value of liquidated projects is inconsequential and has no impact at all on the economy.

Matters look quite different in the economy perturbed by agency conflicts. Here, banks optimally respond to a drop in the collateral value ξ by increasing their liquidity threshold $\bar{\omega}$ as implied by the first-order condition (6).[15] Intuitively, intermediaries need to increase the non-liquidation (i.e. continuation) value of bank loans when the liquidation value falls in order to keep marginal profitability constant. As discussed before, a higher liquidity threshold immediately raises the survival probability of investment projects. Given the trade-off between liquidity reserves and loan scale, this comes at the cost of a contraction in lending. It is not clear *ex ante*, which effect dominates. $\bar{\omega}$ rises by as much as 29% on impact of the shock. This results in a decrease in lending of 2.8%. The credit crunch clearly dominates the effect of higher liquidity reserves, as suggested by the response of net investment

$$I_t^{net} = F(\bar{\omega}_t)\pi_H R I_t \tag{33}$$

which drops by 5.3% on impact. The strong decline in investment drives the response of output: the economy experiences a recession with a loss of 1.1% in the first quarter after the shock - a figure comparable to a recession induced by a TFP-shock. Since the shock directly affects intermediaries' balance sheet constraints, the response of the liquidity threshold $\bar{\omega}$ follows the shock's AR(1) structure and is, thus, much more prolonged than in the case of a technology shock. Intermediaries' liquidity share κ_t increases in line with the liquidity buffer. Again, banks hoard liquidity in a counter-cyclical fashion thereby crowding out lending. Contrasting these results with the response of the frictionless benchmark economy, where the trade-off between liquidity and scale is absent, reveals *liquidity hoarding* by financial intermediaries as the key mechanism which amplifies the initial collateral shock and drives the recession.

Secondly, since bank capital is a stock variable that reacts sluggishly, the decrease in lending is accommodated by a cut-back in external financing, inducing deposits to fall by about 3.1% on impact. Hence, counter-cyclical liquidity hoarding indirectly causes bank leverage to become pro-cyclical. The model can thus rationalize the scramble for liquidity and strong deleveraging

[15] By the IFT,

$$\frac{\partial \bar{\omega}}{\partial \xi} = -\frac{\partial Q/\partial \xi}{\partial Q/\partial \bar{\omega}} = -\frac{1}{(1-F(0))F(\bar{\omega})} \leq 0 \tag{32}$$

of financial intermediaries observed in the data during the Great Recession (Figures 4 and 2, respectively).

Although the initial aggregate shock is amplified through a balance sheet channel, the effects in this model are quite distinct from the financial accelerator framework. In models of the latter kind, fluctuations in borrower net worth affect the borrowing capacity of financially constrained agents. Negative shocks to borrower net worth induce fire-sales which increase the initial losses and lead to further fire-sales. In the present model, the financial shock rather works through the composition of the asset side of constrained borrowers' balance sheets between illiquid and liquid assets. Borrower net worth only drops as a consequence of the negative impact of the credit crunch on investment and the capital stock, but does not cause the crunch. Hence, the model develops a novel type of shock transmission through borrower balance sheets.

Note, further, that the recessionary dynamics in the model are attenuated by households' reaction to the shock. A drop in the collateral value of bank assets tightens the participation constraint of depositors, as it makes saving less attractive. Therefore, households substitute away from saving into consumption. The strong rise in consumption of around 2.1% on impact prevents the economy from sliding into an even deeper recession.[16]

Substitution into consumption occurs despite the rise in the capital price. This rise is due to the fact that the collateral shock leaves the marginal productivity of capital unaffected while supply of capital goods drops.[17] Capital gains due to this price increase also generate the initial jump in bank capital.

Finally, the shock is propagated in much the same way as a technology shock. Depressed investment eats into banks' capital stock, forcing them to curtail lending in future periods as well. The sluggish response of bank capital thus translates into hump-shaped lending, investment, and output. Interestingly, the model is able to replicate this hump-shaped response without recourse to adjustment costs, solely through balance sheet dynamics.

The key insight from this analysis is that even a modest drop in the collateral value of assets held in the financial sector triggers a flight to liquidity

[16] In a benchmark model without nominal rigidities, Del Negro et al. (2011) find that the real interest rate decreases and consumption increases following a liquidity shock. The attenuating effect of rising consumption on output is so strong, that their model only generates a very mild recession. In the presence of price rigidities and a zero lower bound on the nominal interest rate, the real interest rate increases in response to a liquidity shock inducing households to cut back on consumption. Only in this scenario their model predicts a severe recession. This finding suggests nominal frictions as a natural extension of the current set-up (see section 4.4).

[17] This shortcoming is shared by models without alternative means of saving as observed in Kiyotaki and Moore (2012).

associated with strong recessionary pressures. This insight appears critical against the backdrop of a financial crisis which saw large revaluations over a wide range of asset classes.

4.3 Unconventional Policy

During the Great Recession, measures to relieve funding constraints of financial institutions were the cornerstone of unconventional crisis policies. In this vein, the US Government launched the Troubled Asset Relief Program (TARP) and the Federal Reserve adopted extensive bailout and liquidity assistance programs. Modelling unconventional policy in the present framework aims at evaluating the efficacy of such ad hoc crisis measures. The following experiment draws on related attempts to model unconventional credit market policies by Gertler and Karadi (2011), Del Negro et al. (2011) and De Groot (2011).

The distribution of wealth in frictionless RBC models with complete information is irrelevant for the dynamics of real variables. In contrast, models with agency costs are sensitive to the distribution of wealth. In the present model, bankers are endogenously credit constrained. Hence, transfers of wealth from households to bankers – a measure akin to an equity injection ultimately financed by a tax on consumers – will expand the amount of loans extended to the capital-good producing sector. Accordingly, unconventional credit policy is assumed to be aimed at containing the drop in bank capital and lending. Fluctuation in the liquidity share $\kappa_t = \frac{L_t^D}{A_t+D_t}$ on bankers' balance sheets is a measure of the distortion introduced by the agency cost in this model, and, therefore, a potential target for credit policy.

To implement unconventional policy, the wealth transfer is set to be a fraction of the beginning-of-period total net worth of the banking sector, i.e.

$$\begin{aligned} A_t &= A_t^b + A_t^g \quad \text{where} \\ A_t^b &= (q_t(1-\delta) + r_t)K_t^b + w_t^b H_t^b \\ A_t^g &= g_t A_t \end{aligned} \tag{34}$$

with $g_t \in [0,1]$. The policy instrument is determined according to the rule

$$g_t = \gamma^{inst} \min\left(\frac{\kappa_t}{\kappa} - 1, 1\right) \tag{35}$$

Total net worth in the financial sector available for loan-financing thus becomes

$$A_t = \frac{1}{1-g_t} A_t^b \tag{36}$$

The government has access to two funding sources: a lump-sum tax on households as well as bonds issued to the household sector. Hence, the government can run a deficit in the short-run by financing the wealth transfer primarily through debt. Inter-temporal solvency is ensured, however, by a sufficiently stringent tax rule. Specifically, taxes are proportional to government debt, $T_t = \gamma^{tax} B_t$. The government budget balances earnings and expenses:

$$B_{t+1} = \gamma^{eff} S_t + (1 + r_t^d) B_t - T_t \tag{37}$$

where $\gamma^{eff} > 1$ is an efficiency cost associated with government intervention.

Figure 9 compares impulse responses to an aggregate liquidity shock in the presence and absence of unconventional policy. In the simulation exercise, the efficiency cost parameter is set to $\gamma^{eff} = 1.01$, the policy instrument to $\gamma^{inst} = 0.2$ and the parameter of the tax rule to $\gamma^{tax} = 0.3$. With this calibration, the policy instrument rises to 0.09 on impact, indicating that the government acquires 9% of finacial sector equity as an immediate response to the liquidity shock. Since bankers' capital savings amount to 1.1% of steady state GDP, this initial intervention corresponds roughly to a redistribution of 0.1% of GDP, or about $15bn for the US economy. The ratio of government debt to GDP peaks at 2.6% six quarters after the shock, or $370bn in terms of the size of the US economy. Thus, the overall extent of this policy intervention is sizeable, but still modest compared to the expansion of the Federal Reserve balance sheet by over $1tn and the $430bn disbursed through TARP over the course of the Great Recession.

The policy response is strong enough to make bank net worth A_t increase during the duration of the shock, i.e. it off-sets the dampening impact on net worth that increased liquidity buffers exert through a lower lending scale. An increase in bank net worth relaxes the endogenous borrowing constraint and boosts the lending capacity of banks by a factor equal to the leverage ratio $H(\bar{\omega})^{-1}$. Thus, lending falls less and recovers faster under the policy intervention, which translates into smaller losses and accelerated recovery of net investment as well as output.

As this exercise shows, unconventional credit policy in the guise of a wealth transfer to credit constrained agents is able to mitigate the adverse effects on output of a liquidity squeeze. However, this policy analysis has important limitations. For instance, it ignores perverse incentive effects of unconventional policies on the risk-appetite of financial institutions as well as the potential adverse effect of distortionary rather than lump-sum taxes. Similarly, this exercise lacks an explicit welfare analysis to justify the policy intervention. Nonetheless, it does reveal the key mechanisms that *can* make unconventional policy work.

4.4 Financial and Nominal Frictions

During the Great Recession, financial frictions are likely to have interacted with nominal rigidities. Christiano et al. (2011), for instance, emphasize the Fisherian debt-deflation mechanism according to which deflationary pressures inflate the real value of nominal debt. At the same time, nominal frictions affect the consumption-savings decisions of households through their impact on the real interest rate. As mentioned in section 4.2 (footnote 16), rising real interest rates are key for explaining the strong output losses experienced during the Great Recession in the model of Del Negro et al. (2011). The same mechanism deepens the recession triggered by a liquidity shock in the present model.

To see why, I add nominal rigidities in product markets to the model setup. Assume an additional layer in the production process in the form of monopolistically competitive intermediate goods producers. Final goods are assembled from intermediate goods via a standard Dixit-Stiglitz aggregation technology with finite elasticity of substitution between different varieties of intermediate goods. Intermediary producers use their market power to price their goods at a mark-up over marginal costs. Moreover, they face price adjustment costs as in Rotemberg (1982), such that they do not adjust prices fully in response to variations in demand for their respective goods. Optimal price setting, thus, yields the familiar forward-looking New Keynesian Phillips Curve.[18]

$$\pi_t(\pi_t - 1) = Y_t \frac{\epsilon}{\chi}\left[mc_t - \frac{\epsilon - 1}{\epsilon}\right] + \mathbb{E}_t \frac{\beta\lambda_{t+1}}{\lambda_t}(\pi_{t+1} - 1)\pi_{t+1} \tag{38}$$

Monetary policy is assumed to react to deviations of inflation and output from their respective non-stochastic steady states according to the following rule:

$$i_t^d = (1 - \rho_i)i^d + \rho_i i_{t-1}^d + (1 - \rho_i)\left[\rho_\pi(\pi_t - \pi) + \rho_y(y_t - y)\right] \tag{39}$$

Following Faia (2010), I calibrate the elasticity of substitution between intermediate good varieties to $\epsilon = 6$ and the parameter governing price adjustment costs to $\chi = 29$. These choices are also consistent with estimates of the slope coefficient of the log-linear Philipps Curve as derived from the Calvo-Yun model (Galí and Gertler, 1999). The coefficients of the policy reaction function derive from those estimated in Clarida et al. (2000), i.e. $\rho_\pi = 1.5$, $\rho_i = 0.8$, $\rho_y = 0.1$.

[18] For a detailed derivation see Appendix 6.

How do price rigidities affect the propagation of aggregate liquidity shocks in the model? As the impulse responses in Figure 10 reveal, nominal frictions exacerbate the effect of liquidity shocks on output significantly compared to the baseline model with flexible prices.

The stronger decline in output, particularly in the first four quarters after the shock, results both from a further decline in investment as well as a more muted rise in consumption. As saving becomes relatively less attractive after a liquidity shock in the flexible-price baseline, households substitute into consumption. With price rigidities, however, the liquidity shock triggers deflation. Since the nominal interest rate lags economic dynamics, deflation causes the real interest rate to rise until the monetary authority reacts by cutting the nominal rate more aggressively. Higher real interest rates, of course, tilt households towards saving rather than consuming. Unsupported by a strong consumption boom the output decline is much stronger. The interaction of financial with nominal frictions is, hence, an important factor in explaining the severity of the recession. This observation underscores the importance of effective monetary policy and hints at the potential distortions introduced by the zero lower bound.

4.5 Sensitivity Analysis

The least common parameters in the model are those related to financial intermediation, in particular $\{\mu, \xi\}$. Figure 11 displays impulse responses to a technology shock for different values of μ. As this analysis reveals, a sufficient degree of agency costs is crucial for generating the hump-shaped response of output. The key variable in this context is bankers' capital. Higher monitoring costs worsen the agency problem between investors and bankers and require higher compensation for bankers to exercise monitoring. Conversely, the return to investors per unit of loan drops. This negative income effect amplifies the fall in capital demand, which is reflected in the more volatile price of capital. According to optimality condition (6), banks compensate for depressed capital prices by increasing their liquidity buffers. Thus, bank capital is partially shielded from the decline in asset prices and becomes more sluggish. This greater sluggishness translates into lending, investment and, ultimately, output. In sum, bank capital introduces persistence into the model. Changes in the liquidation value of bank assets work in the same direction (Figure 12). Importantly, neither variation changes the qualitative behaviour of the model.

Figure 13 reveals that the model implications are also robust to variations in the persistence of the collateral shock. Crucially, even a completely non-persistent drop in the collateral value of bank assets is amplified through

the balance sheet mechanism identified in section 4.2, i.e. liquidity hoarding. Moreover, some - albeit mild - degree of propagation still obtains due to the sluggishness of bank capital. Altogether, model dynamics are thus found to be robust to a wide range of variation in critical parameters.

5 Conclusion

This paper presents a dynamic stochastic general equilibrium model that studies the interaction between financial frictions and idiosyncratic funding liquidity risk at the bank-level. Bank capital is important in the model, since it mitigates a moral hazard problem between investors and financial intermediaries. Due to an endogenous leverage ratio, bank capital determines the amount of deposits that can be attracted for lending. Demand for liquidity buffers arises from the anticipation of funding outflows during the execution phase of investment projects. Balance sheet constraints force banks to trade off liquidity reserves with initial loan scale.

A shock to the collateral value of bank assets is introduced as a novel source of aggregate risk. Intermediaries react to such a financial-sector specific shock by hoarding liquidity. This makes investment projects safer at the expense of smaller initial loan scale as more idle resources are kept on the books. The level effect dominates such that net investment falls and economic activity contracts sharply. Decreases in bank capital propagate shocks through time and induce a hump-shaped response of output. This credit crunch scenario shares key aspects with the Great Recession, which was triggered by losses on financial assets resulting in a flight to liquidity and a lending squeeze. In the model as in the data, a flight to liquidity occurs and both lending and leverage become pro-cyclical. The key contribution is the identification of a new, quantitatively important type of amplification mechanism working through endogenous portfolio choices of financial intermediaries regarding liquid and illiquid assets. This paper thus contributes to the growing body of literature merging macroeconomic models with financial frictions.

Unconventional credit policy in the form of a wealth transfer from households to credit constrained bankers is shown to mitigate the adverse effects of a liquidity squeeze on output. Nominal frictions, on the other hand, may interact with financial frictions to render business cycle dynamics much more volatile.

Going forward, the model could be extended along two dimensions. A first focus would be a broader analysis of unconventional policy, which may take the form of either direct recapitalizations or direct lending by the gov-

ernment or the central bank. It would be particularly interesting to study the stabilizing potential of unconventional monetary policy at the zero lower bound in the spirit of Del Negro et al. (2011). A second extension would seek to introduce more heterogeneity at the bank level. Frictions in markets for short-term liquidity as in Kharroubi and Vidon (2009), Diamond and Rajan (2005) or Heider et al. (2009), for instance, would explicitly account for an interbank liquidity market that can break down under unfavourable conditions. This extension would allow to meaningfully study regulatory liquidity requirements and liquidity injections in times of liquidity crises.

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c

6 Technical Appendix

6.1 Derivation of the NK Phillips Curve

In the extended model, final goods producers assemble intermediate goods via a Dixit-Stiglitz aggregator

$$Y_t = \left[\int_0^1 Y_{it}^{\frac{\epsilon-1}{\epsilon}} \, \mathrm{d}i\right]^{\frac{\epsilon}{\epsilon-1}} \tag{40}$$

where ϵ is the elasticity of substitution between different varieties of intermediate goods. From the optimization problem of final goods producers demand for intermediate goods is given by

$$Y_{it} = \left[\frac{P_{it}}{P_t}\right]^{-\epsilon} Y_t \tag{41}$$

where P_t is the aggregate price level and P_{it} the price of variety i. Demand from intermediate producers thus depends on the relative price of their product as well as the elasticity of substitution.

Intermediate producers use capital and labour as input into their production function

$$Y_{it} = \exp(z_t) F(K_{it}, H_{it}^h, H_{it}^b) \tag{42}$$

Their optimization problem can be broken down into two separate steps: a cost minimization step in the production of a given quantity of intermediate goods and a price-setting step. To minimize costs, intermediate producers solve

$$\min_{\{K_{it}, H_{it}^h, H_{it}^b\}} r_t K_{it} + w_t^h H_{it}^h + w_t^b H_{it}^b - mc_{it}[exp(z) F(K_{it}, H_{it}^h, H_{it}^b) - Y_{it}] \tag{43}$$

where the Lagrange multiplier can be interpreted as the marginal cost of the firm. The first order conditions to this problem yield

$$r_t = mc_{it} \exp(z_t) F_K(K_t, H_t^h, H_t^b) \tag{44}$$

$$w_t^h = mc_{it} \exp(z_t) F_{H^h}(K_t, H_t^h, H_t^b) \tag{45}$$

$$w_t^b = mc_{it} \exp(z_t) F_{H^b}(K_t, H_t^h, H_t^b) \tag{46}$$

and by implication

$$\frac{H_t^j}{K_t} = \frac{H_{it}^j}{K_{it}} = \frac{\alpha^j}{\alpha^k} \frac{r_t}{w_t^j} \tag{47}$$

$$\frac{H_t^h}{H_t^b} = \frac{H_{it}^h}{H_{it}^b} = \frac{\alpha^h}{\alpha^b} \frac{w_t^b}{w_t^h} \tag{48}$$

for $j = h, b$. Hence, marginal costs are independent of firm-specific variables

$$mc_t = \exp(z_t) \left(\frac{r_t}{\alpha^k}\right)^{\alpha^k} \left(\frac{w_t^h}{\alpha^h}\right)^{\alpha^h} \left(\frac{w_t^b}{\alpha^b}\right)^{\alpha^b} \tag{49}$$

In a second step, intermediate producers set their optimal relative price given quadratic price adjustment costs subject to their individual demand schedule

$$\max_{\{P_{it}\}} \mathbb{E}_t \sum_{s=t}^{\infty} \Lambda_{s,t} \left\{ \left[\frac{P_{is}}{P_s} - mc_s\right] Y_{is} - \frac{\chi}{2} \left[\frac{P_{is}}{P_{is-1}} - 1\right]^2 \right\} \tag{50}$$

subject to $Y_{is} = \left[\frac{P_{is}}{P_s}\right]^{-\epsilon} Y_s$. Let $\tilde{p}_t = \frac{P_{it}}{P_t}$. In a symmetric equilibrium all intermediaries set the same price such that $\tilde{p}_t = 1$. After some manipulations, the first order condition then yields a forward-looking NK Phillips Curve

$$\pi_t(\pi_t - 1) = Y_t \frac{\epsilon}{\chi} \left[mc_t - \frac{\epsilon - 1}{\epsilon}\right] + \mathbb{E}_t \frac{\beta \lambda_{t+1}}{\lambda_t} (\pi_{t+1} - 1)\pi_{t+1} \tag{51}$$

The second sector directly affected by the introduction of nominal rigidities is the household sector. Households now choose the level of nominal rather than real bonds

$$\begin{aligned} \max_{\{c_t^h, k_{t+1}^h, b_{t+1}^h, h_t^h\}} & E_0 \sum_{t=0}^{\infty} \beta^t u(c_t^h, h_t^h) \\ & s.t. \\ & c_t^h + q_t k_{t+1}^h + \frac{b_{t+1}^h}{P_t} = (1 + i_t^d)\frac{b_t^h}{P_t} + (q_t(1-\delta) + r_t)k_t^h + w_t^h h_t^h \end{aligned} \tag{52}$$

and the first order condition for b_{t+1}^h accordingly becomes

$$\lambda_t = \beta E_t \left[\lambda_{t+1} \frac{(1 + i_{t+1}^d)}{\pi_{t+1}}\right] \tag{53}$$

7 Tables and Figures

Table 1: Baseline calibration

	Parameter	Value	Target/Source
Preferences			
Households' discount factor	β	0.99	riskless interest rate: 1%
Relative Risk aversion	θ	1.5	Kato (2006)
Utility weight on leisure	ν	2.713	working time: 30%
Final goods production			
Capital share of output	α^k	0.36	Meh and Moran (2010)
Labour share of output (Households)	α^h	0.63995	Meh and Moran (2010)
Labour share of output (Bankers)	α^b	0.00005	Meh and Moran (2010)
Capital goods production			
Depreciation rate of capital	δ	0.025	Kato (2006)
Return to investment	R	1.0098	one-to-one transformation
Financial Intermediation			
Unit-monitoring cost	μ	0.348	bank-leverage ratio: 13.44
Liquidtation value to outsiders	ξ	0.2	loss-given-default: 39.8%
Probability of success: effort	π_H	0.9903	quarterly failure rate: 0.97%
Probability of success: shirking	π_L	0.75	Meh and Moran (2010)
Std. dev., idiosync. liquidity risk	$\sigma(\omega)$	0.65	liquidity share: 18.78%
Population parameters			
Mass of households	η^h	0.97	Meh and Moran (2010)
Mass of bankers	η^b	0.03	Meh and Moran (2010)
Share of surviving bankers	τ^b	0.0786	stationarity of net worth
Shock processes			
Persistence, productivity shock	ρ	0.9	Kato (2006)
Std. dev., productivity shock	σ	0.007	Kato (2006)
Persistence, liquidity shock	ρ_ξ	0.9	see sensitivity analysis
Std. dev., liquidity shock	σ_ξ	0.04	repo haircut: 20%

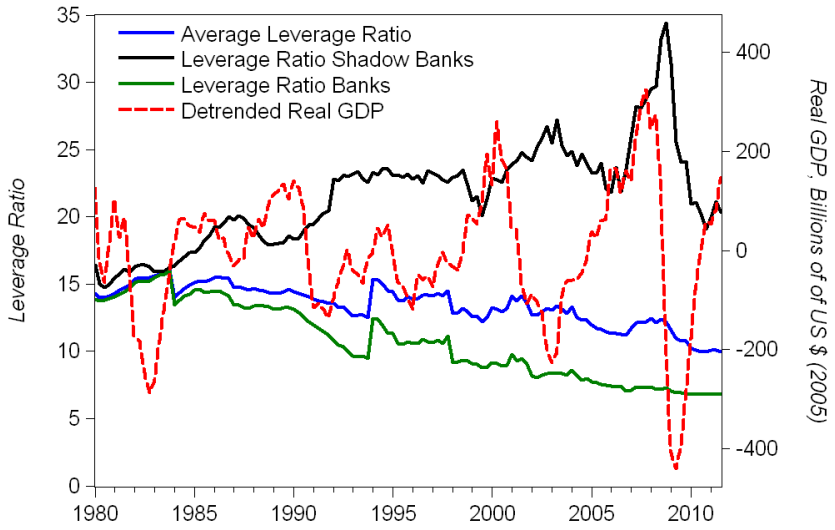
Notes: The model is calibrated for quarterly data.

Table 2: Selected Moments: Data vs. Model

Moment	Concept	Data	Model
Average leverage ratio	$\frac{\eta^h D}{A}$	13.44	14.16
Loss given default	$1 - \frac{q\xi I}{I-A}$	39.8%	40.74%
Share of liquid assets	$\frac{q_t \int_0^{\bar{\omega}} \omega f(\omega)\, \mathrm{d}\omega\, L_t}{A+D}$	18.78%	18.09%

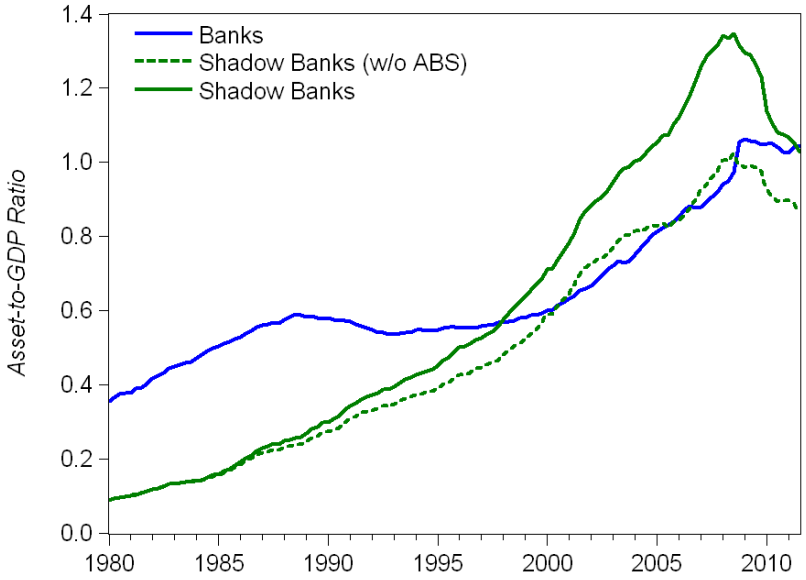
Notes: The average leverage ratio of the US financial industry is an asset-weighted average of the average leverage of bank- and market-based institutions. Due to lack of data for ABS issuers, this value is likely to be downward-biased. Data on loss given default derives from Araten et al. (2004), who report the default experience of a large US bank between 1982 and 1999. The empirical counterpart to the liquidity share is computed as the sum of checkable deposits and currency, cash and reserves at the Federal Reserve, Treasury securities, agency- and GSE-backed securities relative to total assets of the respective institutions. Source: US Flow of Funds (Federal Reserve), Araten et al. (2004)

Figure 2: Leverage Ratios of Bank- vs. Market-based Intermediaries



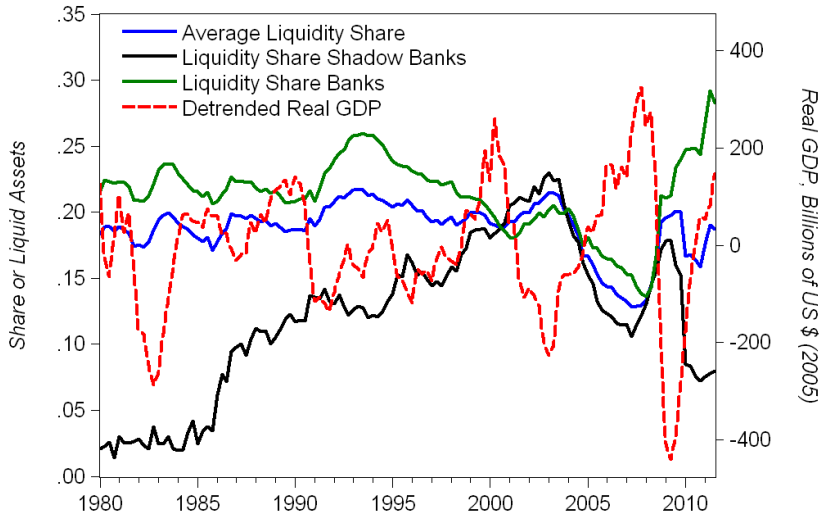
Notes: US-chartered commercial banks, savings institutions and credit unions are identified as traditional banks. The shadow banking sector comprises securities and broker dealers, issuers of asset-backed securities, finance companies and Government-sponsored enterprises. This follows the classification in Adrian and Shin (2009). The leverage ratio is defined as the ratio of debt to equity. Source: US Flow of Funds (Federal Reserve)

Figure 3: Asset-to-GDP Ratio of Bank- vs. Market-based Intermediaries



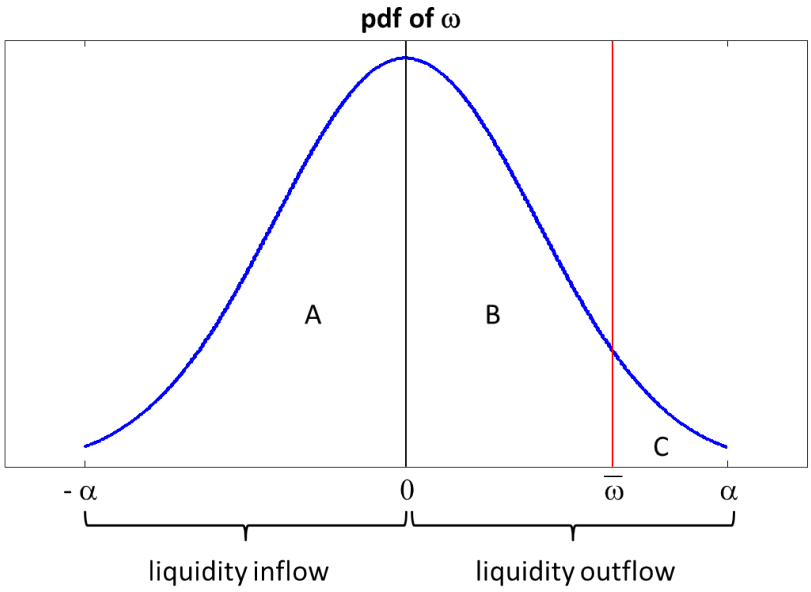
Source: US Flow of Funds (Federal Reserve)

Figure 4: Share of Liquid Assets of Bank- vs. Market-based Intermediaries



Notes: The liquidity share is computed as the sum of checkable deposits and currency, cash and reserves at the Federal Reserve, Treasury securities, agency- and GSE-backed securities relative to total assets of the respective institutions. Source: US Flow of Funds (Federal Reserve)

Figure 5: Distribution of Idiosyncratic Funding Liquidity Shocks



Notes: Banks operate subject to idiosyncratic funding outflows ωl, where ω is a normally distributed random variable on the support $[-\alpha, \alpha]$. Area A shows the density of liquidity inflows. The expected liquidity inflow of a surplus-bank is given by $-\int_{-\alpha}^{0} \omega f(\omega)\,\mathrm{d}\omega$ per unit of loan. Area B designates the density of liquidity outflows that are buffered with liquidity reserves. Accordingly, the liquidity buffer banks hold on their balance sheets is $\int_{0}^{\bar{\omega}} \omega f(\omega)\,\mathrm{d}\omega$ per unit of loan. Finally, C corresponds to the liquidation area where projects suffer from funding outflows larger than the upper threshold $\bar{\omega}$. The ex ante probability of liquidation is $1 - \int_{-\alpha}^{\bar{\omega}} f(\omega)\,\mathrm{d}\omega = 1 - F(\bar{\omega})$, while the probability of survival is $F(\bar{\omega})$.

Figure 6: Optimal Threshold for Liquidity Reserves

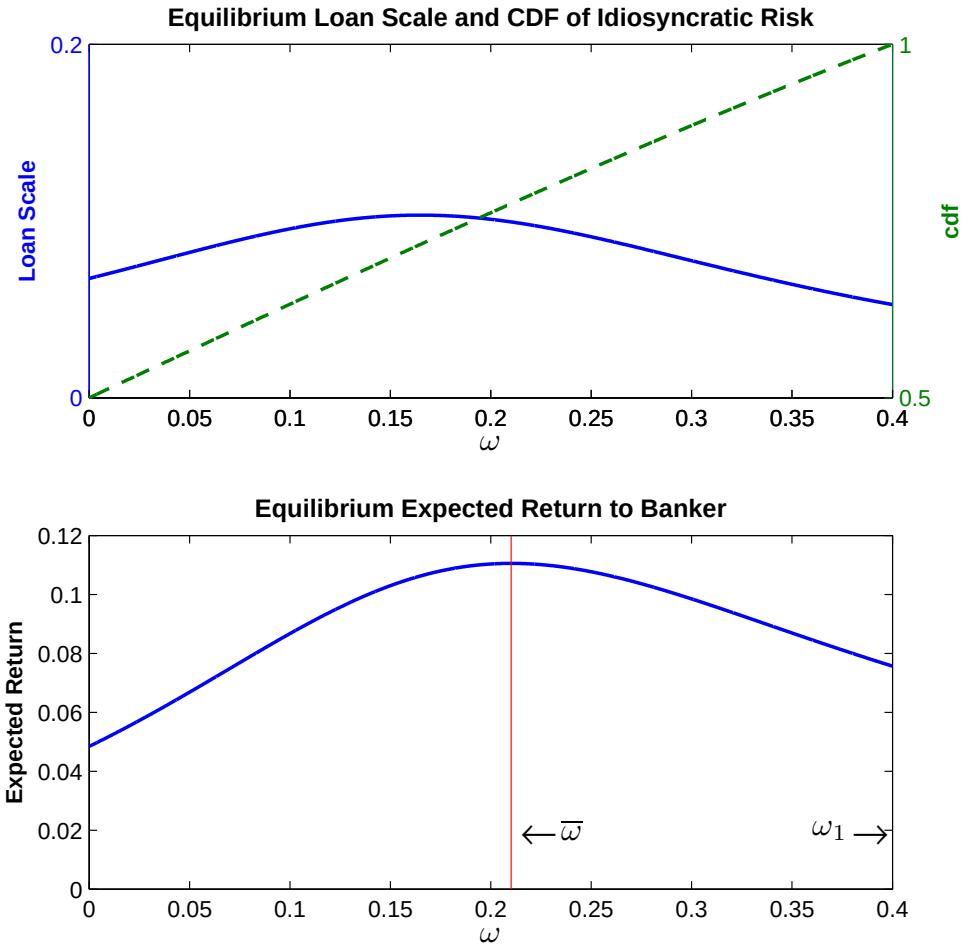
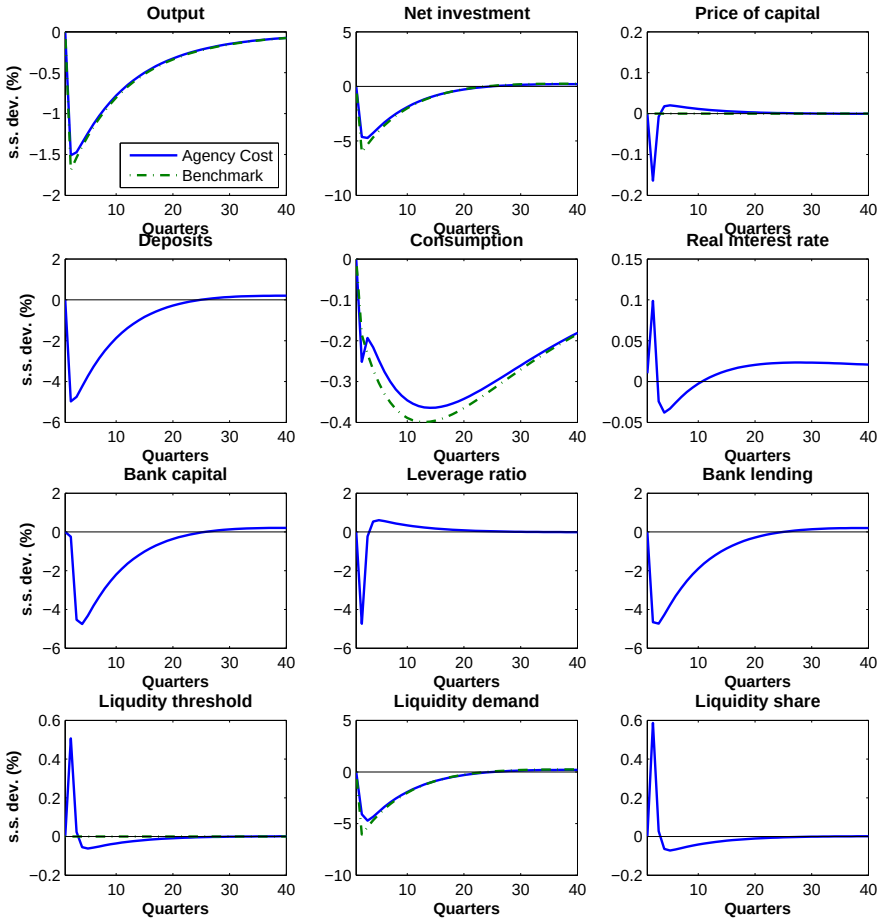
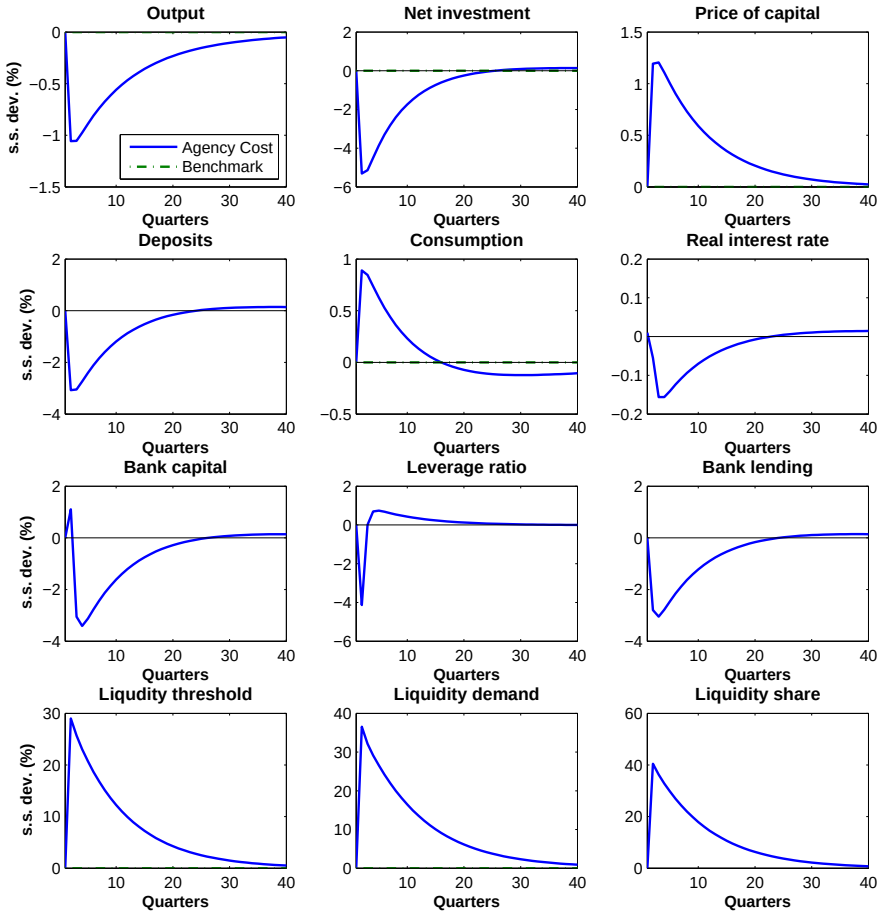


Figure 7: Responses to a Technology Shock



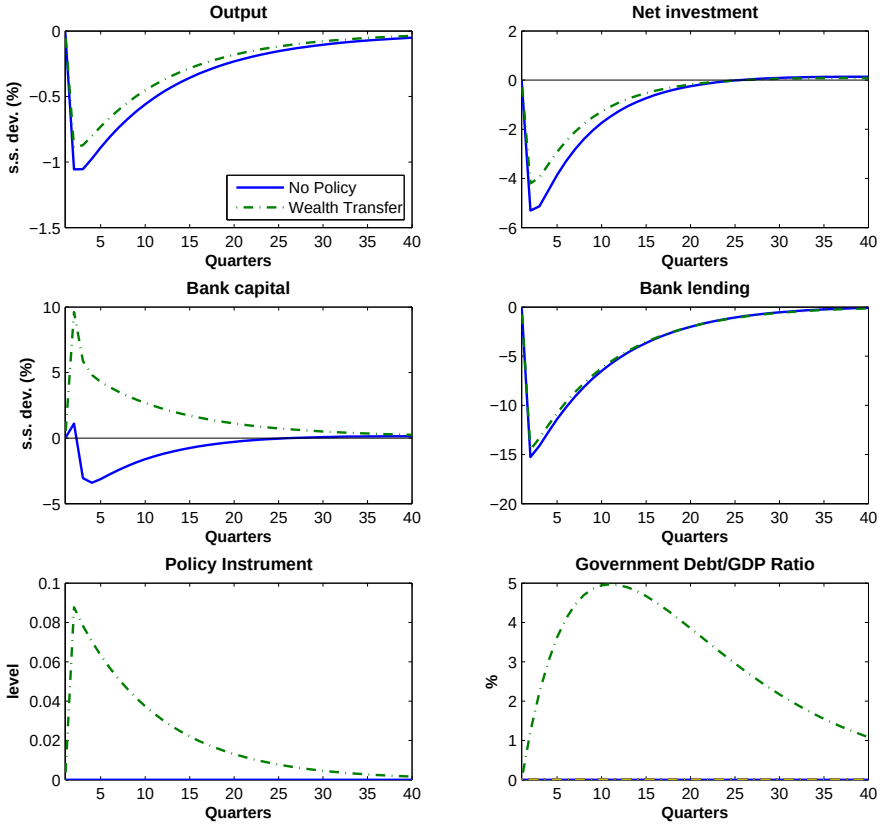
Notes: Impulse responses to a negative one-standard-deviation technology shock. The agency-cost model (solid lines) is contrasted with a frictionless benchmark model where $\mu = 0$ *(dashes lines).*

Figure 8: Responses to a Liquidity Shock



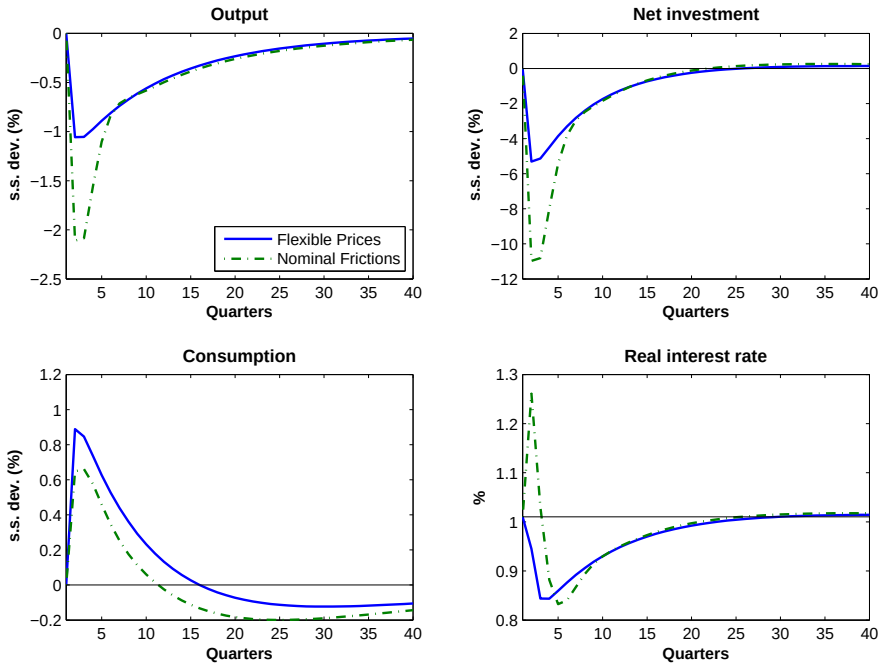
Notes: Impulse responses to a negative one-standard-deviation liquidity shock. The agency-cost model (solid lines) is contrasted with a frictionless benchmark model where $\mu = 0$ (dashes lines).

Figure 9: Responses to a Liquidity Shock with Policy Intervention



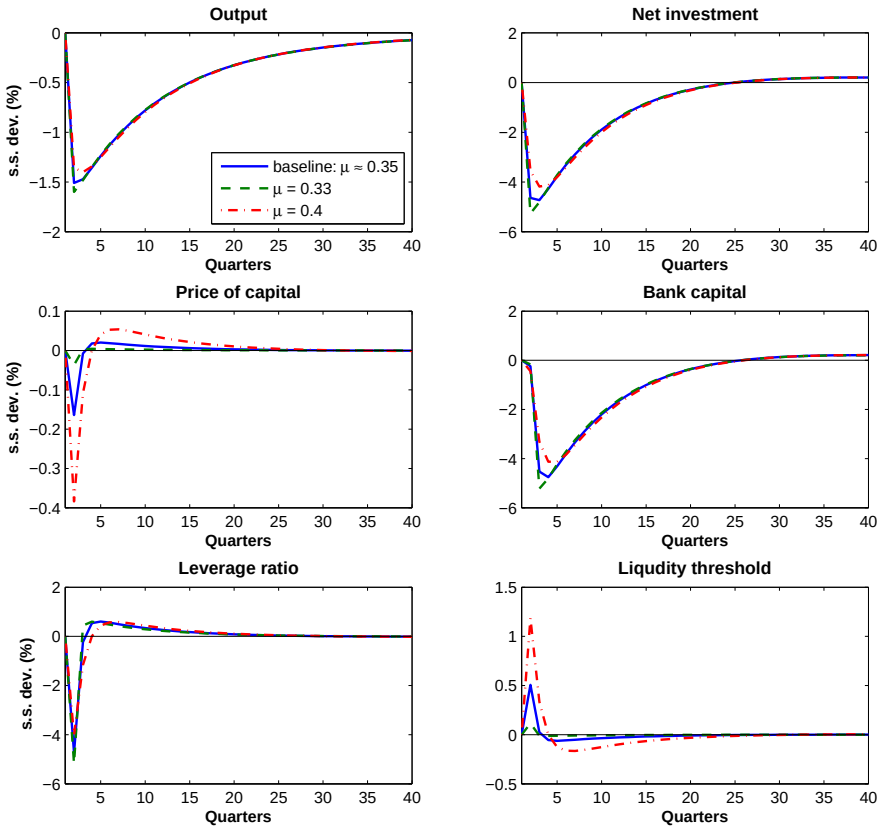
Notes: Impulse responses to a negative one-standard-deviation liquidity shock with vs. without policy intervention. The intervention consists in a recapitalization of banks.

Figure 10: Responses to a Liquidity Shock with Nominal Frictions



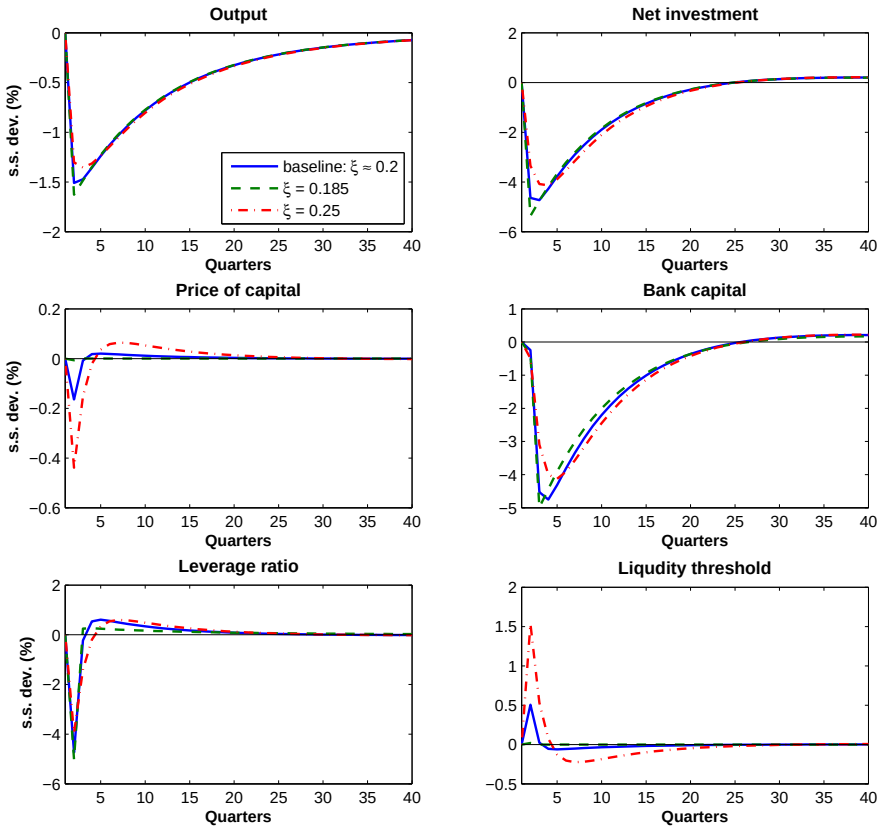
Notes: Impulse responses to a negative one-standard-deviation liquidity shock with vs. without nominal frictions.

Figure 11: Sensitivity to Bank Monitoring Costs



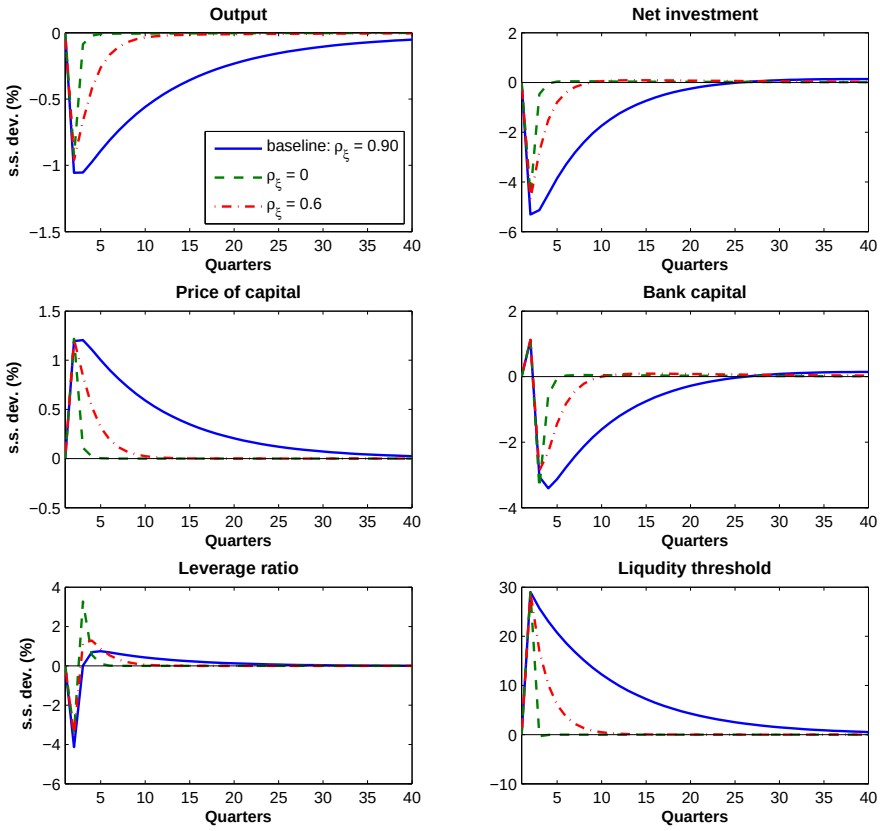
Notes: Impulse responses to a negative one-standard-deviation technology shock. Sensitivity is analysed with respect to changes in unit-monitoring costs μ while holding the remaining exogenous calibration targets and all exogenous parameters constant. Due to non-negativity constraints, $\mu = 0.33$ is a lower bound on monitoring costs.

Figure 12: Sensitivity to Liquidation Value



Notes: Impulse responses to a negative one-standard-deviation technology shock. Sensitivity is analysed with respect to changes in the liquidation value of bank assets ξ while holding the remaining exogenous calibration targets and all exogenous parameters constant. Due to non-negativity constraints, $\xi = 0.185$ is a lower bound on the liquidation value parameter.

Figure 13: Sensitivity to Persistence of the Collateral Shock



Notes: Impulse responses to a negative one-standard-deviation collateral shock. Sensitivity is analysed with respect to changes in the persistence of the collateral shock ρ_ξ while holding the remaining exogenous calibration targets and all exogenous parameters constant.