Liquidity Crises, Banking, and the Great Recession*

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Abstract

This paper presents a dynamic stochastic general equilibrium model which studies the business-cycle implications of financial frictions and liquidity risk at the bank-level. Following Holmström and Tirole (1998), demand for liquidity reserves arises from the anticipation of idiosyncratic operating expenses during the execution phase of bank-financed investment projects. Banks react to adverse aggregate shocks by hoarding liquidity while being forced to decrease their leverage. Both effects amplify recessionary dynamics, since they crowd out funds available for investment financing. This mechanism is triggered by a market liquidity squeeze modelled as a shock to the collateral value of banks' assets. This novel type of aggregate risk induces a credit crunch scenario which shares key features with the Great Recession such as strong output decline, pro-cyclical leverage and counter-cyclical liquidity hoarding. Unconventional credit policy in the form of a wealth transfer from households to credit constrained banks is shown to mitigate the credit crunch.

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

JEL classification: E22; E32; E44.

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. Excessive maturity transformation and high levels of leverage achieved during the run-up to the crisis have been identified as major destabilising factors in the link between the financial and the real side of the economy. However, at the heart of the propagation of initial losses on subprime-related securities lies a liquidity crisis experienced by financial intermediaries. Seeing the values of their assets decline, financial institutions began to have trouble rolling over their debt. They started hoarding liquidity leading to a break-down of interbanklending, particularly in the market for repurchase agreements. In order to service short-term liabilities, many institutions were forced to sell their assets at depressed prices. Given their high leverage ratios, even relatively small losses cut heavily into equity buffers. As financial institutions were compelled to shorten balance sheets further, a financial accelerator mechanism of fire-sales and asset price declines resulted. This eventually disrupted the flow of credit into the economy.

In this paper, I argue that the interaction of a market liquidity shock with a motive for liquidity hoarding by highly leveraged financial intermediaries can explain a credit crunch scenario sharing key features with the Great Recession. In particular, I propose a model in which banks operate subject to financial frictions and idiosyncratic liquidity risk in their intermediation activity. They react to adverse shocks by strengthening their liquidity reserves while being forced to decrease their leverage. Both effects crowd out funds available for investment financing - an instance of the bank lending channel of shock transmission. This amplification mechanism is particularly strong in the presence of the novel type of aggregate liquidity risk introduced as a shock to the collateral value of banks' assets.

Macroeconomic research has long discarded financial frictions in the financial sector as a principal driver of business cycle fluctuations. And indeed, risk factors associated with the US banking sector do not seem to have worsened over the past two to three decades. In fact, US banks have steadily decreased their leverage, i.e. the ratio of debt to equity, since the mid-1980s as shown in Figure 2. However, this development in the commercial banking sector has been sidelined by a strong growth of market-based intermediation in the US, especially through securitisation. In 1998, the assets of market-based intermediaries, or shadow banks, exceeded those of the bank-based sector and the gap steadily widened until the Great Recession (Figure 3). Adrian and Shin (2009, 2010) present evidence of the diverging

characteristics of banks versus market-based institutions. They emphasize the correlation of balance sheet fluctuations of shadow banks with financial risk measures and the business cycle. In particular, shadow banks were able to increase their leverage ratios to unprecedented levels before the onset of the crisis as suggested by Figure 2. Leverage ratios then collapsed abruptly on the heels of the Lehman Brothers bankruptcy in September 2008. This observation squares with evidence of tightening lending conditions presented in Adrian and Shin (2010) and the theory of margin spirals developped by Brunnermeier and Pedersen (2008). The pro-cyclical nature of leverage in the market-based financial sector thus stands out as a distinctly destabilizing factor during the Great Recession.[1]

The availability of credit as a source of external funding is the pivotal link between the real and the financial sector. This link was disturbed during the Great Recession due to a liquidity crisis on financial markets. Several markets for institutional refinancing broke down: The market for asset-backed commercial paper started collapsing in late 2007, followed by a freeze in the interbank-market after the demise of Lehman Brothers epitomized by a surge in the TED spread (Brunnermeier, 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; 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, manifested in a rising share of liquid assets in total balance sheet size as exposed 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.[2] The hoarding of such liquid reserves locked up funds otherwise available for investment into riskier assets thereby curtailing the lending capacity of the financial sector.[3]

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[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.

[2]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.

[3]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

I develop a theoretical framework to study the interaction of financial frictions and liquidity risk. To this end, the canonical Real Business Cycle model is extended to include agency costs in financial intermediation. In this setup, borrower net worth, i.e. 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 to their loan portfolio, which require the input of additional resources into ongoing investment projects. Intermediaries can insure against such shocks by holding liquid assets, which can be thought of as contingent credit lines from a mutual fund or uncommitted resources on banks' own balance sheets. Economically, they amount to an insurance against maturity mismatch as they eliminate the need to seek additional outside funding during the lifetime of banks' illiquid assets. Liquidity reserves trade off two effects: On the one hand, they increase the probability that investment projects survive idiosyncratic shocks. On the other, putting liquidity reserves aside for the execution phase of investment projects locks up resources that cannot be used to increase the loan scale up-front. 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. Idiosyncratic liquidity shocks over and above this threshold lead to the termination and inefficient liquidation of investment projects by the outside financiers.

I introduce a shock to the liquidation - or collateral - value of bank assets, which I interpret as an aggregate liquidity shock. As the dynamic analysis will reveal, intermediaries react to such a shock by propping up their liquidity cushions. This unleashes a powerful amplification mechanism as liquidity buffers crowd out funds for bank lending. These dynamics stand in sharp contrast to a frictionless economy where investment projects would always be refinanced, as long as they provide positive net present value. Hence, the rivalry between liquidity reserves and loan scale would disappear.

The paper also investigates the stabilizing potential of unconventional credit policy. In particular, wealth transfers from households to credit constrained bankers are shown to cushion the impact of the liquidity shock.

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course, if these truly are liquid assets from a macroeconomic viewpoint, they are expected to retain their value during a downturn, while other asset 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 suggests that a flight-to-liquidity occurred and banks' willingness to lend declined.

1.1 Related Literature

The model presented in this paper builds on two distinct strands of literature. The first is concerned with financial frictions as the source of business cycle fluctuations. It investigates 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 in the real sector. Early research in this area focused 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. A more recent line of literature including Gertler and Karadi (2011), Gertler and Kiyotaki (2011) and Christiano et al. (2010) has picked up on this agency cost framework in order to explicitly study financial frictions between investors and financial intermediaries. The main drawback of models in this class is the result that leverage behaves counter-cyclically due to the forward-looking determination of intermediaries' balance sheets. To motivate a role for bank capital I, therefore, follow an alternative framework proposed by 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 micro-structure have been analyzed by Meh and Moran (2010), which is closely related to this paper.

The literature discussed so far cannot accommodate the notion of asset liquidity and liquidity demand, however. I introduce this feature following the second strand of literature initiated by Holmström and Tirole (1998) and Kato (2006). The former develop a finite-horizon partial equilibrium framework to motivate a demand for liquidity reserves. The latter extends this structure to an infinite horizon environment to analyze the business cycle dynamics that result from liquidity risk at the corporate level. Covas and Fujita (2010) expand this analysis by adding regulatory capital requirements in the banking sector.

The present paper merges the literature on the balance sheet channel in the financial sector 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, the collateral value of liquidated investment projects for banks' financiers is assumed to be non-zero. This allows to introduce shocks to the collateral value of bank assets as a new source of aggregate risk. The contribution of the model is twofold: First, it is able to account for a number of key styl-

ized facts from the data regarding liquidity and banking. It replicates the pro-cyclicality of bank lending and leverage, exhibits a bank balance sheet channel of shock transmission and amplification and generates a counter-cyclical liquidity share. Second, the model contributes to the analysis of the interaction of an aggregate liquidity shock with liquidity hoarding by financial intermediaries that results in a credit crunch. This scenario bears strong resemblance to the experience of the Great Recession.

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 some insights into unconventional credit policy. Section 5 concludes and suggests avenues for future research.

[Figures 3-4 about here]

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 fraction $\eta^b = 1 - \eta^h$ of bankers. In addition, there is a continuum of capital-good-producing entrepreneurs and final goods 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. Entrepreneurs can reduce the probability of failure by exerting unobservable effort at some private cost. Monitoring of entrepreneurial projects by banks eliminates the option of shirking and induces effort, thereby alleviating the moral hazard problem betweeen entrepreneurs 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 entrepreneurs, the risk associated with loan portfolios would be mainly borne by investors and hence banks would not be

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compelled to conduct monitoring effectively. As a result, depositors require banks to put up sufficient own funds in the financing of entrepreneurs.

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 projects funded by banks mid-stream. They require further resource input in terms of final goods for the projects to be continued. The desire to insure against such shocks provides an incentive for banks to hold liquid reserves.

2.2 Entrepreneurs

Entrepreneurs manage investment projects to produce 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 entrepreneurs and their financiers is afflicted with moral hazard. Entrepreneurs 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, entrepreneurs 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 entrepreneurs. Capital production as such thus becomes frictionless. Entrepreneurs 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 poduction process, monitoring is taken to be privately costly so that a financial friction emerges in the intermediation of funds. Now, the relation betwen 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.[4]

At the same time, banks engaged in financing and monitoring projects may be hit by idiosyncratic liquidity shocks requiring an uncertain amount of final good input during the project completion period. Liquidity shocks may be interpreted as bank operating costs, entrepreneurs' working capital expenses or other cash needs that arise after the initial fixed investment. Assuming such idiosyncratic shocks at the bank-level serves as a short-cut for modelling heterogeneous loan portfolios across banks.

A failure to supply additional input after a liquidity shock will lead to project liquidation. This motivates banks' demand for liquidity buffers to withstand such shocks. Projects suffering from liquidity shocks in excess of reserves will be abandoned by banks and liquidated by outside investors. Liquidity buffers can be thought of either as liquid assets on banks' balance sheets such as idle consumption goods or contingent credit lines from a mutual fund, which is introduced below.

To finance their investment into entpreneurial projects, banks supplement their equity capital by raising funds from households through deposits. In order to achieve insurance for depositors against idiosyncratic risks, their 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 depositors.

2.3.1 Intra-period Financial Contract

The timing of events is as follows: Every period is divided into four subperiods. 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 fric-

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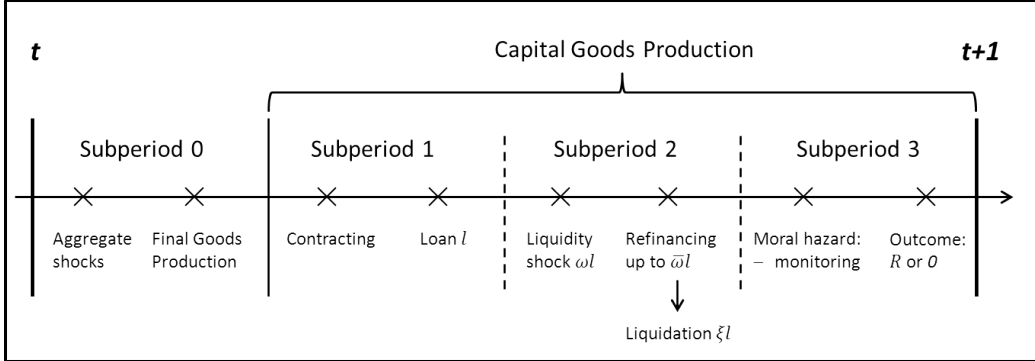[4]The terms equity, capital and net worth will be used interchangeably throughout the paper.

Figure 1: Timing

tions between entrepreneurs and banks, entrepreneurs are not part of these contracts. After successful negociation, the latter finance their initial investments entirely through outside funding in the form of bank loans, i.e. $i_t = l_t$.[5] In the third subperiod, liquidity shocks occur. They are assumed to be proportional to project size, taking the form ωl_t, and distributed according to the cumulative distribution function $\Phi(\omega)$ and density $\phi(\omega)$. Banks refinance their working capital expenses up to the optimal amount $\bar{\omega}$ determined by the financial contract out of liquidity reserves. This is akin to partial insurance against a maturity mismatch, which would require banks to attract new funds during the lifetime of their illiquid asset (Holmström and Tirole, 2011). Projects with liquidity shocks 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.[6] 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 (Figure 1).

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. I focus on equilibria where effort is induced for all bankers. The optimal financial contract then is a set $\{l, r^d, R^b, R^h, \bar{\omega}\}$ designed to maximise the expected return to banks. It specifies the level of loans l_t, the market return to deposits r^d for a given

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

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

amount of deposits, the distribution of total project return R to banks, R^b, and households, R^h, as well as the cut-off level of the liquidity shock, $\bar{\omega}$, up to which banks will refinance projects. Liquidity shocks which exceed the liquidity buffer, i.e. $\omega > \bar{\omega}$, lead to the termination of the associated investment project. The ex ante probability of survival of an investment project is thus $\int_0^{\bar{\omega}} \phi(\omega)\, d\omega = \Phi(\bar{\omega})$.

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 descritption of the optimal contract.

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

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

$$\text{s.t.}$$

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

$$q\left(\Phi(\bar{\omega})\pi_H R^h + (1 - \Phi(\bar{\omega}))\xi\right) l \geq (1 + r^d)d \tag{2}$$

$$d + a \geq (1 + \Phi(\bar{\omega})\mu + q\Phi(\bar{\omega})\mathbb{E}(\omega|\omega \leq \bar{\omega})) l \tag{3}$$

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

The objective function accounts for the fact that the probability of successfully executing a project of scale l is $\Phi(\bar{\omega})\pi_H$, since the ex ante probability of a non-excessive liquidity shock is $\Phi(\bar{\omega})$, and the probability of yielding non-zero output is π_H.[7] 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 entprereneurs. Equation (2) is the participation constraints of households. It determines the market return r^d which accrues to depositors from providing external finance to banks through the mutual fund. This return is financed by the return to successful projects as well as the liquidation value of unsuccessful projects. 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, $\Phi(\bar{\omega})\mu$, and liquidity injections, $q\Phi(\bar{\omega})\mathbb{E}(\omega|\omega \leq \bar{\omega})$.[8] Finally, (4) states that the returns to individual agents from a successful project add up to the total return.

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

[8] Note that $\Phi(\bar{\omega})\mathbb{E}(\omega|\omega \leq \bar{\omega}) = \int_0^{\bar{\omega}} \omega\phi(\omega)\, d\omega$. Thus, an individual bank does not hold

In equilibrium, all constraints hold with equality. Solving constraints (1) - (3) for l gives the loan function

$$
\begin{aligned}
l &= \frac{a+d}{1 + \Phi(\bar{\omega})\mu + q\Phi(\bar{\omega})\mathbb{E}(\omega|\omega \leq \bar{\omega})} \\
&= \frac{a}{1 + \Phi(\bar{\omega})\mu + q\left(\Phi(\bar{\omega})\mathbb{E}(\omega|\omega \leq \bar{\omega}) - \frac{1}{1+r^d}\left(\Phi(\bar{\omega})\pi_H R^h + (1-\Phi(\bar{\omega}))\xi\right)\right)} \\
&\equiv \frac{a}{H(\bar{\omega})}
\end{aligned}
\tag{5}
$$

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

$$
1 = q\left(\int_0^{\bar{\omega}} \Phi(\omega)\,\mathrm{d}\omega + \frac{\xi}{1+r^d}\right) \equiv Q(q, \bar{\omega})
\tag{6}
$$

This condition implicitly defines a function $\bar{\omega} = \psi(q)$ linking $\bar{\omega}$ to the price of capital.

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, $\frac{\partial \Phi(\bar{\omega})}{\partial \bar{\omega}} > 0$. 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
$\mu\Phi(\bar{\omega})l$	d
$q\mathbb{E}(\omega \mid \omega \leq \bar{\omega})\,\Phi(\bar{\omega})l$	

liquidity reserves amounting to $\bar{\omega}$ per unit of loan, but rather an amount equal to the expectation of ω truncated at the liquidity threshold $\bar{\omega}$. Due to the idiosyncratic character of liquidity risk, this ensures that aggregate liquidity supply will suffice to cover aggregate liquidity demand. 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 in *excess* of them. I assume that the mutual fund has such risk-pooling capacity.

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The trade-off between the (internal) marginal and the (external) level effect is also illustrated in Figure 5. As shown in the lower pannel, the expected return to banks clearly achieves a maximum at $\bar{\omega}$.

[Figure 5 about here]

Note that the rivalry between loan scale and liquidity reserves also holds for projects with a positive net present value after the liquidity shock. 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 plegde the returns from investment projects fully to outside investors. Projects would then be refinanced as long as the liquidity shock would not exceed the expected return. The "first-best" refinancing cut-off in the absence of financial frictions due to moral hazard would thus be $\omega_1 = \pi_H R$ (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 $\omega_0 = \pi_H R^h = \pi_H(R - R^b) < \omega_1$. For shocks which exceed the pledgeable return outside funding is unavailable. 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 5). The corresponding inefficiency wedge can, thus, be expressed as the ratio $\frac{\omega_1}{\bar{\omega}}$.

As equation (6) suggests, the dynamic behaviour of the liquidity buffer depends on the path of q_t. By the Implicit Function Theorem

$$
\begin{aligned}
\frac{\partial \bar{\omega}}{\partial q} &= -\frac{\partial Q/\partial q}{\partial Q/\partial \bar{\omega}} \\
&= -\frac{\int_0^{\bar{\omega}} \Phi(\omega)\, \mathrm{d}\omega - \frac{\xi}{1+r^d}}{q\Phi(\bar{\omega})} \leq 0
\end{aligned}
\tag{7}
$$

the liquidity cut-off is negatively correlated with the relative price of capital for sufficiently small values of ξ. Accordingly, it will have the opposite cyclicality. This effect is due to the property that higher capital prices increase the marginal profitability of investment. With higher prices, banks need smaller liquidity reserves to achieve a given marginal profitability of loans. In light of the trade-off described above, a higher capital value thus frees up liquidity reserves which can be used to finance a larger loan volume.

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Given the previous results, the equity multiplier of the loan function can finally be cast in terms of the price of capital, i.e. $l = \frac{a}{H(\psi(q))}$. As will become clear in the dynamic analysis of a technology shock, loans (and investment) are actually upward sloping in the relative price of capital just as in the adjustment cost model of investment.

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.

$$a_t = (q_t(1 - \delta) + r_t)k_t^b + w_t^b \tag{8}$$

The banker invests his entire capital into a loan project yielding $R^b l_t$ if successful and zero if unsuccessful as described above. Saving the entire proceeds from investment-funding in end-of-period capital goods represents the optimal consumption-savings-decision for successfull 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 risk neutral 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 $(\exp(z_t))$.

$$Y_t = \exp(z_t)F(K_t, H_t^h, H_t^b) \tag{9}$$

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 to final goods producers and supply labour to the same sector. Both factors are remunerated with their respective rents. Likewise, the mutual fund pays the gross riskless rate $1 + r_t^d$ on last period's deposits. Then households make their consumption-savings decision. Two assets are available for saving: deposits at the mutual fund d_{t+q}^h and freshly produced capital k_{t+1}^h. Both are pre-determined and will pay off one period later.

The optimization problem thus takes the form

$$\max_{\{c_t^h, k_{t+1}^h, d_{t+1}^h, h_t^h\}} E_0 \sum_{t=0}^{\infty} \beta^t u(c_t^h, h_t^h)$$

$$s.t.$$

$$c_t^h + q_t k_{t+1}^h + d_{t+1}^h = (1 + r_t^d)d_t^h + (q_t(1 - \delta) + r_t)k_t^h + w_t^h h_t^h \tag{10}$$

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

$$u_{c,t} = \lambda_t \tag{11}$$

$$\lambda_t = \beta E_t \left[\lambda_{t+1} \frac{q_{t+1}(1 - \delta) + r_{t+1}}{q_t} \right] \tag{12}$$

$$\lambda_t = \beta E_t \left[\lambda_{t+1}(1 + r_{t+1}^d) \right] \tag{13}$$

$$u_{h,t} = -\lambda_t w_t^h \tag{14}$$

where (12) and (13) are the Euler equations with respect to capital and deposits, 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:

$$
\begin{aligned}
L_t &= \eta^b l_t \\
&= \frac{\eta^b a_t}{H(\bar{\omega}_t)} \\
&= \frac{A_t}{H(\bar{\omega}_t)}
\end{aligned}
\tag{15}
$$

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

The economy-wide equivalent to depositors' participation constraint (2) pins down the return on deposits. This return is riskless since idiosyncratic risk at the level of entrepreneurs is pooled by the mutual fund as described earlier.

$$
(1 + r_t^d) = \frac{q_t \left(\Phi(\bar{\omega}_t)\pi_H R_t^h + (1 - \Phi(\bar{\omega}_t))\xi \right) L_t}{\eta^b d_t}
\tag{16}
$$

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

$$
K_t^b = \eta^b k_t^b, \quad K_t^h = \eta^h k_t^h
\tag{17}
$$

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

$$
H_t^b = \eta^b, \quad H_t^h = \eta^h h_t^h
\tag{18}
$$

Deposits supplied by individual households sum up to aggregate deposit supply and external financing by individual banks adds up to aggregate deposit demand.

$$
D_t^h = \eta^h d_t^h, \quad D_t = \eta^b d_t
\tag{19}
$$

Individual positions add up to aggregate bank net worth.

$$
A_t = (q_t(1 - \delta) + r_t)K_t^b + H_t^b w_t^b
\tag{20}
$$

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 $\Phi(\bar{\omega})\pi_H R^b l_t$. Since only a fraction τ^b survives, next period's capital holdings by the banking sector will be

$$
K_{t+1}^b = \tau^b \Phi(\bar{\omega}_t)\pi_H R_t^b L_t
\tag{21}
$$

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

$$C_t^b = (1 - \tau^b)q_t\Phi(\bar{\omega}_t)\pi_H R_t^b L_t \tag{22}$$

$$C_t^h = \eta^h c_t^h \tag{23}$$

2.7 Market Clearing Conditions and Competitive Equilibrium

In equilibrium markets clear. The corresponding conditions are given by

$$K_t = K_t^b + K_t^h \tag{24}$$

$$H_t = H_t^b + H_t^h \tag{25}$$

$$q_t L_t = q_t I_t \tag{26}$$

$$Y_t = C_t^h + C_t^b + \left[1 + \Phi(\bar{\omega}_t)\mu + q_t\Phi(\bar{\omega}_t)\mathbb{E}(\omega|\omega \leq \bar{\omega}_t)\right]I_t \tag{27}$$

$$K_{t+1} = (1 - \delta)K_t + \Phi(\bar{\omega}_t)\pi_H R I_t \tag{28}$$

$$D_t = D_t^h \tag{29}$$

Equation (24) 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 (25). Investment projects are entirely financed through banks, such that aggregate gross investment equals the aggregate loan volume (26). The aggregate resource constraint (27) states that available resources are spent on aggregate consumption, gross aggregate investment as well as monitoring costs and liquidity injections (both of which are proportional to gross investment). (28) is the law of motion of aggregate capital equating capital supply and demand. Net aggregate investment $\Phi(\bar{\omega}_t)\pi_H R I_t$ reflects the fact that only a fraction $\Phi(\bar{\omega}_t)\pi_H$ of projects survive the different shocks and turn out to be productive. Finally, (29) requires that the market for deposits clears.

A competitive equilibrium of the economy is a collection of (i) decision rules for $c_t^h, k_t^h, D_{t+1}, h_t^h$ 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 $l_t, r_t^d, R_t^b, R_t^h, \bar{\omega}_t$ that solve the maximization problem of banks associated with the financial contract; (iv) consumption and saving 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:

$$u(c_t^h, h_t^h) = \frac{c_t^{h^{1-\theta}}}{1-\theta} + \nu \ln(1 - h_t^h) \tag{30}$$

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

$$F(K_t, H_t^h, H_t^b) = K_t^{\alpha^k} H_t^{h^{\alpha^h}} H_t^{b^{\alpha^b}} \tag{31}$$

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 (0.00005), such that its effect on the dynamics is negligible.

Capital production is characterized by two parameters. A quarterly depreciation rate of capital of $\delta = 0.0248$ is in line with many RBC studies of the US Economy including King and Rebelo (1999), Kato (2006) and Covas and Fujita (2010) and ensures a steady state investment-to-output ratio of 20%. There is less precedent for the second parameter choice, R - the return to investment in capital production. I calibrate this parameter such that in the absence of financial market frictions due to moral hazard the total expected return to investment is one. As elaborated 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 expected return *after* the liquidity shock $\omega_1 = \pi_H R$. Given insurance up to the first-best threshold, the return to investment *before* the realization of the liquidity shock would then be $\Phi(\pi_H R)\pi_H R = 1$, which is the calibration target.

Financial intermediation and the associated frictions are characterized by the set of parameters $\{\mu, \xi, \pi_H, \pi_L, \sigma^2(\omega)\}$. The unit-monitoring cost $\mu = 0.0627$ targets a bank-leverage ratio, defined as the ratio of debt to equity, of 15. This corresponds roughly 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).[9] The liquidation value to outsiders of a project which

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

has failed due to an excessive liquidity shock is governed by the parameter $\xi = 0.3067$. 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

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

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 $\pi_L = 0.75$. Finally, the variance of idiosyncratic liquidity risk $\sigma^2(\omega)$ pins down the share of liquid assets in banks' balance sheets. These are defined as the uncommitted resources, i.e. the liquidity buffer, relative to total balance sheet size. 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 between 13 to 30% for banks and 2 to 23% for shadow banks over the past three decades, the model exhibits a liquidity share of 30%, which is a conservative upper bound. This corresponds to a variance of idiosyncratic liquidity of $\sigma^2(\omega) = 1/3$. The underlying distribution of idiosyncratic liquidity shocks is uniform on the interval $[0, 2]$.[10]

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 which 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)).

The second source of aggregate risk is a liquidity shock. I model this shock as a collapse in the liquidation value of bank loans to outside investors, i.e. a

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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 slightly higher calibration target for average leverage.

[10]Given the zero lower bound on liquidity shocks, pinning down the variance $\sigma^2(\omega) = b^2/12$ is equivalent to fixing the upper bound of the uniform distribution, $b = 2$.

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 which 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 $e_t^\xi \sim \mathcal{N}(0, \sigma_\xi = 0.06)$. This amounts to a far more conservative crisis scenario than, for instance, found in Del Negro et al. (2011), who rather calibrate their liquidity shock on the haircut on subprime-related securities.

4 Results

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

4.1 Aggregate Technology Shock

The impulse response functions of key aggregate variables to a one-standard deviation technology shock are shown in Figure 6. For comparison, the impulses of the frictionless benchmark model without agency costs 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 $\omega_1 = \pi_H R$. 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 (16):

$$(1 + r_t^d)\frac{\eta^b d_t}{L_t} = q_t \left[\Phi(\bar{\omega}_t)\pi_H \left(R - \frac{\mu}{q_t(\pi_H - \pi_L)} \right) + (1 - \Phi(\bar{\omega}_t))\xi \right]$$

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.

[Figure 6 about here]

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 4.2% and reaches a low two quarters after the shock at -4.5%. 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, $\Phi(\bar{\omega}_t)\pi_H R I_t$, 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 capital stocks. This triggers second-round effects and thus propagates the initial shock over time with a financial accelerator mechanism at work (capital channel of shock propagation). Bank capital plummets by about 4.3% four 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 discussed in section 2.3.1, the cut-off for contingent liquidity demand, $\bar{\omega}$, responds negatively to fluctuations in the capital price. With the marginal profitability of loans falling in the

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price of capital, banks choose to demand higher marginal liquidity buffers, i.e. raise $\bar{\omega}$, to compensate the loss in profitability. Total liquidity demand $L_t^D = q_t\Phi(\bar{\omega}_t)\mathbb{E}(\omega|\omega \leq \bar{\omega}_t)L_t$ falls nonetheless, since the increase of the marginal liquidity buffer is outweighed by the drop in the price of capital and the scale of lending. The share of liquid assets in banks' balance sheets

$$\kappa_t = \frac{L_t^D}{A_t + D_t} \tag{32}$$

increases, on the other hand, which suggests that the dependence on external (debt) finance increases in recessions.

4.2 Aggregate Liquidity Shock and the Great Recession

The business cycle effects of deteriorations in bank lending have received substantial attention following the 2007-09 financial crisis. Holmström and Tirole (1997) provide an early comparative static analysis of such a credit crunch scenario on the basis of their theoretical model. Extending this work to a dynamic setting, Meh and Moran (2010) 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.

My financial crisis scenario strikes a middle course between these approaches towards capturing financial-sector specific shocks. As explained before, I interpret a decline in the liquidation value of bank assets as an aggregate liquidity 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), a shock to the collateral value of bank assets only assumes that the value of assets to *outsiders* declines, but not so to *insiders*. In this sense, it can be interpreted as a shock to the market liquidity of bank assets. Finally, the financial shock unfolds its adverse effects through its impact on liquidity hoarding as will become clear from the discussion of the impulse responses reported in Figure 7.

[Figure 7 about here]

When the collateral value ξ drops, the participation constraint of outside investors tightens according to equation (16) and households withdraw deposits. Banks respond to this optimally by increasing their liquidity threshold

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$\bar{\omega}$ as implied by the first-order condition (6) in an effort to make bank loans safer investments and counter-act the loss in their outside value. Given the trade-off between liquidity reserves and loan scale, the higher probability of survival of investment projects 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 7.6% on impact of the shock. This forces a decrease in lending of 13%. Since bank capital is a stock variable which reacts sluggishly, the decrease in lending is accomodated by a cut-back in external financing, inducing deposits to fall by about 14% on impact. The credit crunch clearly dominates the effect of higher liquidity reserves, as suggested by the response of net investment $\Phi(\bar{\omega}_t)\pi_H R I_t$, which drops by 12% on impact. The strong decline in investment drives the response of output: the economy experiences a sharp recession with a loss of 2.7% in the first quarter after the shock.

The recessionary dynamics are attenuated by households' reaction to the shock. The interest rate on deposits is pre-determined. Hence, deposits have to react on impact to the tightening of the participation constraint and deleveraging by banks. Bank assets are expected to be less profitable for outside investors in the future, so that the interest rate falls, too. As a consequence, consumers substitute away from deposits into saving in capital stock and consumption. Unlike after a technology shock, the marginal productivity of capital is not affected by the liquidity shock, such that this asset becomes more attractive relative to deposits. With stronger demand from households, the price of capital increases. Capital gains due to this price increase also generate the initial jump in bank capital. The strong rise in consumption of around 2.1% on impact prevents the economy from sliding into an even deeper recession.[11]

The present liquidity crisis scenario is able to replicate some key features of the Great Recession. In particular, the leverage ratio of financial intermediaries is pro-cyclical as it was during the Financial Crisis (Figure 2), while the liquidity share on banks' balance sheets is counter-cyclical (Figure 4). In other words, stressed institutions scramble for liquidity buffers while they are forced to shorten their balance sheets by deleveraging. These mechanisms have been identified as essential drivers of the break-down of intermediation and the contagion of a financial shock to the real economy.

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[11]In a benchmark model without nominal rigidities Del Negro et al. (2011) also find the real interest rate to decrease and consumption to increase 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 a natural extension of the current set-up.

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. Although the liquidity shock is small compared to Del Negro et al. (2011) it triggers a sizeable recession, suggesting that a liquidity crisis may have driven the recession of 2007-09.

4.3 Unconventional Policy

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, a transfer of wealth from households to bankers will expand the amount of loans extended to the capital-good producing sector. This feature exposes the mechanism through which unconventional policy measures – such as those adopted by the US Federal Reserve during the Great Recession – work. 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).

Unconventional credit policy is assumed to be aimed at containing the drop in bank capital and lending. This can be achieved by transferring wealth from households to bankers - a measure akin to an equity injection financed by a tax on consumers. The counter-cyclical liquidity share 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 S_t is set to be a fraction of the end-of-period wealth of the banking sector, i.e.

$$S_t = g_t q_t \Phi(\bar{\omega}_t) \pi_H R_t^b L_t \tag{33}$$

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

$$g_t = \gamma^{inst} \left(\frac{\kappa_t}{\kappa} - 1 \right) \tag{34}$$

End-of-period capital held in the banking sector thus becomes

$$\begin{aligned} K_{t+1}^b &= \tau^b \left(\Phi(\bar{\omega}_t) \pi_H R_t^b L_t + S_t/q_t \right) \\ &= \frac{1}{1 - g_t} (\tau^b \Phi(\bar{\omega}_t) \pi_H R_t^b L_t) \end{aligned} \tag{35}$$

and, similarly, bankers' consumption

$$C_t^b = \frac{1}{1 - g_t}((1 - \tau^b)q_t \Phi(\bar{\omega}_t)\pi_H R_t^b L_t) \tag{36}$$

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. Government debt accumulated due to the policy intervention can serve as a calibration target to make the strength of the policy response comparable to the actual intervention by the Federal Reserve.[12] Figure 8 compares impulse responses to an aggregate liquidity shock in the presence and absence of unconventional policy. The policy response is calibrated to be strong enough to make bank capital increase, i.e. it off-sets the dampening impact on bank capital that increased liquidity buffers exert through a lower lending scale. An increase in bank capital 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 recovers faster under the policy intervention, which translates into accelerated recovery of net investment as well as output.

[Figure 8 about here]

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 regarding the risk-appetite of financial institutions as well as the potential adverse effect of distortionary rather than lump-sum taxes. Also, I did not conduct an explicit welfare analysis to justify the policy intervention. Therefore, this analysis is simply intended to reveal the key mechanisms that *can* make unconventional policy work.

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[12]Calibration to be completed.

4.4 Sensitivity Analysis

The least common parameters in the model are those related to financial intermediation, in particular $\{\mu, \xi, \sigma(\omega)\}$. As noted by Kato (2006), changes in the standard deviation $\sigma(\omega)$ do not have a material impact on model dynamics. This is because the liquidity threshold $\bar{\omega}$, and hence all functions thereof which appear in the financial contract, are endogenously determined. Shrinking the standard deviation would, for instance, lead to a smaller threshold, such that the fraction of surviving projects $\Phi(\bar{\omega})$ and the amount of liquidity reserves per unit of loans $\Phi(\bar{\omega})\mathbb{E}(\omega|\omega \leq \bar{\omega})$ would hardly be affected.

In constract, the dynamic response of the economy to shocks is strongly sensitive to banks' unit-monitoring costs as displayed in Figure 9. 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.

Changes in the market liquidity of bank assets, on the other hand, leave output dynamics fairly unaffected (Figure 10).

5   Conclusion

This paper presents a dynamic stochastic general equilibrium model which studies the interaction between financial frictions and idiosyncratic 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 idiosyncratic operating expenses during the execution phase of investment projects. Balance sheet constraints force banks to trade off liquidity reserves with initial loan scale.

Simulation results show that the balance sheet channel of shock transmission operates strongly in the model: Decreases in bank capital propagate shocks through time and induce a hump-shaped response of output. The

model replicates a number of stylized facts regarding financial aggregates very well: Both bank equity and bank lending react pro-cyclically. Bank leverage is pro-cyclical, too. This stands in contrast to much of the recent literature on frictions in the financial sector, in particular the financial accelerator strand, which typically predicts endogenously counter-cyclical leverage. Moreover, the share of liquid assets on financial intermediaries' balance sheets is counter-cyclical. In other words, the financial sector hoards liquidity during recessions.

Shocks to the collateral value of bank assets are introduced as a novel source of aggregate risk. Intermediaries react to such shocks by strengthening their liquidity reserves. 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. This credit crunch scenario shares key aspects of the Great Recession, which was triggered by a liquidity freeze on financial markets resulting in a lending squeeze. 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.

Going forward, the model could be extended along two dimensions. A first focus would be the conduct of monetary policy in the presence of liquidity shocks in the spirit of Del Negro et al. (2011). In particular, it would be interesting to study the stabilizing potential of unconventional monetary policy at the zero lower bound in the form of liquidity injections. A second extension would seek to introduce more meaningful heterogeneity at the bank level. Externalities from liquidity provision as in Kharroubi and Vidon (2009) or Diamond and Rajan (2005), for instance, lead to different equilibria depending on the distribution of idiosyncratic liquidity risk. Such a model would explicitly account for an interbank liquidity market which 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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A   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	0.0248	$\bar{I}/\bar{Y} = 20\%$
Return to investment	R	1.4281	one-to-one transformation
Financial Intermediation			
Unit-monitoring cost	μ	0.0627	bank-leverage ratio: 15
Liquidtation value to outsiders	ξ	0.3067	loss-given-default: 40%
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	$\sigma(\omega)$	$\sqrt{1/3}$	liquidity share: 30%
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	0.6991	average survival time: 1 yr
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	
Std. dev., liquidity shock	σ_ξ	0.06	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	15
Loss given default	$1 - \frac{q\xi I}{I-A}$	39.8%	40%
Share of liquid assets	$\frac{q_t\Phi(\bar{\omega}_t)\mathbb{E}(\omega|\omega\leq\bar{\omega}_t)L_t}{A+D}$	2-30%	30.9%

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
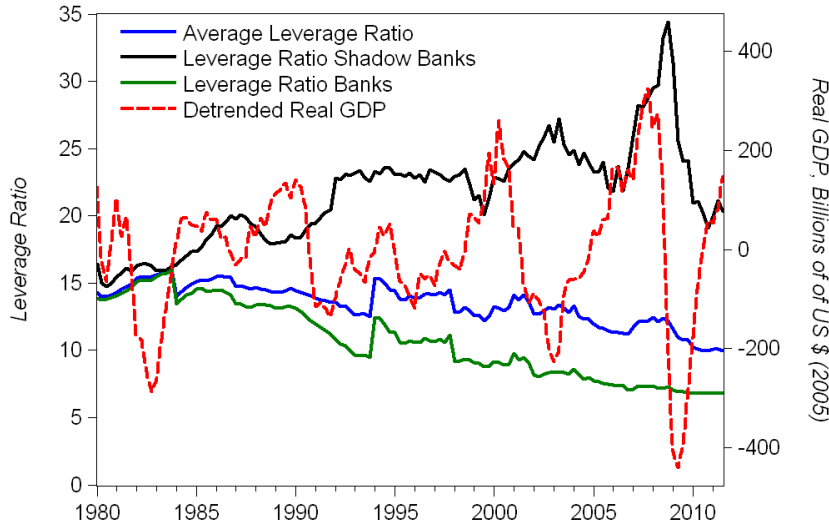
Notes: US-chartered commercial banks, savings institutions and credit unions are identified as traditional banks. The shadow banking sector comprises securities and broker dealers, issuers of asset-backed securities, finance companies and Government-sponsored enterprises. This follows the classification 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-GDP Ratio of Bank- vs. Market-based Intermediaries
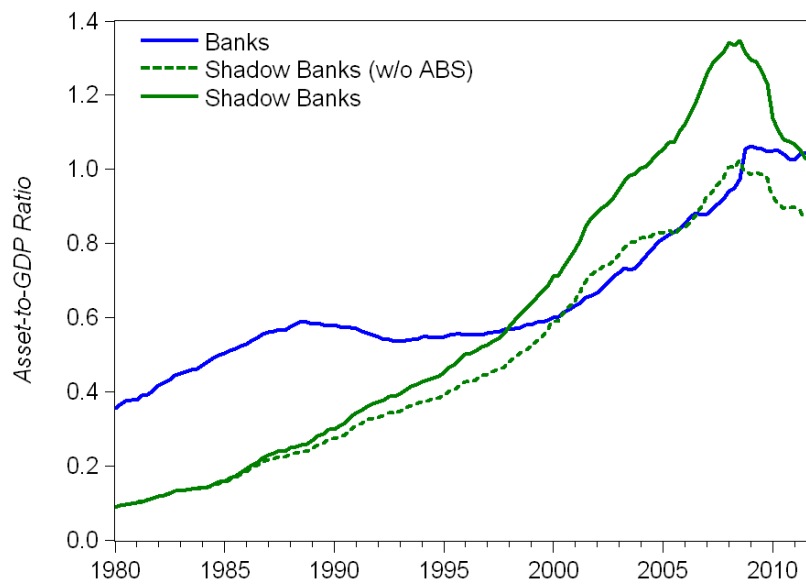
Source: US Flow of Funds (Federal Reserve)

Figure 4: Share of Liquid Assets of Bank- vs. Market-based Intermediaries
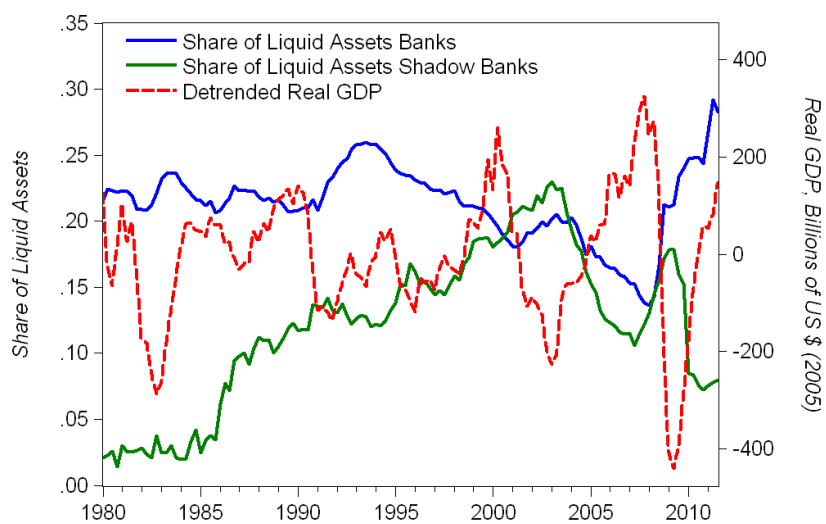
Notes: The empirical counterpart to the liquidity share is computed as the sum of check-able deposits and currency, cash and reserves at the Federal Reserve, Treasury securities, agency- and GSE-backed securities relative to total assets of the respective institutions. Source: US Flow of Funds (Federal Reserve)

Figure 5: Optimal Threshold for Liquidity Reserves
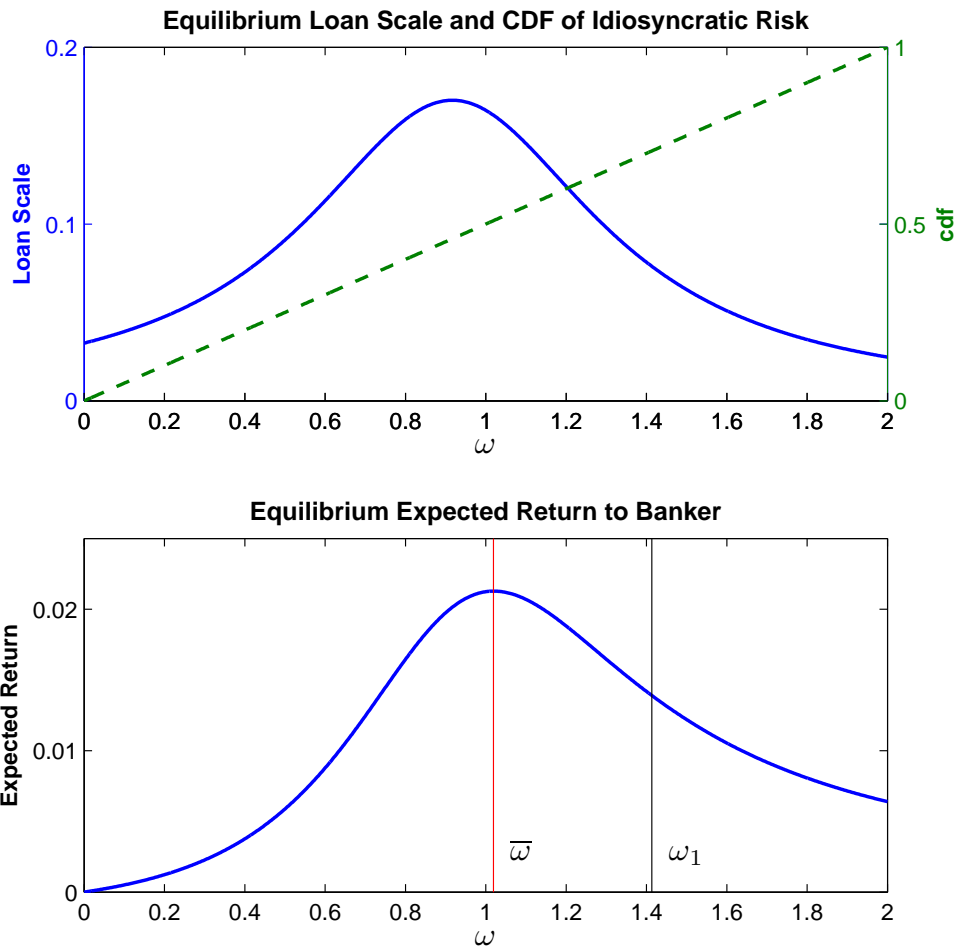
Figure 6: Responses to a Technology Shock
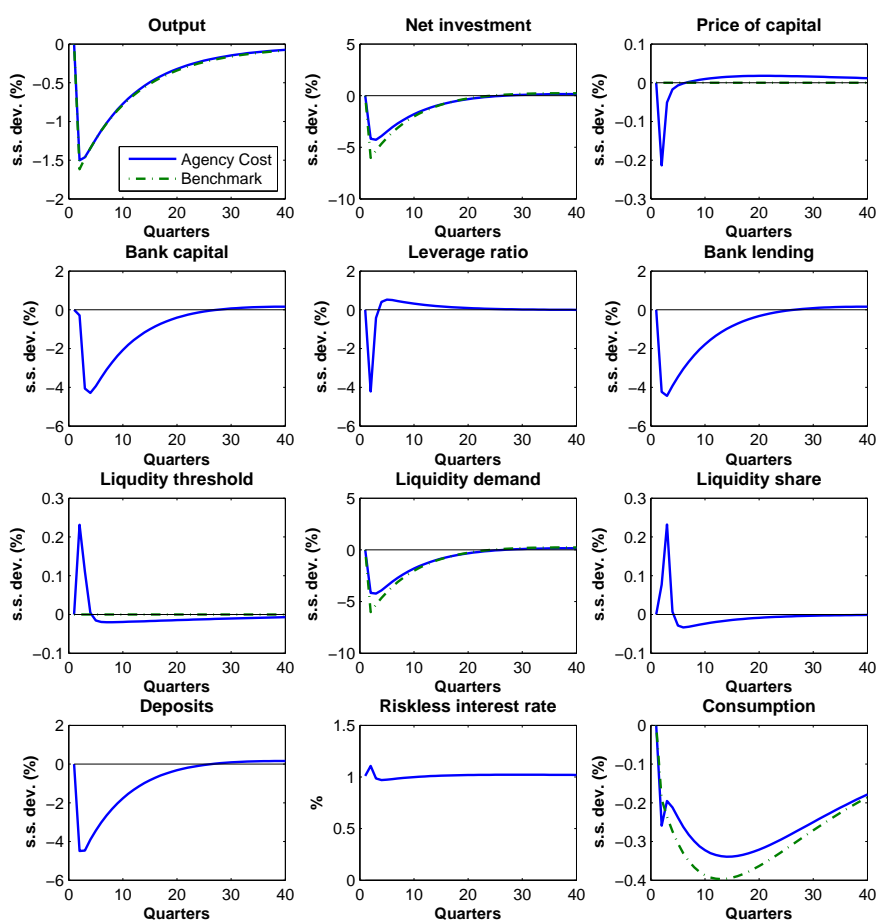
Notes: Impulse responses to a negative one-standard-deviation technology shock. The agency-cost model (solid lines) is contrasted with a frictionless benchmark model (dashes lines), where $\mu = 0$.

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Figure 7: Responses to a Liquidity Shock
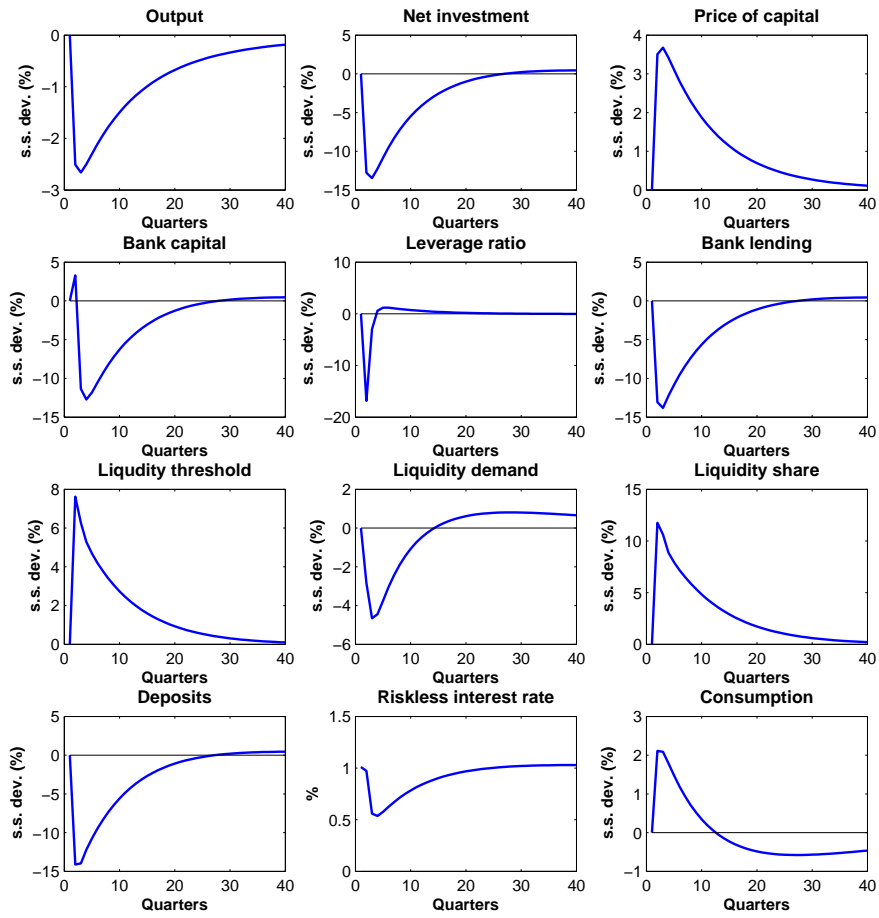
Notes: Impulse responses to a negative one-standard-deviation liquidity shock.

Figure 8: Responses to a Liquidity Shock with Policy Intervention
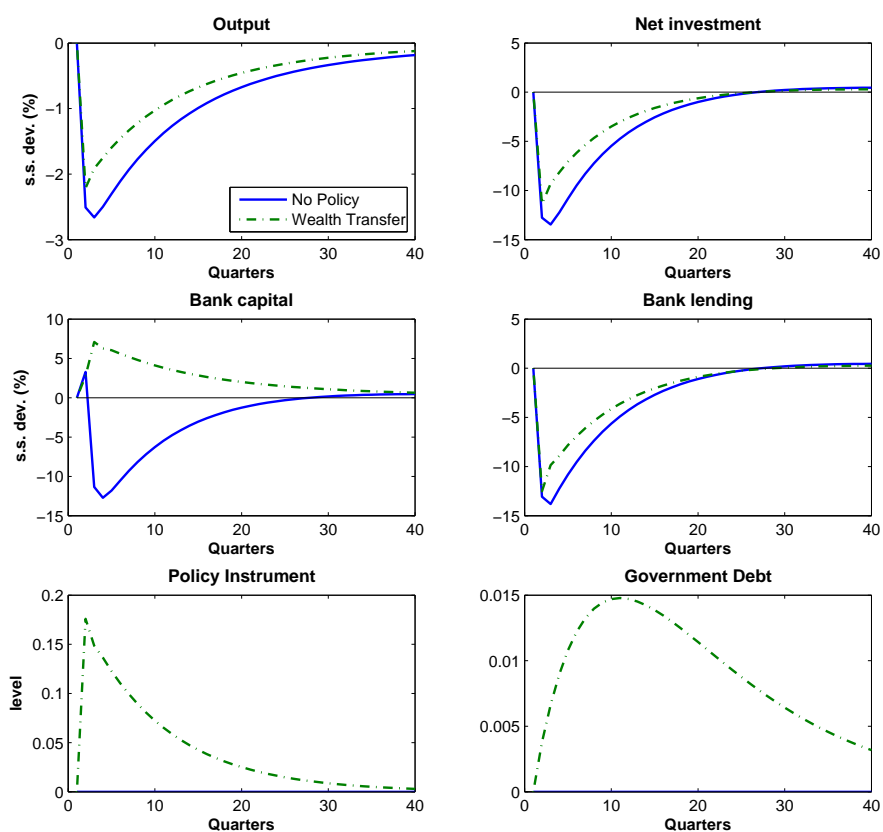
Notes: Impulse responses to a negative one-standard-deviation liquidity shock with vs. without policy intervention. The intervention consists in a wealth transfer from households to bankers.

Figure 9: Sensitivity to Bank Monitoring Costs
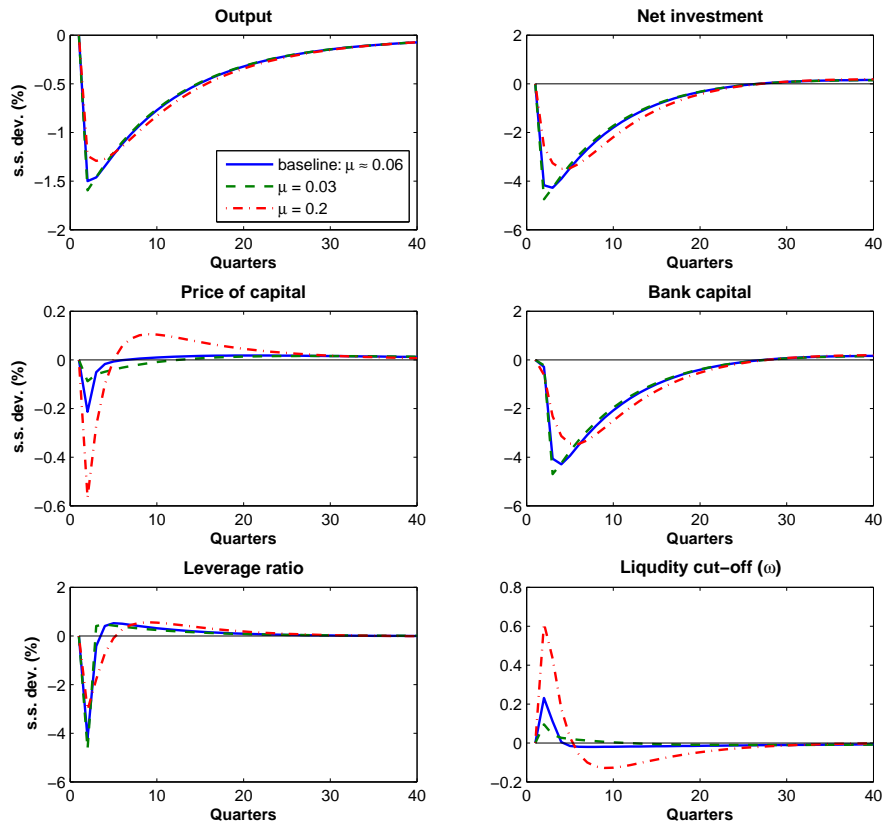
Notes: Impulse responses to a negative one-standard-deviation technology shock. Sensitivity is analysed with respect to changes in unit-monitoring costs μ while holding ξ, the remaining exogenous calibration targets (fraction of working time, investment share, one-to-one transformation, liquidity share) and all exogenous parameters constant. Due to non-negativity constraints, $\mu = 0.03$ is a lower bound on monitoring costs.

Figure 10: Sensitivity to Liquidation Value
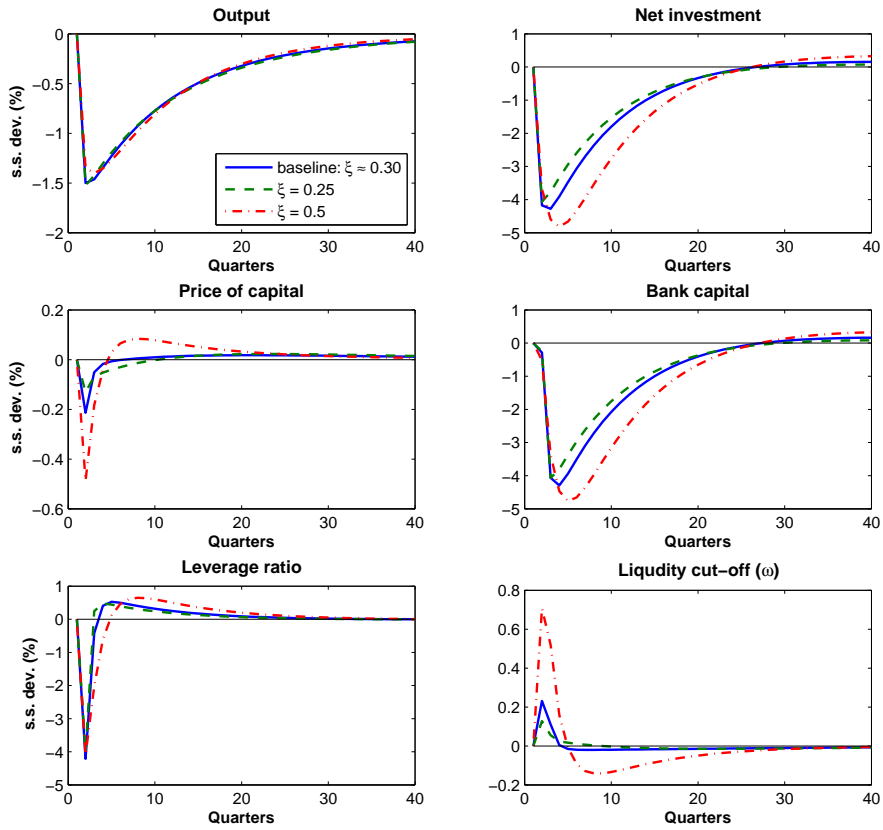
Notes: Impulse responses to a negative one-standard-deviation technology shock. Sensitivity is analysed with respect to changes in the liquidation value of bank assets ξ while holding μ, the remaining exogenous calibration targets and all exogenous parameters constant. Due to non-negativity constraints, $\xi = 0.25$ is a lower bound on the market liquidity parameter.