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Preliminary version

Abstract

In this paper, we investigate the *long-run* effects from central bank bond purchases on financial stability within a New Keynesian DSGE model with financial frictions. Banks have a portfolio choice between safe government bonds and risky corporate securities, and are subject to limited liability. Bond purchases by the central bank induce banks to shift from safe bonds to risky securities, thereby increasing the probability of insolvency, everything else equal. However, bond purchases also lead to capital gains on banks' existing assets, which reduces banks' reliance on deposits. Moreover, a lower return on banks' assets (as a result of the bond purchases by the central bank) decrease banks' profitability, thereby decreasing depositors' willingness to let banks operate with high leverage ratios. Our key conclusion is that bond purchases also enhance financial stability in the long-run.

Keywords: Unconventional Monetary Policy; Financial Fragility; Risk-taking
JEL: E32, E52, E62, E63

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1 Introduction

The Great Financial Crisis (GFC) of 2008 and the subsequent European sovereign debt crisis landed many advanced economies at the Zero Lower Bound (ZLB), at which no further conventional monetary stimulus could be provided by central banks. At that point, many central banks engaged in unconventional monetary policies such as asset purchase programs. While both the theoretical and empirical literature agree that these programs had (mildly) positive short-run effects on bond yields and the wider macroeconomy (Gertler and Kiyotaki, 2010; Gertler and Karadi, 2011; Curdia and Woodford, 2011; Chen et al., 2012), there is relatively little research on their long-run impact.

Therefore, we investigate in this paper what the long-run impact of these unconventional monetary policies is on financial stability as well as their wider long-run macroeconomic impact. We focus on government bond purchases by the central bank when the economy has landed at the ZLB, also referred to as 'Quantitative Easing' or 'QE'. To do so, we build a dynamic general equilibrium model with banks that are subject to limited liability and an occassionally binding leverage constraint. We solve two model versions: the first model is one without asset purchases, while a second model features the central bank buying government bonds when the economy has endogenously landed at the ZLB. Afterwards, we simulate both model versions for many periods, which allows us to assess the long-run impact of this unconventional monetary policy. The main contribution of our paper is that it studies the *long-run* impact of this unconventional monetary policy on financial stability. This sharply contrasts with most of the literature on asset purchases, which typically focus on the *short-run* impact on bond yields and the wider macroeconomy (Gertler and Kiyotaki, 2010; Gertler and Karadi, 2011, 2013; Chen et al., 2012).

Specifically, we construct a New Keynesian DSGE model with financial intermediaries that employ net worth and deposits to acquire government bonds and corporate securities, the last of which finance the 'physical' capital that serves as an input for production by intermediate goods producers (Gertler and Karadi, 2013; Van der Kwaak and Van Wijnbergen, 2014; Bocola, 2016).[1] Following Gete and Melkadze (2020), financial intermediaries take into account how their funding costs are affected by their balance sheet choices. Intermediaries are also subject to an occasionally binding incentive compatibility constraint as in Gertler and Kiyotaki (2010) and Gertler and Karadi (2011, 2013), which prevents them from perfectly elastically arbitraging away return differences. Finally, intermediaries' return on corporate securities is subject to a multiplicative idiosyncratic shock that is drawn from a lognormal distribution that is the same across banks (Bernanke et al., 1999; Clerc et al., 2015; Gete and Melkadze, 2020). The presence of this shock implies the existence of a cut-off value below which intermediaries do not have sufficient funds to repay their creditors. In that case, intermediaries are declared insolvent and stop operating. As a result, intermediaries do not care about the future states of the world in which they will be insolvent, as they are protected by limited liability. This opens up the

[1] We will use 'banks' and '(financial) intermediaries' interchangeably to denote the same group of agents in our economy.

possibility of bank risk taking (Diamond and Rajan, 2011).

The central bank sets the nominal interest rate on a risk-free asset that is in zero net supply. Its interest rate rule is a standard active Taylor rule that is bounded below by the ZLB. The central bank expands its bond holdings when the economy is at the ZLB following an endogenous rule that also responds to inflation and the output gap. Finally, we consider model versions with and without deposit insurance, which introduces moral hazard (Kareken and Wallace, 1978). We solve the model using global solution methods to fully capture the nonlinearities from intermediaries' occassionally binding incentive constraint, the presence of an endogenous ZLB, and from risk-taking incentives of financial intermediaries.

We start the analysis by considering a simplified two-period model version to analytically disentangle the opposing effects that bond purchases by the central bank have on financial stability (as measured by the cut-off value of intermediaries' idiosyncratic shock). The first effect is a risk taking effect that arises through portfolio rebalancing: bond purchases reduce the return on bonds, as a result of which intermediaries' asset portfolio sees a relative shift from government bonds to corporate securities (Gertler and Karadi, 2013). As a result, a larger fraction of intermediaries' assets becomes subject to the idiosyncratic shock, which increases the probability of insolvency, everything else equal, and therefore makes intermediaries' balance sheets more risky. The second effect is a deleveraging effect: bond purchases not only reduce the return on government bonds, but also on corporate securities. As a result, intermediaries' profitability decreases, which tightens intermediaries' incentive compatibility constraint. In response, depositors provide fewer funding, thereby forcing intermediaries to operate with lower leverage ratios. As a result, banks' probability of insolvency decreases, everything else equal. The third effect is a capital gains effect: bond purchases increase the value of intermediaries' existing assets, as a result of which their net worth increases. More net worth implies that intermediaries require fewer deposits to finance their assets as a result of which leverage ratios and intermediaries' cut-off value decrease. Therefore, the probability of insolvency further decreases.

We subsequently employ the full infinite horizon model to study which of these effects are quantitatively more important for long-run financial stability. Specifically, we simulate the model economy for many periods, and subsequently construct event windows around financial crises. This approach contrasts with the current literature, which typically employs impulse response functions to study the impact of asset purchases at the ZLB. Nevertheless, we find that our results are qualitatively similar as in Gertler and Kiyotaki (2010) and Gertler and Karadi (2011, 2013): bond purchases by the central bank increase asset prices (relative to simulations with no bond purchases), as a result of which intermediaries' net worth increases. They subsequently issue fewer deposits, which decreases leverage ratios and the number of insolvencies. Therefore, bond purchases by the central bank enhance financial stability in the middle of financial crises, despite the portoflio rebalancing from safe government bonds to risky corporate securities. We also find that bond purchases have a positive effect on the macroeconomy: more net worth allows intermediaries to expand credit to the real economy, as a result of which the trough in investment and output is substantially reduced. Therefore, bond purchases by the central bank enhance both financial stability as well as macroeconomic outcomes in the middle of financial crises.

Outside financial crisis times, however, we find that financial intermediaries operate on average with lower net worth in the model simulations with bond purchases at the ZLB (relative to simulations without bond purchases at the ZLB). The intuition behind this result is the following, and in line with Karadi and Nakov (2021). After the immediate beneficial effects from bond purchases on net worth at the moment a financial crisis hits the economy, bond purchases reduce net worth because these purchases reduce the spread between the (expected) return on bonds and deposits. As a result, intermediaries relatively shift from government bonds to corporate securities, as a result of which the (expected) spread between the return on corporate securities and deposits also decreases. Hence intermediaries' net worth accumulation slows down relative to model simulations without bond purchases at the ZLB.

However, the relative shift to corporate securities and the fact that bond purchases increase net worth on impact when financial crises hit the economy makes that capital accumulation is higher in the simulations where the central bank employs bond purchases when the economy hits the ZLB (relative to simulations where the central bank does not employ bond purchases at the ZLB). Therefore, the net macroeconomic impact of bond purchases at the ZLB is positive, as the unconditional means of investment, output, and consumption are higher in the simulations with central bank bond purchases at the ZLB.

Literature review

Key to have real effects from asset purchase programs by the central bank is imperfect substitutibility between central bank liabilities and the assets that are purchased with the newly created liabilities (Curdia and Woodford, 2011; Chen et al., 2012). We follow Gertler and Kiyotaki (2010) and Gertler and Karadi (2011, 2013), where the imperfect substitutibility arises from an incentive compatibility constraint that prevents financial intermediaries from perfectly elastically acquiring additional corporate securities and government bonds, which results in a positive spread between the return on intermediaries' assets and liabilities. In such a situation, asset purchases by the central bank increase demand for the assets that are subject to intermediaries' incentive constraint, as a result of which intermediaries incur capital gains on existing assets. These capital gains, in turn, allows intermediaries to expand credit to the real economy with subsequent positive effects on the macroeconomy. A key characteristic of this first generation of general equilibrium models is that they feature no limited liability and are solved through linearization around the deterministic steady state. Therefore, there is no risk taking in these models. Moreover, they focus on the short-run impact of these models while our focus is on the long-run impact.

The model in van der Kwaak et al. (2023) also features limited liability and corporate securities that are subject to a multiplicative idiosyncratic shock. Therefore, their model also features risk taking in the presence of deposit insurance. However, intermediaries only operate for two periods and do not have a portfolio choice between risky corporate securites and safe government bonds, as there is no government debt in the model. Another difference is that van der Kwaak et al. (2023) abstain from a long-run simulation of the model, and focus on how the non-stochastic steady state is affected by the degree of deposit insurance and the volatility of the idiosyncratic shock.

Our paper is also related to the literature that studies the endogenous emergence of financial crises (Boissay et al., 2016, 2022; Rottner, 2023). To properly capture the nonlinearities that arise from transitioning between normal times and financial crisis times, these models are typically solved using global solution methods. Heterogeneity in intermediation efficiency allows for the endogenous emergence of an interbank market in Boissay et al. (2016). However, moral hazard and asymmetric information may freeze this market when a series of positive productivity shocks pushes down the return on credit to a point where it is no longer profitable for unproductive banks to lend to productive banks. However, as Boissay et al. (2016) employ a real business cycle model, there is no role for monetary policy. In similar vein as the interbank market in Boissay et al. (2016), Boissay et al. (2022) feature a market where capital is directly lend by unproductive firms to productive firms, who use it for production of intermediate goods. The presence of New Keynesian pricing frictions subsequently allows the authors to study the central bank's tradeoff between price stability and financial stability. However, the authors only model conventional monetary policy, with no role for unconventional monetary policies. Furthermore, both Boissay et al. (2016) and Boissay et al. (2022) employ models without limited liability and default risk. Therefore, there is no risk taking by banks or firms.

In contrast, Rottner (2023) develops a New Keynesian model with limited liability and endogenous bank runs. Moreover, the presence of risk-shifting incentives and volatility shocks induce intermediaries to extensive leverage accumulation. Like our model, the economy can endogenously land at the ZLB. However, Rottner (2023) focuses on the buildup of the crisis of 2008, and does not feature unconventional monetary policies. Coimbra and Rey (2023) also features endogenous risk taking by financial intermediaries, which arises because of the combination of limited liability and the presence of deposit insurance. Intermediaries are subject to a VaR constraint as in Adrian and Shin (2014), which is heterogenous across intermediaries. They can also invest in a safe storage technology, as a result of which only a subset of intermediaries will participate in the credit market. The combination of these ingredients creates a nonlinear risk taking channel of monetary policy: when the level of interest rates is high, cutting interest rates leads to the entry of less risk-taking intermediaries, as a result of which there is no trade-off between macroeconomic stimulus and financial stability. However, when interest rates are already low, the effect from existing intermediaries increasing leverage dominates, as a result of which financial instability increases with relatively little macroeconomic stimulus. Coimbra and Rey (2023) differ from our paper in the sense that there are no New Keyneisan pricing frictions, and hence there is no endogenous monetary policy. Another difference is that they focus on the short-run impact of shocks through impulse response functions, while we focus on long-run financial stability.

Since the financial crisis of 2008, a steady stream of papers have emerged that investigate the macroeconomic effects of financial crises within continuous time models. The advantage of these models is that more analytical results can be obtained than in their discrete time counterparts. Moreover, as the equilibrium is typically described using a set of partial differential equations, it is possible to solve for the full nonlinear dynamics of these models. One of the first papers in this literature is Brunnermeier and Sannikov (2014), who focus on the amplification of financial sector shocks and their implications for the macroeconomy. Brunnermeier and Sannikov (2016) extend this framework to incorporate both conventional and unconventional monetary poliocy.

Both Brunnermeier and Sannikov (2016) and Silva (2020) show that asset purchases by the central bank *reduce* risk taking by financial intermediaries, which is in line with our results, where the probability of insolvency decreases when the central bank engages in bond purchases at the ZLB. However, while continuous time models are well suited to capture nonlinearities from financial crises and risk taking, the policy rules are typically expressed in terms of a state variable that captures the wealth share of less risk averse agents, while the central bank's policy rules in our model respond to inflation and the output gap.

There is also an empirical literature that studies the impact of monetary policy on risk taking by financial institutions. Schularick et al. (2021) study whether increasing interest rates can defuse financial stability risks during booms. They find that the risk of a financial crisis actually *increases* by raising interest rates rather than decreasing it. Moreover, they do not find evidence that raising rates decreases the negative effect from the resulting financial crisis on GDP. Grimm et al. (2023) are the first to investigate whether loose monetary policy increases macro-level financial instability. They show that loose monetary policy substantially increases the probability of financial crises, and that overheated credit markets play an important role: when interest rates remain below the natural rate for an extended period there is a buildup in asset prices and credit growth, both of which lead to greater financial fragility. Finally, they provide empirical evidence for risk taking through reaching for yield, which is one of the mechanisms through which unconventional monetary policies affect the economy in our model. However, the focus of their paper is on conventional monetary policy, while we focus on unconventional monetary policies.

Finally, Jafarov and Minnella (2023) study whether extended periods of ultra easy monetary policy might have harmful effects. However, they focus on the degree to which unconventional monetary policies lead to zombification, which in turn reduces economic growth, everything else equal. They abstract from investigating the impact that unconventional monetary policies have on the probability of new financial crises.

2 Model

2.1 Financial intermediaries

There is a continuum of financial intermediaries $j \in [0,1]$, which start period t with pre-dividend net worth $n_{j,t}$. Their first action in period t is to pay a fraction σ of net worth as dividends to households, where σ is exogenous and constant over time. Therefore, intermediaries operate with a post dividend amount of net worth $(1-\sigma)\, n_{j,t}$. Next, financial intermediaries issue deposits $d_{j,t}$ at price q_t. Together with net worth $(1-\sigma)\, n_{j,t}$, these deposits finance the acquisition of corporate securities $s^k_{j,t}$ at a price q^k_t and government bonds $s^b_{j,t}$ at price q^b_t. Therefore, intermediary j's balance sheet constraint is given by:

$$q^k_t s^k_{j,t} + q^b_t s^b_{j,t} = (1-\sigma)\, n_{j,t} + q_t d_{j,t}. \tag{1}$$

The aggregate gross return on corporate securities in period $t+1$ is denoted by R^k_{t+1}, and the gross return on government bonds by R^b_{t+1}. Period t deposits $d_{j,t}$ pay an amount $d_{j,t}/\pi_{t+1}$ in period $t+1$, where $\pi_t \equiv P_t/P_{t-1}$ denotes gross the gross inflation rate of final goods and P_t their price level. The return on corporate securities, however, does not only depend on aggregate shocks, but is also subject to a multiplicative idiosyncratic shock $\omega_{j,t+1}$ (Bernanke et al., 1999). The cumulative density function $F(\omega)$ from which the idiosyncratic shocks ω are drawn is lognormal with mean one and volatility σ_ω, and is the same across financial intermediaries. Therefore, the pre-dividend net worth $n_{j,t+1}$ at the beginning of period $t+1$ is given by:

$$n_{j,t+1} = \omega_{j,t+1} R^k_{t+1} q^k_t s^k_{j,t} + R^b_{t+1} q^b_t s^b_{j,t} - \frac{d_{j,t}}{\pi_{t+1}}. \tag{2}$$

The above law of motion allows us to define a cut-off value $\bar{\omega}_{j,t+1}$, below which intermediary j is insolvent:

$$\bar{\omega}_{j,t+1} = \frac{d_{j,t}/\pi_{t+1} - R^b_{t+1} q^b_t s^b_{j,t}}{R^k_{t+1} q^k_t s^k_{j,t}} = \frac{1}{\pi_{t+1} R^k_{t+1}} \cdot \frac{d_{j,t}}{q^k_t s^k_{j,t}} - \frac{R^b_{t+1}}{R^k_{t+1}} \cdot \frac{q^b_t s^b_{j,t}}{q^k_t s^k_{j,t}}. \tag{3}$$

From this expression, we can draw two conclusions. First, we see that the cut-off value is increasing in the ratio of deposits over corporate securities. Therefore, the more deposits for a given value of corporate securities, the higher the cut-off value $\bar{\omega}_{j,t+1}$. Second, we see that the larger the ratio of government bonds over corporate securities, the lower the cut-off value. Therefore, a relative shift from corporate securities to government bonds will reduce the probability of insolvency, everything else equal. This implies that the portfolio composition of financial intermediaries opens up a channel through which intermediaries can increase risk-taking, namely by a relative shift from government bonds to corporate securities.

When $\omega_{j,t+1} < \bar{\omega}_{j,t+1}$, intermediary j is insolvent and declared bankrupt. It is taken over by a deposit insurance agency that is owned by the government. Deposit insurance is partial in the sense that full repayment is guaranteed for a fraction γ of households' deposits, while the remainder $1-\gamma$ comes from the funds that can be recouped from the assets of the insolvent intermediary (Clerc et al., 2015; van der Kwaak et al., 2023). Following Bernanke et al. (1999), however, we assume that recouping the assets of intermediary j involves deadweight costs for corporate securities, which amount to a fraction μ per euro of corporate securities. Therefore, the deposit insurance agency is effectively capable of only recouping a fraction $1-\mu$ from the cash flow $\omega_{j,t+1}R^k_{t+1}q^k_t s^k_{j,t}$ of the corporate securities owned by intermediary j. In contrast, we assume that there are no deadweight costs for the government bonds of intermediary j, as goverrnment bonds can typically be sold easily in highly liquid bond markets.

Following Gete and Melkadze (2020), we assume that intermediaries take into account how their balance sheet decisions affect their funding costs $R^{n,d}_t \equiv 1/q_t$. In other words, they take households' pricing equation into account when determining how many deposits to issue. To derive the pricing equation, we first observe that housseholds' marginal costs from acquiring an additional unit of deposits is the deposit price q_t in period t. The marginal benefit is $1/\pi_{t+1}$ in period $t+1$ in case the realization of the idiosyncratic shock is larger than the cut-off value, i.e. $\omega_{j,t+1} \geq \bar{\omega}_{j,t+1}$. In case of bankruptcy, $\omega_{j,t+1} < \bar{\omega}_{j,t+1}$, the marginal benefit from an additional unit of deposits is γ/π_{t+1} plus a fraction $1-\gamma$ of the gross return on recouped assets from the insolvent bank $(1-\mu)\,\omega_{j,t+1}R^k_{t+1}q^k_t s^k_{j,t} + R^b_{t+1}q^b_t s^b_{j,t}$, divided by total deposits $d_{j,t}$. Therefore, households' pricing equation is given by:

$$\begin{aligned} q_t \;=\; & E_t\Bigg(\mathcal{M}_{t,t+1}\Bigg\{\int_{\bar{\omega}_{j,t+1}}^{\infty}\frac{1}{\pi_{t+1}}\cdot f\left(\omega_{j,t+1}\right)d\omega_{j,t+1} \\ & + \int_0^{\bar{\omega}_{j,t+1}}\left[\gamma\cdot\frac{1}{\pi_{t+1}} + (1-\gamma)\,\frac{(1-\mu)\,\omega_{j,t+1}R^k_{t+1}q^k_t s^k_{j,t} + R^b_{t+1}q^b_t s^b_{j,t}}{d_{j,t}}\right]\cdot f\left(\omega_{j,t+1}\right)d\omega_{j,t+1}\Bigg\}\Bigg). \end{aligned} \tag{4}$$

where the expected cash flows in period $t+1$ are discounted by households' stochastic discount factor $\mathcal{M}_{t,t+1}$. As the distribution of the idiosyncratic shock is identical for all intermediaries, it will turn out that intermediaries will choose the same leverage ratio and portfolio composition between corporate securities and government bonds in equilibrium, as a result of which we will have that $\bar{\omega}_{j,t+1} = \bar{\omega}_{t+1}$. Therefore, households' ex ante expected cash flows from a unit of deposits is identical across financial intermediaries, which warrants the uniform deposit price q_t. As a result, households will hold deposits across all financial intermediaries in equilibrium.

Financial intermediaries are owned by households, as a result of which future cash flows in period $t+s$ are discounted using households' stochastic discount factor $\mathcal{M}_{t,t+s}$. Intermediaries are interested in maximizing the beginning-of-period continuation value $V_{j,t}$, which consists of the dividends $\sigma n_{j,t}$ paid to households and the expected discounted continuation value in period

$t+1$:

$$V_{j,t} = \max_{\left\{s^k_{j,t}, s^b_{j,t}, d_{j,t}\right\}} \sigma n_{j,t} + E_t \left\{\mathcal{M}_{t,t+1} \max\left[V_{j,t+1}, 0\right]\right\}. \tag{5}$$

Next, we follow Faria-e Castro (2021) by defining the ex post dividend continuation value $\mathcal{V}_{j,t}$:

$$\mathcal{V}_{j,t} \equiv V_{j,t} - \sigma n_{j,t},$$

which allows us to rewrite financial intermediaries' optimization objective (5) as:

$$\mathcal{V}_{j,t} = \max E_t \left[\mathcal{M}_{t,t+1} \int_{\bar{\omega}_{j,t+1}}^{\infty} \left(\sigma n_{j,t+1} + \mathcal{V}_{j,t+1}\right) f\left(\omega_{j,t+1}\right) d\omega_{j,t+1}\right]. \tag{6}$$

Financial intermediaries, however, cannot perfectly elastically expand their balance sheet because of a moral hazard problem that is captured by the following incentive compatibility constraint (Gertler and Kiyotaki, 2010; Gertler and Karadi, 2011, 2013):

$$\mathcal{V}_{j,t} \geq \lambda_k q^k_t s^k_{j,t} + \lambda_b q^b_t s^b_{j,t}. \tag{7}$$

Intermediaries' optimization problem consists of maximizing (6) subject to the balance sheet constraint (1), the law of motion for net worth (2), the cut-off value (3), the debt pricing equation (4), and the incentive compatibility constraint (7). This results in the following first order conditions, the details of which can be found in Appendix A.1:

$$\begin{aligned} s^k_{j,t} \quad &: \quad E_t \left[\Omega_{t,t+1} \int_{\bar{\omega}_{j,t+1}}^{\infty} \omega_{j,t+1} R^k_{t+1} f\left(\omega_{j,t+1}\right) d\omega_{j,t+1}\right] \\ &= \quad \frac{\chi_t}{1+\mu_t}\left(1 - \frac{d_{j,t}}{q^k_t} \cdot \frac{\partial q_t}{\partial s^k_{j,t}}\right) + \lambda_k \left(\frac{\mu_t}{1+\mu_t}\right), \end{aligned} \tag{8}$$

$$\begin{aligned} s^b_{j,t} \quad &: \quad E_t \left[\Omega_{t,t+1} \int_{\bar{\omega}_{j,t+1}}^{\infty} R^b_{t+1} f\left(\omega_{j,t+1}\right) d\omega_{j,t+1}\right] \\ &= \quad \frac{\chi_t}{1+\mu_t}\left(1 - \frac{d_{j,t}}{q^b_t} \cdot \frac{\partial q_t}{\partial s^b_{j,t}}\right) + \lambda_b \left(\frac{\mu_t}{1+\mu_t}\right), \end{aligned} \tag{9}$$

$$d_{j,t} \quad : \quad E_t \left[\Omega_{t,t+1} \int_{\bar{\omega}_{j,t+1}}^{\infty} \left(\frac{1}{\pi_{t+1} q_t}\right) f\left(\omega_{j,t+1}\right) d\omega_{j,t+1}\right] = \frac{\chi_t}{1+\mu_t}\left(1 + \frac{d_{j,t}}{q_t} \cdot \frac{\partial q_t}{\partial d_{j,t}}\right), \tag{10}$$

where χ_t denotes intermediaries' shadow value of the balance sheet constraint (1), and μ_t the shadow value of their incentive compatibility constraint (7). Intermediaries' stochastic discount factor is given by $\Omega_{t,t+1} \equiv \mathcal{M}_{t,t+1}\left[\sigma + (1-\sigma)\chi_{t+1}\right]$, and can be interpreted as households' stochastic discount factor $\mathcal{M}_{t,t+1}$ multiplied by a factor that captures financial frictions.

Finally, we show in Appendix A.1 that intermediaries' incentive compatibility constraint (7) can be written as:

$$\chi_t (1-\sigma) n_{j,t} = \lambda_k q_t^k s_{j,t}^k + \lambda_b q_t^b s_{j,t}^b. \tag{11}$$

2.2 Households

There is a continuum of identical households of measure one. They receive income from supplying labor h_t at wage rate w_t, repayment of deposits d_{t-1}/π_t acquired in period $t-1$. They also earn a return R_t^k on their holdings of corporate securities $q_{t-1}^k s_{t-1}^{k,h}$ acquired in period $t-1$, and a return R_t^b on their holdings of government bonds $q_{t-1}^b s_{t-1}^{b,h}$. Finally, households also receive income from profits ω_t of financial and non-financial firms.

They use their income for consumption c_t, lump sum taxes τ_t, deposits d_t, corporate securities $s_t^{k,h}$, and government bonds $s_t^{b,h}$. In addition, households face quadratic transaction costs when changing their holdings of corporate securities and government bonds (Gertler and Karadi, 2013). Therefore, households' budget constraint is given by:

$$\begin{aligned} c_t + \tau_t + q_t d_t + q_t^k s_t^{k,h} + q_t^b s_t^{b,h} &+ \frac{1}{2}\kappa_k \left(s_t^{k,h} - \hat{s}^{k,h}\right)^2 + \frac{1}{2}\kappa_b \left(s_t^{b,h} - \hat{s}^{b,h}\right)^2 \\ &= w_t h_t + \frac{d_{t-1}}{\pi_t} + R_t^k q_{t-1}^k s_{t-1}^{k,h} + R_t^b q_{t-1}^b s_{t-1}^{b,h} + \omega_t. \end{aligned} \tag{12}$$

Household's lifetime utility follows Rudebusch and Swanson (2012) in their formulation of Epstein-Zin (EZ) preferences:

$$V_t = u(c_t, h_t) + \beta \left\{\mathbb{E}_t \left[V_{t+1}^{1-\psi}\right]\right\}^{\frac{1}{1-\psi}},$$

where $u(c_t, h_t) = \frac{c_t^{1-\sigma_c}-1}{1-\sigma_c} - \frac{\chi}{1+\varphi} h_t^{1+\varphi}$ is the period utility kernel, σ_c the inverse elasticity of intertemporal substitution, and φ the inverse Frisch elasticity. ψ captures the degree of risk aversion, which implies that households are more risk averse if ψ is larger. However, since $u(c_t, h_t) < 0$ in our numerical simulations, we follow Rudebusch and Swanson (2012) by employing the following preferences:

$$V_t = u(c_t, h_t) - \beta \left\{\mathbb{E}_t \left[-V_{t+1}^{1-\psi}\right]\right\}^{\frac{1}{1-\psi}}, \tag{13}$$

Households' stochastic discount factor $\mathcal{M}_{t,t+1}$ is then given by:

$$\mathcal{M}_{t,t+1} = \beta \left(\frac{c_{t+1}}{c_t}\right)^{-\sigma_c} \left(\frac{V_{t+1}}{\left\{\mathbb{E}_t \left[V_{t+1}^{1-\psi}\right]\right\}^{\frac{1}{1-\psi}}}\right)^{-\psi}. \tag{14}$$

After setting up the Lagrangian and taking derivatives, we arrive at the following first order conditions for labor supply, corporate securities, and government bonds:

$$h_t \quad : \quad w_t c_t^{-\sigma_c} = \chi h_t^{\varphi}, \tag{15}$$

$$s_t^{k,h} \quad : \quad \mathbb{E}_t \left\{ \mathcal{M}_{t,t+1} \left[\frac{R_{t+1}^k q_t^k}{q_t^k + \kappa_k \left(s_t^{k,h} - \hat{s}^{k,h} \right)} \right] \right\} = 1, \tag{16}$$

$$s_t^{b,h} \quad : \quad \mathbb{E}_t \left\{ \mathcal{M}_{t,t+1} \left[\frac{R_{t+1}^b q_t^b}{q_t^b + \kappa_b \left(s_t^{b,h} - \hat{s}^{b,h} \right)} \right] \right\} = 1, \tag{17}$$

2.3 Production sector

2.3.1 Final goods producers

Final goods producers purchase retail goods from all retail goods producers, and combine the different retail goods y_t^f into final goods y_t using the following constant elasticity of substitution production function:

$$y_t = \left[\int_0^1 \left(y_t^f \right)^{\frac{\epsilon-1}{\epsilon}} df \right]^{\frac{\epsilon}{\epsilon-1}}. \tag{18}$$

Final goods producers operate in a perfectly competitive market, and therefore take the price of final goods P_t and aggregate demand y_t as given. They also take the price of retail goods P_t^f as given, and choose how many retail goods y_t^f to purchase from each retail goods producer f. Therefore, final goods producers' goal is to maximize profits:

$$\max_{y_t^f} \quad P_t y_t - \int_0^1 P_t^f y_t^f df,$$

subject to the production technology (18). This results in the following familiar demand equation for retail good f:

$$y_t^f = \left(\frac{P_t^f}{P_t} \right)^{-\epsilon} y_t. \tag{19}$$

2.3.2 Retail goods producers

Retails goods producers f purchase intermediate output from intermediate goods producers $y_{j,t}$ for a nominal price P_t^m, which they subsequently convert one-for-one into retail goods y_t^f. These are sold to final goods producers for a price P_t^f. Retail goods firm operate in a monopolistically competitive environment, and thus charge a markup. This earns them nominal profits $\left(P_t^f - P_t^m \right) y_t^f$.

We introduce price adjustment costs following Cao et al. (2023).[2] A retail goods producer's

[2]The more common price adjustment cost functions are quadratic following Rotemberg (1982). However, such adjustment costs lead to severe deflationary episodes which increase the frequency of a binding ZLB to unrealistic levels. See Cao et al. (2023) for more details.

optimization problem is therefore given by:

$$\max_{P_t^f} \mathbb{E}_t \left\{ \sum_{s=0}^{\infty} \mathcal{M}_{t,t+s} \left[P_{t+s}^f y_{t+s}^f - P_{t+s}^m y_{t+s}^f \right.\right.$$
$$\left.\left. -\kappa_p \left[\frac{P_{t+s}^f / P_{t+s-1}^f - \pi}{\sqrt{\pi - \overline{\underline{\pi}}}} - 2\sqrt{P_{t+s}^f / P_{t+s-1}^f - \overline{\underline{\pi}}} + 2\sqrt{\pi - \overline{\underline{\pi}}} \right] y_{t+s} \right] \right\},$$

subject to the demand function (19) of final goods producers, and where π is the steady state gross inflation rate, and $\overline{\underline{\pi}}$ is a parameter that governs the curvature of the cost function as inflation falls. After taking the derivative with respect to P_t^f and observing that all retail goods producers set the same price $P_t^f = P_t$ in equilibrium, we end up with the following nonlinear New Keynesian Philips curve:

$$\kappa_p \left(\frac{1}{\sqrt{\pi - \overline{\underline{\pi}}}} - \frac{1}{\sqrt{\pi_t - \overline{\underline{\pi}}}} \right) \pi_t = 1 - \epsilon + \epsilon m_t + \kappa_p E_t \left[\mathcal{M}_{t,t+1} \left(\frac{1}{\sqrt{\pi - \overline{\underline{\pi}}}} - \frac{1}{\sqrt{\pi_{t+1} - \overline{\underline{\pi}}}} \right) \pi_{t+1} \frac{y_{t+1}}{y_t} \right], \tag{20}$$

where $\pi_t \equiv P_t / P_{t-1}$ denotes the gross inflation rate, and $m_t \equiv P_t^m / P_t$ the price of intermediate goods expressed in terms of final goods.

2.3.3 Intermediate goods producers

There is a continuum of measure one of intermediate goods producers that operate in a perfectly competitive market. At the end of period $t-1$, intermediate goods producer j issues corporate securities at price q_{t-1}^k to acquire physical capital $k_{j,t-1}$ from capital goods producers. Intermediate goods producers are capable of perfectly credibly committing after-labor profits to the owners of the corporate securities (Gertler and Kiyotaki, 2010). At the beginning of period t, the productivity shock z_t is realized, after which intermediate goods producer j hires labor $h_{j,t}$ in a perfectly competitive market at wage rate w_t. Subsequently, intermediate good producer j produces intermediate goods using a constant returns to scale production function with capital and labor as inputs:

$$y_{j,t} = z_t k_{j,t-1}^{\alpha} h_{j,t}^{1-\alpha}. \tag{21}$$

After production, intermediate goods producer j sells the intermediate goods at price m_t to retail goods producers. In addition, it sells the depreciated capital stock at price q_t^k to capital goods producers, pays salaries to its workers, and transfers the remaining funds to the owners of the corporate securities. Therefore, profits $\Pi_{j,t}^i$ of intermediate goods producer j are given by:

$$\Pi_{j,t}^i = m_t y_{j,t} + q_t^k (1-\delta) k_{j,t-1} - w_t h_{j,t} - R_t^k q_{t-1}^k k_{j,t-1}.$$

After substitution of the production technology (21), we take the derivative with respect to labor to find the familiar first order condition for labor demand $h_{j,t}$ of intermediate goods producer j:

$$w_t = (1-\alpha)\, m_t z_t k_{j,t-1}^{\alpha} h_{j,t}^{-\alpha}. \tag{22}$$

Next, we remember that intermediate goods producers pay all after-wage profits to the owners of the corporate securities. Therefore, we have that $\Pi_{j,t}^{i} = 0$, which allows us to solve for the ex post return on corporate securities R_t^k:

$$R_t^k = \frac{\alpha m_t z_t k_{j,t-1}^{\alpha-1} h_{j,t}^{1-\alpha} + q_t^k (1-\delta)}{q_{t-1}^k}, \tag{23}$$

where we substituted equation (22) to eliminate the wage rate.

2.3.4 Capital goods producers

There is a continuum of capital goods producers that operate in a perfectly competitive market. Therefore, all capital goods producers take prices as given. At the end of period t, they acquire the remaining capital stock $(1-\delta)\, k_{t-1}$ at price q_t^k. They also acquire i_t final goods which they convert into new capital goods. However, the conversion is subject to adjustment costs, as a result of which i_t of final goods convert into $\Gamma(i_t)$ units of new capital goods. Therefore, the law of motion for capital is given by:

$$k_t = \Gamma(i_t) + (1-\delta)\, k_{t-1}. \tag{24}$$

After production of the new capital goods, capital goods producers sell the capital stock k_t at a price q_t^k to intermediate goods producers. Therefore, period t profits Π_t^k are given by:

$$\Pi_t^k = q_t^k k_t - q_t^k (1-\delta)\, k_{t-1} - i_t = q_t^k \Gamma(i_t) - i_t.$$

Therefore, we see that capital goods producers maximization problem is static, and we find the following first order condition for investment:

$$q_t^k \Gamma'(i_t) = 1. \tag{25}$$

2.4 Government

2.4.1 Central bank

The central bank follows a standard active Taylor rule when away from the Zero Lower Bound (ZLB):

$$R_t^{n,T} = \left[\bar{R}^{n,T} \left(\frac{\pi_t}{\bar{\pi}}\right)^{\kappa_\pi} \left(\frac{m_t}{\bar{m}}\right)^{\kappa_m}\right]^{1-\rho_r} \left(R_{t-1}^{n,T}\right)^{\rho_r}. \tag{26}$$

The central bank is constrained by the Zero Lower Bound (ZLB), therefore the policy rate R_t^n is given by:

$$R_t^n = \max\left\{R_t^{n,T}, 1\right\}. \tag{27}$$

The central bank engages in asset purchases when the economy hits the ZLB. In that case, the central bank expands its portfolio of government bond holdings according to the following policy rule:

$$s_t^{b,cb} = qe_t^{1-\rho_r}\left(\bar{s}^{b,cb}\right)^{\rho_r}, \tag{28}$$

where qe_t is given by:

$$qe_t = \bar{s}^{b,cb}\max\left[1, \left(\frac{\pi_t}{\pi}\right)^{\Psi\kappa_\pi}\left(\frac{m_t}{m}\right)^{\Psi\kappa_m}\mathcal{E}_t\right], \tag{29}$$

where $\mathcal{E}_t$ is given by:

$$\mathcal{E}_t = \frac{\exp\left[\zeta\left(1 - \frac{R_t^{n,T}}{R_t^n}\right)\right]}{1 + \exp\left[\zeta\left(1 - \frac{R_t^{n,T}}{R_t^n}\right)\right]}. \tag{30}$$

The central bank finances these purchases by issuing central bank reserves m_t^r to households at the nominal policy rate R_t^n.[3] Therefore, the central bank balance sheet is given by:

$$q_t^b s_t^{b,cb} = m_t^r. \tag{31}$$

Government bonds earn the gross real return R_t^b, while central bank reserves are paid a real gross return $R_t^r \equiv R_{t-1}^n/\pi_t$. As the central bank operate with zero net worth, central bank dividends d_t^{cb} are given by:

$$d_t^{cb} = R_t^b q_{t-1}^b s_{t-1}^{b,cb} - R_t^r m_{t-1}^r \tag{32}$$

2.4.2 Fiscal authority

The fiscal authority issues debt b_t at price q_t^b, lump sum taxes τ_t, and receives central bank dividends d_t^{cb}. Government debt is long-term a la Woodford (1998, 2001): a bond issued in period $t-1$ pays a coupon x_c in period t, a coupon $\rho_b x_c$ in period $t+1$, a coupon $\rho_b^2 x_c$ in period $t+2$, etc. Therefore, the cash flows from a bond issued in period $t-1$ are equal to a fraction ρ_b of the cash flows of a bond issued in period t. Hence the price of a bond issued in period $t-1$ is equal to $\rho_b q_t^b$, where q_t^b is the price of a bond issued in period t. Therefore, the gross real return R_t^b of a bond issued in period $t-1$ is equal to:

$$R_t^b = \frac{x_c + \rho_b q^b}{\pi_t q_{t-1}^b}, \tag{33}$$

[3]In reality, central bank reserves are held by financial intermediaries, see also van der Kwaak (2023). However, when central bank reserves are not subject to the incentive compatibility constraint, the interest rate on reserves and deposits are equal in equilibrium, and the equilibrium allocation is the same as our model version where reserves are held by households, see also Gertler and Karadi (2011) for this point.

where π_t denotes the gross inflation rate of final goods.

The deposit insurance agency takes ownership of insolvent banks. It repays a fraction γ of outstanding deposit liabailities d_{t-1}/π_t in full, and a fraction $1-\gamma$ of the cash flows from the recouped assets of insolvent intermediaries (Clerc et al., 2015; van der Kwaak et al., 2023). Therefore, the funds paid out by the deposit insurance agency are given by:

$$\begin{aligned}\mathcal{D}_t &= \int_0^{\bar{\omega}_t} \left\{ \gamma \frac{d_{t-1}}{\pi_t} + (1-\gamma) \left[(1-\mu) \omega_t R_t^k q_{t-1}^k s_{t-1}^k + R_t^b q_{t-1}^b s_{t-1}^b \right] \right. \\ &- \left. \left[(1-\mu) \omega_t R_t^k q_{t-1}^k s_{t-1}^k + R_t^b q_{t-1}^b s_{t-1}^b \right] \right\} f(\omega_t)\, d\omega_t \\ &= \gamma \int_0^{\bar{\omega}_t} \left\{ \frac{d_{t-1}}{\pi_t} - \left[(1-\mu) \omega_t R_t^k q_{t-1}^k s_{t-1}^k + R_t^b q_{t-1}^b s_{t-1}^b \right] \right\} f(\omega_t)\, d\omega_t\end{aligned}$$

The government revenues are spent on liabilities $R_t^b q_{t-1}^b b_{t-1}$ from outstanding government bonds and deposit insurance. Therefore, the budget constraint of the fiscal authority is given by:

$$q_t^b b_t + \tau_t + d_t^{cb} = R_t^b q_{t-1}^b b_{t-1} + \mathcal{D}_t. \tag{34}$$

Finally, we assume that lump sum taxes adjust period by period to ensure that the outstanding stock of government debt is constant across time: $b_t = \bar{b}$.

2.5 Market clearing & equilibrium

Clearing in the markets for corporate securities and government bonds occurs when the supply is equal to the demand by intermediaries and households:

$$k_t = s_t^k + s_t^{k,h}, \tag{35}$$

$$b_t = s_t^b + s_t^{b,h} + s_t^{b,cb}, \tag{36}$$

Clearing in the market for final goods requires the following equation to hold in equilibrium:

$$y_t = c_t + i_t + \text{adjustment costs}. \tag{37}$$

Finally, we show in Appendix A.1 that all intermediaries make the same choices for the ratio of deposits over corporate securities $d_{j,t}/\left(q_t^k s_{j,t}^k\right)$ and the market value of bonds over corporate securities $q_t^b s_{j,t}^b/\left(q_t^k s_{j,t}^k\right)$. Therefore, the cut-off value will be the same across intermediaries, i.e. $\bar{\omega}_{j,t+1} = \bar{\omega}_{t+1}$. This allows for straightforward aggregation.

3 Analytical results in a two-period model

In this section, we consider a simplified two-period model version of the infinite-horizon model of Section 2. We do so to highlight the potential channels through which financial intermediaries can engage in risk-taking.

3.1 Specifics of the two-period model

We consider a simplified version of the infinite-horizon economy of Section 2. Our focus is on intermediaries' balance sheet decisions in period $t = 0$, both the portfolio decision between corporate securities and government bonds as well as the leverage ratios with which intermediaries operate in equilibrium. The economy stops operating after period $t = 1$. Variables x_t determined in period $t = 0$ are denoted by x, while variables determined in period $t = 1$ are denoted by $\tilde{x}$. At the beginning of period $t = 0$, there is an exogenous expansion of central bank reserves m^R, as a result of which the market value of the central bank's bond holdings increases. Afterwards, no new shocks occur and there is perfect foresight. Therefore, the analysis in this section is deterministic.

We deviate from Section 2 in several dimensions. For example, we assume that households do not hold any corporate securities, which are instead entirely held by financial intermediaries. We also abstract from menu costs. Hence, prices can perfectly flexibly adjust. We also assume an infinite elasticity of substitution between different retail goods. Therefore, the price of intermediate goods is equal to the price of final goods, i.e. $m_t = 1$. We also assume that households supply an inelastic amount of labor $h = \tilde{h} = 1$. Furthermore, we assume full depreciation of the capital stock between period $t = 0$ and $t = 1$, hence we have that $\delta = 1$. Finally, we assume that one unit of investment by capital goods producers translates into one unit of physical capital. Therefore, $\Gamma'(i_t) = 1$, as a result of which we have that $q_t^k = 1$. Substitution of $m_t = 1$, $\delta = 1$, $q_t^k = 1$, and $h_t = 1$ in equation (23) gives the following expression for the return on corporate securities R^k:

$$R^k = \alpha k^{\alpha - 1}. \tag{38}$$

As a result, the gross return on corporate securities is effectively determined in period $t = 0$, and is taken as given by intermediaries when determining the number of corporate securities to acquire in period $t = 0$. However, changes in the aggregate credit supply k will endogenously adjust the gross return on corporate securities R^k, as a result of which the market for corporate securities clears in equilibrium.

We deviate from Section 2.4.2 by assuming that the fiscal authority enters period $t = 0$ with a stock of outstanding zero-coupon bonds b_{-1}, which promise repayment of the principal at the beginning of period $t = 1$. The fiscal authority does not spend or levy taxes in period $t = 0$, hence the stock of government debt b at the end of period $t = 0$ is equal to the stock b_{-1} at the beginning of period $t = 0$, i.e. $b = b_{-1}$. The outstanding bonds are traded in period $t = 0$ in financial markets at price q^b by households, intermediaries, and the central bank. Hence the return R^b on government bonds acquired in period $t = 0$ that are held to maturity in period $t = 1$ is given by:

$$R^b = \frac{1}{q^b}. \tag{39}$$

We eliminate the idiosyncratic shock by setting $\omega_t = 1$ for all financial intermediaries. In addition, we assume that there is no limited liability. The fact that there is no limited liability also implies that deposits are risk-free, as a result of which households will charge the risk-free rate on deposits. For analytical tractability, we assume that the deposit rate is constant in this section. Therefore, the derivatives of the deposit price q_t with respect to corporate securities, government bonds, and deposits will be zero in this section. Finally, we set $\sigma = 1$, implying that all net worth is paid out in period $t = 1$. As a result, intermediaries' first order conditions (8) - (10) are now given by:

$$s^k \quad : \quad \beta\tilde{\Lambda}R^k = \frac{\chi}{1+\mu} + \lambda_k \left(\frac{\mu}{1+\mu}\right), \tag{40}$$

$$s^b \quad : \quad \beta\tilde{\Lambda}R^b = \frac{\chi}{1+\mu} + \lambda_b \left(\frac{\mu}{1+\mu}\right), \tag{41}$$

$$d \quad : \quad \beta\tilde{\Lambda}R^d = \frac{\chi}{1+\mu}, \tag{42}$$

where $\beta\tilde{\Lambda} \equiv \beta\left(\tilde{c}/c\right)^{-\sigma_c}$ since the third factor in equation (14) is equal to 1 in the absence of stochastic shocks in period $t = 1$. Furthermore, we define the interest on deposits $R^d \equiv 1/\left(\tilde{\pi}q\right)$ and assume that the central bank directly controls R^d.

Next, we substitute the first order condition for deposits (42) into the first order conditions for corporate securities (40) and government bonds (41). Afterwards, we solve for $\mu/\left(1+\mu\right)$ from the first order condition of corporate securities, and substitute the resulting expression into the first order condition for government bonds to obtain:

$$R^b - R^d = \frac{\lambda_b}{\lambda_k}\left(R^k - R^d\right). \tag{43}$$

The left hand side of the equation denotes the marginal benefit from acquiring an additional unit of government bonds, which is equal to the spread between the return R^b earned on bonds and the return R^d that is paid on the deposits that finance the additional bonds on the margin. On the right hand side is the marginal cost from reducing corporate securities by one unit, which is equal to the spread between the return R^k earned on corporate securities and the return R^d on deposits that finance the corporate securities on the margin, multiplied by the relative diversion rates λ_b/λ_k.

Setting $\sigma = 1$ not only implies that all net worth will be paid out in period $t = 1$ but also that intermediaries would operate with zero net worth in period $t = 0$, which we deem unrealistic. Therefore, we follow van der Kwaak (2023) and assume that net worth in period $t = 0$ is given by an exogenous component $\bar{n}$ plus the bond holdings s^b_{-1} that were acquired by the previous generation of intermediaries in period $t = -1$. As these bonds are valued at price q^b in period $t = 0$, the net worth of intermediaries that start operating in period $t = 0$ is equal to:

$$n = \bar{n} + q^b s^b_{-1}. \tag{44}$$

The absence of idiosyncratic shocks and limited liability also implies that equation (4) boils down to:[4]

$$\beta \tilde{\Lambda} R^d = 1. \tag{45}$$

Substitution of this equation into intermediaries' first order condition for deposits (42) immediately allows us to infer that $\chi = 1 + \mu$.

Intermediaries' balance sheet constraint (1) is given by:

$$k + q^b s^b = n + qd, \tag{46}$$

where we remember that initial net worth n in period $t = 0$ is given by equation (44). Financial intermediaries' incentive compatibility constraint (11) becomes:

$$\chi n = \lambda_k k + \lambda_b q^b s^b. \tag{47}$$

Next, we define the weighted leverage ratio ϕ^w as:

$$\phi^w = \frac{k + \left(\frac{\lambda_b}{\lambda_k}\right) q^b s^b}{n} = \frac{\chi}{\lambda_k}, \tag{48}$$

where we used equation (47) to obtain the final expression for ϕ^w. The unweighted leverage ratio is given by:

$$\phi^u = \frac{k + q^b s^b}{n}. \tag{49}$$

Finally, we look at intermediaries' cut-off value (3). By itself, this variable is meaningless in the context of our two-period model, as this model version does not feature insolvency of financial intermediaries. However, it will turn out to be useful for our analysis of the infinite-horizon model (that features insolvency of intermediaries), as some of the relevant mechanisms can already be identified within the current two-period model. Therefore, we define below the two-period model equivalent of equation (3), which is given by:

$$\bar{\omega} = \frac{R^d qd - R^b q^b s^b}{R^k k}, \tag{50}$$

where we remember that $R^d \equiv 1/\left(\tilde{\pi} q\right)$.

[4]Setting $\bar{\omega} = 0$ and $\gamma = 1$ immediately gives the above expression.

3.2 Analysis of asset purchases

In this section, we investigate the impact of an exogenous expansion of central bank reserves m^R, which are used by the central bank to acquire additional government bonds s^{cb} at price q^b. We start by inspecting the impact of central bank bond purchases on the return on government bonds R^b and corporate securities R^k in Proposition 1, as well as on credit provision to the real economy.

Proposition 1. *Bond purchases by the central bank decrease the return on government bonds, the return on corporate securities, and the credit spread, while they increase credit provision to the real economy.*

Proof of Proposition 1. We show in Appendix B that asset purchases increase the bond price, i.e. $\frac{dq^b}{dm^R} > 0$, as a result of which we know from equation (39) that the return on government bonds decreases:

$$\frac{dR^b}{dm^R} = -\frac{1}{\left(q^b\right)^2} \cdot \frac{dq^b}{dm^R} < 0. \tag{51}$$

Implicit differentiation of intermediaries' portfolio choice between government bonds and corporate securities (43) with respect to central bank reserves m^R gives the following relation:

$$\frac{dR^b}{dm^R} = \left(\frac{\lambda_b}{\lambda_k}\right) \frac{dR^k}{dm^R}, \tag{52}$$

from which we can immediately see that the return on corporate securities decreases in response to an expansion of the central bank balance sheet:

$$\frac{dR^k}{dm^R} < 0.$$

Since the deposit rate is constant, it immediately follows that the credit spread decreases with an increase in central bank reserves m^R.

Finally, we prove that bond purchases by the central bank expand credit provision to the real economy. To do so, we implicitly differentiate equation (38) to obtain:

$$\frac{dR^k}{dm^R} = -\left(1-\alpha\right) \alpha k^{\alpha-2} \cdot \frac{dk}{dm^R}. \tag{53}$$

Hence we immediately conclude that $\frac{dk}{dm^R} > 0$, which concludes the proof. □

The intuition behind Proposition 1 is straightforward, and has been documented extensively in the literature, see Gertler and Karadi (2013) among others. An increase in bond purchases by the central bank increases the demand for government bonds, everything else equal, as a result of which the bond price increases. A higher bond price decreases the return on government bonds, which induces intermediaries to shift from government bonds to corporate securities. As a result, credit supply to intermediate goods producers increases, which in turn decreases the return on corporate securities and the credit spread (since the return on deposits is constant).

Next, we show in Proposition 2 that intermediaries' market value of government bonds $q^b s^b$ decreases in response to an expansion in central bank reserves m^R.

Proposition 2. *The market value of intermediaries' bond holdings $q^b s^b$ decreases as a result of an bond purchases by the central bank, i.e.* $\frac{d(q^b s^b)}{dm^R} < 0$.

Proof of Proposition 2. Implicit differentiation of $q^b s^b$ with respect to m^R gives the following expression:

$$\frac{d\left(q^b s^b\right)}{dm^R} = s^b \cdot \frac{dq^b}{dm^R} + q^b \cdot \frac{ds^b}{dm^R} < 0,$$

see Appendix B for the proof. □

The intuition behind this result is that additional bond purchases by the central bank imply that households and financial intermediaries sell part of their bond holdings to the central bank, as the total supply of government bonds is fixed in this model. However, the additional demand for bonds from the central bank implies that the bond price increases in equilibrium, which increases the market value of intermediaries' bond holdings, everything else equal. However, this price effect is dominated by the direct effect from intermediaries selling bonds to the central bank, as a result of which the market value of intermediaries' bond holdings decreases in equilibrium.

We establish the above results in preparation for two results that initially might seem at odds with each other, but which will turn out to be relevant in the numerical analysis of the full infinite-horizon model in subsequent sections: we show that it is possible to simultaneously have that i) leverage ratios decrease (Proposition 3), and ii) the cut-off value $\bar{\omega}$ *increases* in equilibrium (Proposition 4). These results imply that it is possible that the probability of bank insolvency increases in the full infinite-horizon model, while intermediaries simultaneously operate with lower leverage ratios.

We start with Proposition 3, which shows that intermediaries' leverage ratios decrease in response to bond purchases by the central bank:

Proposition 3. *Both the weighted leverage ratio* (48) *and the unweighted leverage ratio* (49) *decrease in response to bond purchases by the central bank.*

Proof of Proposition 3. Implicit differentiation of equation (48) gives the following expression for the change in the weighted leverage ratio, a formal derivation of which can be found in Appendix B:

$$\frac{d\phi^w}{dm^R} = \frac{1}{\lambda_k} \cdot \frac{d\chi}{dm^R} = -\frac{C}{\lambda_k} \cdot \frac{dk}{dm^R},$$

where $C > 0$. Since we know from Proposition 1 that $\frac{dk}{dm^R} > 0$, we can immediately conclude that $\frac{d\phi^w}{dm^R} < 0$, which concludes the proof for the weighted leverage ratio.

Next, we can rewrite the unweighted leverage ratio (49) in the following way with the help of equation (48):

$$\phi^u = \phi^w + \left(1 - \frac{\lambda_b}{\lambda_k}\right) \frac{q^b s^b}{n},$$

Implicit differentiation of $q^b s^b / n$ gives the following expression:

$$\frac{d}{dm^R}\left(\frac{q^b s^b}{n}\right) = \frac{n \cdot \frac{d\left(q^b s^b\right)}{dm^R} - q^b s^b \cdot \frac{dn}{dm^R}}{n^2} < 0,$$

because we know from Proposition 2 that $\frac{d\left(q^b s^b\right)}{dm^R} < 0$, while implicit differentiation of equation (44) gives:

$$\frac{dn}{dm^R} = s^b_{-1} \cdot \frac{dq^b}{dm^R} > 0.$$

Since $\frac{d\phi^w}{dm^R} < 0$ and $\frac{d}{dm^R}\left(\frac{q^b s^b}{n}\right) < 0$, we immediately conclude that $\frac{d\phi^u}{dm^R} < 0$. This concludes the proof. □

The intuition behind Proposition 3 can be explained in the following way. As the return on corporate securities decreases (as a result of the central bank's bond purchases), intermediaries' marginal benefit from an additional unit of corporate securities decreases. As a result, the marginal benefit χ from a relaxation of the balance sheet constraint (through an additional unit of net worth) decreases, which decreases intermediaries' continuation value χn. As a result, depositors force financial intermediaries to reduce the size of their balance sheet and both the weighted and unweighted leverage ratio.

Next, we study how the central bank's bond purchases affect the cut-off value $\bar{\omega}$ in equation (50). As mentioned above, doing so within our two-period model version is by itself meaningless, as this model version does not feature bank insolvency. However, it turns out that doing so allows us to highlight some of the key mechanisms that will be at play within the full infinite-horizon model.

Proposition 4. *The cut-off value $\bar{\omega}$ increases in response to bond purchases by the central bank unless intermediaries incur large capital gains on their existing bond holdings s^b_{-1}.*

Proof of Proposition 4. We start by solving for qd in equation (46), after which we substitute the resulting expression into equation (50):

$$\bar{\omega} = \frac{R^d k - \left(R^b - R^d\right) q^b s^b - R^d n}{R^k k}. \tag{54}$$

We show in Appendix B that implicit differentiation gives the following expression for the change in the cut-off value $\frac{d\bar{\omega}}{dm^R}$:

$$\frac{d\bar{\omega}}{dm^R} = \frac{\left(R^d - \alpha\bar{\omega}R^k\right) \cdot \frac{dk}{dm^R} - q^b s^b \cdot \frac{dR^b}{dm^R} - \left(R^b - R^d\right) \cdot \frac{d}{dm^R}\left(q^b s^b\right) - R^d s^b_{-1} \cdot \frac{dq^b}{dm^R}}{R^k k}. \tag{55}$$

The term $R^d - \alpha\bar{\omega}R^k$ will be larger than zero for most reasonable calibrations, since $\alpha < 1$ and $\bar{\omega} < 1$, the last of which can be seen by further rewriting equation (54):

$$\bar{\omega} = \frac{R^d}{R^k} - \frac{\left(R^b - R^d\right) q^b s^b + R^d n}{R^k k} < 1.$$

Since the return on deposits R^d will be below that on corporate securities R^k, the first term will be smaller than one, while the second term is negative. Hence $\bar{\omega} < 1$.

Now that we have established that the first term in equation (55) is positive, we inspect the other terms in equation (55). We immediately see that the second term will be positive since $\frac{dR^b}{dm^R} < 0$, see Proposition 1, and the third term will also be positive since $\frac{d\left(q^b s^b\right)}{dm^R} < 0$, see Proposition 2. Finally, the fourth term will be negative since $\frac{dq^b}{dm^R} < 0$, see Proposition 1. □

The intuition behind equation (55) is the following. First, additional bond purchases by the central bank increase credit supply to the real economy, as a result of which intermediaries need to attract additional deposits. As intermediaries need to pay interest on these additional deposits, the cut-off value $\bar{\omega}$ increases, everything else equal. However, additional corporate securities also increase the gross return on corporate securities $R^k k$, which reduces the cut-off value, everything else equal. However, while credit provision increases, the return R^k decreases, see Proposition 1, which is the reason why the total effect from additional lending $\left(R^d - \alpha\bar{\omega}R^k\right) \cdot \frac{dk}{dm^R}$ will increase the cut-off value $\bar{\omega}$.

Next, bond purchases by the central bank also negatively affect intermediaries' profits from holding government bonds via two channels, which are captured by the second and third term in equation (54). First, the return on government bonds R^b decreases. Second, the market value of intermediaries' bond holdings decreases. Both of these channels decrease intermediaries' profits from bond holdings $\left(R^b - R^d\right) q^b s^b$, which in turn increases the cut-off value $\bar{\omega}$, everything else equal. Finally, the last term in equation (55) captures intermediaries' capital gains on existing bond holdings s^b_{-1}. Capital gains decrease the cut-off value, everything else equal, as more net worth decreases the amount of deposits that intermediaries have to attract.

Concluding this section, we see that an important channel through which risk-taking will occur in the infinite-horizon model is by intermediaries making their balance sheet more vulnerable to low realizations of the idiosyncratic shock. They do so through a relative shift from safe government bonds to risky corporate securities, which increases the cut-off value $\bar{\omega}$ in equation (50) and thus the probability of insolvency. While risk-taking could theoretically also occur via intermediaries operating with higher leverage ratios, we show in this section that bond purchases by the central bank in fact *decrease* the weighted and unweighted leverage ratio in equilibrium. Hence the risk-taking channel of central bank bond purchases solely arises through the relative portfolio shift from safe government bonds to risky corporate securities.

4 Calibration

We calibrate the model on a quarterly frequency. We do so for the model version with deposit insurance but without any unconventional monetary policies. Specifically, we set households' subjective discount factor $\beta = 0.995$. Together with the central bank's inflation target of 2% annual inflation, this implies a long-run risk-free real interest rate approximately equal to 2% per year. We set households' intertemporal elasticity of substitution $1/\sigma_c$ equal to 1/2 and the inverse Frisch elasticity φ equal to 2, the last of which is in line with micro estimates by Chetty et al. (2011). Regarding the implicit coefficient of relative risk aversion (CRRA), Swanson (2012, 2018) show that it is less straightforward to calibrate the degree of risk aversion in models with endogenous labor supply, as the labor margin influences households' risk appetite. However, they are able to show that the CRRA is approximately equal to:

$$\text{CRRA} \approx \frac{\sigma_c}{1 + \frac{\sigma_c}{\varphi}} + \psi \frac{1 - \sigma_c}{1 + \frac{\sigma_c - 1}{1 + \varphi}}.$$

In what follows, we set $\psi = -115$. Together with $\sigma_c = \varphi = 2$, we then find that CRRA ≈ 87.25. This is higher than what most papers in the finance/asset pricing use, but is pretty much in line with papers in the quantitative New Keynesian DSGE literature.[5] We set households' transaction costs from corporate securities κ_k and bond holdings κ_b, respectively, equal to 0.05 and 0.01, respectively. The elasticity of substitution between different retail goods producers ϵ is set to 11, which implies a (non-stochastic) steady state markup equal to 10%. We set $\overline{\underline{\pi}}$ equal to 0.97, after which we adjust κ_P to hit the average slope of the New Keynesian Phillips curve being equal to 0.04 (Cao et al., 2023). The capital share α in the production function and the depreciation rate are set to 1/3 and 0.025, values that are commonly employed in the literature. Finally, we choose the following functional form for the capital producers' investment adjustment cost function:

$$\Gamma(i_t) = a_k + \left(\frac{b_k}{1 - 1/\gamma_k} \right) i_t^{1 - 1/\gamma_k},$$

where a_k, b_k, and γ_k are parameters. We set b_k such that $\bar{q}^k = 1$ and a_k such that $\bar{i} = \delta \bar{k}$ in the non-stochastic steady state.

Next, we discuss the calibration of the financial sector. We set $\sigma = 0.08$, implying that 8% of net worth is paid out to households in dividends. As a result, 92% of realized net worth remains in the financial sector, which is close to the value used in Gertler et al. (2019). Furthermore, we target an unweighted leverage ratio of 5 (Gertler and Karadi, 2011, 2013), an annual credit spread that is equal to 150 annual basis points (Akinci and Queralto, 2022), an annual probability of bank default equal to 0.665% (Mendicino et al., 2020), and the diversion rate of government bonds being equal to half the diversion rate of corporate securities, i.e.$\lambda_b = \lambda_k/2$. We hit these targets by adjusting the transfer χ_b to newly starting bankers, the diversion rate λ_k of corporate

[5] Rudebusch and Swanson (2012) set risk aversion to 75, while Basu and Bundick (2017) use 80. Finally, Van Binsbergen et al. (2012) find estimates between 50 and 85.

Parameter	Value	Definition
Households		
β	0.995	Discount rate
$1/\sigma_c$	1/2	Coefficient of intertemporal elasticity of substitution
φ	2	Inverse Frisch elasticity
ψ	-115	Coefficient of relative risk-aversion
κ_k	0.05	Coefficient HHs transaction costs corporate securities
κ_b	0.01	Coefficient HHs transaction costs bond holdings
Financial intermediaries		
σ	0.08	Dividend payout rate
$E\left[\bar{r}^k - \bar{r}^d\right]$	0.00375	Spread between corporate securities and deposits
$F\left(\bar{\omega}\right)$	0.16625	Probability of bank default
σ_ω	0.0867	Probability of bank default
λ_k	0.265	Diversion rate corp. securities
λ_b	0.1325	Diversion rate gov't bonds
χ_b	0.2784	Starting net worth new bankers
$\bar{s}^k/\bar{k}$	0.8	Average state corp. securities FI over total securities
$\bar{q}^b\bar{s}^b/\bar{p}$	0.14	Average bonds held by FI (as percentage of assets)
μ	0.12	Deadweight losses from bank default
Goods producers		
α	1/3	Capital share
δ	0.025	Depreciation rate
ϵ	11	Elasticity of substitution
κ_P	9.8	Elasticity of substitution
$\overline{\underline{\pi}}$	0.97	Rotemberg parameter
γ_k	4	Investment adjustment costs
a_k	-0.2184	Constant in investment adjustment costs
b_k	0.8997	Constant in investment adjustment costs
Fiscal policy		
$\bar{b}/\bar{y}$	2.4	60% of annual GDP
x_c	0.0621	Coupon payment bonds
ρ_b	0.95	parameter determining effective duration bonds
Monetary policy		
$\bar{\pi}$	1.005	Steady state gross inflation rate
κ_π	2.500	Inflation feedback on nominal interest rate
κ_m	0.25	Output feedback on nominal interest rate
ρ_r	0	Interest rate smoothing parameter
Ψ_π	-20	QE smoothing parameter inflation
Ψ_m	-20	QE smoothing parameter inflation
Autoregressive processes		
ρ_z	0.95	AR(1) parameter productivity shock
ρ_ϕ	0.75	AR(1) parameter risk-premium shock (standard 0.85)
σ_z	0.05	Standard deviation productivity shock
σ_ϕ	0.29	Standard deviation risk-premium shock

Table 1: Calibration targets.

securities, and the standard deviation σ_ω of the idiosyncratic shock. The deadweight losses from bank default μ are equal to 0.12, in line with Bernanke et al. (1999). Finally, we target that financial intermediaries hold 80% of the total supply of corporate securities, while intermediaries' government bonds are equal to 14% of total assets. We do so by adjusting the parameters $\hat{s}^{k,h}$ and $\hat{s}^{b,h}$ in households' quadratic transactions costs.

For fiscal policy, we target the long-run government debt over annual output ratio to equal 60%. We set the parameter ρ_b that effectively determines the maturity of government debt equal to 0.95, implying an approximate average duration equal to 20 quarters (5 years). Finally, we adjust the coupon payment x_c to target a bond price q^b that is approximately equal to 1 in the long-run.

The central bank's inflation target $\bar{\pi}$ is set to 0.5% per quarter, implying an annual inflation target of 2%, in line with the inflation target of the European Central Bank (ECB). We set the inflation feedback coefficient $\kappa_\pi = 2.5$ and the output gap coefficient $\kappa_m = 0.25$, while we follow Gertler et al. (2019) in setting the interest rate smoothing parameter.

Regarding the autoregressive processes, we set the AR(1) coefficient ρ_z and standard deviation σ_z to values commonly found in the literature. Finally, we use the usual Rouwenhorst procedure to discretize the process for λ_t^k as a five point Markov chain with autocorrelation 0.85 and a standard deviation of 10.5%. These choices ensure that the frequency with which the economy is at the ZLB is 6.6%.

5 Numerical results

In this section we report the results from numerical simulations. We start by comparing the unconditional means of a model version with asset purchases by the central bank with a model version without purchases. We do so for model versions with and without deposit insurance. We will see that there are relatively limited long-run effects from asset purchases, both on the financial sector as well as on the real economy. However, it is well established in the literature that asset purchases mitigate the contractionary impact that financial crises have Gertler and Kiyotaki (2010); Gertler and Karadi (2011). Therefore, we check that asset purchases mitigate the impact of crises within our model, after which we study the impact of asset purchases on the post-crisis period. We end the section with a discussion of our results and several robustness checks.

5.1 The impact of risk-taking: deposit insurance versus no deposit insurance

It is well known from the finance literature that the presence of deposit insurance can induce banks to take more risk (Kareken and Wallace, 1978). The reason is that when deposits are protected by deposit insurance, bank creditors do not properly price in the probability of bank default. Therefore, banks' funding costs are lower than in the absence of deposit insurance, which increases their profitability, everything else equal, and can therefore induce them to lever up. Therefore, we start this section by comparing in Table 2 the baseline model version without deposit insurance ('no DI' with $\gamma = 0$) with a model version with insurance ('DI' with $\gamma = 1$).

Variable	No DI	DI
Output: y	2.9258	2.9396
Consumption: c	2.2743	2.2810
Physical capital: k	25.8219	26.1998
Net worth: n	4.6798	4.6937
Capital price: q^k	0.9961	0.9998
Bank securities: k^b	20.5718	20.9591
Bank bonds: b^b	3.7064	3.5992
Bond price: q^b	1.0742	1.0491
Leverage: l	5.2557	5.2833
Weighted leverage: l^w	4.8289	4.8808
Fraction of insolvent banks: $F(\bar{\omega})$	0.2021%	0.2097%
Max. fraction of insolvent banks: $F(\bar{\omega})$	14.4055%	6.8745%
Gross bank funding cost: R^d	1.0087	1.0088
Gross nominal policy rate: R^n	1.0089	1.0089
Gross real policy rate: R	1.0048	1.0048
Annualized net nominal policy rate: R^n	3.3746%	3.5405%
Annualized net real policy rate: R	1.9098%	1.9110%
Prob. of financial crisis:	2.6130%	2.6080%
Prob. of financial crisis and ZLB:	1.7950%	1.9420%
Prob. of binding leverage constraint:	61.3784%	93.2081%
Prob. of ZLB:	10.7049%	7.9679%

Table 2: Ergodic means of selected variables for the model version without deposit insurance (column 'No DI') and with deposit insurance (column 'DI').

We see that deposit insurance has a positive effect on the macroeconomy: the ergodic means of output, consumption, and capital are larger than their counterpart in the model version without deposit insurance. The quantitative difference, however, is rather small, and in most cases less than 1%.

Looking at the ergodic means of the financial sector variables, we see that intermediaries are more profitable in the model version with deposit insurance, as net worth is on average higher. However, financial intermediaries also take more risk in the model version with deposit insurance: they hold more corporate securities ("Bank securities" in Table 2) and less government bonds ("Bank bonds") than in the model version without deposit insurance. The resulting decrease in the ratio of bond holdings over corporate securities increases the cut-off value $\bar{\omega}_{t+1}$, see equation (3), everything else equal, which increases the probability of insolvency. Furthermore, we see that both the weighted and unweighted leverage ratio are higher in the model version with deposit insurance, which is driven by the fact that intermediaries are more profitable than in the model version without deposit insurance (because of lower funding costs), which allows them to take on more debt Katz and van der Kwaak (2022).

In line with the higher leverage ratios, we see that the financial system is more fragile in the model version with deposit insurance: the average fraction of intermediaries that default each quarter is higher, the probability of financial crises at the ZLB is higher, and the incentive compatibility constraint is more likely to bind. However, the ZLB itself is less likely to bind, and the maximum fraction of intermediaries that default across the entire simulation is less than half the maximum fraction of intermediaries that default in the model version without deposit insurance.

To explain these observations, we compare the two model versions around financial crisis times in Figures 1 - 2, where a financial crisis is defined as a period in which lending by creditors to intermediaries drops by 2 standard deviations *and* the ZLB binds.[6] Specifically, we construct Figures 1 - 2 by identifying all financial crisis periods in our long-run simulation, after which we create an event window of 15 periods before and after a financial crisis hits the economy. Importantly, we only include financial crises episodes that are common to both model versions.[7]

We see in Figures 1 - 2 that the observation that the maximum number of insolvent banks across the entire simulation is higher in the model version without deposit insurance is driven by the fact that this model version features a negative feedback loop between banks' funding costs and the probability of bank default (panel 'Deposit interest rate: R_t^d'): in financial crisis times, the probability of bank default increases, as a result of which bank creditors charge a higher interest rate. Higher funding costs, however, decrease banks' profitability which in turn further increases the probability of bank default. As this feedback loop is absent in the model version with deposit insurance, the fraction of banks that default in financial crisis times is substantially lower than in the model version without deposit insurance (compare the sharp increase in the deposit rate for the model version without deposit insurance with the small increase in the model version with deposit insurance in Figure 2).[8]

Next, observe that the unconditional average interest rate on bank debt is approximately equal in both model versions. This is the case, despite the fact that bank creditors price in the probability of bank default in the model version without deposit insurance, which would lead to higher funding costs, everything else equal. The reason why this is not the case is that financial crises are more severe in the model version without deposit insurance as a result of the above-mentioned feedback loop between banks' funding costs and probability of default. Therefore, the credit contraction in financial crises is larger in the model version without deposit insurance, which leads to larger contractions in investment and output, see Figures 1 - 2. Less economic activity, in turn, leads to lower interest rates via the Taylor rule.

[6]Bianchi (2016) and Gete and Melkadze (2020) define financial crises as periods in which bank deposits fall by at least 2 times the unconditional standard deviation of the entire long-run simulation.

[7]For our long-run simulations, we feed both model versions (with and without deposit insurance) the exact same time series of exogenous shocks. It turns out that there are instances in which the economy with deposit insurance is not in a financial crisis whereas the model version without insurance is or vice versa.

[8]See Katz and van der Kwaak (2022) for a description of the same negative feedback loop when comparing bank recapitalizations through bail-ins with bailouts.

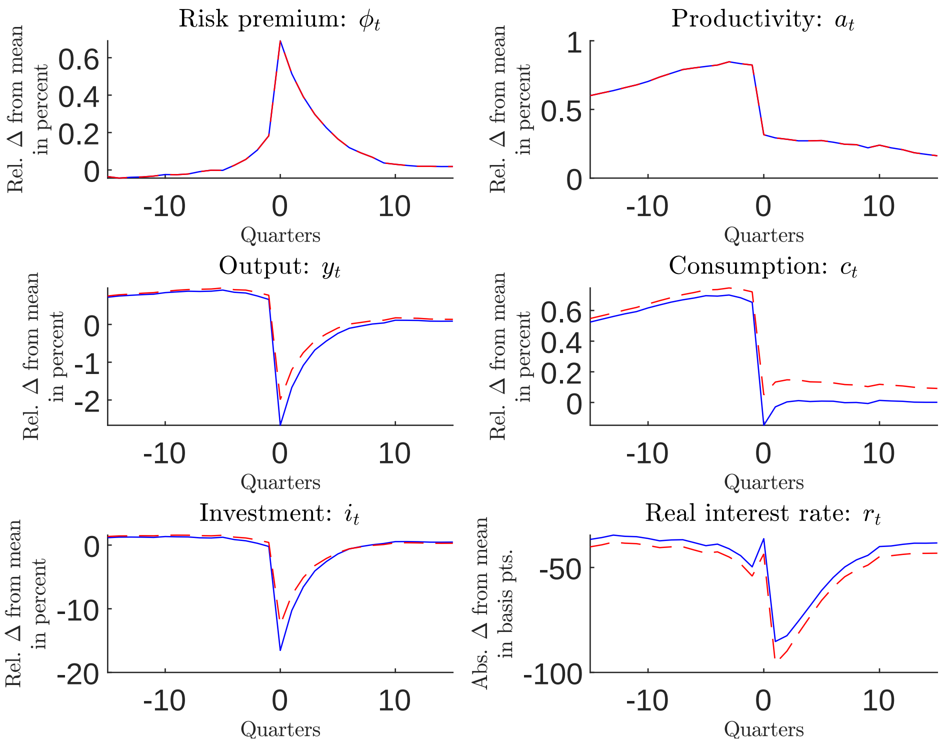

Figure 1: Dynamics around financial crisis events in economy without (blue, solid) and with (red, dashed) deposit insurance.

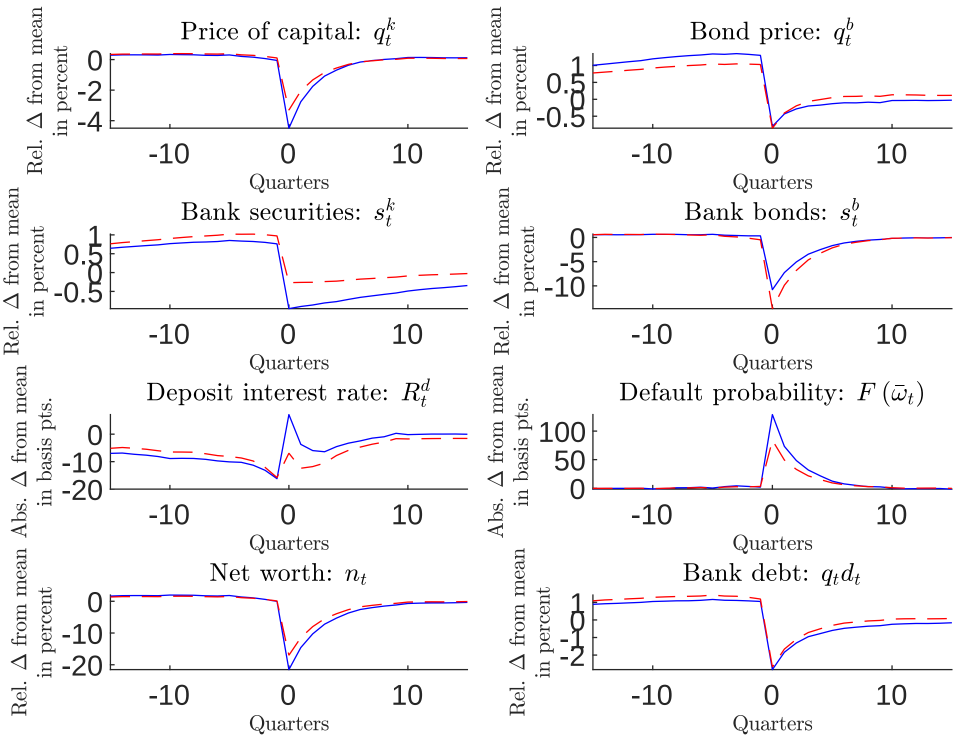

Figure 2: Dynamics around financial crisis events in economy without (blue, solid) and with (red, dashed) deposit insurance.

Finally, our results are qualitatively in line with the results from the finance literature. However, quantitatively, the risk-taking effects are relatively small: the difference between the two model versions is less than 1 percent for the macroeconomic variables, except for the stock of physical capital. It is slightly larger for the financial sector variables, where the probability of financial crises, the weighted leverage ratio, and the quarterly fraction of insolvent intermediaries increase by more than 1% with respect to no deposit insurance, and the probability of a binding leverage constraint by more than 50%. The intuition behind this result is the following: on the one hand, the economy with deposit insurance experiences more frequent financial crises at the ZLB, during which there are substantial contractions of investment and output. On the other hand, the impact from such crises at the ZLB is substantially smaller in the model version with deposit insurance, as the negative feedback loop between funding costs and the probability of insolvency is absent. Therefore, the trough in investment and output is substantially smaller than in the model version without deposit insurance. As a result of these two counterbalancing effects, the unconditional quantitative difference in macroeconomic variables is relatively small.

5.2 The impact of bond purchases by the central bank

In this section we will investigate both the immediate impact and the long-run impact of bond purchases by the central bank when the economy hits the ZLB. Specifically, we start with the immediate impact of bond purchases around financial crisis times in Section 5.2.1. Afterwards, we investigate the long-run impact in Section 5.2.2.

5.2.1 The impact of bond purchases around financial crises

There is a large literature that studies the short-run impact from asset purchases by the central bank in financial crisis times (see Gertler and Kiyotaki (2010); Gertler and Karadi (2011, 2013) among others). Therefore, we first investigate how our model compares to this literature, after which we move on to study the long-run impact of asset purchases. In contrast to the rest of the literature, we do not study the impact of asset purchases in response to a specific negative shock that activates an asset purchase program, but instead we look at the average impact of asset purchases in financial crisis times. To do so, we simulate a model version with and without asset purchases for 500,000 periods, after which we identify financial crisis periods and create event windows as in the previous sections. We perform this comparison both for the model version with deposit insurance and for the model version without deposit insurance. As described in Section 2, asset purchases by the central bank are only employed when the economy hits the ZLB, as the central bank can use conventional monetary policy when the economy is not at the ZLB. This is also in line with central bank policy in most advanced economies.

We start by discussing the impact of financial crises in Figures 3 and 4 for the model version without deposit insurance ($\gamma = 0$), and in Figures 5 and 6 for the model version with deposit insurance ($\gamma = 1$). The blue solid lines denote the simulations without bond purchases by the central bank, while the red dashed lines denote the simulations where the central bank engages in bond purchases when the economy lands at the ZLB. To construct these figures, we identify for each model version (deposit insurance and no deposit insurance) the episodes in which the economy enters a financial crisis *and* the central bank engages in bond purchases, and compare these episodes with the *exact same* periods in the simulation without bond purchases. This immediately explains why the blue and red line in the event windows for the risk premium and the productivity shock exactly overlap in Figures 3 and 5. Finally, both the simulations with *and* without bond purchases by the central bank are expressed as percentage deviations from the ergodic mean of the simulations *without* bond purchases in order to capture level effects. One exception is the bond holdings of the central bank, which are displayed as the percentage deviation from the ergodic mean in the simulations *with* bond purchases by the central bank.

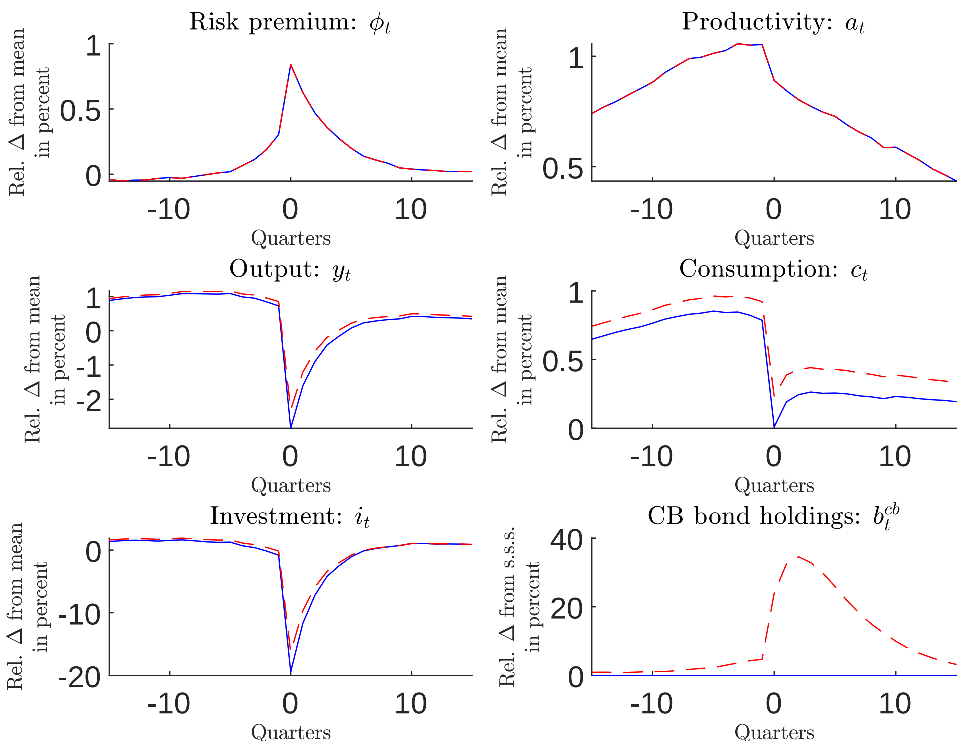

Figure 3: Dynamics around financial crisis events that are accompanied by a binding ZLB in economy without deposit insurance. The blue solid lines denote a model version without endogenous bond purchases, while the red dashed lines denote a model version with endogenous bond purchases with $\Psi = -20$ in equation (28).

We start by discussing the impact of financial crises in the absence of bond purchases, which is qualitatively similar for both model versions and very similar to the impact of financial crises

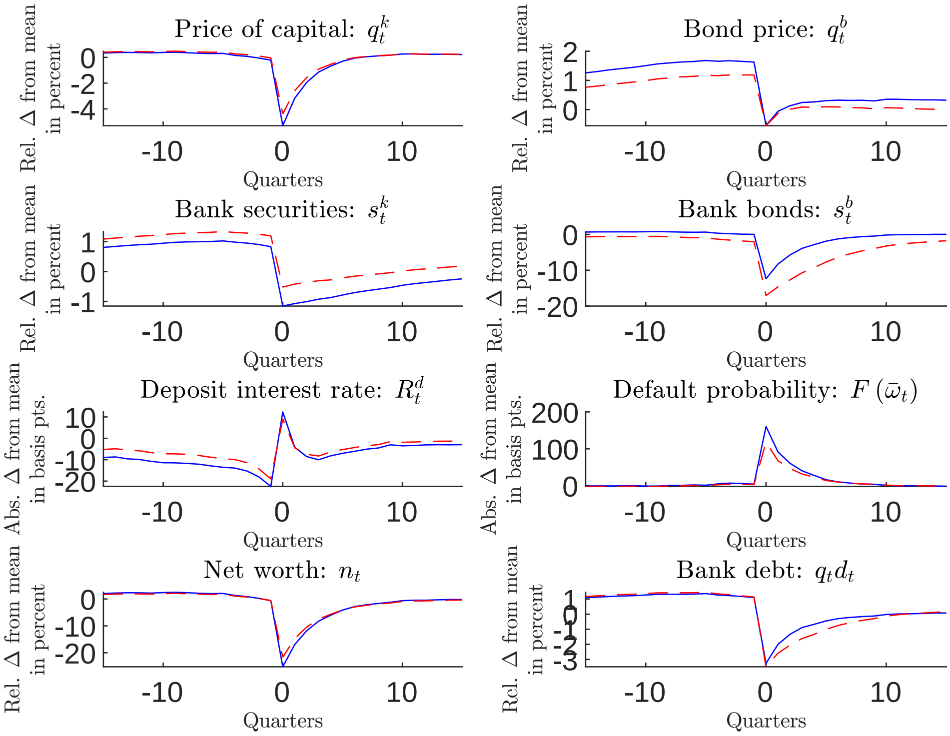

Figure 4: Dynamics around financial crisis events that are accompanied by a binding ZLB in economy without deposit insurance. The blue solid lines denote a model version without endogenous bond purchases, while the red dashed lines denote a model version with endogenous bond purchases with $\Psi = -20$ in equation (28).

found in Gertler and Kiyotaki (2010) and Gertler and Karadi (2011, 2013). Financial crises are times which feature a sharp decrease in macroeconomic variables: output, consumption, and investment all sharply decrease at the moment a financial crisis hits. The large drop in investment is driven by banks reducing their credit supply to the real economy, see panel 'Bank securities'. This credit contraction, in turn, is driven by the fact that intermediaries' incentive compatibility constraint suddenly starts to bind when a financial crisis hits the economy (not shown), which forces intermediaries to shrink the size of the balance sheet by selling (part of) their corporate securities and bond holdings to households. However, as households' holdings of corporate securities and government bonds are subject to quadratic transaction costs, they cannot perfectly elastically acquire the securities and bonds sold by the banks. Therefore, the price of bonds and capital decreases, which imposes capital losses on intermediaries' existing holdings of bonds and securities. As a result, net worth falls by around 20% of the ergodic mean. The sharp decrease in net worth increases bank leverage (not shown), as a result of which banks' probability of default increases by at least 75 basis points. Furthermore, the contraction in net worth forces intermediaries to further decrease their holdings of corporate securities and government bonds, as a result of which a feedback loop arises between capital losses on intermediaries' existing assets and the reduction of the size of their balance sheet that amplifies the credit contraction to the real economy (Gertler and Kiyotaki, 2010; Gertler and Karadi, 2011).

In line with Boissay et al. (2016) and Boissay et al. (2022), we see that for both model versions (with and without deposit insurance) financial crises are preceded by a persistent increase in productivity during the 15 quarters preceding the crisis. Afterwards, the financial crisis is initiated when the trend in productivity reverses and starts to decrease, which is subsequently followed by a persistent decline. However, in our model, the productivity drop is relatively small, and accompanied by a sharp increase in the risk premium shock, which is absent in Boissay et al. (2022). Interestingly, while consumption drops when the financial crisis hits, we see that it remains above its unconditional mean after the crisis hits. There are two reasons for this. First, despite the productivity drop that initiates the financial crisis, the productivity level remains above the unconditional average. As such, household incomes are above their unconditional long-run average. Second, the drop in consumption is also driven by the risk-premium shock. Upon reversal of this shock to its long-run average, consumption increases again in the first quarters after the crisis hits, after which it starts to follow the persistent decline in productivity.

Next, we consider the impact of bond purchases by the central bank, which are displayed by the red dashed lines in Figures 3 and 4 (model version without deposit insurance) and in Figures 5 and 6 (model version with deposit insurance). The impact of bond purchases is very similar for both model versions and very similar to that found in Gertler and Kiyotaki (2010) and Gertler and Karadi (2011, 2013): bond purchases by the central bank reduce the drop in the bond price that occurs at the moment a financial crisis hits the economy.[9] We also see that bond

[9]While the level of the bond price for the simulations with bond purchases is below that without bond purchases in the run up to a financial crisis, the two bond prices are at the same level in the quarter in which the crisis hits the economy. Therefore, the *decrease* in the bond price is smaller in the simulations with bond purchases by the

purchases by the central bank reduce intermediaries' holdings of government bonds, as a result of which space is created for intermediaries to buy more corporate securities (see panel "Bank securities"). The larger demand for corporate securities increases the price of capital in turn, as a result of which intermediaries incur capital gains on their existing holdings of corporate securities. As a result, intermediaries' net worth increases, which allows them to further expand credit provision to the real economy (Gertler and Kiyotaki, 2010; Gertler and Karadi, 2011, 2013). The expansion of credit (relative to the simulations without bond purchases by the central bank) reduces the trough in investment, which in turn leads to higher output in the first quarters of the financial crisis. Finally, observe that consumption in the simulations with bond purchases is persistently above consumption in the simulations without bond purchases, although the difference is quantitatively small. We will see in the next section that this is driven by the fact that the capital stock is on average slightly larger in the simulations with bond purchases by the central bank.

When it comes to the impact of bond purchases on financial stability, we see that capital gains on intermediaries' existing holdings of corporate securities increase net worth, which together with smaller bond holdings allow financial intermediaries to operate with fewer deposits. Therefore, leverage ratios decrease, which is in line with Proposition 3 and the simulations in Gertler and Kiyotaki (2010) and Gertler and Karadi (2011, 2013). The cut-off value $\bar{\omega}_t$ decreases as well, as the positive effect from lower leverage ratios dominates the negative effect from the relative portfolio shift from bonds to corporate securities, see Proposition 4 for a disentangling of these two channels. A lower cut-off value, in turn, decreases the probability of intermediaries' default as well as the ex post number of insolvent intermediaries, the last of which decreases by 20% (relative to the simulations without bond purchases). Therefore, bond purchases are capable of mitigating the impact of financial crises on both the macroeconomy as well as the financial sector, in line with Gertler and Kiyotaki (2010) and Gertler and Karadi (2011, 2013).[10]

Another observation is that bond prices in the simulation with central bank bond purchases are below the bond prices in the simulation without central bank purchases, see Figures 4 and 6. While initially counterintuitive, this result is driven by the fact that the deposit rate is higher in the simulation with bond purchases by the central bank (see again Figures 4 and 6), which increases the return on bonds and consequently leads to lower bond prices. Higher deposit rates, in turn, are driven by the fact that macroeconomic activity increases as a result of bond purchases by the central bank, which in turn increases the central bank's policy rate via the Taylor rule (26).

Finally, one clear difference between the two model versions (with and without deposit insur-

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central bank, which is in line with the result that the bond price increases in response to bond purchases by the central bank in Proposition 1. We also check that the return on bonds in the simulations with bond purchases is below that in the simulations without bond purchases in subsequent quarters. We will explain in the next section why the bond price in the simulations with bond purchases by the central bank is persistently below the simulations without bond purchases.

[10]An important difference with Gertler and Kiyotaki (2010) and Gertler and Karadi (2011, 2013) is that our model features limited liability and endogenous insolvency of intermediaries, whereas insolvency risk is absent in Gertler and Kiyotaki (2010) and Gertler and Karadi (2011, 2013).

ance) is the average volume of bond purchases: central bank bond purchases equal on average 40% from the ergodic mean in the model version without deposit insurance, while they only equal 20% from the ergodic mean in the model version with deposit insurance. This is driven by the fact that the negative macroeconomic impact from financial crises is substantially larger in the model version without deposit insurance: comparing Figures 3 and 5, we see that the drop in output and investment is almost double the drop in the model version with deposit insurance, both for the simulations with and without bond purchases by the central bank. Similarly, inflation decreases by much more in the model version without deposit insurance (not shown), as a result of which the central bank's rule for bond purchases (28) prescribes substantially larger volumes of bond purchases.

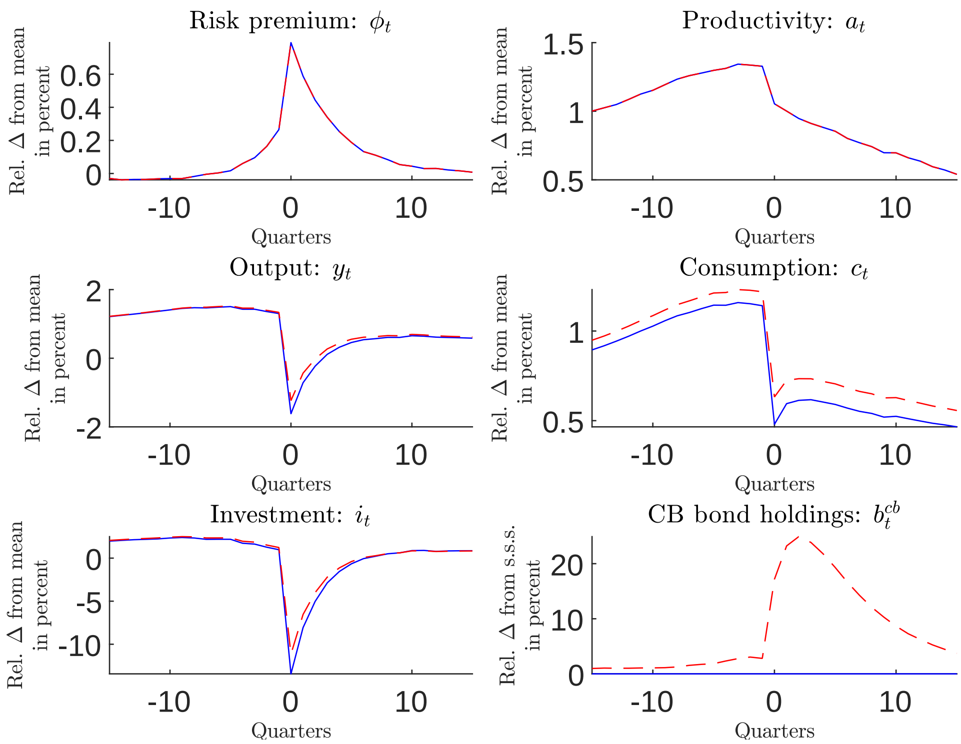

Figure 5: Dynamics around financial crisis events that are accompanied by a binding ZLB in economy with deposit insurance. The blue solid lines denote a model version without endogenous asset purchases, while the red dashed lines denote a model version with endogenous asset purchases with $\Psi = -20$ in equation (28).

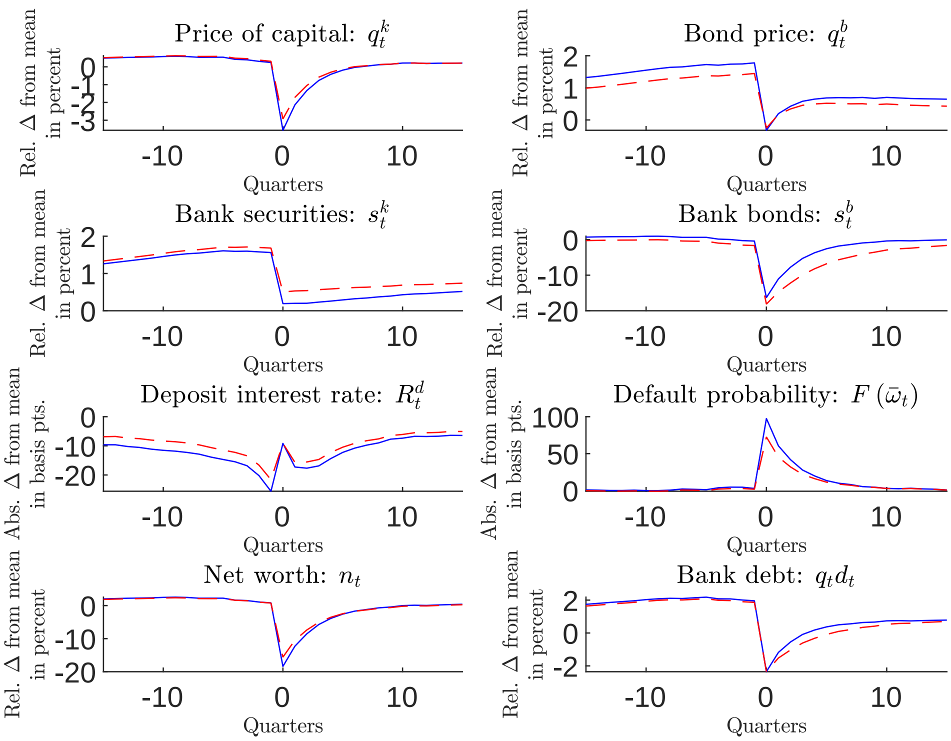

Figure 6: Dynamics around financial crisis events that are accompanied by a binding ZLB in economy with deposit insurance. The blue solid lines denote a model version without endogenous asset purchases, while the red dashed lines denote a model version with endogenous asset purchases with $\Psi = -20$ in equation (28).

5.2.2 The long-run impact of central bank bond purchases

In this section, we investigate the long-run impact of bond purchases by the central bank. To do so, we study the unconditional means of key variables. We do so for the model version without deposit insurance in Table 3, while we report the unconditional means of the model version with deposit insurance in Table 4.

Variable	No QE	QE: $\Psi = -20$
Output: y	2.9258	2.9271
Consumption: c	2.2743	2.2760
Physical capital: k	25.8219	25.8675
Net worth: n	4.6798	4.6710
Capital price: q^k	0.9961	0.9966
Bank securities: k^b	20.5718	20.6198
Bank bonds: b^b	3.7064	3.6639
Bond price: q^b	1.0742	1.0699
Central bank bonds: b^{cb}	0.7051	0.7495
Leverage: l	5.2557	5.2568
Weighted leverage: l^w	4.8289	4.8368
Fraction of insolvent banks: $F(\bar{\omega})$	0.2021%	0.1932%
Max. fraction of insolvent banks: $F(\bar{\omega})$	14.4055%	11.2014%
Gross bank funding cost: R^d	1.0087	1.0089
Gross nominal policy rate: R^n	1.0084	1.0087
Gross real policy rate: R	1.0048	1.0048
Annualized net nominal policy rate: R^n	3.3746%	3.4826%
Annualized net real policy rate: R	1.9098%	1.9081%
Prob. of financial crisis:	2.6130%	2.2380%
Prob. of financial crisis and ZLB:	1.7950%	1.7650%
Prob. of binding leverage constraint:	61.3784%	65.6803%
Prob. of ZLB:	10.7049%	9.3039%

Table 3: Ergodic means of selected variables for the model version without deposit insurance ($\gamma = 0$). 'QE' stands for quantitative easing, and refers to bond purchases by the central bank in our model.

We see that bond purchases by the central bank have a beneficial macroeconomic effect: output, consumption, and physical capital increase when the central bank employs asset purchases at the ZLB.

However, while bond purchases by the central bank increase net worth at the moment a financial crisis hits (as a result of capital gains on intermedaries' existing assets), they *reduce* intermediaries' net worth in the medium run: bond purchases by the central bank reduce the spread between the (expected) return on bonds and deposits, everything else equal, which decreases banks' profitability. In response, banks shift from government bonds to corporate securities, as a result of which the (expected) return on corporate securities also decreases. As a result, net worth accumulates at a slower rate than in the simulations without bond purchases by the central bank (Karadi and Nakov, 2021). Therefore, intermediaries operate on average with less net worth (relative to no bond purchases by the central bank), both in the model version with and without deposit insurance.

However, the simulations with bond purchases by the central bank seem to enhance financial stability, despite intermediaries operating with fewer net worth on average: the average fraction of insolvent banks (and thus the unconditional probability of insolvency) decreases, the maximum fraction of banks that become insolvent decreases, the probability of hitting the ZLB decreases, as well as the probability of a simultaneous financial crisis. The intuition behind this result is that bond purchases by the central bank are particularly effective in mitigating the impact of financial crises, see Figures 3 - 4 and Figures 5 - 6 in the previous section.[11] Therefore, the beneficial effects from central bank bond purchases on financial stability during financial crisis times more than offset the negative effects from intermediaries operating with fewer net worth outside financial crisis times.

Moreover, the beneficial impact on the macroeconomy from central bank bond purchases in financial crisis times and intermediaries' persistent portfolio shift from government bonds to corporate securities ensure that the unconditional average of output, consumption, investment, and capital increases: higher asset prices (as a result of central bank bond purchases) lead to higher net worth in crisis times, which allows intermediaires to expand credit to the real economy. As a result, investment and capital accumulation increase, which ultimately increase output and consumption. Observe, however, that the quantitative impact of central bond purchases is relatively small, as net worth accumulation is slower outside financial crisis times.

[11] Most financial crises are accompanied by the economy hitting the ZLB. Therefore, the central bank will engage in additional bond purchases in the majority of financial crises. To see this, compare "Prob. of financial crisis" in Tables 3 and 4 with "Prob. of financial crisis and ZLB".

Variable	No QE	QE: $\Psi = -20$
Output: y	2.9396	2.9399
Consumption: c	2.2810	2.2818
Physical capital: k	26.1998	26.2124
Net worth: n	4.6937	4.6907
Capital price: q^k	0.9998	0.9999
Bank securities: k^b	20.9591	20.9724
Bank bonds: b^b	3.5992	3.5718
Bond price: q^b	1.0491	1.0466
Central bank bonds: b^{cb}	0.7051	0.7343
Leverage: l	5.2833	5.2782
Weighted leverage: l^w	4.8808	4.8798
Fraction of insolvent banks: $F(\bar{\omega})$	0.2097%	0.2031%
Max. fraction of insolvent banks: $F(\bar{\omega})$	6.8745 %	5.2170%
Gross bank funding cost: R^d	1.0088	1.0090
Gross nominal policy rate: R^n	1.0089	1.0090
Gross real policy rate: R	1.0048	1.0048
Annualized net nominal policy rate: R^n	3.5405%	3.6089%
Annualized net real policy rate: R	1.9110%	1.9087%
Prob. of financial crisis:	2.6080%	2.5710%
Prob. of financial crisis and ZLB:	1.9420%	1.8720%
Prob. of binding leverage constraint:	93.2081%	94.9861%
Prob. of ZLB:	7.9679%	7.0279%

Table 4: Ergodic means of selected variables for the model version with deposit insurance ($\gamma = 1$). 'QE' stands for quantitative easing, and refers to asset purchases by the central bank in our model.

6 Conclusion

In this paper we study the *long-run* impact of government bond purchases by the central bank in times of financial crises, in the popular press referred to as 'Quantitative Easing' or 'QE'. This contrasts with most of the literature, which focuses on the *short-run* impact of these asset purchase programs (Gertler and Kiyotaki, 2010; Gertler and Karadi, 2011, 2013). By focusing on the long-run, we are the first to be able to study the *long-run* financial stability implications of these programs.

To do so, we employ a New Keynesian DSGE model inspired by Gertler and Karadi (2011) and Gertler and Karadi (2013), which features financial intermediaries that have a portoflio choice between safe government bonds and risky corporate securities that finance the stock of physical capital used for production (Bocola, 2016). These assets are financed through deposits held by households and net worth. Financial intermediaries are subject to an incentive compatibility constraint a la Gertler and Kiyotaki (2010) and Gertler and Karadi (2011). We extend this model in two directions following Gete and Melkadze (2020). First, the corporate securities are subjective to a multiplicative idiosyncratioc shock, which for all intermediaries is drawn from the same distribution. Therefore, there is a cut-off value for the realization of this shock, below which intermediaries are insolvent and stop operating. Second, intermediaries take into account the impact that their balance sheet decisions have on their funding costs. The model also features a central bank which is in charge of setting the nominal interest rate following a standard Taylor rule that is subject to the Zero Lower Bound (ZLB). We assume that the central bank only expands its bond holdings when the short-term policy rate has hit the ZLB. At that point, the volume of bonds acquired follows a rule similar to the Taylor rule in the sense that it depends on inflation and the output gap. Finally, we consider model versions with and without deposit insurance.

We start by studying a simplified two-period model version of our infinite-horizon model. Doing so allows us to analytically disentangle the two opposing effects that bond purchases by the central bank have on financial stability (as measured by the cut-off value for the idiosyncratic shock). The first is a risk shifting effect: central bank bond purchases reduce intermediaries' holdings of government bonds via a portfolio substitution effect which induces them to acquire more corporate securities. As a result, a larger fraction of intermediaries' assets become subject to the idiosyncratic shock, which increases intermediaries' probability of insolvency, everything else equal, and makes their balance sheets more risky. The second effect is a capital gains effect: central bank bond purchases increase the value of intermediaries' existing assets, as a result of which their net worth increases. More net worth implies that intermediaries have to issue fewer deposits as a result which intermediaries' cut-off value (and thus their probability of insolvency) directly decreases. Leverage ratios also decrease because the lower return on intermediaries' assets (as a result of bond purchases) reduces intermediaries' profitability. In response, depositors force intermediaries to operate with lower leverage ratios, which enhances financial stability.

Next, we employ the full infinite-horizon model to study which of these two effects on financial stability dominate. Specifically, we solve the model using global solution methods to properly capture nonlinearities that may arise from precautionary behaviour and bank risk taking. Afterwards, we simulate the model for 500,000 periods, and identify the episodes that feature financial crises. Subsequently, we first study the impact of bond purchases by the central bank in financial crisis times by creating event windows between the 15 quarters before and after a financial crisis hits the economy. This approach contrasts with most of the current literature, which typically studies the effects from asset purchase programs with the help of impulse response functions. Nevertheless, the short-run impact from central bank bond purchases in financial crisis times are in line with the literature (Gertler and Kiyotaki, 2010; Gertler and Karadi, 2011, 2013): bond purchases increase asset prices relative to simulations without bond purchases, which leads to capital gains on intermediaries' existing assets. Intermediaries' net worth increases, which allows them to operate with fewer deposits, as a result of which leverage ratios decrease. As a result, the number of bank insolvencies decreases, despite the fact that intermediaries' balance sheet composition between government bonds and corporate securities makes the balance sheet more risky. Hence, we find that the capital gains effect dominates the risk shifting effect. Furthermore, more net worth allows intermediaries to expand credit to the real economy (relative to no bond purchases), as a result of which the trough of investment and output is substantially reduced. Therefore, central bank bond purchases mitigate the impact of financial crises, both on the macroeconomy and on financial stability.

Outside financial crisis times, we find that the simulations with bond purchases by the central bank reduce net worth as measured by the unconditional mean across the entire simulation: after the stabilizing effects at the moment financial crises hit, we find that bond purchases by the central bank reduce the expected return on bonds, as a result of which intermediaries shift to corporate securities. Therefore, the expected return on corporate securities decreases as well, as a result of which intermediaries' profitability and net worth accumulation decrease with respect to the simulations without central bank bond purchases (Karadi and Nakov, 2021). Hence the unconditional mean of net worth is lower in the simulations with central bank bond purchases (relative to the simulations without bond purchases by the central bank). However, central bank bond purchases induce a persistent shift from government bonds to corporate securities in intermediaries' assets portfolio, both in times of financial crisis and in normal times. Together with the fact that bond purchases in the middle of financial crises mitigate the drop in credit provision to the real economy, we see that capital accumulation is on average higher in the simulations with central bank bond purchases. As a result, we have that the unconditional mean of investment, output, and consumption are higher for the simulations with bond purchases. We also find that the positive effects on financial stability from bond purchases in financial crisis times dominate the negative spillover effect on net worth accumulation outside financial crisis times.

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Appendix “NWO Bank Risk Taking”

A Additional mathematical derivations infinite-horizon model

A.1 Financial intermediaries

The Lagrangian accompanying financial intermediaries’ optimization problem is given by:

$$
\begin{aligned}
\mathcal{L} &= (1+\mu_t)\,E_t\left\{\mathcal{M}_{t,t+1}\int_{\bar{\omega}_{j,t+1}}^{\infty}\left[\sigma\left(\omega_{j,t+1}R^k_{t+1}q^k_t s^k_{j,t}+R^b_{t+1}q^b_t s^b_{j,t}-\frac{d_{j,t}}{\pi_{t+1}}\right)+\mathcal{V}_{j,t+1}\right]f\left(\omega_{j,t+1}\right)d\omega_{j,t+1}\right\}\\
&- \mu_t\left(\lambda_k q^k_t s^k_{j,t}+\lambda_b q^b_t s^b_{j,t}\right)\\
&+ \chi_t\left[(1-\sigma)\left(\omega_{j,t}R^k_t q^k_{t-1}s^k_{j,t-1}+R^b_t q^b_{t-1}s^b_{j,t-1}-\frac{d_{j,t-1}}{\pi_t}\right)+q_t d_{j,t}-q^k_t s^k_{j,t}-q^b_t s^b_{j,t}\right].
\end{aligned}
$$

The resulting first order conditions are given by:

$$
\begin{aligned}
s^k_{j,t} &: (1+\mu_t)\,E_t\left[\mathcal{M}_{t,t+1}\int_{\bar{\omega}_{j,t+1}}^{\infty}\left(\sigma\omega_{j,t+1}R^k_{t+1}q^k_t+\frac{\partial\mathcal{V}_{j,t+1}}{\partial s^k_{j,t}}\right)f\left(\omega_{j,t+1}\right)d\omega_{j,t+1}\right]\\
&- \mu_t\lambda_k q^k_t-\chi_t\left(q^k_t-d_{j,t}\cdot\frac{\partial q_t}{\partial s^k_{j,t}}\right)=0, \qquad (56)\\
s^b_{j,t} &: (1+\mu_t)\,E_t\left[\mathcal{M}_{t,t+1}\int_{\bar{\omega}_{j,t+1}}^{\infty}\left(\sigma R^b_{t+1}q^b_t+\frac{\partial\mathcal{V}_{j,t+1}}{\partial s^b_{j,t}}\right)f\left(\omega_{j,t+1}\right)d\omega_{j,t+1}\right]\\
&- \mu_t\lambda_b q^b_t-\chi_t\left(q^b_t-d_{j,t}\cdot\frac{\partial q_t}{\partial s^b_{j,t}}\right)=0, \qquad (57)\\
d_{j,t} &: (1+\mu_t)\,E_t\left[\mathcal{M}_{t,t+1}\int_{\bar{\omega}_{j,t+1}}^{\infty}\left(-\sigma\cdot\frac{1}{\pi_{t+1}}+\frac{\partial\mathcal{V}_{j,t+1}}{\partial d_{j,t}}\right)f\left(\omega_{j,t+1}\right)d\omega_{j,t+1}\right]\\
&+ \chi_t\left(q_t+d_{j,t}\cdot\frac{\partial q_t}{\partial d_{j,t}}\right)=0, \qquad (58)
\end{aligned}
$$

Next, we apply the envelope theorem to further work out the above first order conditions:

$$
\frac{\partial\mathcal{V}_{j,t}}{\partial s^k_{j,t-1}} = \chi_t\,(1-\sigma)\,\omega_{j,t}R^k_t q^k_{t-1}, \qquad (59)
$$

$$
\frac{\partial\mathcal{V}_{j,t}}{\partial s^b_{j,t-1}} = \chi_t\,(1-\sigma)\,R^b_t q^b_{t-1}, \qquad (60)
$$

$$
\frac{\partial\mathcal{V}_{j,t}}{\partial d_{j,t-1}} = \chi_t\,(1-\sigma)\left(-\frac{1}{\pi_t}\right), \qquad (61)
$$

Iterating one period forward, and substitution into the respective first order conditions gives us the first order conditions (8) - (10).

Next, I calculate the partial derivatives of the deposit price q_t in equation (4). To do so, we employ the Leibniz-rule:

$$\frac{d}{dx}\left(\int_{a(x)}^{b(x)} f(x,t)\,dt\right) = f(x,b(x))\cdot\frac{d}{dx}b(x) - f(x,a(x))\cdot\frac{d}{dx}a(x) + \int_{a(x)}^{b(x)}\frac{\partial}{\partial x}f(x,t)\,dt$$

We start with the partial derivative with respect to $s_{j,t}^k$:

$$\begin{aligned}
\frac{\partial q_t}{\partial s_{j,t}^k} &= E_t\Bigg(\mathcal{M}_{t,t+1}\Bigg\{-\frac{1}{\pi_{t+1}}\cdot f(\bar{\omega}_{j,t+1})\cdot\frac{\partial\bar{\omega}_{j,t+1}}{\partial s_{j,t}^k} \\
&+ \left[\gamma\cdot\frac{1}{\pi_{t+1}} + (1-\gamma)\frac{(1-\mu)\,\bar{\omega}_{j,t+1}R_{t+1}^k q_t^k s_{j,t}^k + R_{t+1}^b q_t^b s_{j,t}^b}{d_{j,t}}\right] f(\bar{\omega}_{j,t+1})\cdot\frac{\partial\bar{\omega}_{j,t+1}}{\partial s_{j,t}^k} \\
&+ \int_0^{\bar{\omega}_{j,t+1}}(1-\gamma)\frac{(1-\mu)\,\omega_{j,t+1}R_{t+1}^k q_t^k}{d_{j,t}}\cdot f(\omega_{j,t+1})\,d\omega_{j,t+1}\Bigg\}\Bigg) \\
&= E_t\Bigg(\mathcal{M}_{t,t+1}\Bigg\{-\frac{1}{\pi_{t+1}}\cdot f(\bar{\omega}_{j,t+1})\cdot\frac{\partial\bar{\omega}_{j,t+1}}{\partial s_{j,t}^k} \\
&+ \left[\gamma\cdot\frac{1}{\pi_{t+1}} + (1-\gamma)\frac{1}{\pi_{t+1}} - (1-\gamma)\frac{\mu\bar{\omega}_{j,t+1}R_{t+1}^k q_t^k s_{j,t}^k}{d_{j,t}}\right]\cdot f(\bar{\omega}_{j,t+1})\cdot\frac{\partial\bar{\omega}_{j,t+1}}{\partial s_{j,t}^k} \\
&+ (1-\gamma)\int_0^{\bar{\omega}_{j,t+1}}\frac{(1-\mu)\,\omega_{j,t+1}R_{t+1}^k q_t^k}{d_{j,t}}\cdot f(\omega_{j,t+1})\,d\omega_{j,t+1}\Bigg\}\Bigg) \\
&= E_t\Bigg\{\mathcal{M}_{t,t+1}\Bigg[-(1-\gamma)\frac{\mu\bar{\omega}_{j,t+1}R_{t+1}^k q_t^k s_{j,t}^k}{d_{j,t}}\cdot f(\bar{\omega}_{j,t+1})\cdot\frac{\partial\bar{\omega}_{j,t+1}}{\partial s_{j,t}^k} \\
&+ (1-\gamma)\int_0^{\bar{\omega}_{j,t+1}}\frac{(1-\mu)\,\omega_{j,t+1}R_{t+1}^k q_t^k}{d_{j,t}}\cdot f(\omega_{j,t+1})\,d\omega_{j,t+1}\Bigg]\Bigg\}, \qquad (62)
\end{aligned}$$

where we used the cut-off value (3) in the second line.

Similarly, we find that the partial derivative with respect to $s_{j,t}^b$ is given by:

$$\begin{aligned}
\frac{\partial q_t}{\partial s_{j,t}^b} &= E_t\Bigg\{\mathcal{M}_{t,t+1}\Bigg[-(1-\gamma)\frac{\mu\bar{\omega}_{j,t+1}R_{t+1}^k q_t^k s_{j,t}^k}{d_{j,t}}\cdot f(\bar{\omega}_{j,t+1})\cdot\frac{\partial\bar{\omega}_{j,t+1}}{\partial s_{j,t}^b} \\
&+ (1-\gamma)\int_0^{\bar{\omega}_{j,t+1}}\frac{R_{t+1}^b q_t^b}{d_{j,t}}\cdot f(\omega_{j,t+1})\,d\omega_{j,t+1}\Bigg]\Bigg\}. \qquad (63)
\end{aligned}$$

Similarly, we find that the partial derivative with respect to $d_{j,t}$ is given by:

$$\begin{aligned}
\frac{\partial q_t}{\partial d_{j,t}} &= E_t\Bigg\{\mathcal{M}_{t,t+1}\Bigg[-(1-\gamma)\frac{\mu\bar{\omega}_{j,t+1}R_{t+1}^k q_t^k s_{j,t}^k}{d_{j,t}}\cdot f(\bar{\omega}_{j,t+1})\cdot\frac{\partial\bar{\omega}_{j,t+1}}{\partial d_{j,t}} \\
&- (1-\gamma)\int_0^{\bar{\omega}_{j,t+1}}\frac{(1-\mu)\,\omega_{j,t+1}R_{t+1}^k q_t^k s_{j,t}^k + R_{t+1}^b q_t^b s_{j,t}^b}{(d_{j,t})^2}\cdot f(\omega_{j,t+1})\,d\omega_{j,t+1}\Bigg]\Bigg\}. \qquad (64)
\end{aligned}$$

Taking the partial derivative of equation (3) with respect to $s^k_{j,t}$, $s^b_{j,t}$ and $d_{j,t}$ and substituting in equations (62), (63), and (64), we find the following expressions:

$$\begin{aligned}\frac{\partial q_t}{\partial s^k_{j,t}} &= E_t\Bigg\{\mathcal{M}_{t,t+1}\Bigg[(1-\gamma)\frac{\mu\bar{\omega}^2_{j,t+1}R^k_{t+1}q^k_t}{d_{j,t}}\cdot f(\bar{\omega}_{j,t+1}) \\ &+ (1-\gamma)\int_0^{\bar{\omega}_{j,t+1}}\frac{(1-\mu)\,\omega_{j,t+1}R^k_{t+1}q^k_t}{d_{j,t}}\cdot f(\omega_{j,t+1})\,d\omega_{j,t+1}\Bigg]\Bigg\},\end{aligned} \tag{65}$$

$$\begin{aligned}\frac{\partial q_t}{\partial s^b_{j,t}} &= E_t\Bigg\{\mathcal{M}_{t,t+1}\Bigg[(1-\gamma)\frac{\mu\bar{\omega}_{j,t+1}R^b_{t+1}q^b_t}{d_{j,t}}\cdot f(\bar{\omega}_{j,t+1}) \\ &+ (1-\gamma)\int_0^{\bar{\omega}_{j,t+1}}\frac{R^b_{t+1}q^b_t}{d_{j,t}}\cdot f(\omega_{j,t+1})\,d\omega_{j,t+1}\Bigg]\Bigg\},\end{aligned} \tag{66}$$

$$\begin{aligned}\frac{\partial q_t}{\partial d_{j,t}} &= E_t\Bigg\{\mathcal{M}_{t,t+1}\Bigg[-(1-\gamma)\frac{\mu\bar{\omega}_{j,t+1}}{\pi_{t+1}d_{j,t}}\cdot f(\bar{\omega}_{j,t+1}) \\ &- (1-\gamma)\int_0^{\bar{\omega}_{j,t+1}}\frac{(1-\mu)\,\omega_{j,t+1}R^k_{t+1}q^k_t s^k_{j,t}+R^b_{t+1}q^b_t s^b_{j,t}}{(d_{j,t})^2}\cdot f(\omega_{j,t+1})\,d\omega_{j,t+1}\Bigg]\Bigg\}.\end{aligned} \tag{67}$$

Next, we solve for the continuation value $\mathcal{V}_{j,t}$. To do so, we follow Gertler and Kiyotaki (2010); Gertler and Karadi (2011) and guess the following value function, which we later check:

$$\mathcal{V}_{j,t} \equiv \eta^k_t q^k_t s^k_{j,t} + \eta^b_t q^b_t s^b_{j,t} - \eta^d_t q_t d_{j,t}, \tag{68}$$

where η^k_t, η^b_t, and η^d_t are given by:

$$\eta^k_t \equiv E_t\left[\Omega_{t,t+1}\int_{\bar{\omega}_{j,t+1}}^{\infty}\omega_{j,t+1}R^k_{t+1}f(\omega_{j,t+1})\,d\omega_{j,t+1}\right], \tag{69}$$

$$\eta^b_t \equiv E_t\left[\Omega_{t,t+1}\int_{\bar{\omega}_{j,t+1}}^{\infty}R^b_{t+1}f(\omega_{j,t+1})\,d\omega_{j,t+1}\right], \tag{70}$$

$$\eta^d_t \equiv E_t\left[\Omega_{t,t+1}\int_{\bar{\omega}_{j,t+1}}^{\infty}\left(\frac{1}{\pi_{t+1}q_t}\right)f(\omega_{j,t+1})\,d\omega_{j,t+1}\right]. \tag{71}$$

Substitution of the first order conditions (8) - (10) into the guess for the value function (68) gives:

$$
\begin{aligned}
\mathcal{V}_{j,t} &= \frac{\chi_t}{1+\mu_t}\left(q_t^k s_{j,t}^k + q_t^b s_{j,t}^b - q_t d_{j,t}\right) \\
&- \left(\frac{\chi_t}{1+\mu_t}\right)\left(\frac{d_{j,t}}{q_t^k}\cdot\frac{\partial q_t}{\partial s_{j,t}^k}\cdot q_t^k s_{j,t}^k + \frac{d_{j,t}}{q_t^b}\cdot\frac{\partial q_t}{\partial s_{j,t}^b}\cdot q_t^b s_{j,t}^b + \frac{d_{j,t}}{q_t}\cdot\frac{\partial q_t}{\partial d_{j,t}}\cdot q_t d_{j,t}\right) \\
&+ \left(\frac{\mu_t}{1+\mu_t}\right)\left(\lambda_k q_t^k s_{j,t}^k + \lambda_b q_t^b s_{j,t}^b\right) \\
&= \frac{\chi_t}{1+\mu_t}\left(q_t^k s_{j,t}^k + q_t^b s_{j,t}^b - q_t d_{j,t}\right) - \left(\frac{\chi_t}{1+\mu_t}\right) d_{j,t}\Xi_t + \left(\frac{\mu_t}{1+\mu_t}\right)\left(\lambda_k q_t^k s_{j,t}^k + \lambda_b q_t^b s_{j,t}^b\right),
\end{aligned} \tag{72}
$$

where Ξ_t is defined as:

$$
\Xi_t \equiv \frac{\partial q_t}{\partial s_{j,t}^k}\cdot s_{j,t}^k + \frac{\partial q_t}{\partial s_{j,t}^b}\cdot s_{j,t}^b + \frac{\partial q_t}{\partial d_{j,t}}\cdot d_{j,t}. \tag{73}
$$

Substitution of equations (65) - (67) allow us to rewrite Ξ_t:

$$
\begin{aligned}
\Xi_t &= (1-\gamma) E_t\Bigg\{\mathcal{M}_{t,t+1}\Bigg[\frac{\mu\bar{\omega}_{j,t+1}^2 R_{t+1}^k q_t^k s_{j,t}^k}{d_{j,t}}\cdot f\left(\bar{\omega}_{j,t+1}\right) \\
&+ \int_0^{\bar{\omega}_{j,t+1}} \frac{(1-\mu)\,\omega_{j,t+1} R_{t+1}^k q_t^k s_{j,t}^k}{d_{j,t}}\cdot f\left(\omega_{j,t+1}\right) d\omega_{j,t+1}\Bigg]\Bigg\} \\
&+ (1-\gamma) E_t\Bigg\{\mathcal{M}_{t,t+1}\Bigg[\frac{\mu\bar{\omega}_{j,t+1} R_{t+1}^b q_t^b s_{j,t}^b}{d_{j,t}}\cdot f\left(\bar{\omega}_{j,t+1}\right) \\
&+ \int_0^{\bar{\omega}_{j,t+1}} \frac{R_{t+1}^b q_t^b s_{j,t}^b}{d_{j,t}}\cdot f\left(\omega_{j,t+1}\right) d\omega_{j,t+1}\Bigg]\Bigg\} \\
&+ (1-\gamma) E_t\Bigg\{\mathcal{M}_{t,t+1}\Bigg[-\frac{\mu\bar{\omega}_{j,t+1}}{\pi_{t+1}}\cdot f\left(\bar{\omega}_{j,t+1}\right) \\
&- \int_0^{\bar{\omega}_{j,t+1}} \frac{(1-\mu)\,\omega_{j,t+1} R_{t+1}^k q_t^k s_{j,t}^k + R_{t+1}^b q_t^b s_{j,t}^b}{d_{j,t}}\cdot f\left(\omega_{j,t+1}\right) d\omega_{j,t+1}\Bigg]\Bigg\} \\
&= (1-\gamma) E_t\left\{\mathcal{M}_{t,t+1}\left[\frac{\mu\bar{\omega}_{j,t+1}}{d_{j,t}} f\left(\bar{\omega}_{j,t+1}\right)\left(\bar{\omega}_{j,t+1} R_{t+1}^k q_t^k s_{j,t}^k + R_{t+1}^b q_t^b s_{j,t}^b - \frac{d_{j,t}}{\pi_{t+1}}\right)\right]\right\} \\
&= 0,
\end{aligned}
$$

where we used equation (3) in the final line.

Therefore, we can write expression (72) as:

$$
\mathcal{V}_{j,t} = \frac{\chi_t}{1+\mu_t}(1-\sigma)\, n_{j,t} + \left(\frac{\mu_t}{1+\mu_t}\right)\left(\lambda_k q_t^k s_{j,t}^k + \lambda_b q_t^b s_{j,t}^b\right), \tag{74}
$$

where we used intermediaries' balance sheet constraint (1). When intermediaries' incentive compatibility constraint (7) is not binding, we find that $\mathcal{V}_{j,t} = \chi_t (1 - \sigma) n_{j,t}$. When the constraint binds, we get that:

$$\frac{\chi_t}{1 + \mu_t} (1 - \sigma) n_{j,t} + \left(\frac{\mu_t}{1 + \mu_t} \right) \left(\lambda_k q_t^k s_{j,t}^k + \lambda_b q_t^b s_{j,t}^b \right) = \lambda_k q_t^k s_{j,t}^k + \lambda_b q_t^b s_{j,t}^b,$$

which we can rewrite as:

$$\chi_t (1 - \sigma) n_{j,t} = \lambda_k q_t^k s_{j,t}^k + \lambda_b q_t^b s_{j,t}^b. \tag{75}$$

After substitution of the above expression into equation (74), we find that $\mathcal{V}_{j,t} = \chi_t (1 - \sigma) n_{j,t}$. Therefore, irrespective of whether intermediaries' incentive compatibility constraint (7) is binding or not, we have that intermediaries' value function $\mathcal{V}_{j,t}$ is given by:

$$\mathcal{V}_{j,t} = \chi_t (1 - \sigma) n_{j,t}. \tag{76}$$

Finally, we check whether our guess for the value function (68) is consistent with (6). To do so, we substitute expression (74) into the right hand side of (6):

$$\begin{aligned}
\mathcal{V}_{j,t} &= E_t \left\{ \mathcal{M}_{t,t+1} \int_{\bar{\omega}_{j,t+1}}^{\infty} [\sigma + (1 - \sigma) \chi_{t+1}] n_{j,t+1} f(\omega_{j,t+1}) d\omega_{j,t+1} \right\} \\
&= E_t \left\{ \mathcal{M}_{t,t+1} \int_{\bar{\omega}_{j,t+1}}^{\infty} [\sigma + (1 - \sigma) \chi_{t+1}] \omega_{j,t+1} R_{t+1}^k f(\omega_{j,t+1}) d\omega_{j,t+1} \right\} q_t^k s_{j,t}^k \\
&+ E_t \left\{ \mathcal{M}_{t,t+1} \int_{\bar{\omega}_{j,t+1}}^{\infty} [\sigma + (1 - \sigma) \chi_{t+1}] R_{t+1}^b f(\omega_{j,t+1}) d\omega_{j,t+1} \right\} q_t^b s_{j,t}^b, \\
&- E_t \left\{ \mathcal{M}_{t,t+1} \int_{\bar{\omega}_{j,t+1}}^{\infty} [\sigma + (1 - \sigma) \chi_{t+1}] \left(\frac{1}{\pi_{t+1} q_t} \right) f(\omega_{j,t+1}) d\omega_{j,t+1} \right\} q_t d_{j,t},
\end{aligned}$$

which coincides exactly with the guess (68).

Finally, we prove that in equilibrium all intermediaries make the same choices for the cut-off value, the ratio $d_{j,t} / \left(q_t^k s_{j,t}^k \right)$, and the market value of bonds over corporate securities $q_t^b s_{j,t}^b / \left(q_t^k s_{j,t}^k \right)$.

Proposition 5. *All intermediaries make the same choices for the cut-off value $\bar{\omega}_{j,t+1}$, the ratio $d_{j,t} / \left(q_t^k s_{j,t}^k \right)$, and the market value of bonds over corporate securities $q_t^b s_{j,t}^b / \left(q_t^k s_{j,t}^k \right)$ in equilibrium.*

Proof. To prove the proposition, let us first use expressions (65) - (67) to find the following expressions for the terms that show up in the first order conditions (8) - (10):

$$\frac{d_{j,t}}{q_t^k} \cdot \frac{\partial q_t}{\partial s_{j,t}^k} = (1-\gamma) E_t \left\{ \mathcal{M}_{t,t+1} \left[\mu \bar{\omega}_{j,t+1}^2 f(\bar{\omega}_{j,t+1}) + \int_0^{\bar{\omega}_{j,t+1}} (1-\mu) \omega_{j,t+1} f(\omega_{j,t+1}) d\omega_{j,t+1} \right] R_{t+1}^k \right\}, \tag{77}$$

$$\frac{d_{j,t}}{q_t^b} \cdot \frac{\partial q_t}{\partial s_{j,t}^b} = (1-\gamma) E_t \left\{ \mathcal{M}_{t,t+1} \left[\mu \bar{\omega}_{j,t+1} f(\bar{\omega}_{j,t+1}) + \int_0^{\bar{\omega}_{j,t+1}} f(\omega_{j,t+1}) d\omega_{j,t+1} \right] R_{t+1}^b \right\}, \tag{78}$$

$$\begin{aligned} \frac{d_{j,t}}{q_t} \cdot \frac{\partial q_t}{\partial d_{j,t}} &= \frac{1-\gamma}{q_t} E_t \left\{ \mathcal{M}_{t,t+1} \left[-\frac{\mu \bar{\omega}_{j,t+1}}{\pi_{t+1}} \cdot f(\bar{\omega}_{j,t+1}) \right.\right. \\ &- \left.\left. \int_0^{\bar{\omega}_{j,t+1}} \frac{(1-\mu)\omega_{j,t+1} R_{t+1}^k q_t^k s_{j,t}^k + R_{t+1}^b q_t^b s_{j,t}^b}{d_{j,t}} \cdot f(\omega_{j,t+1}) d\omega_{j,t+1} \right] \right\}. \end{aligned} \tag{79}$$

Hence we see that the first order conditions for corporate securities (8) and for government bonds (9) only contain one intermediary-specific variable, namely the cut-off value $\bar{\omega}_{j,t+1}$, since the shadow values for the balance sheet constraint χ_t and the incentive compatibility constraint μ_t are the same across intermediaries (Gertler and Kiyotaki, 2010; Gertler and Karadi, 2011). Therefore, we immediately conclude that all intermediaries will choose the same (expected) cut-off value $\bar{\omega}_{j,t+1} = \bar{\omega}_{t+1}$ in equilibrium.

We see from the formula for the cut-off value (3) that financial intermediaries, however, could theoretically make different choices for the ratio of deposits over corporate securities $d_{j,t}/\left(q_t^k s_{j,t}^k\right)$ and the ratio of government bonds over corporate securities $q_t^b s_{j,t}^b/\left(q_t^k s_{j,t}^k\right)$, as long as it delivers the same $\bar{\omega}_{j,t+1}$. To show that all intermediaries choose the same ratio of deposits over corporate securities $d_{j,t}/\left(q_t^k s_{j,t}^k\right)$ and the same ratio of government bonds over corporate securities $q_t^b s_{j,t}^b/\left(q_t^k s_{j,t}^k\right)$, we rewrite the integrand of the second term of equation (79) in the following way with the help of equation (3):

$$\frac{(1-\mu)\omega_{j,t+1} R_{t+1}^k q_t^k s_{j,t}^k + R_{t+1}^b q_t^b s_{j,t}^b}{d_{j,t}} = \left[(1-\mu)\omega_{j,t+1} - \bar{\omega}_{j,t+1}\right] R_{t+1}^k \cdot \frac{q_t^k s_{j,t}^k}{d_{j,t}} + \frac{1}{\pi_{t+1}}.$$

Hence we conclude that equation (79) has two intermediary-specific variables, namely $\bar{\omega}_{j,t+1}$ and $d_{j,t}/\left(q_t^k s_{j,t}^k\right)$. We can see from the first order condition for deposits (10) that the terms other than $\frac{d_{j,t}}{q_t} \cdot \frac{\partial q_t}{\partial d_{j,t}}$ only have $\bar{\omega}_{j,t+1}$ as intermediary-specific variable. And since that variable is uniquely pinned down by first order conditions (8) and (9), we immediately conclude from equation (10) that all intermediaries will choose the same ratio of deposits over corporate securities in equilibrium:: $d_{j,t}/\left(q_t^k s_{j,t}^k\right) = d_t/\left(q_t^k s_t^k\right)$.

Finally, we rewrite the cut-off value (3) in the following way:

$$\frac{q_t^b s_{j,t}^b}{q_t^k s_{j,t}^k} = \frac{1}{\pi_{t+1} R_{t+1}^b} \cdot \frac{d_{j,t}}{q_t^k s_{j,t}^k} - \frac{R_{t+1}^k}{R_{t+1}^b} \cdot \bar{\omega}_{j,t+1} = \frac{1}{\pi_{t+1} R_{t+1}^b} \cdot \frac{d_t}{q_t^k s_t^k} - \frac{R_{t+1}^k}{R_{t+1}^b} \cdot \bar{\omega}_{t+1}.$$

Therefore, all intermediaries will choose the same ratio $q_t^b s_{j,t}^b / \left(q_t^k s_{j,t}^k\right) = q_t^b s_t^b / \left(q_t^k s_t^k\right)$ of government bonds over corporate securities in equilibrium. This concludes the proof. □

B Two-period model

Proof of Proposition 1

We start by substituting intermediaries' first order condition for deposits (42) into intermediaries' first order condition for corporate securities (40) and government bonds (41) to obtain:

$$\beta\tilde{\Lambda}\left(R^k - R^d\right) = \lambda_k \left(\frac{\mu}{1+\mu}\right), \tag{80}$$

$$\beta\tilde{\Lambda}\left(R^b - R^d\right) = \lambda_b \left(\frac{\mu}{1+\mu}\right), \tag{81}$$

Solving for μ from equation (80) gives the following expression:

$$\mu = \frac{\beta\tilde{\Lambda}\left(R^k - R^d\right)}{\lambda_k - \beta\tilde{\Lambda}\left(R^k - R^d\right)}. \tag{82}$$

Implicit differentiation with respect to central bank reserves m^R gives the following expression:

$$\frac{d\mu}{dm^R} = \frac{\lambda_k \beta\tilde{\Lambda}}{\left[\lambda_k - \beta\tilde{\Lambda}\left(R^k - R^d\right)\right]^2} \cdot \frac{dR^k}{dm^R}. \tag{83}$$

With the help of equation (82), we can write:

$$1 + \mu = \frac{\lambda_k}{\lambda_k - \beta\tilde{\Lambda}\left(R^k - R^d\right)}.$$

Next, we use this equation to replace the denominator in equation (83) to obtain:

$$\frac{d\mu}{dm^R} = \frac{(1+\mu)^2}{\lambda_k}\beta\tilde{\Lambda} \cdot \frac{dR^k}{dm^R} = -C \cdot \frac{dk}{dm^R}, \tag{84}$$

where we employed equation (53), and where C is given by:

$$C = \frac{(1+\mu)^2}{\lambda_k}\beta\tilde{\Lambda}\left(1-\alpha\right)\alpha k^{\alpha-2} > 0. \tag{85}$$

Implicit differentiation of equation (47) with respect to central bank reserves m^R gives:

$$n \cdot \frac{d\chi}{dm^R} + \chi \cdot \frac{dn}{dm^R} = \lambda_k \cdot \frac{dk}{dm^R} + \lambda_b \left(s^b \cdot \frac{dq^b}{dm^R} + q^b \cdot \frac{ds^b}{dm^R}\right).$$

Since $\chi = 1 + \mu$, we have that $\frac{d\chi}{dm^R} = \frac{d\mu}{dm^R}$, and we substitute (83) into the above expression. We also substitute equation (44) after implicit differentiation to get:

$$(Cn + \lambda_k) \cdot \frac{dk}{dm^R} = (1 + \mu)\, s^b_{-1} \cdot \frac{dq^b}{dm^R} - \lambda_b \left(s^b \cdot \frac{dq^b}{dm^R} + q^b \cdot \frac{ds^b}{dm^R} \right). \tag{86}$$

Next, we solve for the change in intermediaries' bond holdings. To do so, we implicitly differentiate the market clearing condition (36):

$$\frac{ds^b}{dm^R} = -\frac{ds^{b,h}}{dm^R} - \frac{ds^{b,cb}}{dm^R}, \tag{87}$$

where we remember that the supply of bonds b in period $t = 0$ is constant. To find the derivative for the change in central bank bond holdings, we implicitly differentiate equation (31) to obtain:

$$\frac{ds^{b,cb}}{dm^R} = \frac{1}{q^b} \left(1 - s^{b,cb} \cdot \frac{dq^b}{dm^R} \right).$$

Households' first order condition for government bonds (17) boils down to:

$$\beta \tilde{\Lambda} \left[\frac{1}{q^b + \kappa_b \left(s^{b,h} - \hat{s}^{b,h} \right)} \right] = 1, \tag{88}$$

where we employed equation (39) to eliminate $R^b q^b$. From households' first order condition for deposits (45), we know that $\beta \tilde{\Lambda}$ is constant. Therefore, implicit differentiation of equation (88) allows us to obtain the following expression for the change in households' bond holdings:

$$\frac{ds^{b,h}}{dm^R} = -\frac{1}{\kappa_b} \cdot \frac{dq^b}{dm^R}.$$

Hence we can write equation (87) as:

$$\frac{ds^b}{dm^R} = \frac{1}{\kappa_b} \cdot \frac{dq^b}{dm^R} + \frac{1}{q^b} \left(s^{b,cb} \cdot \frac{dq^b}{dm^R} - 1 \right). \tag{89}$$

Substitution of the above expression into equation (86) gives:

$$(Cn + \lambda_k) \cdot \frac{dk}{dm^R} = \left[(1 + \mu)\, s^b_{-1} - \lambda_b \left(s^b + s^{b,cb} + \frac{q^b}{\kappa_b} \right) \right] \cdot \frac{dq^b}{dm^R} + \lambda_b. \tag{90}$$

Hence we are left with an equation that relates the change in the bond price to the change in credit supply by financial intermediaries. To find a closed-form expression for the change in the bond price and credit supply, we need another equation in which these two variables are related. We can find this other equation by substituting the return on government bonds (51) and the return on corporate securities (53) into the differentiated equation for intermediaries' portfolio choice (52):

$$\frac{1}{(q^b)^2} \cdot \frac{dq^b}{dm^R} = \left(\frac{\lambda_b}{\lambda_k}\right)(1-\alpha)\,\alpha k^{\alpha-2} \cdot \frac{dk}{dm^R}, \tag{91}$$

Solving for $\frac{dk}{dm^R}$, and afterwards substituting the resulting expression in equation (90) gives the following expression for $\frac{dq^b}{dm^R}$:

$$\frac{dq^b}{dm^R} = \frac{\lambda_b}{\frac{Cn+\lambda_k}{(q^b)^2\left(\frac{\lambda_b}{\lambda_k}\right)(1-\alpha)\alpha k^{\alpha-2}} - (1+\mu)\, s^b_{-1} + \lambda_b \left(s^b + s^{b,cb} + \frac{q^b}{\kappa_b}\right)} > 0. \tag{92}$$

Hence the bond price always increases with an expansion of central bank reserves, which is the claim made in Proposition 1. However, the presence of the term $-(1+\mu)\, s^b_{-1}$ in the denominator makes that it is not directly obvious why the bond price unambiguously increases with bond purchases by the central bank. To explicitly prove that this term is dominated by the other terms in the denominator, we introduce the variable A:

$$A \equiv \frac{Cn}{(q^b)^2\left(\frac{\lambda_b}{\lambda_k}\right)(1-\alpha)\,\alpha k^{\alpha-2}} - (1+\mu)\, s^b_{-1}.$$

Hence we see that if $A > 0$, we automatically have that the denominator of equation (92) is larger than zero, and hence that the bond price always increases with an expansion in central bank reserves. To prove $A > 0$, we start by substituting the expression for C in (85):

$$\begin{aligned}
A &= \frac{(1+\mu)^2 \beta\tilde{\Lambda} n}{(q^b)^2 \lambda_b} - (1+\mu)\, s^b_{-1} \\
&= (1+\mu)\left[\frac{\beta\tilde{\Lambda}R^b(1+\mu)\, n}{\lambda_b q^b} - s^b_{-1}\right] \\
&= (1+\mu)\left[\frac{\beta\tilde{\Lambda}R^b(1+\mu)\left(\bar{n} + q^b s^b_{-1}\right)}{\lambda_b q^b} - s^b_{-1}\right] \\
&= (1+\mu)\left[\frac{\beta\tilde{\Lambda}R^b(1+\mu)\,\bar{n}}{\lambda_b q^b} + \frac{\beta\tilde{\Lambda}R^b(1+\mu)\, s^b_{-1}}{\lambda_b} - s^b_{-1}\right] \\
&= (1+\mu)\left[\frac{\beta\tilde{\Lambda}R^b(1+\mu)\,\bar{n}}{\lambda_b q^b} + \frac{\left(\beta\tilde{\Lambda}R^d + \lambda_b\frac{\mu}{1+\mu}\right)(1+\mu)\, s^b_{-1}}{\lambda_b} - s^b_{-1}\right] \\
&= (1+\mu)\left[\frac{\beta\tilde{\Lambda}R^b(1+\mu)\,\bar{n}}{\lambda_b q^b} + \left(\frac{\beta\tilde{\Lambda}R^d(1+\mu) + \lambda_b\mu}{\lambda_b}\right) s^b_{-1} - s^b_{-1}\right] \\
&= (1+\mu)\left[\frac{\beta\tilde{\Lambda}R^b(1+\mu)\,\bar{n}}{\lambda_b q^b} + \left(\frac{1+\mu}{\lambda_b} + \mu\right) s^b_{-1} - s^b_{-1}\right] \\
&= (1+\mu)\left[\frac{\beta\tilde{\Lambda}R^b(1+\mu)\,\bar{n}}{\lambda_b q^b} + \left(\frac{1+\mu-\lambda_b}{\lambda_b} + \mu\right) s^b_{-1}\right] > 0,
\end{aligned}$$

where we used equation (39) going from the first to the second line, where we used equation (44) when moving from the second to the third line, where we used equation (81) when moving from the fourth to the fifth line, and where we used households' first order condition for deposits (45) when moving from the sixth line to the seventh line.

Proof of Proposition 2

Implicit differentiation of $q^b s^b$ with respect to central bank reserves m^R gives the following expression:

$$\begin{aligned} \frac{d\left(q^b s^b\right)}{dm^R} &= s^b \cdot \frac{dq^b}{dm^R} + q^b \cdot \frac{ds^b}{dm^R} \\ &= \left(s^b + s^{b,cb} + \frac{q^b}{\kappa_b}\right) \cdot \frac{dq^b}{dm^R} - 1 \end{aligned} \tag{93}$$

where we used equation (89). Next, we substitute the expression for the change in the bond price (92) to get:

$$\begin{aligned} \frac{d\left(q^b s^b\right)}{dm^R} &= \frac{\lambda_b\left(s^b + s^{b,cb} + \frac{q^b}{\kappa_b}\right)}{\frac{Cn+\lambda_k}{(q^b)^2\left(\frac{\lambda_b}{\lambda_k}\right)(1-\alpha)\alpha k^{\alpha-2}} - (1+\mu)\, s^b_{-1} + \lambda_b\left(s^b + s^{b,cb} + \frac{q^b}{\kappa_b}\right)} - 1 \\ &= \frac{\lambda_b\left(s^b + s^{b,cb} + \frac{q^b}{\kappa_b}\right)}{\frac{\lambda_k}{(q^b)^2\left(\frac{\lambda_b}{\lambda_k}\right)(1-\alpha)\alpha k^{\alpha-2}} + A + \lambda_b\left(s^b + s^{b,cb} + \frac{q^b}{\kappa_b}\right)} - 1 < 0, \end{aligned}$$

since the first two terms in the denominator in the second line are positive. This concludes the proof.

Proof of Proposition 3

We start by proving that the weighted leverage ratio ϕ^w defined in equation (48) decreases in central bank reserves m^R. To do so, we need to show that $\frac{d\chi}{dm^R} = -C \cdot \frac{dk}{dm^R}$, after which the proof automatically follows in Proposition 3. To prove $\frac{d\chi}{dm^R} = -C \cdot \frac{dk}{dm^R}$, we remember that $\chi = 1 + \mu$, and hence that $\frac{d\chi}{dm^R} = \frac{d\mu}{dm^R}$. With the help of equation (83), we then immediately establish that $\frac{d\chi}{dm^R} = -C \cdot \frac{dk}{dm^R}$.

Proof of Proposition 4

We start by rewriting equation (54) in the following way:

$$\bar{\omega} R^k k = R^d k - \left(R^b - R^d\right) q^b s^b - R^d n. \tag{94}$$

Implicit differentiation with respect to central bank reserves m^R gives the following expression:

$$R^k k \cdot \frac{d\bar{\omega}}{dm^R} + \bar{\omega}\left(k \cdot \frac{dR^k}{dm^R} + R^k \cdot \frac{dk}{dm^R}\right) = R^d \cdot \frac{dk}{dm^R} - q^b s^b \cdot \frac{dR^b}{dm^R} - \left(R^b - R^d\right) \cdot \frac{d\left(q^b s^b\right)}{dm^R} - R^d \cdot \frac{dn}{dm^R}.$$

Substitution of the change in the return on corporate securities (53) and the derivative of the initial level of net worth (44) gives the following expression:

$$R^k k \cdot \frac{d\bar{\omega}}{dm^R} + \alpha\bar{\omega}R^k \cdot \frac{dk}{dm^R} = R^d \cdot \frac{dk}{dm^R} - q^b s^b \cdot \frac{dR^b}{dm^R} - \left(R^b - R^d\right) \cdot \frac{d\left(q^b s^b\right)}{dm^R} - R^d s^b_{-1} \cdot \frac{dq^b}{dm^R}.$$

Hence the change in the cut-off value $\bar{\omega}$ is given by:

$$\frac{d\bar{\omega}}{dm^R} = \frac{\left(R^d - \alpha\bar{\omega}R^k\right) \cdot \frac{dk}{dm^R} - q^b s^b \cdot \frac{dR^b}{dm^R} - \left(R^b - R^d\right) \cdot \frac{d\left(q^b s^b\right)}{dm^R} - R^d s^b_{-1} \cdot \frac{dq^b}{dm^R}}{R^k k},$$

which exactly coincides with expression (55) in the main text.

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