Unintended Consequences of Central Bank Lending in Financial Crises

van der Kwaak, Christiaan

Published in:
Economic Journal

DOI:
10.1093/ej/uead078

THE ECONOMIC JOURNAL

The Economic Journal, **134** (*February*), 728–765 https://doi.org/10.1093/ej/uead078
Advance Access Publication Date: 21 September 2023

UNINTENDED CONSEQUENCES OF CENTRAL BANK LENDING IN FINANCIAL CRISES*

Christiaan van der Kwaak

I investigate the macroeconomic impact of central bank funding becoming a more attractive funding source to financial intermediaries in times of crisis. I show that the requirement to pledge collateral has a contractionary effect on private credit, everything else equal, and thereby reduces the expansionary effect that such lending otherwise has. I use an estimated New Keynesian model with financial frictions to show that the collateral effect explains the limited growth of Italian banks' private credit in response to the European Central Bank's three-year longer-term refinancing operations. Finally, I explore whether changes in lending policy can offset the cumulative negative effects from the collateral effect.

In this paper I investigate the macroeconomic implications of central bank funding becoming a more attractive funding source to undercapitalised financial intermediaries in times of financial crises. I show that the requirement to pledge collateral gives rise to a collateral effect that has a contractionary impact on the macroeconomy, everything else equal, and thereby reduces the expansionary effect that such lending otherwise has. This effect arises because (*i*) central banks typically provide more funding for one euro of government bonds than for one euro of private credit and (*ii*) it is typically easier for intermediaries to acquire additional collateral by buying bonds than by expanding private credit. Consequently, central bank funding becoming a more attractive funding source can induce intermediaries to reduce private credit to create additional space for government bonds when they have limited balance sheet capacity in a financial crisis.

I apply the framework developed in this paper to the unconventional three-year longer-term refinancing operations (LTROs) of December 2011 and February 2012, as this unconventional European Central Bank (ECB) funding was more attractive to Italian commercial banks than regular ECB funding: Italian commercial banks borrowed €170 billion from the ECB under this program (Carpinelli and Crosignani, 2021), which amounted to 80% of Italian banks' total volume of ECB funding by March 2012, and therefore replaced most regular ECB funding (Bank of Italy, 2012a). The collateral effect simultaneously explains why Italian banks' private credit only grew

* Corresponding author: Christiaan van der Kwaak, Department of Economics and Business, University of Groningen, Nettelbosje 2, 9747 AE Groningen, Netherlands. Email: c.g.f.van.der.kwaak@rug.nl

This paper was received on 27 January 2022 and accepted on 14 September 2023. The Editor was Francesco Lippi.

The data and codes for this paper are available on the Journal repository. They were checked for their ability to reproduce the results presented in the paper. The replication package for this paper is available at the following address: https://doi.org/10.5281/zenodo.8296473.

I am grateful to Francesco Lippi, four anonymous referees, Ben Heijdra, Sweder van Wijnbergen, Wouter den Haan, Nicola Gennaioli, Jose Victor Rios-Rull, Ricardo Reis, Franklin Allen, Ethan Ilzetzki, Lukas Schmid, Thomas Eisenbach, Toni Ahnert, Christian Stoltenberg, Bjoern Bruggeman, Petr Sedlacek, Omar Rachedi, Anatoli Segura, Nuno Palma, Jens van 't Klooster, Matthijs Katz, Agnese Leonello, Enrico Mallucci, Alex Clymo, Patrick Tuijp, Oana Furtuna, Damiaan Chen, Lucyna Gornicka and Egle Jakucionyte, as well as seminar participants at the University of Manchester, the University of Kent, the National Bank of Hungary, the University of Groningen, Bank of Lithuania, the University of Amsterdam and the Tinbergen Institute for helpful comments and suggestions. The first draft of this paper (2015) circulated under the title 'Financial Fragility and Unconventional Central Bank Lending Operations'.

I acknowledge the generous support of the Dutch Organization for Sciences, through the NWO Research Talent Grant No. 406-13-063.

by 2% relative to no intervention (Carpinelli and Crosignani, 2021), and provides an additional explanation why Italian banks accumulated substantial amounts of domestic government bonds in response to the three-year LTROs (which grow by 10% in my model). While my framework is applied to the three-year LTROs, it can be applied to any program that makes central bank funding a more attractive funding source in times of financial crises, such as the Federal Reserve's Term Auction Facility and the Treasury Securities Lending Facility.

My framework is a New Keynesian DSGE model with financial frictions and standard price and wage stickiness. I capture the fact that Italian banks were undercapitalised since the Great Financial Crisis (International Monetary Fund, 2011; Hoshi and Kashyap, 2015) by employing the Gertler and Karadi (2011) framework, in which an incentive compatibility constraint limits the size of intermediaries' balance sheets by the amount of net worth. I extend this framework in two directions. First, financial intermediaries have a portfolio choice between government bonds, central bank reserves and corporate securities, the last of which is used by non-financial corporations to finance productive 'physical' capital (Gertler and Karadi, 2013; van der Kwaak and van Wijnbergen, 2014; Bocola, 2016; Kirchner and van Wijnbergen, 2016; Sims and Wu, 2021). Second, I introduce collateralised central bank lending, which represents an alternative form of funding in addition to net worth and deposits. Intermediaries have to pledge collateral to obtain central bank funding, for which both government bonds and corporate securities can be used. However, one euro of government bonds provides more funding than one euro of corporate securities. Afterwards, the central bank supplies any amount of funding as long as sufficient collateral has been pledged. It also sets the interest rate on central bank funding and reserves, the last of which turns out to be equal to the interest rate on deposits in equilibrium. Central bank funding becomes more attractive by reducing the interest rate on it with respect to that on reserves and deposits (Bocola, 2016; Engler and Große Steffen, 2016). Doing so captures the fact that the three-year LTROs allowed Italian commercial banks to reduce their average funding costs by 10 basis points (Bank of Italy, 2012a). Afterwards, the interest rate on central bank funding reverts back to that on reserves following an AR(1) process. I capture the fact that the three-year LTROs made ECB funding a more attractive funding source for a longer period of time (everything else equal) by increasing the AR(1) coefficient of this process.[1] I introduce sovereign default risk as in Corsetti *et al.* (2013), Schabert and van Wijnbergen (2014) and van der Kwaak and van Wijnbergen (2017) to capture the fact that Italy was in the middle of a sovereign debt crisis at the end of 2011. I estimate the resulting model with the help of Bayesian techniques using Italian data, after which I investigate the impact of the three-year LTROs in response to a sovereign debt crisis.[2]

The main contribution of the paper is the identification of the collateral effect, and the key parameters that determine its strength. I show how this effect reduces the expansionary effect that central bank lending to intermediaries has on the macroeconomy in other New Keynesian models with financial frictions (Gertler and Kiyotaki, 2010; Bocola, 2016; Engler and Große

[1] Both Bocola (2016) and Engler and Große Steffen (2016) model the three-year LTROs as the central bank offering funding at interest rates below that on private market funding. I discuss these and other aspects of the three-year LTROs such as the maturity of the loans in Section 6. I also explain in Section 6 that my results continue to hold for an alternative mechanism through which central bank funding becomes a more attractive funding source, as well as other robustness checks.

[2] I do so within a closed economy in the main text, and check in Section 6 that the results regarding the impact of the three-year LTROs carry over to a small open economy that is a member of a currency union; these economies capture the two extremes in terms of the influence that Italian macrodevelopments have on the Italian policy rate, which is in reality set by the ECB and is based on macrodevelopments in the eurozone as a whole.

Steffen, 2016; Cahn *et al.*, 2017). The modelling innovation that gives rise to this effect is the combination of (*i*) balance-sheet-constrained financial intermediaries that are subject to (*ii*) differential collateral requirements when obtaining central bank funding. A second contribution is that the collateral effect simultaneously explains (part of) the substantial accumulation of domestic government bonds by Italian commercial banks in response to the three-year LTROs, as well as the limited growth of Italian private credit by 2% (relative to no intervention; Carpinelli and Crosignani, 2021). A third contribution is to quantify the collateral effect, which allows me to show that the cumulative negative effect on credit provision to the real economy, investment and output can be offset by the central bank providing more funding per euro of corporate securities.

A final contribution is to show that the longer central bank funding is offered at more attractive terms (captured by a larger AR(1) coefficient) the larger its expansionary effect, despite the collateral effect being present for longer: the longer financial intermediaries can profit from lower funding costs, the larger the increase in the expected discounted sum of future profits, and the larger the relaxation of their incentive compatibility constraints. While the collateral effect still induces a relative shift from corporate credit to government bonds, the additional balance sheet capacity that is now created is sufficient to simultaneously expand the level of credit provision to the real economy.

Early papers that investigate the effects of longer-maturity LTROs do so using estimations based on aggregate data. For example, Giannone *et al.* (2012) perform a Bayesian estimation of a Vector Autoregression (VAR) model using a sample up to April 2011, while Darracq Pariès and De Santis (2015) estimate a panel-VAR for euro area countries, and focus their analysis on the three-year LTROs. Both papers find an expansion of bank lending to non-financial corporations and real activity.

While these papers perform their analysis at the level of the aggregate banking system, Drechsler *et al.* (2016), Garcia-Posada and Marchetti (2016), Andrade *et al.* (2019), Crosignani *et al.* (2020) and Carpinelli and Crosignani (2021) study the impact of the ECB's three-year LTROs at the level of individual banks.

Garcia-Posada and Marchetti (2016), Andrade *et al.* (2019) and Carpinelli and Crosignani (2021) find a positive effect on credit provision to the real economy in Spain, France and Italy, respectively. In addition, both Andrade *et al.* (2019) and Carpinelli and Crosignani (2021) stress the longer maturity as the key reason for an expansion in loan supply.

Carpinelli and Crosignani (2021) also document that Italian banks used €85 billion of the €170 billion borrowed under the three-year LTROs to buy government bonds. Crosignani *et al.* (2020) find that the three-year LTROs induced Portuguese banks to acquire government bonds, which they ascribe to a collateral trade: banks would use their existing reserves to purchase bonds of the same maturity as the ECB funding, after which they would pledge these bonds at the ECB as collateral to replenish their reserves. By doing so, they were also making a profit on the newly acquired bonds, as sovereign default risk caused the yield on them to be higher than the interest rate on the ECB funding.

Drechsler *et al.* (2016) focus on the role of the ECB as a lender of last resort (LOLR) after the start of the European sovereign debt crisis in 2010. They show that the active acquisition of distressed sovereign debt by weakly capitalised banks was due to risk-taking behaviour, as strongly capitalised banks reduced their exposure to distressed sovereign debt in the same period. Their sample, however, does not include the three-year LTROs of February 2012. Acharya and Steffen (2015) report how the accumulation of government bonds around the time of the three-year LTROs arises from risk-shifting by commercial banks. Other papers that highlight risk shifting as a cause for banks accumulating government bonds during the European sovereign debt crisis are Acharya and Steffen (2015), Drechsler *et al.* (2016), Acharya *et al.* (2018) and Crosignani (2021), while Uhlig (2014), Acharya and Steffen (2015), De Marco and Macchiavelli (2016), Altavilla *et al.* (2017), Becker and Ivashina (2018) and Ongena *et al.* (2019) (also) point at moral suasion. Such an accumulation of government bonds reduced credit provision to the real economy during the sovereign debt crisis (Acharya and Steffen, 2015; Popov and van Horen, 2015; Altavilla *et al.*, 2017; Acharya *et al.*, 2018; Becker and Ivashina, 2018; Gennaioli *et al.*, 2018), which is caused by capital losses on banks' sovereign bond holdings (Acharya and Steffen, 2015; Popov and van Horen, 2015; Altavilla *et al.*, 2017; Acharya *et al.*, 2018; Bofondi *et al.*, 2018; Gennaioli *et al.*, 2018; De Marco, 2019; Bottero *et al.*, 2020).

Finally, banks having large holdings of government bonds on their balance sheet imply that they are indirectly recapitalised when bond prices increase, such as happened after ECB President Draghi's speech announcing the Outright Monetary Transactions program (Acharya *et al.*, 2019).

I contribute to the literature on government bond accumulation by being the first to explicitly link the incentive that banks have to acquire government bonds for collateral purposes with the impact this has on credit provision to the real economy. Doing so within a fully specified dynamic stochastic general equilibrium (DSGE) model allows me to investigate how bond accumulation induced by the collateral effect subsequently affects the macroeconomy. This contrasts with most of the above-mentioned papers, which employ regression analysis and are therefore not able to study the macroeconomic impact.

My paper also relates to Gertler and Kiyotaki (2010) and Gertler and Karadi (2011; 2013), who study the transmission to the macroeconomy of shocks to the balance sheets of financial intermediaries. The key property of these papers is that the size of intermediaries' balance sheets are limited by the amount of net worth through an endogenous leverage constraint.

A key result of this paper is that there is crowding out of credit provision to the real economy by government bonds through the collateral effect. Other theoretical papers that feature crowding out are Kirchner and van Wijnbergen (2016) and Crosignani (2021), where it is caused by a debt-financed fiscal expansion increasing commercial banks' bond holdings (Kirchner and van Wijnbergen, 2016) and risk shifting (Crosignani, 2021). Other reasons for a reduction in credit provision to the real economy within theory papers are capital losses on government bonds that reduce intermediaries' net worth through the so-called bank-sovereign nexus, both within stylised two-period models (Bolton and Jeanne, 2011; Acharya *et al.*, 2014; Gennaioli *et al.*, 2014; Brunnermeier *et al.*, 2016; Cooper and Nikolov, 2018; Farhi and Tirole, 2018; Leonello, 2018) as well as DSGE models (van der Kwaak and van Wijnbergen, 2014; Bocola, 2016). My DSGE model also features this bank-sovereign nexus.

My paper is also related to the LOLR literature, of which Bagehot (1873) was the first to argue that central banks should lend freely against good collateral at high rates. In order for banks to take out central bank funding during a financial crisis, LOLR funding must be subsidised in some way relative to funding sources in private markets; otherwise, LOLR lending would offer no benefit over the private market, and banks would not borrow from it. In my paper, central bank funding becomes a more attractive source of funding by temporarily reducing the interest rate on it relative to that on deposit funding, which is in line with Bocola (2016) and Engler and Große Steffen (2016), where the interest rate on central bank funding is also (temporarily) below that on private funding.

The more recent literature that investigates the effects from central bank lending within the standard DSGE framework can broadly speaking be distinguished between collateralised and uncollateralised lending. One of the first papers to explicitly model uncollateralised central bank lending is Gertler and Kiyotaki (2010). Bocola (2016) and Cahn *et al.* (2017) extend this framework to investigate the impact of the ECB's unconventional LTROs. These papers do not feature a collateral requirement, and therefore miss the contractionary collateral effect. As a result, LTROs only have an expansionary effect on bank lending and output because central bank lending directly relaxes intermediaries' incentive compatibility constraints.

A second strand of literature features a collateral requirement to obtain central bank funding, but the agents who borrow from the central bank are not balance sheet constrained (Hörmann and Schabert, 2015; Schabert, 2015; Engler and Große Steffen, 2016). As a result, these agents can perfectly elastically acquire additional collateral in case central bank funding becomes more attractive. This contrasts with my paper, where the combination of collateral requirements and endogenous leverage constraints causes a trade-off to emerge between acquiring additional government bonds (which provide the most central bank funding per euro) and credit provision to the real economy.

Finally, my paper also relates to the literature that studies the collateral requirements of the central bank. Koulischer and Struyven (2014) find that the central bank should relax its collateral requirements when the quality of collateral drops below a threshold, as the economy enters a credit crunch otherwise. Choi *et al.* (2021) also find that central banks should lend against low-quality collateral, but for a different reason: pledging low-quality collateral at the central bank allows high-quality collateral to be pledged in private market transactions, and thereby improves liquidity in financial markets. While I also find that relaxing collateral requirements can have a positive effect on credit provision to the real economy, these papers perform their analysis within stylised two-period models. Another difference is that financial intermediaries are endowed with collateral, whereas intermediaries in my model endogenously choose how much collateral to acquire.

I describe some stylised facts in Section 1. The infinite-horizon DSGE model is presented in Section 2, after which I analyse a simplified two-period model version in Section 3. Section 4 discusses the calibration and estimation procedure, while Section 5 presents the results from my simulations. Section 6 discusses the results and evaluates several robustness checks, after which Section 7 concludes the paper.

1. Stylised Facts

In this section I present some stylised facts regarding the aggregated balance sheets of monetary financial institutions (MFIs) excluding the European System of Central Banks from Italy, Portugal and Spain at the time of the three-year LTROs.[3] I do so for MFIs, as they are the only financial institutions that can participate in the ECB's refinancing operations.[4] I do so for two reasons. First,

[3] MFIs as defined by the ECB include the European System of Central Banks and 'credit institutions and non-credit institutions (mainly money market funds) whose business is to receive deposits from entities other than MFIs and to grant credit and/or invest in securities' (European Central Bank, 2011). The vast majority of euro area commercial MFIs are credit institutions (i.e., commercial banks, savings banks, postbanks, specialised credit institutions, among others; European Central Bank, 2011). In this paper, the abbreviation 'MFIs' will refer to MFIs excluding the European System of Central Banks.

[4] The ECB refers to its lending operations as 'refinancing operations'. Regular open market operations of the Eurosystem consist of main refinancing operations (MROs) and LTROs. MROs are one-week liquidity-providing operations in euros, while regular LTROs are three-month liquidity-providing operations. The main policy rate of the ECB is the interest rate charged on MROs, which is also called the MRO rate. This information can be found at https://www.ecb.europa.eu/mopo/implement/omo/html/index.en.html.

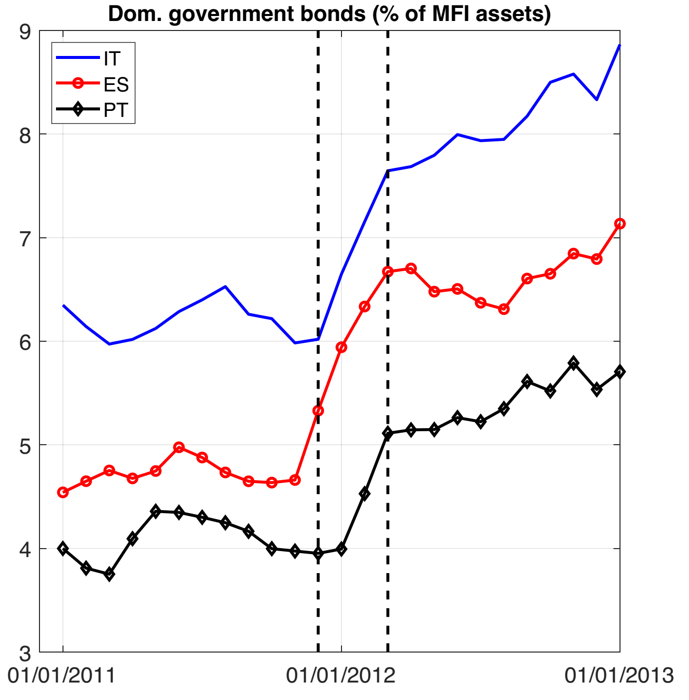

Fig. 1. *Southern European MFIs' Domestic Bond Holdings.*
Notes: Domestic government bond holdings as a percentage of total assets for MFIs in Italy (IT), Spain (ES) and Portugal (PT) from January 2011 to January 2013. The two dashed vertical lines refer to December 1, 2011 and March 1, 2012, respectively, which mark the beginning and the end of the period in which the two three-year LTROs took place, respectively.
Source: European Central Bank (2015).

I will show that the three-year LTROs induced MFIs from these countries to purchase substantial amounts of domestic government bonds. Second, I will argue that the three-year LTROs were a much more attractive funding source for Italian MFIs than funding from the ECB's regular refinancing operations.

Balance sheet data of MFIs were collected from the ECB's statistical warehouse (European Central Bank, 2015). They have a monthly frequency, and are available at a country level. The figure with data of Italian MFIs' recourse to the refinancing operations of the ECB was obtained from Bank of Italy (2012a).

Figure 1 shows domestic government bond holdings as a percentage of total assets for MFIs from Italy, Spain and Portugal. From the figure we see a clear increase in holdings of domestic government bonds of one to one-and-a-half percentage points of total MFI assets for all three countries during the period in which the three-year LTROs took place. In addition, there is a clear break around the time of the three-year LTROs, which makes it plausible that this increase can at least partially be attributed to the three-year LTROs. This is confirmed for Italy by Carpinelli and Crosignani (2021), who report that out of €170 billion borrowed under the three-year LTROs, Italian MFIs invested €85 billion in government bonds.

Figure 2 displays the recourse of Italian MFIs to Eurosystem credit under the refinancing operations of the ECB, where the light bars refer to refinancing operations with maturities of up

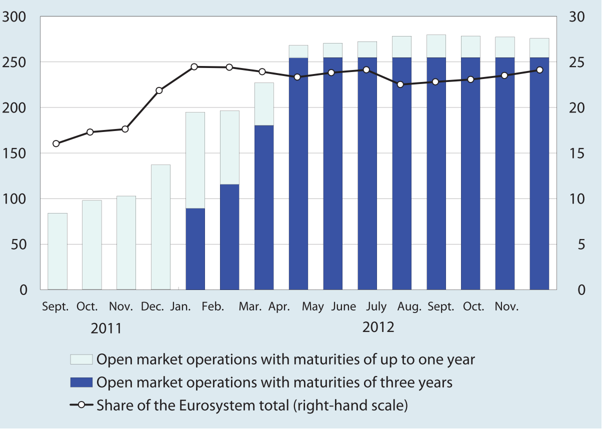

Fig. 2. *Italian MFIs' Recourse to Refinancing with ECB.*
Notes: The figure displays Italian MFIs' recourse to refinancing with the ECB, which is referred to as 'open market operations'. The left vertical axis is denoted in billions of euros, while the right-hand scale is denoted in per cent.
Source: Bank of Italy (2012a, p. 48).

to one year, and the dark bars to refinancing operations with maturities of three years. Therefore, the dark bars refer to ECB funding taken out under the three-year LTROs of December 2011 and February 2012.[5]

It is clear from Figure 2 that funding obtained under the three-year LTROs was much more attractive to Italian MFIs than ECB funding with shorter maturities. First, Italian MFIs expanded their total reliance on ECB funding from approximately €140 billion in December 2011 to approximately €230 billion in March 2012. Second, Italian MFIs used the funds obtained under the three-year LTROs to (partially) replace funding with shorter maturities, as Figure 2 shows that funding obtained under the three-year LTROs accounted for almost 80% of the total volume of ECB funding held by Italian MFIs by March 2012.

It is not directly clear, however, why the three-year LTROs were more attractive than the ECB's regular refinancing operations or private market funding; the interest rate was 'fixed at the average rate of the main refinancing operations over the life of the respective operation'.[6] As a result, there was no difference in terms of funding costs between a strategy where MFIs borrowed from the ECB at a three-year maturity and a strategy where they borrowed at a weekly maturity, and rolled over for three years (Carpinelli and Crosignani, 2021). However, we can safely conclude from Figure 2 that three-year ECB funding was much more attractive to Italian MFIs than regular ECB funding, and that it induced them to substantially expand their recourse to ECB funding. As a result, Italian MFIs had to pledge additional collateral, which is precisely the situation in which the collateral effect can potentially emerge.

[5] The difference between the €170 billion mentioned above, and the approximately €180 billion in March 2012 in Figure 2 is explained by foreign branches and subsidiaries of Italian banks (Carpinelli and Crosignani, 2021). Bank of Italy (2012a) does not explain why the volume of funds provided under the three-year LTROs continues to increase after the second and final leg of the three-year LTROs on February 29, 2012.

[6] The entire statement can be found at https://www.ecb.europa.eu/press/pr/date/2011/html/pr111208_1.en.html.

2. Model

In this section I employ a closed economy New Keynesian model that features households, production firms, financial intermediaries and a government that consists of a fiscal authority and a central bank.[7] The central bank lends to financial intermediaries, as a result of which reserves are created. The central bank sets the nominal interest rate on central bank funding and reserves, the last of which follows a standard active Taylor rule (Sims and Wu, 2021). Unconventional LTROs are modelled as a reduction of the interest rate on central bank funding with respect to the interest rate on reserves (Bocola, 2016; Engler and Große Steffen, 2016).

Financial intermediaries hold corporate securities from intermediate goods producers, government bonds and central bank reserves, presenting intermediaries with a portfolio choice similar to Gertler and Karadi (2013), Bocola (2016) and Sims and Wu (2021). These assets are financed through central bank funding, household deposits and net worth. Intermediaries have access to unlimited amounts of central bank funding, provided that they pledge sufficient corporate securities and government bonds as collateral. In addition, they are subject to an incentive compatibility constraint as in Gertler and Karadi (2011), which prevents them from perfectly elastically expanding the balance sheet in case of arbitrage opportunities.

Households maximise the sum of expected discounted utility with habit formation in consumption to more realistically capture consumption dynamics (Christiano *et al.*, 2005). They save through deposits, corporate securities and government bonds, the last two of which are subject to quadratic adjustment costs. These costs capture in a simple way limited participation by households in asset markets (Gertler and Karadi, 2013). Nominal wages are sticky, as households' wage and labour decisions are modelled as in Erceg *et al.* (2000). Households receive profits from ownership of all firms in the economy, and pay lump sum taxes to the government. The government also issues long-term debt to finance outstanding obligations and purchases of final goods. It is subject, however, to a stochastic maximum level of taxation (Corsetti *et al.*, 2013; Schabert and van Wijnbergen, 2014; van der Kwaak and van Wijnbergen, 2017), which might prevent it from raising sufficient taxes. In that case, the government partially defaults on its outstanding obligations.

Intermediate goods producers issue corporate securities to financial intermediaries and households to finance purchases of physical capital from capital goods producers that are subject to convex adjustment costs. Final labour and physical capital are then used for the production of the intermediate goods, which are sold to retail goods producers who face monopolistic competition and sticky price adjustments as in Calvo (1983). Final goods producers purchase retail goods to produce a final good that is sold in a perfectly competitive market. The final good is used by households for consumption, by capital goods producers for investment and by the government. Below I explain the key elements of the model, details of which can be found in Online Appendix A.

[7] I check in Section 6 how my results depend on the way conventional monetary policy is modelled. I do so by analysing a model version of a small open economy that is a member of a monetary union. These two model versions (closed and small open economies) capture the two extremes in terms of the influence that Italian macrodevelopments have on the policy rate of the central bank.

2.1. *Government*

2.1.1. *Fiscal authority*

The fiscal authority raises revenues through lump sum taxes and debt issue $q_t^b b_t$, where q_t^b denotes the bond price and b_t the number of bonds. Government debt is long term, and its maturity structure follows Woodford (1998; 2001): bonds pay a coupon x_c that decays at a rate $1 - \rho$ per period. Hence, ρ effectively determines the maturity structure of the bonds.[8] In Online Appendix A.4.1 I formally show that the real rate of return r_t^b on a bond issued in period $t - 1$ (in the absence of a sovereign default) is given by

$$1 + r_t^b = [x_c + (1 - \rho)q_t^b]/(\pi_t q_{t-1}^b), \tag{1}$$

where $\pi_t \equiv P_t/P_{t-1}$ denotes the gross inflation rate of the final good.

Revenues are used to pay for government purchases of the final good g_t, which follow an AR(1) process, and to service outstanding government liabilities $(1 + r_t^b)q_{t-1}^b b_{t-1}$ in the absence of a sovereign default. In that case, the government budget constraint (in terms of the price level of the final good P_t) is given by

$$q_t^b b_t + \tau_t = g_t + (1 + r_t^b)q_{t-1}^b b_{t-1}, \tag{2}$$

where τ_t denotes the level of lump sum taxes in the absence of sovereign default, and is given by a rule that ensures that the intertemporal government budget constraint is satisfied (Bohn, 1998):

$$\tau_t = \bar{\tau} + \zeta_b(b_{t-1} - \bar{b}). \tag{3}$$

Government bonds, however, are subject to default risk because of the existence of a stochastic maximum level of taxation (Corsetti *et al.*, 2013; Schabert and van Wijnbergen, 2014; van der Kwaak and van Wijnbergen, 2017): at the beginning of period t, there is a probability p_t^{def} that the no-default level of taxes τ_t will turn out to be above the realisation of the period-t maximum level of taxation. In that case, there is a haircut ϑ on outstanding liabilities, as a result of which the return on bonds will be equal to $(1 - \vartheta)(1 + r_t^b)$.[9] With probability $1 - p_t^{def}$, however, τ_t will be below the maximum level of taxation, in which case the return on bonds will be equal to $1 + r_t^b$. Therefore, at the beginning of period t (before realisation of the period-t maximum level of taxation), the expected return on bonds r_t^{b*} is equal to

$$1 + r_t^{b*} = (1 - p_t^{def})(1 + r_t^b) + p_t^{def}(1 - \vartheta)(1 + r_t^b) = (1 - p_t^{def}\vartheta)(1 + r_t^b). \tag{4}$$

The probability of default p_t^{def} is given by a generalised beta distribution that depends on the debt-GDP ratio b_t/y_t and b_t^{max} (Corsetti *et al.*, 2013):[10]

$$p_t^{def} = F_\beta(b_t/(4y_t b_t^{max}); \alpha_b, \beta_b), \tag{5}$$

with α_b and β_b parameters of the beta distribution. Here b_t^{max} is given by the process

$$\log(b_t^{max}/\bar{b}_{max}) = \rho_{b_{max}} \log(b_{t-1}^{max}/\bar{b}_{max}) + \varepsilon_{b_{max},t}, \tag{6}$$

[8] Average maturity is calculated as $\sum_{j=1}^{\infty} j(1-\rho)^j / \sum_{j=1}^{\infty}(1-\rho)^j = 1/\rho$.

[9] Creditors are aware of the fiscal authority's inability to raise sufficient funds, and therefore voluntarily accept a haircut ϑ on their claims (with ϑ assumed to be constant across time).

[10] Note that b_t^{max} does not refer to a maximum level of debt. In both Corsetti *et al.* (2013) and my setup there is only a stochastic maximum level of taxation, while there is no limit to the amount of debt that the sovereign can issue. Instead, b_t^{max} can be interpreted in a similar way as the maximum debt-GDP ratio of 60% in the stability and growth pact of the eurozone. Countries can increase government debt above that level, but might face higher borrowing costs and a higher probability of default as a result.

where $\bar{b}_{max}$ denotes the steady-state value of b_t^{max}. In the case of default, payments to creditors are reduced by an amount $\vartheta(1+r_t^b)q_{t-1}^b b_{t-1}$. Just as in Corsetti *et al.* (2013) and Schabert and van Wijnbergen (2014), however, these gains are effectively transferred to households by reducing their lump sum taxes from the no-default level of taxes τ_t to $\tilde{\tau}_t = \tau_t - \vartheta(1+r_t^b)q_{t-1}^b b_{t-1}$. As a result, the government budget constraint in the case of default is given by

$$q_t^b b_t + \tilde{\tau}_t = g_t + (1-\vartheta)(1+r_t^b)q_{t-1}^b b_{t-1}. \tag{7}$$

Substitution of $\tilde{\tau}_t = \tau_t - \vartheta(1+r_t^b)q_{t-1}^b b_{t-1}$ into (7) shows that the ex post default budget constraint collapses to the budget constraint in the case of no default (2). Observe, however, that sovereign default risk will still affect the equilibrium, as the probability of default will affect the bond price q_t^b, which in turn affects the return on bonds (1) and (4). A more elaborate description of the fiscal authority can be found in Online Appendix A.4.1.

2.1.2. *Central bank*

Central bank reserves m_t^R enter the economy through lending d_t^{cb} to financial intermediaries. I assume that the central bank operates with zero net worth. Therefore, the central bank's balance sheet constraint (in terms of the price level of the final good P_t) is given by

$$d_t^{cb} = m_t^R. \tag{8}$$

The central bank operating with zero net worth implies that all profits and losses are transferred to the fiscal authority. The fiscal authority, in turn, transfers central bank profits on to households in lump sum fashion, or raises lump sum taxes to cover for central bank losses. Therefore, central bank profits and losses do not show up in the government budget constraint (2), and do not affect how much debt is issued by the fiscal authority.[11]

The central bank sets the nominal interest rate $r_t^{n,r}$ on reserves m_t^R by employing a standard Taylor rule:

$$r_t^{n,r} = (1-\rho_r)[\bar{r}_{n,r} + \kappa_\pi(\pi_t - \bar{\pi}) + \kappa_y \log(y_t/y_{t-1})] + \rho_r r_{t-1}^{n,r} + \varepsilon_{r,t}. \tag{9}$$

Here π_t denotes the gross inflation rate of the final good, y_t the output, ρ_r an interest smoothing parameter and $\varepsilon_{r,t}$ an independent and identically distributed (i.i.d.) shock with standard deviation σ_r. I assume that the Taylor principle is satisfied, i.e., $\kappa_\pi > 1$.

To obtain central bank funding, financial intermediaries have to pledge collateral in the form of corporate securities $q_t^k s_{j,t}^k$ and/or government bonds $q_t^b s_{j,t}^b$, with q_t^a the market price of asset class $a \in \{k, b\}$ and $s_{j,t}^a$ the volume of asset class a held by financial intermediary j. The central bank provides θ^a euros in funding for one euro of collateral from asset class a. Therefore, the collateral constraint has the functional form

$$d_{j,t}^{cb} \leq \theta^k q_t^k s_{j,t}^k + \theta^b q_t^b s_{j,t}^b. \tag{10}$$

In line with the ECB's fixed rate full allotment policy, the central bank provides as much funding as demanded by financial intermediaries (full allotment), provided intermediaries pledge sufficient collateral. Intermediaries remain the legal owner of the assets they pledge as collateral,

[11] Central bank profits and losses are therefore effectively transferred to households; otherwise, central bank profits and losses would affect debt issue by the sovereign, which in turn would affect the collateral effect. In reality, dividends from the ECB and the Bank of Italy to the Italian Treasury are small compared with total outstanding Italian debt, which is in line with this choice.

and therefore receive the accompanying cash flows after repayment of the central bank loan in period $t+1$.[12]

The central bank receives a nominal interest rate $r_t^{n,cb}$ on loans d_t^{cb} to financial intermediaries. The central bank sets the nominal interest rate $r_t^{n,cb}$ by adjusting the spread Γ_t:

$$r_t^{n,cb} = r_t^{n,r} - \Gamma_t, \quad \text{where} \quad \Gamma_t = \bar{\Gamma} + \varkappa_{b_{max}} \log(b_t^{max,*}/\bar{b}_{max}), \tag{11}$$

with $\bar{\Gamma}$ the steady-state spread. Here $\varkappa_{b_{max}}$ affects the change in the nominal interest rate on central bank funding for a given change in $b_t^{max,*}$, which is given by

$$\log(b_t^{max,*}/\bar{b}_{max}) = \rho^*_{b_{max}} \log(b_{t-1}^{max,*}/\bar{b}_{max}) + \varepsilon_{b_{max},t}. \tag{12}$$

Therefore, an increase in Γ_t will decrease the interest rate on central bank funding with respect to that on reserves, and therefore on deposits, as we will see in Section 2.2. As a result, central bank funding becomes a more attractive funding source, just as the three-year LTROs were a more attractive funding source to Italian commercial banks than regular ECB funding; see Section 1. In addition, an increase in Γ_t will reduce intermediaries' (weighted) average funding costs, which is in line with the fact that the three-year LTROs of December 2011 and February 2012 reduced Italian commercial banks' average funding costs by allowing them to replace foreign wholesale funding by ECB funding with substantially lower interest rates (Bank of Italy, 2012b). Modelling the three-year LTROs in this way is, to the best of my knowledge, also in line with the literature: Bocola (2016) and Engler and Große Steffen (2016) also model central bank loans under the three-year LTROs as a loan that is provided at an interest rate below that offered by the private sector.[13]

Finally, observe that $b_t^{max,*}$ in (12) is driven by the same shock $\varepsilon_{b_{max},t}$ that drives b_t^{max} in (6). The difference with (6) is the AR(1) coefficient $\rho^*_{b_{max}}$, which allows me to have process Γ_t decay at a different rate than the exogenous process (6) that is driving the probability of sovereign default. Increasing the AR(1) parameter $\rho^*_{b_{max}}$ in (12) implies a slower reversion to the steady-state spread, which means that central bank funding remains more attractive to financial intermediaries for a longer period of time. This captures a key aspect of the three-year LTROs, namely that they expanded Italian banks' reliance on central bank funding for a longer period of time, everything else equal, because the maturity was not three months as under regular LTROs, but three years.[14]

2.2. *Financial Intermediaries*

Financial intermediaries purchase corporate securities $s_{j,t}^k$ that are issued by intermediate goods producers at a price q_t^k, and government bonds $s_{j,t}^b$ at a price q_t^b. In addition, they hold reserves $m_{j,t}^R$ at the central bank. They fund their assets through net worth $n_{j,t}$, household deposits $d_{j,t}$

[12] Financial intermediaries are not subject to limited liability in the Gertler and Karadi (2011) framework employed in this paper, and will therefore always repay their creditors. In addition, I calibrate the model in such a way that intermediaries never have negative net worth in equilibrium.

[13] Observe, however, that funding costs under a strategy where Italian commercial banks borrowed for three years from the ECB were equal to funding costs under a strategy where they borrowed short term and rolled over for three years; see https://www.ecb.europa.eu/press/pr/date/2011/html/pr111208_1.en.html. I discuss this issue and others in Section 6, as well as several robustness checks.

[14] However, the maturity of my central bank loans is still one period, which is in line with Engler and Große Steffen (2016). An exception is Cahn *et al.* (2017), who explicitly model longer-maturity central bank loans and also captured the fact that long-term funding costs are equal to short-term funding costs. I discuss in Section 6, however, why incorporating these features would have zero effect in my model.

and central bank funding $d_{j,t}^{cb}$, for which they need to pledge collateral; see (10). Total assets $p_{j,t}$ are given by

$$p_{j,t} = q_t^k s_{j,t}^k + q_t^b s_{j,t}^b + m_{j,t}^R = n_{j,t} + d_{j,t} + d_{j,t}^{cb}. \tag{13}$$

Net worth in period $t+1$ is the difference between the return on assets and the return on liabilities:

$$n_{j,t+1} = (1 + r_{t+1}^k) q_t^k s_{j,t}^k + (1 + r_{t+1}^{b*}) q_t^b s_{j,t}^b + (1 + r_{t+1}^R) m_{j,t}^R \\ - (1 + r_{t+1}^d) d_{j,t} - (1 + r_{t+1}^{cb}) d_{j,t}^{cb}. \tag{14}$$

Here r_t^k is the net real return on corporate securities in period t, r_t^{b*} the net real return on government bonds (including default), r_t^R the net real return on central bank reserves, r_t^d the net real return on deposits and r_t^{cb} the net real return on central bank funding. Intermediaries operate in a perfectly competitive market, and therefore take all returns as given.

Following Gertler and Karadi (2011), intermediaries are forced to shut down with probability σ, which is i.i.d. and exogenous, both in time and the cross section. Intermediaries that are forced to stop operating pay out all remaining net worth to their respective household, the ultimate owner of the intermediary. As long as they operate, intermediaries maximise their continuation value $V_t(s_{j,t-1}^k, s_{j,t-1}^b, m_{j,t-1}^R, d_{j,t-1}, d_{j,t-1}^{cb})$, which is the sum of expected discounted future profits:

$$V_t(s_{j,t-1}^k, s_{j,t-1}^b, m_{j,t-1}^R, d_{j,t-1}, d_{j,t-1}^{cb}) \\ = \max E_t\{\beta \Lambda_{t,t+1}[(1-\sigma) n_{j,t+1} + \sigma V_{t+1}(s_{j,t}^k, s_{j,t}^b, m_{j,t}^R, d_{j,t}, d_{j,t}^{cb})]\}, \tag{15}$$

with $\beta \Lambda_{t,t+1}$ denoting the household's stochastic discount factor. However, intermediaries face an incentive compatibility constraint as in Gertler and Karadi (2011) that arises from the possibility to costlessly divert a fraction λ_a of asset $a \in \{k, b\}$ at the end of period t.[15] Depositors, however, anticipate this possibility, and will in equilibrium only provide deposits up to the point where the continuation value of the intermediary is larger than or equal to the benefits from diverting assets:

$$V_t(s_{j,t-1}^k, s_{j,t-1}^b, m_{j,t-1}^R, d_{j,t-1}, d_{j,t-1}^{cb}) \geq \lambda_k q_t^k s_{j,t}^k + \lambda_b q_t^b s_{j,t}^b. \tag{16}$$

The optimisation problem of intermediary j is given by maximising $V_t(s_{j,t-1}^k, s_{j,t-1}^b, m_{j,t-1}^R, d_{j,t-1}, d_{j,t-1}^{cb})$ subject to the collateral constraint (10), the balance sheet constraint (13), the law of motion for net worth (14) and the incentive compatibility constraint (16). The resulting first-order conditions are derived in Online Appendix A.2, where I employ these conditions together with the law of motion for net worth (14) to rewrite the incentive compatibility constraint (16):

$$\chi_t n_{j,t} \geq \lambda_k q_t^k s_{j,t}^k + \lambda_b q_t^b s_{j,t}^b, \tag{17}$$

with χ_t denoting the Lagrangian multiplier on the intermediary's balance sheet constraint (13). This (in)equality says that the weighted sum of corporate securities $q_t^k s_{j,t}^k$ and government bonds $q_t^b s_{j,t}^b$ is limited by the amount of net worth $n_{j,t}$ when constraint (17) is binding. In that case,

[15] Note that λ_k and λ_b do not represent the legal capital requirements from Basel III (according to which λ_b should be equal to zero), but capture an agency problem between two groups of *private* agents (namely, depositors and financial intermediaries). Such an interpretation is consistent with $\lambda_b > 0$, which will be the case in my simulations. As central bank reserves are electronic accounts administered by the central bank, I assume that it is impossible to divert these reserves.

equality (17) can be interpreted as the intermediary being undercapitalised, which is the relevant case in this paper as the Italian banking system was undercapitalised at the time of the three-year LTROs (International Monetary Fund, 2011; Hoshi and Kashyap, 2015). Therefore, I assume this constraint to be binding throughout my simulations.

The first-order conditions also show that the interest rates on reserves and deposits are the same in equilibrium, as intermediaries can perfectly elastically obtain reserves by attracting additional deposits to arbitrage away any (expected) return difference between reserves and deposits. I also show in Online Appendix A.2 that an intermediary's portfolio choice between corporate securities and government bonds is given by

$$(\lambda_b/\lambda_k)E_t[\Omega_{t,t+1}(r^k_{t+1} - r^d_{t+1})]$$
$$= E_t[\Omega_{t,t+1}(r^{b*}_{t+1} - r^d_{t+1})] + \underbrace{[\theta^b - (\lambda_b/\lambda_k)\theta^k]E_t[\Omega_{t,t+1}(r^d_{t+1} - r^{cb}_{t+1})]}_{\substack{\text{collateral value government bonds minus} \\ \text{collateral value corporate securities}}}, \quad (18)$$

where $\Omega_{t,t+1} = \beta\Lambda_{t,t+1}[(1-\sigma) + \sigma\chi_{t+1}]$ is the intermediary's stochastic discount factor.[16] This discount factor can be interpreted as the household's stochastic discount factor $\beta\Lambda_{t,t+1}$, augmented by an additional term to incorporate the effect of the financial frictions (Gertler and Karadi, 2011).

The first two terms are familiar from Gertler and Karadi (2013). The left-hand side denotes the marginal cost from reducing corporate securities by one euro, as expected net worth decreases by $r^k_{t+1} - r^d_{t+1}$, everything else equal. This wedge between the return on corporate securities and deposits exists because of the binding incentive compatibility constraint (17). Similarly, the first term on the right-hand side denotes an increase in expected net worth from increasing government bonds by one euro. However, the first-order condition contains an additional term relative to Gertler and Karadi (2013) that captures the collateral value that government bonds provide: an additional euro of government bonds provides θ^b euros of central bank funding, which reduces intermediaries' funding costs when $r^{cb}_t < r^d_t$, and thereby raises their expected net worth, everything else equal. This effect is mitigated by the fact that a reduction in corporate securities by one euro reduces central bank funding by θ^k euros, the collateral value of which is augmented by the relative diversion ratio λ_b/λ_k.

Observe that the collateral effect is eliminated when $\theta^b = (\lambda_b/\lambda_k)\theta^k$. However, since central banks typically provide more funding for one euro of bonds than for one euro of corporate securities ($\theta^b > \theta^k$), and since I will explain in Section 4 that $\lambda_k > \lambda_b$, we see that the collateral effect will be present in my simulations when $r^{cb}_t < r^d_t$. In addition, observe that the collateral value increases with the interest rate difference $r^d_t - r^{cb}_t$: in that case an additional euro of government bonds decreases funding costs by more, and intermediaries will therefore want to increase their stock of government bonds, everything else equal. Finally, central bank lending will not affect intermediaries' portfolio decisions when $r^d_t = r^{cb}_t$. In that case, intermediaries are indifferent between deposit funding and central bank funding, the collateral value of assets becomes zero and intermediaries' portfolio choices between corporate securities and government bonds are only determined by the expected return differences between corporate securities and government bonds on the one hand, and deposits on the other.

[16] I show in Online Appendix A.2 that intermediary j's continuation value $V_t(s^k_{j,t-1}, s^b_{j,t-1}, m^R_{j,t-1}, d_{j,t-1}, d^{cb}_{j,t-1})$ can be written as $V_t(n_{j,t}) = \chi_t n_{j,t}$ with the help of intermediary j's first-order conditions. Therefore, an intermediary's stochastic discount factor can be written as $\Omega_{t,t+1} = \beta\Lambda_{t,t+1}[(1-\sigma) + \sigma\partial V_{t+1}(n_{j,t+1})/\partial n_{j,t+1}]$, which coincides with the stochastic discount factor used in Gertler and Karadi (2013) and Gertler and Kiyotaki (2015).

As in Gertler and Karadi (2011), a constant exogenous fraction σ of intermediaries is allowed to continue to operate, whereas a fraction $1-\sigma$ of intermediaries is forced to stop operating at the beginning of each period. Exiting intermediaries are replaced by an equal number of new intermediaries, whose aggregate starting net worth is equal to $\chi_b n_{t-1}$. Remember from Section 2.1.1 that households' aggregate lump sum taxes are effectively reduced by an amount $\vartheta(1+r_t^b)q_{t-1}^b b_{t-1}$ in the case of default. Households keep an amount $\vartheta(1+r_t^b)q_{t-1}^b s_{i,t-1}^{b,h}$ (with $s_{i,t-1}^{b,h}$ denoting household i's bond holdings in period $t-1$), and use the remainder of this gain to recapitalise their respective financial intermediary (van der Kwaak and van Wijnbergen, 2017). However, because intermediaries differ in size, this lump sum payment is not proportional to the sizes of intermediaries' individual bond holdings, and is therefore not taken into account by them when determining how many bonds to purchase.[17] As a result of the transfer, however, the wealth effect from sovereign default is eliminated in the aggregate law of motion for net worth, which therefore features the default-exclusive return on government bonds r_t^b (see (1)):[18]

$$\begin{aligned} n_t = \sigma[&(1+r_t^k)q_{t-1}^k s_{t-1}^k + (1+r_t^b)q_{t-1}^b s_{t-1}^b + (1+r_t^R)m_{t-1}^R \\ &- (1+r_t^d)d_{t-1} - (1+r_t^{cb})d_{t-1}^{cb}] + \chi_b n_{t-1}. \end{aligned} \tag{19}$$

The presence of r_t^b contrasts with an intermediary's portfolio choice between corporate securities and government bonds (18), which features the default-inclusive return r_t^{b*}. As a result, sovereign default risk will still affect the equilibrium through intermediaries pricing in the risk of sovereign default ex ante.[19]

2.3. *Production Sector*

The production sector is modelled in standard New Keynesian fashion. I will shortly outline the setup below, with a more detailed exposition in Online Appendix A.3. There is a continuum $i \in [0, 1]$ of intermediate goods producers that operate in a perfectly competitive market. They issue corporate securities at the end of period $t-1$ and use the proceeds to purchase physical capital $k_{i,t-1}$ from capital producers at a price q_{t-1}^k. As in Gertler and Kiyotaki (2010), intermediate goods producers can credibly pledge all after-wage revenues from period t to the buyers of these securities. Shocks are realised at the beginning of period t, among which a capital quality shock that transforms capital $k_{i,t-1}$ into $\xi_t k_{i,t-1}$ effective units of capital (Gertler and Karadi, 2011).[20] Next, intermediate goods producers hire labour $h_{i,t}$ in a perfectly competitive market from labour agencies at a wage rate w_t, and start producing intermediate goods with a constant-returns-to-scale Cobb–Douglas production function with effective capital $\xi_t k_{i,t-1}$ and labour $h_{i,t}$ as inputs, and capital income share α. Output $y_{i,t}$ is sold to retail firms at a price m_t, while the effective

[17] Financial intermediaries differ in size because of the finite lifetime with which they operate. Therefore, an intermediary that starts operating in the current period will have a different level of net worth than intermediaries that have been accumulating net worth over many periods (Gertler and Karadi, 2011).

[18] Alternative modelling strategies of sovereign risk will introduce a discontinuity in intermediaries' net worth in case of default that cannot be captured properly by solution methods that employ a first-order approximation around the steady state. I have to employ such a first-order approximation because my model features too many state variables to solve the model using global solution methods, unlike Bocola (2016), whose real business cycle model features substantially fewer state variables.

[19] Observe that the sovereign debt crisis of 2011–13 did not see a default of the Italian sovereign ex post, but affected the Italian economy entirely through financial markets pricing in the probability of an Italian sovereign default ex ante, a feature that is captured by my setup.

[20] I follow Cahn *et al.* (2017), and include the capital quality shock to have sufficient exogenous shocks for the Bayesian estimation of the model. However, capital quality will be at its steady-state value in the simulations of Section 5.

capital stock (after depreciation δ per effective unit of capital) is sold to capital producers at a price q_t^k. As the remaining after-wage revenues are paid out to corporate securities' holders, I get the following expression for the net return r_t^k on these securities:

$$1 + r_t^k = [\alpha m_t y_{i,t}/k_{i,t-1} + q_t^k(1-\delta)\xi_t]/q_{t-1}^k. \tag{20}$$

Capital producers purchase the after-production capital stock $(1-\delta)\xi_t k_{t-1}$ from intermediate goods producers at price q_t^k, and convert it one for one into new capital. In addition, they purchase final goods to produce additional capital. However, the conversion from final goods to capital goods is subject to quadratic adjustment costs. As a result, one unit of investment typically results in less than one unit of capital goods. The newly produced capital stock is sold to intermediate goods producers at a price q_t^k.

A continuum of retail firms transforms intermediate goods one for one into differentiated retail goods. Retail firms operate in a monopolistic competitive market, and are therefore price setters that charge a markup over the input price m_t. Following Calvo (1983), each retail firm faces a probability ψ_p that it cannot choose a new price in the current period. In that case, it can partially index with previous period inflation. Final good producers purchase goods from all retail firms to produce a final good with a constant elasticity of substitution production function, and sell in a perfectly competitive market.

2.4. *Households*

A continuum of households $i \in [0, 1]$ with measure one are infinitely lived, and exhibit identical preferences and asset endowments. Each household consists of bankers and workers. There is perfect consumption insurance within the household (Gertler and Kiyotaki, 2010; Gertler and Karadi, 2011). Household members derive utility from consumption and leisure, with habit formation in consumption to capture consumption dynamics in a more realistic way (Christiano *et al.*, 2005). Utility is subject to a preference shock, the log of which is a regular AR(1) process.

As each household provides a unique type of labour, households have the power to set the nominal wage rate, subject to wage stickiness, as in Erceg *et al.* (2000). I explain the households' wage decisions in detail in Online Appendix A.3.5. Households can save through deposits at financial intermediaries $d_{i,t}$, which yield a net real return r_{t+1}^d in period $t+1$. Households can also invest in corporate securities and government bonds with net real returns r_{t+1}^k and r_{t+1}^{b*}, respectively, on their holdings $q_t^k s_{i,t}^{k,h}$ and $q_t^b s_{i,t}^{b,h}$, respectively. Here q_t^a and $s_{i,t}^{a,h}$ denote the price and volume, respectively, of asset $a \in \{k, b\}$ in period t. In addition, households receive profits $\Pi_{i,t}$ from the production sector and the financial sector. Income is used for consumption $c_{i,t}$, lump sum taxes $\tau_{i,t}$ and savings. However, households incur pecuniary quadratic adjustment costs when their holdings $s_{i,t}^{a,h}$ of financial asset a deviate from the target level $\hat{s}_{a,h}$ (Gertler and Karadi, 2013). These adjustment costs are meant to capture limited participation in the markets for corporate securities and government bonds by households (Gertler and Karadi, 2013; Darracq Pariès and Kühl, 2016; Kühl, 2018).[21] Therefore, the household's budget constraint is given by

$$\begin{aligned} c_{i,t} + \tau_{i,t} + d_{i,t} + q_t^k s_{i,t}^{k,h} + q_t^b s_{i,t}^{b,h} + (1/2)\kappa_k(s_{i,t}^{k,h} - \hat{s}_{k,h})^2 + (1/2)\kappa_b(s_{i,t}^{b,h} - \hat{s}_{b,h})^2 \\ = w_{i,t}h_{i,t} + (1+r_t^d)d_{i,t-1} + (1+r_t^k)q_{t-1}^k s_{i,t-1}^{k,h} + (1+r_t^{b*})q_{t-1}^b s_{i,t-1}^{b,h} + \Pi_{i,t}. \end{aligned}$$

[21] See Gertler and Karadi (2013) for an extensive discussion on the economic interpretation of these adjustment costs.

Looking at the quadratic adjustment costs in more detail, we can see that κ_a affects households' marginal costs from changing their holdings of asset a: when κ_a is large, an increase in households' holdings of asset a by one euro changes transaction costs by more than when κ_a is small. Therefore, households will be less willing to buy and sell asset a for larger values of κ_a, everything else equal. As a result, κ_a will be crucial in determining the extent to which intermediaries will be able to buy additional assets from households in case central bank funding becomes a more attractive source of funding.

2.5. *Market Clearing and Equilibrium*

In equilibrium, the aggregate capital stock k_t must be equal to the sum of the securities purchased by households $s_t^{k,h}$ and financial intermediaries s_t^k. Similarly, the total supply of bonds b_t must be equal to the number of bonds purchased by households $s_t^{b,h}$ and financial intermediaries s_t^b:

$$k_t = s_t^{k,h} + s_t^k, \tag{21}$$

$$b_t = s_t^{b,h} + s_t^b. \tag{22}$$

The aggregate resource constraint is given by

$$y_t = c_t + i_t + g_t. \tag{23}$$

Finally, a definition of the equilibrium can be found in Online Appendix A.8.

3. Analytical Results within a Two-Period Model Version

In this section I study a two-period model that is a special case of the infinite-horizon model of the previous section. Doing so allows me to analytically highlight the key mechanisms that affect private lending by undercapitalised intermediaries when central bank funding becomes a more attractive funding source, which occurs when the central bank decreases the interest rate on central bank funding with respect to that on reserves and deposits. I show that such a policy can potentially have a *contractionary* effect on lending, despite lower funding costs for financial intermediaries. I also investigate the way in which some of the deep parameters affect lending decisions to prepare for the quantitative analysis in Section 5.

3.1. *Model Simplifications*

I consider a simplified version of the economy of Section 2, in which I focus on intermediaries' portfolio decisions between corporate securities and government bonds in period $t = 0$, and in which the economy stops operating after period $t = 1$. A variable x_t is denoted by x in period $t = 0$, and by $\tilde{x}$ in period $t = 1$. I analyse a shock that increases Γ in period $t = 0$, which reduces the interest rate on central bank funding relative to that on reserves. Afterwards, no further shocks occur and there is perfect foresight. Therefore, the analysis in this section is deterministic.

I deviate from Section 2 in several other dimensions. I assume that the central bank directly controls the real interest rates r^R and r^{cb} on reserves and central bank funding, respectively. For analytical tractability, I assume that the real interest rate on reserves is constant, as a result of which the real interest rate on deposits is constant; see Section 2.2. Two other assumptions that enhance analytical tractability are that (*i*) households do not hold corporate securities and (*ii*) financial intermediaries cannot pledge corporate securities as collateral, i.e., $\theta^k = 0$.

Unlike Section 2, there is no wage stickiness and households supply an inelastic amount of labour $h = \tilde{h} = 1$. The physical capital acquired by intermediate goods producers in period $t = 0$ has fully depreciated at the end of period $t = 1$; hence, $\delta = 1$. Meanwhile, I assume that investment adjustment costs are zero, as a result of which the price of physical capital in period $t = 0$ is equal to one, i.e., $q^k = 1$. I assume that there is no price stickiness and no markups (i.e., $m_t = 1$ in (20)), as a result of which the return on corporate securities (20) in period $t = 1$ is equal to $r^k = \alpha k^{\alpha-1} - 1$, since $\delta = 1$. Therefore, the return is effectively determined in period $t = 0$, which financial intermediaries take as given when determining how many corporate securities to acquire in period $t = 0$. Changes in aggregate lending by intermediaries, however, will endogenously adjust the return r^k, which allows the market for corporate securities to clear.

The fiscal authority deviates from Section 2 in two ways. First, there is no sovereign default risk. Second, the government enters period $t = 0$ with a stock of outstanding real, zero-coupon bonds b_{-1} that the government repays at the beginning of period $t = 1$. Government spending and lump sum taxes are zero in period $t = 0$, as a result of which the stock of long-term bonds b at the end of period $t = 0$ is equal to the stock b_{-1} at the beginning of period $t = 0$. These bonds are traded in financial markets by households and intermediaries in period $t = 0$ at a price q^b, as a result of which the return r^b in period $t = 1$ on bonds acquired in period $t = 0$ is equal to $1 + r^b = 1/q^b$. The return r^b is therefore effectively determined in period $t = 0$.

Next, I set $\sigma = 0$ in (15), as a result of which all financial intermediaries stop operating at the end of period $t = 1$. In that case, the intermediary's continuation value in period $t = 0$ is equal to $\beta\tilde{\Lambda}\tilde{n}$, as a result of which the intermediary's (binding) incentive compatibility constraint (16) is given by

$$\beta\tilde{\Lambda}\tilde{n} = \lambda_k s^k + \lambda_b q^b \cdot s^b, \tag{24}$$

where period $t = 1$ net worth $\tilde{n}$ is given by the equivalent of (14):

$$\tilde{n} = (1 + r^k)s^k + (1 + r^b)q^b \cdot s^b + (1 + r^R)m^R - (1 + r^d)d - (1 + r^{cb})d^{cb}. \tag{25}$$

I show in Online Appendix B that $\chi = 1 + \mu$ for $\sigma = 0$, where μ denotes the Lagrangian multiplier on the intermediary's incentive compatibility constraint (16). As a result, the (binding) incentive compatibility constraint (17) can be written as

$$(1 + \mu)n = \lambda_k s^k + \lambda_b q^b \cdot s^b, \tag{26}$$

where n denotes the intermediary's net worth in period $t = 0$. With perfect foresight and $\theta^k = 0$, (18) boils down to

$$(\lambda_b/\lambda_k)(r^k - r^d) = r^b - r^d + \theta^b(r^d - r^{cb}). \tag{27}$$

Finally, I deviate from (19), and instead assume that the government bonds s^b_{-1} acquired by the previous generation of intermediaries are transferred to the new-born intermediaries at the beginning of period $t = 0$. Assuming that new-born intermediaries hold existing bonds s^b_{-1} captures the fact that commercial banks in Southern Europe already had large holdings of domestic government bonds when the three-year LTROs were announced. As government bonds are traded at a price q^b in period $t = 0$, they represent a net worth $q^b \cdot s^b_{-1}$ to new-born intermediaries. In addition, new-born intermediaries receive an exogenous starting net worth $n^{ex} > 0$. Therefore, aggregate net worth n with which new-born intermediaries start operating in period $t = 0$ is equal to

$$n = n^{ex} + q^b \cdot s^b_{-1}. \tag{28}$$

Therefore, an increase in the bond price q^b relaxes the intermediary's incentive compatibility constraint (26), everything else equal, and allows them to expand their balance sheet.

3.2. *Analysis of a Decrease in Central Bank Funding Costs*

The focus of my paper is on highlighting how collateral requirements affect intermediaries' credit provision to the real economy when central bank funding suddenly becomes a more attractive funding source. The most obvious way to do so is by decreasing the interest rate on central bank funding r^{cb} relative to the interest rate on reserves r^R. Since the interest rates on reserves and deposits are equal in equilibrium (see Section 2.2), a decrease of the interest rate on central bank funding will reduce funding costs relative to deposit funding $\Gamma \equiv r^R - r^{cb} = r^d - r^{cb}$, which will induce financial intermediaries to increase borrowing from the central bank, everything else equal (Engler and Große Steffen, 2016).

It turns out, however, that the results below do not rely upon this particular way of making central bank funding more attractive. In an alternative model version I follow Gertler and Kiyotaki (2010), Bocola (2016) and Cahn *et al.* (2017) by allowing central bank funding to relax the incentive compatibility constraint (24). In that model version, I make central bank funding more attractive by increasing the extent to which one euro of central bank funding relaxes the incentive compatibility constraint instead of decreasing the interest rate on central bank funding. I find that the results to be derived in this section carry over to that model version.[22]

The main goal of this section is to study how credit provision to the real economy is affected by a decrease in the interest rate on central funding, as this is the key transmission mechanism through which such a decrease will affect the macroeconomy. A second goal of this section is to determine which deep parameters are driving the short-run impact of such a policy to inform my estimation procedure for the infinite-horizon model.

In my analysis, I assume that $\Gamma \leq [\lambda_b \mu/(1+\mu)]/(\theta^b \beta \tilde{\Lambda})$, which ensures that $r^b \geq r^d$; see Online Appendix B.2.[23] I start the analysis by differentiating the incentive compatibility constraint (26), the first-order condition for an intermediary's portfolio choice between corporate securities and government bonds (27) and the market clearing condition for government bonds (22) with respect to Γ. I subsequently substitute the last two expressions into the first to obtain the following results, the details of which can be found in Online Appendix B.

PROPOSITION 1. *The bond price q^b always increases in response to an increase in Γ, i.e., $dq^b/d\Gamma > 0$.*

PROOF. See Online Appendix B. □

The intuition is the following. An increase in Γ induces intermediaries to shift from deposit funding to central bank funding. As they need to pledge additional government bonds as collateral,

[22] Specifically, I replace constraint (24) by $\beta\tilde{\Lambda}\tilde{n} = \lambda_k s^k + \lambda_b q \cdot s^b - \lambda_d d^{cb}$. Central bank funding becomes more attractive by increasing λ_d. The additional derivations and proofs are available upon request.

[23] At the ECB, the interest rate on central bank funding is typically equal to that on (required) reserves, which would imply that $\Gamma = 0$.

the demand for bonds increases while the supply is unchanged. Therefore, the bond price has to increase to clear the market. This result is in line with Carpinelli and Crosignani (2021), who report that Italian short-term sovereign yields would have been 60 basis points higher in the absence of the three-year LTROs.

The above intuition regarding the expansion of intermediaries' holdings of government bonds is formally captured in the following proposition.

PROPOSITION 2. *Financial intermediaries' bond holdings* $q^b \cdot s^b$ *always increase in response to an increase in* Γ, *i.e.,* $d(q^b \cdot s^b)/d\Gamma > 0$.

PROOF. I can write

$$\frac{d(q^b \cdot s^b)}{d\Gamma} = s^b \cdot \frac{dq^b}{d\Gamma} + q^b \cdot \frac{ds^b}{d\Gamma} > 0,$$

because I prove in Online Appendix B that $ds^b/d\Gamma > 0$, while Proposition 1 shows that $dq^b/d\Gamma > 0$. □

The driver behind this result is what I refer to as the subsidy effect: we can see from (25) that a decrease in the interest rate on central bank funding r^{cb} increases an intermediary's net worth $\tilde{n}$ in period $t = 1$, everything else equal. This relaxes the intermediary's incentive compatibility constraint in the sense that the left-hand side of (24) directly increases, everything else equal, which allows the intermediary to expand the balance sheet by buying additional government bonds as collateral. The additional bonds can then be pledged at the central bank to obtain even more central bank funding d^{cb}, which further reduces the intermediary's funding costs. This, in turn, leads to a second round of relaxation of the intermediary's incentive compatibility constraint (24).

Having established that bond prices will always increase, we can immediately see that the intermediary's net worth n in period $t = 0$ will always increase as a result of the cut in the interest rate on central bank funding.

PROPOSITION 3. *Net worth* n *always increases in response to an increase in* Γ, *i.e.,* $dn/d\Gamma > 0$.

PROOF. Differentiation of (28) gives the derivative $dn/d\Gamma = s^b_{-1} \cdot (dq^b/d\Gamma) > 0$, where the last inequality follows from Proposition 1. □

Hence, the interest rate cut always increases the intermediary's net worth n as a result of capital gains $s^b_{-1} \cdot (dq^b/d\Gamma)$ on the intermediary's existing bond holding s^b_{-1}, thereby relaxing the intermediary's incentive compatibility constraint in the sense that higher net worth directly raises the left-hand side of equality (26), everything else equal. This, in turn, allows the intermediary to expand its balance sheet by holding more government bonds $q^b \cdot s^b$, and by (potentially) expanding credit provision to the real economy. Indeed, such an indirect recapitalisation of the financial sector was found to have an empirically relevant effect on credit supply in the context of the ECB's Outright Monetary Transactions program (Acharya *et al.*, 2019).

Interestingly, we see in Proposition 4 below that such an indirect recapitalisation does not necessarily expand credit provision to the real economy, and can even have a *contractionary* effect on credit provision.

PROPOSITION 4. *The impact of a marginal increase in* Γ *on credit provision to the real economy is ambiguous, i.e.,* $ds^k/d\Gamma \lesseqgtr 0$.

PROOF. Differentiation of the incentive compatibility constraint (26) with respect to Γ, and subsequent substitution of Proposition 3 and the differentiated market clearing condition for government bonds (22) gives the following expression for lending to the real economy:

$$\frac{ds^k}{d\Gamma} = [1/(\lambda_k - Cn)]\left[\underbrace{(1+\mu)s^b_{-1}}_{\substack{\text{capital gains}\\ \text{effect}}} - \underbrace{\lambda_b(s^b + q^b/\kappa_b)}_{\substack{\text{collateral}\\ \text{effect}}}\right]\cdot\frac{dq^b}{d\Gamma} \tag{29}$$

with $C < 0$ and $\kappa_b > 0$, the last of which denotes the coefficient in front of households' quadratic adjustment costs; see Section 2.4. The sign of (29) is ambiguous, since the collateral effect and the capital gains effect have opposite signs. Details can be found in Online Appendix B. □

Besides the above-mentioned capital gains effect that directly raises the left-hand side of the incentive compatibility constraint (26), we see the emergence of a collateral effect that reduces credit provision to the real economy, everything else equal: the shift from deposit funding to central bank funding forces intermediaries to purchase additional government bonds to be pledged as collateral, as corporate securities cannot be pledged. As a result, the market value of intermediaries' holdings of government bonds increases because of higher bond prices (first term of the collateral effect) and additional bonds purchased from households (second term of the collateral effect). As the size of their balance sheets is limited by the amount of net worth, lending to the real economy s^k decreases, everything else equal. Interestingly, we see from (29) that the net effect of the interest rate cut on credit provision to the real economy can be *negative* if the collateral effect dominates the capital gains effect. This suggests that the policy could be counterproductive in improving short-run macroeconomic conditions.

Note from (29) that the collateral effect is eliminated when $\lambda_b = 0$, in which case intermediaries can expand their holdings of government bonds without tightening the incentive compatibility constraint (26). Alternatively, if existing bond holdings s^b_{-1} are zero, intermediaries will not incur any capital gains on existing bond holdings while there is crowding out of lending to the real economy when acquiring additional government bonds in case of $\lambda_b > 0$. In that case, the interest rate cut on central bank funding always has a contractionary effect. Also, observe that the direct effect of an increase in intermediaries' initial bond holdings s^b_{-1} is a strengthening of the capital gains effect with respect to the collateral effect, as net worth increases by more per euro increase in the bond price $dq^b/d\Gamma$.

In addition to disentangling the capital gains effect and the collateral effect, the analysis also shows the crucial role of the coefficient governing households' transaction costs κ_b in determining the strength of the collateral effect. To see how κ_b affects the collateral effect, I take the partial derivative of (29), which captures the direct effect of a change in κ_b.

PROPOSITION 5. *The direct effect from a marginal increase in* κ_b *raises lending to the real economy,* $\partial(ds^k/d\Gamma)/\partial\kappa_b > 0$, *while also leading to a higher bond price,* $\partial(dq^b/d\Gamma)/\partial\kappa_b > 0$.

PROOF. See Online Appendix B. □

An increase in κ_b raises households' marginal costs from changing their holdings of government bonds, which makes them less willing to sell government bonds, everything else equal. Therefore, intermediaries will be able to buy fewer bonds in equilibrium, which reduces the strength of the collateral effect. At the same time, bond prices have to increase by more to achieve market clearing, which strengthens the capital gains effect. Therefore, lending to the real economy will increase in equilibrium.

To sum up, I show that the interest rate cut on central bank funding (relative to that on reserves) has an ambiguous effect on lending by financial intermediaries to the real economy, which is the key transmission mechanism through which the policy can affect macroeconomic conditions. I disentangle an expansionary capital gains effect and a contractionary collateral effect. This contractionary effect arises because intermediaries need to acquire additional government bonds to pledge as collateral. The possibility that the general equilibrium effect on credit provision to the real economy can be contractionary rather than expansionary sharply contrasts with the existing DSGE literature, in which central bank discount window lending always has an expansionary effect (Gertler and Kiyotaki, 2010; Bocola, 2016; Engler and Große Steffen, 2016; Cahn *et al.*, 2017). In addition, the collateral effect has the potential to explain why Italian banks only invested €18 billion in private credit out of €170 billion in three-year LTRO funding, while they invested more than four times this amount (€85 billion) in Italian government bonds (Carpinelli and Crosignani, 2021).

To quantitatively investigate whether this is the case, I will estimate the infinite-horizon DSGE model of Section 2 on Italian data. From the above analysis we see that κ_b and λ_b are key parameters in determining the strength of the collateral effect. Perhaps this is unsurprising, as both parameters determine the ease with which households and intermediaries can adjust their holdings of government bonds, respectively.

In line with the collateral policy of the ECB, I will also allow corporate securities to be pledged as collateral in the quantitative evaluation of the infinite-horizon model from Section 2. While this will obviously reduce the strength of the collateral effect, we remember from Section 2.2 that the collateral effect will not be eliminated, as central banks typically provide more funding for one euro of government bonds than for one euro of private loans.

4. Calibration and Estimation

I solve the infinite-horizon model from Section 2 using a first-order perturbation around the non-stochastic steady state using the Dynare software (Adjemian *et al.*, 2011). I employ a mix of calibration and estimation with Bayesian methods to match the Italian economy as close as possible. To do so, I employ data downloaded from Eurostat, the ECB, the Bank of Italy and the Italian National Institute for Statistics, an elaborate description of which can be found in Online Appendix C.

I break the identification of parameter values into two stages. I partially calibrate my model in the first stage by either taking parameter values that are standard in the macroeconomic literature or targeting first-order moments such as the steady-state labour supply. I subsequently estimate the remaining parameters in the second stage by employing Bayesian techniques over the period 1998Q1–2009Q4.[24] Finally, I provide a validation exercise to show that my model reasonably matches the data.

[24] Even though the euro was officially introduced on January 1, 1999, there was effectively a fixed exchange rate system in place between the future eurozone countries in the run up to the introduction of the euro. This fixed exchange

To save space, I will only discuss the calibration/estimation of key parameters and targets, and refer the interested reader to Online Appendix D for more information on how the remaining parameters are determined, as well as tables with calibrated and estimated parameter values.

First, I set $\bar{r}^{n,r} = \bar{r}^{n,cb}$, which ensures that $r_t^{n,r} = r_t^{n,cb}$ in the absence of unconventional LTROs.[25] Next, we remember from Section 3 that λ_b is a key parameter in determining the strength of the collateral effect. I determine the ratio λ_b/λ_k by comparing the average spread between the interest rate on credit claims to non-financial corporations and the ECB policy rate with the average spread between the Italian bond yield and the ECB policy rate using interest rate data from the Bank of Italy.[26] This results in $\lambda_b/\lambda_k = 0.5$; see Online Appendices C and D.1.

Two key parameters for the strength of the collateral effect are θ^k and θ^b. While the ECB does not publish the haircut $1 - \theta^a$ it applies to different asset types $a \in \{k, b\}$, Bruegel (2018) replicates them using long-term credit ratings and finds that the haircut on Italian government bonds was between 3% and 7% during the sovereign debt crisis of 2011–13. I therefore set $\theta^b = 0.95$.

Next, I set $\theta^k = 0.65$, which implies a haircut of 35% on corporate securities. I establish this number by looking at data from the ECB, which tells me how much funding it provides per euro of credit claim of a certain credit quality and maturity. I combine this with data from the Bank of Italy, which provides a breakdown of MFIs' credit claims on non-financial corporations across time and across different maturities.[27] Doing so allows me to obtain an estimate for θ^k, a detailed explanation of which can be found in Online Appendix D.1.1.

There are nine exogenous shocks in the model version that is estimated using Bayesian techniques. Therefore, I employ nine observable quarterly time series from the period 1998Q1–2009Q4 in the estimation: real GDP per capita, real consumption per capita, real investment per capita, the real wage rate, hours worked, inflation, the three-month nominal interest rate, and MFIs' per capita volume of loans to non-financial corporations and government bond holdings, the last two of which are included as time series for s_t^k, and s_t^b, respectively. These two time series allow me to identify the parameters κ_k and κ_b, which are key parameters in determining the strength of the collateral effect; see Proposition 5.[28,29] A second benefit from including the time series for MFIs' per capita volume of government bonds is that it allows me to estimate ζ_b, the parameter that determines the feedback from the level of government debt b_{t-1} on the level of

rate system was effectively converted into the euro on January 1, 1999. Therefore, it is unlikely that there is a structural break between the 1998 data and the 1999–2009 data. See also Burriel *et al.* (2010), who estimate their model of the Spanish economy using time series that start in 1997.

[25] Before October 2008 the interest rate on reserves was (approximately) equal to the interest rate at which MFIs borrowed from the ECB; ECB liquidity would be auctioned to eurozone MFIs, allowing the interest rate on the ECB loans to be slightly higher than the interest rate on required reserves (MRO rate). In October 2008 the ECB switched to a fixed rate full allotment procedure, under which eurozone MFIs can borrow at the MRO rate (European Central Bank, 2011). The last case exactly corresponds with $r_t^{n,r} = r_t^{n,cb}$ in my model.

[26] I can write (18) as $\lambda_b/\lambda_k = (\bar{r}^{b*} - \bar{r}^d)/(\bar{r}^k - \bar{r}^d)$ in the non-stochastic steady state, since the second term on the right-hand side is equal to zero because $\bar{\Gamma} = \bar{r}^{n,r} - \bar{r}^{n,cb} = 0$. I employ the ECB policy rate, as the interest rate on deposits is equal to the interest rate on required reserves in my model.

[27] MFIs refers to monetary and financial institutions excluding the European System of Central Banks; see Section 1.

[28] Although κ_k is absent in Proposition 5, I can argue along similar lines as in Section 3 that this parameter will influence the strength of the collateral effect, as it determines the extent to which households are willing to sell corporate securities to intermediaries when the latter want to acquire additional collateral.

[29] I choose time series for asset holdings of MFIs, rather than time series that represent households' asset holdings, as one of the goals of the estimation is to properly capture the extent to which Italian MFIs' holdings of government bonds and credit provision to non-financial corporations change over time, and therefore the extent to which they can expand their collateral base when central bank funding becomes more attractive.

Table 1. *Numerical Values of Key Parameters.*

Parameter	Value	Description	Data
λ_b/λ_k	0.5	Diversion rate bonds over corporate securities	Bank of Italy
θ^k	0.65	Haircut parameter for corporate securities	Bank of Italy
θ^b	0.95	Haircut parameter for government bonds	Bruegel (2018)
κ_k	0.2826	Adjustment costs for households' corporate securities	Bayesian estimation
κ_b	0.0026	Adjustment costs for households' bond holdings	Bayesian estimation

lump sum taxes τ_t; see (3). As such, the value of ζ_b influences the supply of government bonds, and therefore has a first-order effect on the quantitative importance of the collateral effect.

All time series are filtered using a one-sided Hodrick–Prescott (HP) filter with frequency 1,600, after which I drop the first four observations as a burn-in and demean the resulting time series.[30] During the Bayesian estimation I set $\varkappa_{b_{max}} = 0$ in (11), which implies that $r_t^{n,r} = r_t^{n,cb}$. In that case, we see from (18) that the collateral effect is eliminated, as a result of which the particular values of θ^k and θ^b do not affect the estimation results. I follow Bocola (2016) by setting the probability of sovereign default equal to zero during the estimation, as Italian sovereign credit default swap (CDS) spreads only started to rise substantially after the start of the European sovereign debt crisis in 2010. This is captured by replacing (5) by $p_t^{def} = 0$. I set the probability of default back to (5) when I investigate the impact of the three-year LTROs of December 2011 and February 2012. The unconventional LTROs are initiated in response to a sovereign debt crisis by setting $\varkappa_{b_{max}} = -0.0048$, as a result of which Γ_t in (11) increases by 20 basis points on impact.[31]

After performing the Bayesian estimation of the model, I set the parameters equal to their posterior mean, which implies that $\kappa_k = 0.2826$ and $\kappa_b = 0.0026$. Therefore, households will be much more willing to change their holdings of government bonds than their holdings of corporate securities, everything else equal, which will directly affect the strength of the collateral effect.

An overview of the parameter values discussed in this section can be found in Table 1. The remaining estimates, as well as a more detailed explanation of the calibration and the estimation procedure can be found in Online Appendix D.2. Finally, Online Appendix D.4 displays the results from a validation exercise, for which I find that the standard deviation and first-order autocorrelation of several key variables generated by the estimated model version match the empirical second-order moments over the estimation period. In addition, I find that key second-order moments generated by the model version with sovereign default risk match their empirical counterpart over the period 2010Q1–2011Q4.

5. Results

In this section I show the results from numerical simulations of the full, infinite-horizon model of Section 2. As mentioned above, I will model unconventional LTROs by (temporarily) reducing the nominal interest rate on central bank funding relative to that on reserves, in line with Bocola (2016) and Engler and Große Steffen (2016).

I set the stage by showing the results to a central bank funding shock $\Gamma_t > 0$ (see (11)) in the absence of a sovereign debt crisis. Doing so allows me to highlight the key mechanisms that

[30] See Pfeifer (2013) for the motivation behind employing a one-sided HP filter.

[31] Sovereign debt crises arise through a negative shock $\varepsilon_{b_{max},t}$, which not only decrease b_t^{max} in (6), but also $b_t^{max,*}$ in (12).

are operative under the unconventional LTROs. In addition, I show that the collateral effect is typically dominated by the subsidy effect and the capital gains effect. Therefore, the net effect of unconventional LTROs is likely to increase intermediaries' credit provision to the real economy.

Next, I look at a scenario where the unconventional LTROs are employed in the middle of a sovereign debt crisis to capture the fact that the three-year LTROs took place in the middle of the European sovereign debt crisis, a crisis that severely affected the Italian banking system. I do so to investigate to what extent unconventional LTROs can mitigate the negative impact of sovereign debt crises. I also investigate the role of the length of the unconventional LTROs.

Finally, I calculate the cumulative impact of the collateral effect on credit provision, investment and output of the unconventional LTROs.

5.1. *The Collateral Effect*

I start by investigating a shock to $b_t^{max,*}$ in (12) that increases $\Gamma_t = r_t^{n,r} - r_t^{n,cb}$ by 20 basis points on impact, while setting $\rho^*_{b_{max}} = 0.5$ in (12). The solid line in Figure 3 refers to the base case with $\kappa_b = 0.0026$, which denotes the posterior mean of κ_b. In addition, I plot the lower and upper bounds of the 90% highest posterior density (HPD) interval of κ_b from the Bayesian estimation to assess the robustness of the results. The lower bound ($\kappa_b = 0.0013$) is given by the dash-dot line, while the upper bound ($\kappa_b = 0.0039$) is given by the dashed line. In addition, I temporarily replace (6) by $b_t^{max} = \bar{b}_{max}$ to isolate the impact of the unconventional LTROs from the exogenous impact that b_t^{max} otherwise has on the probability of default; see (5). Observe, though, that the probability of default p_t^{def} will still be affected by the LTROs, as it also depends on the endogenous variables b_t and y_t.

As a result of the unconventional LTROs, the nominal interest rate on central bank funding decreases by 20 basis points (bps) on impact with respect to the nominal interest rate on reserves, after which it reverts back to steady state; see panel 'Interest rate difference' in Figure 3.

Let us first focus on the solid line, which denotes the base case. Figure 3 shows that a reduction of the interest rate on central bank funding relative to that on reserves has a positive effect on the macroeconomy: financial intermediaries expand lending to the real economy (see panel 'Corporate securities (b)'). As a result, both investment and capital accumulation (not shown) increase, which ultimately leads to higher output, a mechanism that is well known from the bank lending channel literature (Bernanke and Gertler, 1995). We also see that the collateral effect is quantitatively important as the market value of intermediaries' holdings of corporate securities $q_t^k s_t^k$ only increases by 0.5% of the steady state on impact, while their holdings of government bonds $q_t^b s_t^b$ increase by 5%, which is approximately 10 times the percentage point increase in corporate securities. Finally, observe that consumption decreases in equilibrium, as the expansion of intermediaries' balance sheets is not only financed by attracting additional central bank funding, but also through an expansion of deposits. Higher household savings are achieved through higher nominal and real interest rates, which result from higher inflation and output.

Next, I investigate how the collateral effect changes for different values of κ_b. Let us first focus on the dash-dot line with $\kappa_b = 0.0013$, which denotes the lower bound of the 90% HPD interval. In line with Proposition 5 of Section 3 we see that the direct effect of a decrease in κ_b is a reduction in credit provision to the real economy (relative to the case $\kappa_b = 0.0026$). Observe, however, that the impact on intermediaries' credit provision is relatively small, as the market value of

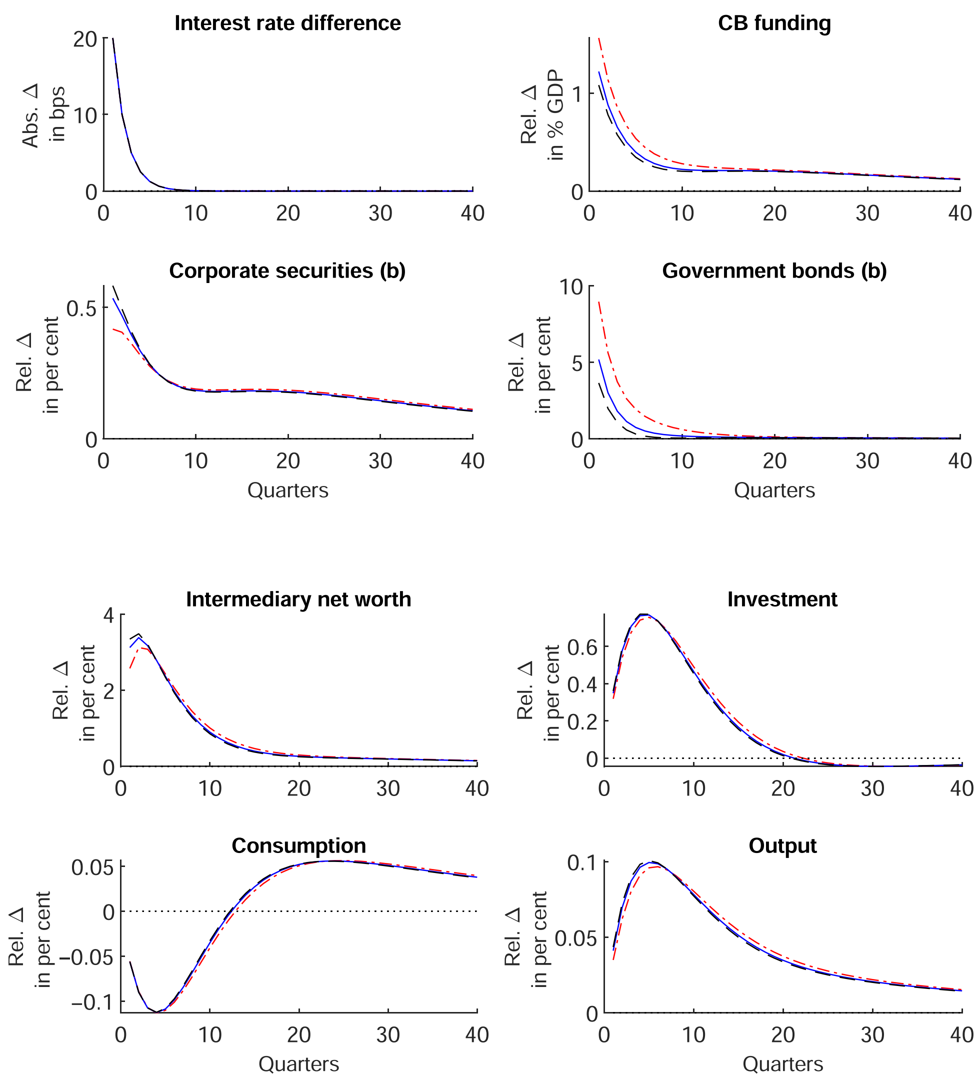

Fig. 3. *Central Bank Funding Shock of 20 Basis Points.*
Notes: Impulse response functions for unconventional LTROs that are initiated by the central bank increasing Γ_t by 20 quarterly basis points on impact ('Interest rate difference') and $\rho^*_{b_{max}} = 0.5$ for the base case $\kappa_b = 0.0026$ (solid line) versus the case where $\kappa_b = 0.0013$ (dash-dot line) versus the case where $\kappa_b = 0.0039$ (dashed line). The panel 'Corporate securities (b)' denotes the value of intermediaries' corporate securities $q^k_t s^k_t$. Similarly, the panel 'Government bonds (b)' denotes the value of intermediaries' government bonds $q^b_t s^b_t$.

corporate securities only decreases from 0.5% to 0.4% of the steady state on impact. Therefore, the impact of decreasing κ_b on the real economy is small, as investment, output and consumption hardly decrease with respect to the base case. Intermediaries' bond holdings, however, increase substantially with respect to the base case.

Finally, I increase the value of κ_b to 0.0039 (dashed line), which denotes the upper bound of the 90% HPD interval. Intermediaries' credit provision to the real economy increases with respect to the base case, while their bond holdings decrease. Just as for the lower bound of the 90% HPD interval, however, the quantitative impact on the real economy is small with respect to the base case.

From this section, I draw two conclusions. First, the collateral effect is quantitatively relevant when the central bank initiates unconventional LTROs, as intermediaries' expansions of government bonds are approximately 10 times that of corporate securities in the base case. Second, the subsidy effect and the capital gains effect will most likely dominate the collateral effect. Therefore, the net effect of central bank lending to balance-sheet-constrained intermediaries will still be expansionary, despite the collateral effect. Central bank lending to financial intermediaries, however, is especially important in times of crises, in which central banks might lend at attractive conditions to prevent a credit contraction (Bagehot, 1873). Therefore, I will next investigate the impact of such lending during the European sovereign debt crisis of 2011–13.

5.2. *Unconventional LTROs in a Sovereign Debt Crisis*

In the previous section I investigated the effects from a temporary decrease in central bank funding costs relative to the interest rates on reserves and deposits. I found that such a policy increases credit provision to the real economy, investment and output despite the presence of the collateral effect. I also found this result to be robust, as the policy is still expansionary for values of κ_b at the lower and upper bounds of the 90% HPD interval. The unconventional three-year LTROs of December 2011 and February 2012, however, occurred against the backdrop of a sovereign debt crisis in Southern Europe, which started to affect Italy in the middle of 2011.

In this section, I will investigate the extent to which the unconventional LTROs can mitigate the negative effects from such a crisis, which I initiate through a negative shock $\varepsilon_{b_{max},t}$ in (6) that increases the probability of sovereign default; see (5).[32] The results can be found in Figure 4, where I show three simulations. First, the solid impulse response functions denote the impact from a sovereign debt crisis in the absence of unconventional LTROs ($\varkappa_{b_{max}} = 0$ in (11)). Second, the dash-dot impulse response functions denote the unconventional LTROs from Section 5.1 (with $\rho^*_{b_{max}} = 0.5$ in (12)), but now in response to the sovereign debt crisis. The difference between the dash-dot line and the solid line is exactly equal to the base case simulation in Figure 3.[33] The first purpose of showing these 'limited LTROs' is to investigate the extent to which they are capable of mitigating the negative impact from the sovereign debt crisis. A second purpose is to have a benchmark against which I can investigate the impact of extending the effective length of the unconventional LTROs by setting $\rho^*_{b_{max}} = 0.9167$ (dashed impulse response functions), a policy that I refer to as 'three-year LTROs'.[34] I determine the impact increase in Γ_t by matching the impact increase in central bank funding d_t^{cb} under the three-year LTROs (relative to no

[32] I calibrate the size of the shock to match the cumulative decrease in Italian per capita investment of 5.4% from trend to the trough in 2013Q1, which is obtained by applying a one-sided HP filter to the above-described per capita time series from 1998Q1–2018Q4.

[33] This is the case since I solve the model using a first-order perturbation around the steady state, in which case the impact of two shocks is additive. The difference between Figures 3 and 4 is the shock to b_t^{max}, which was absent in Figure 3.

[34] Setting $\rho^*_{b_{max}} = 0.9167$ implies that the cumulative interest rate difference $\sum_{s=0}^{\infty} \Gamma_{t+s}$ from a one-time shock $\varepsilon_{b_{max},t} = x$ in (11) is equal to the cumulative interest rate difference from setting $\Gamma_t = \varkappa_{b_{max}} x$ for 12 quarters and afterwards equal to zero. The underlying calculation is the following. Given a one-time shock $\varepsilon_{b_{max},t} = x$ in period $t = 1$, I know that $\Gamma_t = \varkappa_{b_{max}} x a^{t-1}$ in period t, where $a \equiv \rho^*_{b_{max}}$. Therefore, the cumulative interest rate difference is equal

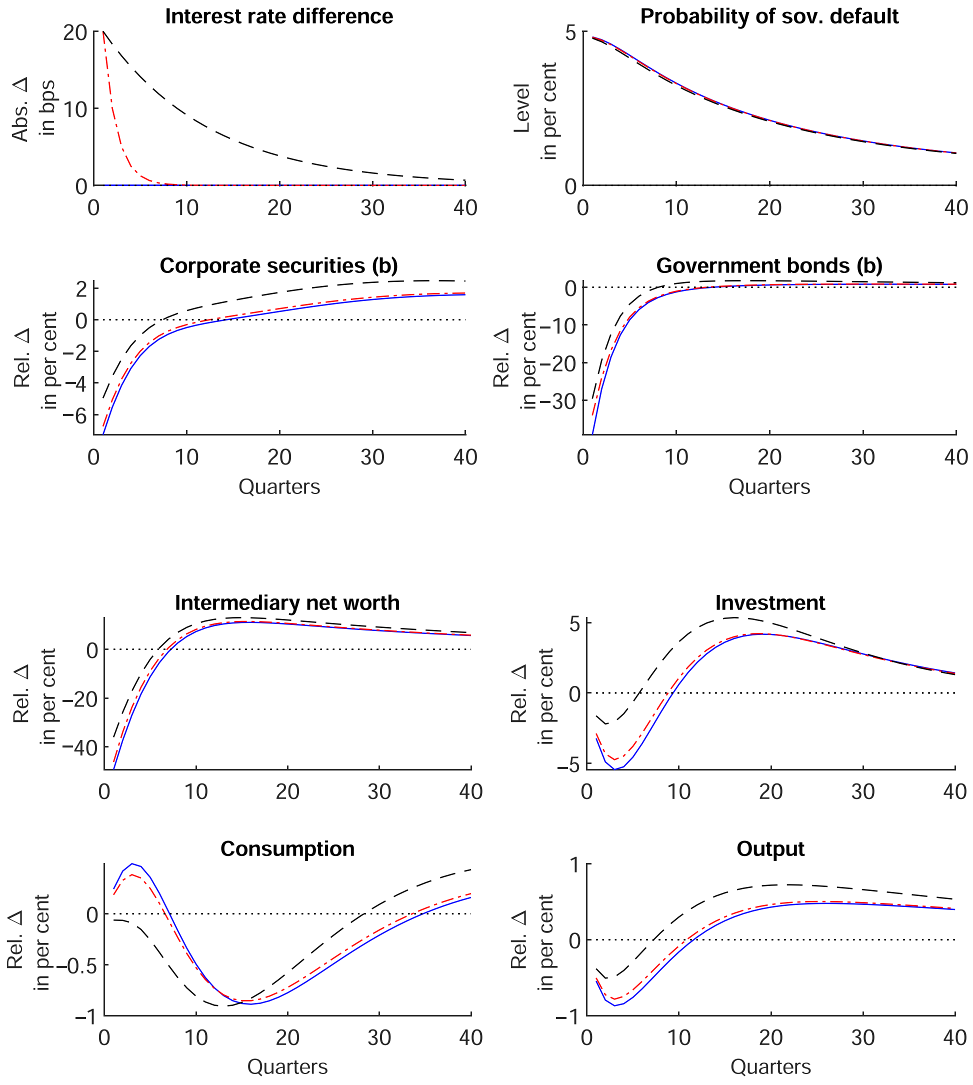

Fig. 4. *Sovereign Debt Crisis: No Policy versus Limited LTROs versus Three-Year LTROs.*
Notes: Impulse response functions for a sovereign debt crisis, initiated by a negative shock to b_t^{max} equal to 42% of the steady state. The figure compares a scenario with no unconventional LTROs (solid line), with the limited LTROs for which Γ_t increases by 20 quarterly basis points on impact with $\rho^*_{b_{max}} = 0.5$ (dash-dot line) and with the three-year LTROs for which Γ_t increases by 20 basis points on impact with $\rho^*_{b_{max}} = 0.9167$ (dashed line). The panel 'Corporate securities (b)' denotes the value of intermediaries' corporate securities $q_t^k s_t^k$. Similarly, the panel 'Government bonds (b)' denotes the value of intermediaries' government bonds $q_t^b s_t^b$.

unconventional LTROs) with the net uptake of ECB funding by the aggregate Italian commercial banking system under the three-year LTROs, which amounted to 3.7% of annual Italian GDP.[35] I thus find that Γ_t is equal to 20 quarterly basis points on impact (or 80 annual basis points), which is achieved by setting $\varkappa_{b_{max}} = -0.0048$ in (6).

Consider first the solid impulse response functions, which display the economy's response to a sovereign debt crisis in the absence of unconventional LTROs. The resulting simulations are qualitatively very similar to those in Bocola (2016): the increase in sovereign default risk increases the risk of future losses on government bonds. As a result, the price of bonds decreases, which imposes capital losses on intermediaries' existing holdings of government bonds, thereby reducing intermediaries' net worth. Therefore, intermediaries' incentive compatibility constraints tighten, which in turn reduces the amount of funding that intermediaries can provide to intermediate goods producers for purchasing physical capital. As a result, the price of capital drops, which decreases the ex post return on corporate securities, as can be seen from the second term of (20). Intermediaries' net worth falls further, leading to a second round of balance sheet tightening.

The impact on credit provision to the real economy amounts to a drop of more than 7% in equilibrium, as net worth drops by 50%. As a result, investment drops by 5.4% with respect to the steady state, which in turn decreases output. Households, however, initially increase consumption as a result of lower nominal and real interest rates. Therefore, the drop in output amounts to less than 1% in equilibrium.

Next, I investigate the extent to which the unconventional LTROs are capable of mitigating the impact of the sovereign debt crisis. A first observation is that the positive effects from the limited LTROs from Section 5.1 (dash-dot line in Figure 4) are dominated by the negative effects that the sovereign debt crisis has on intermediaries' balance sheets. Therefore, the limited LTROs are relatively ineffective in ameliorating the macroeconomic impact of the sovereign debt crisis. A second observation is that the three-year LTROs (dashed line in Figure 4) are substantially better capable of mitigating the impact from the sovereign debt crisis. We immediately see that decreasing the interest rate on central bank funding for longer substantially increases the effectiveness of unconventional LTROs in expanding credit provision to the real economy, investment and output (relative to no unconventional LTROs). The trough in investment decreases by more than 50%, while output is persistently 0.4% of the steady state above the simulation with no unconventional LTROs. However, we see that the collateral effect is still present in Figure 5, as intermediaries' expansion of government bonds by almost 10% of the steady state (line with circles) is more than four times the percentage point expansion of corporate securities (line with crosses), which amounts to slightly more than 2% of the steady state.

Therefore, the longer central bank funding is offered at attractive terms (captured by a slower reversion of Γ_t to its steady-state value), the larger the expansionary effect on the real economy (relative to no unconventional LTROs). This result is driven by the subsidy effect: the longer financial intermediaries can borrow at an interest rate below that on reserves, the larger the

to $\sum_{t=1}^{\infty} \Gamma_t = \varkappa_{b_{max}} \sum_{t=1}^{\infty} x a^{t-1} = \varkappa_{b_{max}} x/(1-a)$. The cumulative interest rate difference from setting $\Gamma_t = \varkappa_{b_{max}} x$ for T periods and afterwards equal to zero is $T \varkappa_{b_{max}} x$. Equating the two expressions gives $\varkappa_{b_{max}} x/(1-a) = T \varkappa_{b_{max}} x$, from which I find that $a \equiv \rho^*_{b_{max}} = 1 - 1/T$. Setting $T = 12$ gives $\rho^*_{b_{max}} = 0.9167$.

[35] To do so, I calculate the time path of the volume of central bank funding d_t^{cb} in the absence of unconventional LTROs and the time path under the three-year LTROs. I calculate the difference between the two, and adjust $\varkappa_{b_{max}}$ in (11) subsequently until the impact difference between the two time paths amounts to 3.7% of annual steady-state output for Γ_t equal to 20 quarterly basis points.

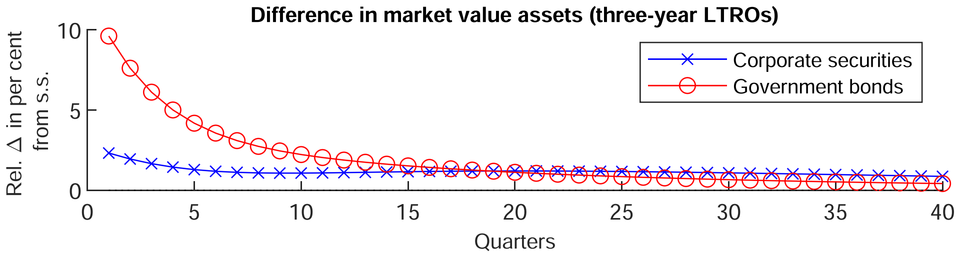

Fig. 5. *Sovereign Debt Crisis: Impact Collateral Effect.*
Notes: The figure shows the difference between the three-year LTROs (dashed line in Figure 4) and the case with no unconventional LTROs (solid line in Figure 4), expressed as a percentage of the respective steady state.

cumulative decrease in funding costs, and the larger the relaxation of intermediaries' incentive compatibility constraints. This, in turn, allows for a larger balance sheet expansion compared with the limited LTROs. Therefore, despite the fact that the collateral effect still induces intermediaries to use most of the additional balance sheet capacity to expand their bond holdings, the increase in balance sheet capacity is now large enough to also allow a substantial expansion of credit provision to the real economy.

Finally, observe that my three-year LTROs are capable of matching two key, untargeted moments. First, the increase in the market value of intermediaries' corporate securities under the three-year LTROs amounts to slightly more than 2% with respect to no unconventional LTROs, which is very close to the empirical estimate reported by Carpinelli and Crosignani (2021). Second, the impact reduction in the weighted average cost of debt funding by 14 annual basis points (relative to no unconventional LTROs) is close to the reduction in Italian commercial banks' overall funding costs by 10 basis points (Bank of Italy, 2012b), as the interest rates on the three-year LTROs of December 2011 and February 2012 were substantially below that on the foreign wholesale funding it (more than) replaced.[36] Together with the fact that the model reasonably matches the data in the run-up to the three-year LTROs (see Section 4), the model seems to be able to provide results that are quantitatively reasonable.

5.3. *Cumulative Impact of the Collateral Effect*

In the previous sections I have investigated how unconventional LTROs affect the macroeconomy by studying impulse response functions. In this section I will look at the cumulative impact that the unconventional LTROs have on intermediaries' credit provision to the real economy, investment and output with the goal of quantifying the collateral effect.

To do so, I need a benchmark against which to measure its impact. For that purpose, remember from (18) that the collateral effect is eliminated when $\theta^b = (\lambda_b/\lambda_k)\theta^k$. In that case, the fact that corporate securities and government bonds can be pledged as collateral does not affect intermediaries' portfolio decisions between corporate securities and government bonds. One way of achieving $\theta^b = (\lambda_b/\lambda_k)\theta^k$ is by increasing θ^k, the amount of central bank funding obtained

[36] I define the weighted average cost of debt funding as $(r_t^n d_t + r_t^{n,cb} d_t^{cb})/(d_t + d_t^{cb})$, where r_t^n is the nominal interest rate on deposits, and $r_t^{n,cb}$ the nominal interest rate on central bank funding.

Table 2. *Limited LTROs Cumulative Impact Collateral Effect ((30), % of the Steady State).*

Variable	Base case	No collateral effect	$\theta^k = 0.75$, $\theta^b = 0.95$	$\kappa_k = \kappa_b = 0.0026$
y_t	2.07	2.26	2.35	2.19
i_t	6.22	6.78	7.07	6.99
$q_t^k s_t^k$	10.01	11.06	11.41	28.44
$q_t^b s_t^b$	16.21	10.44	16.99	10.31

per euro of corporate securities. However, doing so increases the total amount of central bank funding obtained for a given composition of an intermediary's balance sheet, as a result of which the intermediary's incentive compatibility constraint is relaxed alongside the elimination of the collateral effect. Therefore, I choose θ^k and θ^b in such a way that the impact increase in central bank funding under the unconventional three-year LTROs is approximately equal to 3.7% of annual steady-state output (with respect to no unconventional LTROs), while ensuring that $\theta^b = (\lambda_b/\lambda_k)\theta^k$.[37] This is the case for $\theta^k = 0.765$ and $\theta^b = 0.3825$, which I refer to as the 'no collateral effect' case.

To quantify the collateral effect, I perform the following steps. First, I calculate the cumulative impact of the unconventional LTROs on output, investment and intermediaries' bond holdings and credit provision to the real economy with respect to no unconventional LTROs under the baseline parameterisation

$$x^{cum} = \sum_{j=0}^{T} \beta^j \left(x_{t+j}^{LTROs} - x_{t+j}^{no\ LTROs}\right)/\bar{x}, \tag{30}$$

where β denotes the household's subjective discount factor, x_t^{LTROs} refers to the variable x_t under the unconventional LTROs of Section 5.2, $x_t^{no\ LTROs}$ refers to the variable x_t in the absence of unconventional LTROs in Section 5.2 and $\bar{x}$ refers to the (quarterly) steady-state value of variable x_t. Therefore, (30) captures the cumulative (discounted) difference between the unconventional LTROs and the solid line in Figure 4.[38] Next, I set $\theta^k = 0.765$ and $\theta^b = 0.3825$, and again employ (30) to calculate the cumulative impact of the unconventional LTROs in the absence of the collateral effect.[39]

The subsequent results are reported in Table 2 for the limited LTROs of Section 5.2, and in Table 3 for the three-year LTROs with $T = 1{,}000$. We see from Table 2 that elimination of the collateral effect has a relatively minor impact for the limited LTROs: output cumulatively increases by 0.19% of quarterly steady-state output (= 2.26 − 2.07, the difference between the columns 'no collateral effect' and 'base case'), investment by 0.56% of quarterly steady-state

[37] Similarly to Section 5.2, I calculate the time path of central bank funding under the unconventional three-year LTROs and the time path of central bank funding in the absence of unconventional LTROs, and calculate the impact difference between the two time paths. However, I keep the impact increase in Γ_t equal to 20 basis points as in Section 5.2, and adjust θ^b and θ^k to have an impact difference equal to 3.7% of annual steady-state output for $\theta^k = 0.765$ and $\theta^b = 0.3825$, which ensures that $\theta^b = (\lambda_b/\lambda_k)\theta^k$.

[38] Since the model is solved using a first-order approximation around the steady state, the effects from shocks are additive and there is no state dependence. Therefore, the cumulative impact of the LTROs in the presence of the sovereign debt crisis (see (30)) is the same as the cumulative impact $x^{cum} = \sum_{j=0}^{T} \beta^j x_{t+j}^{LTROs}/\bar{x}$ from the unconventional LTROs in Section 5.1, in which there is no sovereign debt crisis.

[39] Observe that the steady state of the relevant variables does not change when calculating the impact under different values for θ^k and θ^b.

Table 3. *Three-Year LTROs Cumulative Impact Collateral Effect ((30), % of the Steady State).*

Variable	Base case	No collateral effect	$\theta^k = 0.75$, $\theta^b = 0.95$	$\kappa_k = \kappa_b = 0.0026$
y_t	14.43	16.31	16.51	14.91
i_t	44.79	50.62	51.27	47.86
$q_t^k s_t^k$	67.54	76.42	77.32	177.12
$q_t^b s_t^b$	82.28	41.45	83.93	59.21

investment and credit provision to the real economy by 1.05% of the quarterly steady state. In addition, observe the substantial contraction in intermediaries' government bond holdings by 5.77% (= 16.21 − 10.44) of the quarterly steady state, as corporate securities have become much more attractive as collateral with respect to government bonds.

Table 3 shows that the results are qualitatively similar for the three-year LTROs, except that the quantitative impact of the three-year LTROs is larger, which is unsurprising given the results in Section 5.2. We also see that the impact of the collateral effect is larger for the three-year LTROs: output now increases by 1.88% (= 16.31 − 14.43) of quarterly steady-state output with respect to the base case, investment by 5.83%, intermediaries' credit provision to the real economy by 8.88%, while bond holdings decrease by 40.83%, which implies that intermediaries' bond holdings are halved. Therefore, the key conclusion from comparing the limited and three-year LTROs is that the cumulative impact of the collateral effect increases with the effective length of the unconventional LTROs: the longer the unconventional LTROs, the longer intermediaries' portfolios of assets are tilted away from credit provision to the real economy and towards government bonds. Therefore, the impact from removing the collateral effect increases for the three-year LTROs.

However, removing the collateral effect by decreasing the amount of central bank funding per euro of government bonds by half is likely to be unpopular with governments, especially when it is done in the middle of a sovereign debt crisis. Therefore, the question arises whether the central bank can (partially) offset the impact of the collateral effect by providing more central bank funding per euro of corporate securities while keeping the amount of funding per euro of government bonds equal to $\theta^b = 0.95$, as doing so reduces intermediaries' incentives to tilt their asset portfolios towards government bonds.

Tables 2 and 3 show that the central bank is indeed capable of offsetting the negative impact of the collateral effect by providing more central bank funding per euro of corporate securities. In fact, output, investment and credit provision for $\theta^k = 0.75$ and $\theta^b = 0.95$ are (slightly) larger than for $\theta^k = 0.765$ and $\theta^b = 0.3825$, despite the fact that the collateral effect is still present. The reason is that financial intermediaries obtain more low-interest rate central bank funding for a given composition of intermediaries' balance sheets, as intermediaries receive almost as much funding per euro of corporate securities while they receive substantially more funding per euro of government bonds. As a result, intermediaries' funding costs reduce by more for $\theta^k = 0.75$ and $\theta^b = 0.95$ than for the case with no collateral effect, which alleviates their incentive compatibility constraint to such an extent that the negative impact from the collateral effect on the real economy is (more than) offset.

Whereas changes in θ^b and θ^k affect intermediaries' demand for government bonds, Section 3 also shows that the strength of the collateral effect depends on κ_b, the parameter that determines households' marginal costs from changing their holdings of government bonds. Therefore, κ_b affects the supply of government bonds by households when intermediaries' demand for bonds increase. However, since households also own corporate securities in the infinite-horizon model, the supply side of the collateral effect will not so much be determined by κ_b, but (predominantly) by the difference between κ_k and κ_b.

Remember from Section 4 that the posterior mean of κ_k is approximately 100 times larger than that of κ_b. This implies that households are much more willing to sell government bonds than corporate securities when intermediaries' demand for collateral increase. Therefore, I now investigate whether a reduction in κ_k by setting it equal to κ_b is capable of offsetting the collateral effect. We see from Tables 2 and 3 that such a reduction in marginal costs would indeed be able to tilt intermediaries' asset portfolios from government bonds to corporate securities: in fact, the increases in intermediaries' holdings of corporate securities by 28.44% and 177.12% for the limited and three-year LTROs (with respect to no unconventional LTROs), respectively, are more than twice the increases of 11.06% and 76.42% for the case where the collateral effect has been eliminated.

However, the impact on the real economy is relatively small, as the increase in output (2.19% and 14.91% for the limited and three-year LTROs, respectively) and investment (6.99% and 47.86%) is smaller than the increase in output (2.26% and 16.31%) and investment (6.78% and 50.62%) for the case without the collateral effect, and only slightly larger than the increase under the base case for the three-year LTROs. The reason for this result is that the reduction in κ_k does not increase the balance sheet capacity of financial intermediaries, but effectively only changes the composition of their balance sheet since households are now more willing to sell corporate securities to intermediaries. And since households were not balance sheet constrained to begin with, the reduction in their transaction costs only leads to a small overall increase in the total amount of corporate securities held by intermediaries and households. This contrasts with the case where the collateral effect has been eliminated, as well as with the case in which $\theta^k = 0.75$ and $\theta^b = 0.95$, where more low-interest-rate central bank funding relaxes intermediaries' incentive compatibility constraints.

6. Discussion and Robustness

In this section I discuss the results of the previous sections, and check the influence of some of the assumptions that I have made.[40]

The first modelling issue is that I study central bank lending in a closed economy model. Within such a model, the nominal interest rate is determined by a standard Taylor rule through which macrodevelopments affect the policy rate one for one. However, Italy being part of the eurozone implies that the Italian nominal interest rate is determined by the ECB, which adjusts its monetary policy in response to macrodevelopments in the eurozone as a whole, rather than to Italian macrodevelopments alone. As a result, the monetary policy response in my closed economy model will overstate the extent to which the ECB responds to Italian macrodevelopments, as the Italian economy comprises around 15% of eurozone GDP. To check whether this modelling choice influences my results, I construct a small open economy that is a member of a monetary union. In this model, the nominal interest rate on reserves is permanently fixed at its steady-state value, which will therefore understate the extent to which the ECB responds to Italian

[40] Additional derivations and impulse response functions of the robustness checks in this section are available upon request.

macrodevelopments. I find that the *relative* results, i.e., the difference between the simulations with and without unconventional LTROs, are hardly affected by the switch from a closed to a small open economy model. The intuition is that the difference between unconventional LTROs and no LTROs is entirely driven by a decrease of the interest rate on central bank funding *relative* to that on reserves. Therefore, the specific modelling of the interest rate on reserves hardly affects the relative results.

Next, remember from Section 2.1.2 that the modelling of my LTROs does not capture two dimensions of the three-year LTROs of December 2011 and February 2012. First, my unconventional LTROs are effectively one-period loans, whereas the maturities of the LTROs of December 2011 and February 2012 were three years. This point is important because Carpinelli and Crosignani (2021) show that the maturity extension (with respect to regular ECB refinancing operations) was key in expanding credit provision to the real economy in Italy. Second, funding costs from a strategy under which commercial banks borrowed for three years from the ECB were equal to funding costs under a strategy where commercial banks borrowed short term and rolled these loans over for three years.[41] This suggests that the interest rate on central bank funding should also be equal to that on reserves for my LTROs, whereas I model the three-year LTROs as a temporary reduction of the interest rate on central bank funding relative to that on reserves.

Before I explain why my model does not incorporate the above two features, let us remember that the focus of my paper is on the *implications* of central bank funding becoming a more attractive source of funding. Therefore, as long as my model is capable of matching key moments surrounding the three-year LTROs, it might be less relevant *why* central bank funding becomes more important in my model. And we saw in the previous sections that my model is indeed capable of matching two key (untargeted) moments, namely the change in intermediaries' credit provision to the real economy and the reduction in intermediaries' weighted average funding costs.

Also, observe that whether or not the collateral effect arises does a priori not depend on the maturity of the central bank loans, as financial intermediaries need to pledge collateral *irrespective* of whether they borrow for three years from the central bank or borrow short term and roll over for three years (for a given amount of central bank funding).

However, I still construct an alternative model version in which I introduce long-term central bank loans. I do so by following Cahn *et al.* (2017), who find that lengthening the maturity has an expansionary effect on credit provision to the real economy in the context of the ECB's one-year LTROs of July 2009. In addition, Cahn *et al.* (2017) also capture the other above-mentioned feature by setting the interest rate on long-term loans equal to that on short-term loans. In contrast to Cahn *et al.* (2017), however, I find that incorporating such a maturity extension has zero impact in my economy (relative to the central bank only providing short-term loans).

These different results are driven by different modelling choices regarding the central bank's lending policy. In my model, and in line with the fixed rate full allotment policy of the ECB at the time, the central bank sets the interest rate on central bank funding, after which financial intermediaries endogenously choose the volume of central bank funding. Since funding costs are the same for short-term and long-term loans, introducing long-term loans only affects the composition between short-term and long-term central bank loans, but has no impact on intermediaries' total volume of central bank loans.

41 See https://www.ecb.europa.eu/press/pr/date/2011/html/pr111208_1.en.html.

In Cahn *et al.* (2017), however, the central bank determines the volume of central bank funding, after which the interest rate on it endogenously adjusts to clear the market. Under such a policy, extending the maturity of central bank loans increases the total volume of future central bank loans for a given series of liquidity injections (everything else equal), which pushes down future interest rates on these loans. Since intermediaries are forward looking, the anticipated reduction in funding costs alleviates their incentive compatibility constraint today, which allows credit provision to the real economy to expand as a result.

Because maturity extension has zero impact in my current model, I would need to introduce additional model features to have real effects from extending the maturity of central bank loans. One potential way of doing so is by introducing rollover risk, as suggested by Carpinelli and Crosignani (2021). They argue that providing unlimited amounts of ECB funding at regular, short-term maturities did not induce commercial banks to expand (long-term) credit provision to the real economy, because financing new credit to the real economy with short-term ECB loans would leave commercial banks with a funding gap once the ECB would revert to its pre-crisis policy of auctioning pre-set, limited amounts of liquidity. Such rollover risk was (at least partially) eliminated by the ECB lending to commercial banks at a maturity of three years, and therefore allowed commercial banks to expand credit to the real economy. However, the few DSGE models that feature (some form of) rollover risk are typically solved using non-linear global solution methods (Gertler *et al.*, 2020). Solving my model using global solution methods would present quite a numerical challenge because of the large number of state variables that my model features.

Next, to address the issue that in reality the interest rate on central bank funding was equal to that on reserves, I perform a robustness check in which I employ an alternative mechanism to make central bank funding more attractive. In that setup, the three-year LTROs are captured by central bank funding temporarily relaxing the intermediary's incentive compatibility constraint, as in Gertler and Kiyotaki (2010), Bocola (2016) and Cahn *et al.* (2017). Doing so allows me to make central bank funding a more attractive funding source without having to decrease the interest rate on it relative to that on reserves. I find that the results are qualitatively and quantitatively very similar to those in the main text.

Finally, I check how the steady-state level of government bonds on intermediaries' balance sheets affects the results, while keeping the steady-state level of corporate securities the same. I find that the smaller the initial level of government bonds on intermediaries' balance sheets, the larger the accumulation of government bonds as a result of the unconventional LTROs. The initial level of bonds, however, hardly affects the increase in credit provision to the real economy that arises from the unconventional LTROs.

7. Conclusion

In this paper I investigate the macroeconomic implications of central bank funding becoming a more attractive funding source to balance-sheet-constrained financial intermediaries in times of financial crises. A key feature of such lending operations is the requirement to pledge collateral. I find that this requirement can give rise to a collateral effect that reduces credit provision to the real economy, everything else equal, for two reasons. First, it arises when central banks provide more funding for one euro of government bonds than for one euro of corporate credit. Second, it arises when it is easier for financial intermediaries to acquire additional government bonds as collateral than to expand credit provision to the real economy. Therefore, intermediaries with limited balance sheet capacity will shift from corporate credit to government bonds, everything else equal, so as to increase the amount of central bank funding they can obtain. As a result, the collateral effect reduces in equilibrium the expansionary effects of central bank lending to intermediaries that occur in other DSGE models (Gertler and Kiyotaki, 2010; Bocola, 2016; Engler and Große Steffen, 2016; Cahn *et al.*, 2017).

For the analysis, I extend a standard New Keynesian model with price and wage stickiness and financial frictions a la Gertler and Karadi (2011) to include central bank lending to financial intermediaries. Intermediaries have to pledge government bonds and corporate securities as collateral, but one euro of corporate securities provides less central bank funding than one euro of government bonds. Central bank funding becomes a more attractive funding source by reducing the interest rate on it relative to that on deposits and reserves (Engler and Große Steffen, 2016). Afterwards, the interest rate on central bank funding reverts back to that on reserves following an AR(1) process. I capture the three-year LTROs by increasing the AR(1) coefficient of this process. Finally, I employ a Bayesian estimation procedure using Italian data to match the Italian economy as close as possible.

A quantitative exercise shows that the collateral effect caused Italian commercial banks to increase their holdings of domestic government bonds by 10% as a result of the three-year LTROs, while credit provision to the real economy expanded by a mere 2%, the last of which is in line with the empirical estimate by Carpinelli and Crosignani (2021). These results also seem to be in line with the substantial accumulation of domestic government debt by Italian commercial banks (Carpinelli and Crosignani, 2021). My simulations also show that the cumulative impact on credit provision to the real economy, investment and output can be offset by the central bank providing more funding per euro of corporate securities.

Finally, my model confirms that the longer central bank funding is offered at more attractive terms, the larger the net expansionary effect on credit provision to the real economy (Carpinelli and Crosignani, 2021): the longer intermediaries can profit from lower funding costs, the larger the increase in the sum of expected discounted future profits, and the larger the relaxation of intermediaries' incentive compatibility constraints. While the collateral effect remains operative, and still induces a relative shift from corporate securities to government bonds, the additional balance sheet capacity that is now created is large enough to also allow for an expansion of the level of credit provision to the real economy. Importantly, this result does not rely upon the particular way in which central bank funding becomes more attractive.

The presence of the collateral effect could also explain why the three-year LTROs of December 2011 and February 2012 were adjusted in subsequent ECB lending operations; under the so-called targeted longer-term refinancing operations, commercial banks can still borrow long term, but the amount they can borrow is linked to the volume of their loans to non-financial corporations and households.[42] However, I leave a study of this particular policy for future research.

Finally, although I focus on the three-year LTROs, the framework developed in this paper can be applied to any situation in which central bank funding is offered at more attractive conditions at the height of financial crises, and could therefore also be used to investigate other central banks' lending programs, such as the Federal Reserve's Term Auction Facility and the Treasury Securities Lending Facility.

[42] See https://www.ecb.europa.eu/mopo/implement/omo/tltro/html/index.en.html.

University of Groningen, Netherlands

Additional Supporting Information may be found in the online version of this article:

Online Appendix
Replication Package

References

Acharya, V.V., Drechsler, I. and Schnabl, P. (2014). 'A pyrrhic victory? Bank bailouts and sovereign credit risk', *The Journal of Finance*, vol. 69(6), pp. 2689–739.

Acharya, V.V., Eisert, T., Eufinger, C. and Hirsch, C. (2018). 'Real effects of the sovereign debt crisis in Europe: Evidence from syndicated loans', *Review of Financial Studies*, vol. 31(8), pp. 2855–96.

Acharya, V.V., Eisert, T., Eufinger, C. and Hirsch, C. (2019). 'Whatever it takes: The real effects of unconventional monetary policy', *Review of Financial Studies*, vol. 32(9), pp. 3366–411.

Acharya, V.V. and Steffen, S. (2015). 'The "greatest" carry trade ever? Understanding eurozone bank risks', *Journal of Financial Economics*, vol. 115(2), pp. 215–36.

Adjemian, S., Bastani, H., Juillard, M., Karamé, F., Maih, J., Mihoubi, F., Perendia, G., Pfeifer, J., Ratto, M. and Villemot, S. (2011). 'Dynare: Reference manual version 4', Dynare Working paper, CEPREMAP.

Altavilla, C., Pagano, M. and Simonelli, S. (2017). 'Bank exposures and sovereign stress transmission', *Review of Finance*, vol. 21(6), pp. 2103–39.

Andrade, P., Cahn, C., Fraisse, H. and Mésonnier, J.S. (2019). 'Can the provision of long-term liquidity help to avoid a credit crunch? Evidence from the eurosystem's LTRO', *Journal of the European Economic Association*, vol. 17(4), pp. 1070–106.

Bagehot, W. (1873). *Lombard Street: A Description of the Money Market*, London: SMK Books.

Bank of Italy. (2012a). 'Financial stability report', Report 2012-04, https://www.bancaditalia.it/pubblicazioni/rapporto-stabilita/2012-4/Financial-Stability-Report-4.pdf?language_id=1 (last accessed: 18 November 2021).

Bank of Italy. (2012b). 'Financial stability report', Report 2012-03, https://www.bancaditalia.it/pubblicazioni/rapporto-stabilita/2012-3/1-Financial-Stability-Report.pdf?language_id=1 (last accessed: 05 November 2021).

Becker, B. and Ivashina, V. (2018). 'Financial repression in the European sovereign debt crisis', *Review of Finance*, vol. 22, pp. 83–115.

Bernanke, B.S. and Gertler, M. (1995). 'Inside the black box: The credit channel of monetary policy transmission', *Journal of Economic Perspectives*, vol. 9(4), pp. 27–48.

Bocola, L. (2016). 'The pass-through of sovereign risk', *Journal of Political Economy*, vol. 124(4), pp. 879–926.

Bofondi, M., Carpinelli, L. and Sette, E. (2018). 'Credit supply during a sovereign debt crisis', *Journal of the European Economic Association*, vol. 16(3), pp. 696–729.

Bohn, H. (1998). 'The behavior of U.S. public debt and deficits', *The Quarterly Journal of Economics*, vol. 113(3), pp. 949–63.

Bolton, P. and Jeanne, O. (2011). 'Sovereign default risk and bank fragility in financially integrated economies', *IMF Economic Review*, vol. 59(2), pp. 162–94.

Bottero, M., Lenzu, S. and Mezzanotti, F. (2020). 'Sovereign debt exposure and the bank lending channel: Impact on credit supply and the real economy', *Journal of International Economics*, vol. 126, 103328.

Bruegel. (2018). 'Is the ECB collateral framework compromising the safe-asset status of euro-area sovereign bonds?', *Bruegel* (blog), https://www.bruegel.org/2018/06/is-the-ecb-collateral-framework-compromising-the-safe-asset-status-of-euro-area-sovereign-bonds/ (last accessed: 08 June 2020).

Brunnermeier, M.K., Garicano, L., Lane, P.R., Pagano, M., Reis, R., Santos, T., Thesmar, D., Nieuwerburgh, S.V. and Vayanos, D. (2016). 'The sovereign-bank diabolic loop and ESBies', *American Economic Review*, vol. 106(5), pp. 508–12.

Burriel, P., Fernández-Villaverde, J. and Rubio-Ramírez, J. (2010). 'MEDEA: a DSGE model for the Spanish economy', *SERIEs: Journal of the Spanish Economic Association*, vol. 1(1), pp. 175–243.

Cahn, C., Matheron, J. and Sahuc, J. (2017). 'Assessing the macroeconomic effects of LTROs during the Great Recession', *Journal of Money, Credit and Banking*, vol. 49(7), pp. 1443–82.

Calvo, G.A. (1983). 'Staggered prices in a utility-maximizing framework', *Journal of Monetary Economics*, vol. 12(3), pp. 383–98.

Carpinelli, L. and Crosignani, M. (2021). 'The design and transmission of central bank liquidity provisions', *Journal of Financial Economics*, vol. 141, pp. 27–47.

Choi, D.B., Santos, J.A. and Yorulmazer, T. (2021). 'A theory of collateral for the lender of last resort', *Review of Finance*, vol. 25(4), pp. 973–96.

Christiano, L.J., Eichenbaum, M. and Evans, C.L. (2005). 'Nominal rigidities and the dynamic effects of a shock to monetary policy', *Journal of Political Economy*, vol. 113(1), pp. 1–45.

Cooper, R. and Nikolov, K. (2018). 'Government debt and banking fragility: The spreading of strategic uncertainty', *International Economic Review*, vol. 59(4), pp. 1905–25.
Corsetti, G., Kuester, K., Meier, A. and Müller, G.J. (2013). 'Sovereign risk, fiscal policy, and macroeconomic stability', Economic Journal, vol. 123, pp. F99–132.
Crosignani, M. (2021). 'Bank capital, government bond holdings, and sovereign debt capacity', *Journal of Financial Economics*, vol. 141(2), pp. 693–704.
Crosignani, M., Faria-e Castro, M. and Fonseca, L. (2020). 'The (unintended?) consequences of the largest liquidity injection ever', *Journal of Monetary Economics*, vol. 112, pp. 97–112.
Darracq Pariès, M. and De Santis, R.A. (2015). 'A non-standard monetary policy shock: The ECB's 3-year LTROs and the shift in credit supply', *Journal of International Money and Finance*, vol. 54(C), pp. 1–34.
Darracq Pariès, M. and Kühl, M. (2016). 'The optimal conduct of central bank asset purchases', Working Paper 1973, European Central Bank.
De Marco, F. (2019). 'Bank lending and the European sovereign debt crisis', *Journal of Financial and Quantitative Analysis*, vol. 54, pp. 155–82.
De Marco, F. and Macchiavelli, M. (2016). 'The political origin of home bias: The case of Europe', FEDS Working Paper 2016-60, Board of Governors of the Federal Reserve System, doi: 10.17016/FEDS.2016.060.
Drechsler, I., Drechsel, T., Marques-Ibanez, D. and Schnabl, P. (2016). 'Who borrows from the lender of last resort?', *Journal of Finance*, vol. 71(5), pp. 1933–74.
Engler, P. and Große Steffen, C. (2016). 'Sovereign risk, interbank freezes, and aggregate fluctuations', *European Economic Review*, vol. 87(C), pp. 34–61.
Erceg, C.J., Henderson, D.W. and Levin, A.T. (2000). 'Optimal monetary policy with staggered wage and price contracts', *Journal of Monetary Economics*, vol. 46(2), pp. 281–313.
European Central Bank. (2011). *The Monetary Policy of the ECB 2011*, European Central Bank, https://www.ecb.europa.eu/pub/pdf/other/monetarypolicy2011en.pdf.
European Central Bank. (2015). 'Statistical data warehouse', https://sdw.ecb.europa.eu/ (last accessed: 01 December 2021).
Farhi, E. and Tirole, J. (2018). 'Deadly embrace: Sovereign and financial balance sheets doom loops', *Review of Economic Studies*, vol. 85(3), pp. 1781–823.
Garcia-Posada, M. and Marchetti, M. (2016). 'The bank lending channel of unconventional monetary policy: The impact of the VLTROs on credit supply in Spain', *Economic Modelling*, vol. 58, pp. 427–41.
Gennaioli, N., Martin, A. and Rossi, S. (2014). 'Sovereign default, domestic banks, and financial institutions', *Journal of Finance*, vol. 69(2), pp. 819–66.
Gennaioli, N., Martin, A. and Rossi, S. (2018). 'Banks, government bonds, and default: What do the data say?', *Journal of Monetary Economics*, vol. 98(C), pp. 98–113.
Gertler, M. and Karadi, P. (2011). 'A model of unconventional monetary policy', *Journal of Monetary Economics*, vol. 58(1), pp. 17–34.
Gertler, M. and Karadi, P. (2013). 'QE 1 vs. 2 vs. 3...: a framework for analyzing large-scale asset purchases as a monetary policy tool', *International Journal of Central Banking*, vol. 9(1), pp. 5–53.
Gertler, M. and Kiyotaki, N. (2010). 'Financial intermediation and credit policy in business cycle analysis', in (B.M. Friedman and M. Woodford, eds.), *Handbook of Monetary Economics*, vol. 3, pp. 547–99, Amsterdam: Elsevier.
Gertler, M. and Kiyotaki, N. (2015). 'Banking, liquidity, and bank runs in an infinite horizon economy', *American Economic Review*, vol. 105(7), pp. 2011–43.
Gertler, M., Kiyotaki, N. and Prestipino, A. (2020). 'A macroeconomic model with financial panics', *Review of Economic Studies*, vol. 87(1), pp. 240–88.
Giannone, D., Lenza, M., Pill, H. and Reichlin, L. (2012). 'The ECB and the interbank market', Economic Journal, vol. 122(564), pp. F467–86.
Hörmann, M. and Schabert, A. (2015). 'A monetary analysis of balance sheet policies', Economic Journal, vol. 125(589), pp. 1888–917.
Hoshi, T. and Kashyap, A.K. (2015). 'Will the U.S. and Europe avoid a lost decade? Lessons from Japan's postcrisis experience', *IMF Economic Review*, vol. 63(1), pp. 110–63.
International Monetary Fund. (2011). *Global Financial Stability Report*, Washington, DC: International Monetary Fund.
Kirchner, M. and van Wijnbergen, S. (2016). 'Fiscal deficits, financial fragility, and the effectiveness of government policies', *Journal of Monetary Economics*, vol. 80(C), pp. 51–68.
Koulischer, F. and Struyven, D. (2014). 'Central bank liquidity provision and collateral quality', *Journal of Banking & Finance*, vol. 49(C), pp. 113–30.
Kühl, M. (2018). 'The effects of government bond purchases on leverage constraints of banks and non-financial firms', *International Journal of Central Banking*, vol. 14(4), pp. 93–161.
Leonello, A. (2018). 'Government guarantees and the two-way feedback between banking and sovereign debt crises', *Journal of Financial Economics*, vol. 130(3), pp. 592–619.
Ongena, S., Popov, A. and van Horen, N. (2019). 'The invisible hand of the government: Moral suasion during the European sovereign debt crisis', *American Economic Journal: Macroeconomics*, vol. 11(4), pp. 346–79.
Pfeifer, J. (2013). 'A guide to specifying observation equations for the estimation of DSGE models', University of Bundeswehr Muenchen. Unpublished manuscript.

Popov, A. and van Horen, N. (2015). 'Exporting sovereign stress: Evidence from syndicated bank lending during the euro area sovereign debt crisis', *Review of Finance*, vol. 19(5), pp. 1825–66.
Schabert, A. (2015). 'Optimal central bank lending', *Journal of Economic Theory*, vol. 157, pp. 485–516.
Schabert, A. and van Wijnbergen, S.J.G. (2014). 'Sovereign default and the stability of inflation-targeting regimes', *IMF Economic Review*, vol. 62(2), pp. 261–87.
Sims, E. and Wu, J.C. (2021). 'Evaluating central banks' tool kit: Past, present, and future', *Journal of Monetary Economics*, vol. 118(C), pp. 135–60.
Uhlig, H. (2014). 'Sovereign default risk and banks in a monetary union', *German Economic Review*, vol. 15(1), pp. 23–41.
van der Kwaak, C. and van Wijnbergen, S. (2014). 'Financial fragility, sovereign default risk and the limits to commercial bank bail-outs', *Journal of Economic Dynamics and Control*, vol. 43, pp. 218–40.
van der Kwaak, C. and van Wijnbergen, S. (2017). 'Financial fragility and the Keynesian multiplier', Discussion paper, Center for Economic and Policy Research.
Woodford, M. (1998). 'Public debt and the price level', Unpublished manuscript, Columbia University.
Woodford, M. (2001). 'Fiscal requirements for price stability', *Journal of Money, Credit and Banking*, vol. 33(3), pp. 669–728.

The Economic Journal, **134** (*February*), 728–765 https://doi.org/10.1093/ej/uead078 © The Author(s) 2023. Published by Oxford University Press on behalf of Royal Economic Society. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (https://creativecommons.org/licenses/by/4.0/), which permits unrestricted reuse, distribution, and reproduction in any medium, provided the original work is properly cited.
Advance Access Publication Date: 21 September 2023