The Interaction of Monetary and Macroprudential Policies in Dynamic Macro Models

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Abstract

This thesis contributes to the debate on the interaction of monetary and macroprudential policies in dynamic macro models, specifically using New Keynesian dynamic stochastic general equilibrium (DSGE) models.

First, we propose a general equilibrium framework that highlights the interaction of reserve requirements and a conventional monetary policy in a model that combines endogenous housing loan defaults and financial intermediation frictions due to the costs of enforcing contracts. We use the model to examine how the interaction of these policies affect (i) the credit and business cycle; (ii) the distribution of welfare between savers and borrowers; and (iii) the overall welfare objectives when monetary and macroprudential policies are optimised together or separately. We find that models with an optimised reserve ratio rule are effective in reducing the sudden boom and bust of credit and the business cycle. We also find that there are distributive implications of the introduction of reserve ratio where borrowers gain at the expense of savers. However, there is no difference in the overall welfare results whether monetary and macroprudential policies are optimised together or separately. This chapter is co-authored with Professor Joseph Pearlman and Professor Michael Ben-Gad (both from City, University of London) and has been accepted for publication by the Economic Modelling Journal.

Second, we use a DSGE framework to assess the macroeconomic effects of the output floor, a new regulatory constraint recently introduced in the Basel III framework. The main purpose of the output floor is to reduce the excessive variability of banks' risk-weighted assets and ensure a robust level of capital requirements. Our assessment concludes that the output floor counters the downward pressures generated by modelled risk weights on risk-weighted assets and, in turn, reduces the cyclicality of capital to risks-weighted assets ratio. This contributes to mitigate the excessive expansions of credit. Our model also predicts that the output floor might trigger behavioural reactions by banks. More specifically, banks may have the incentive to shift their portfolio from assets with a large gap between internally modelled and standardised risk weights (mortgages) to non-financial corporation loans which display a smaller gap. This chapter is

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Finally, the current low interest environment prompted many questions on how financial stability and the conduct of macroprudential policy should be implemented. On the one hand, low interest rate environment leads to a decrease in banks' profitability, bank capital, and eventually bank lending, calling for a lower capital regulation. On the other hand, this environment encourages more indebtedness by borrowers and banks excessive risk taking, calling for a higher capital regulation. We study the consequences of capital regulation when the interest rate is at zero lower bound (ZLB) using a DSGE framework. We use the UK data to calibrate the parameters of the model. Our assessment concludes that the benefits of high capital regulation when the monetary policy is constrained at ZLB is greater than the model with low capital regulation. This chapter is also co-authored with Professor Joseph Pearlman and Professor Michael Ben-Gad.

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Chapter 1

Thesis Introduction

This thesis collects three individual papers studying macroprudential policy instruments and its interaction with monetary policy in dynamic macro models with the aim of contributing to the current academic debate and informing policy decisions. With the 2007-2009 global financial crisis (GFC) came the realisation that monetary policy alone could not ensure macroeconomic stability, prompting renewed interest in macroprudential policies. However successful implementation of macroprudential policy requires a modelling framework that can provide clear guidance as to how policy authorities should set their objective functions. To build these models means resolving several questions. What constitutes financial stability? What are the market failures that warrant macroprudential policy intervention in the first place and what are the appropriate instruments to ameliorate them? How will macroprudential policy, once implemented interact with monetary policy?

Modelling framework. The Dynamic Stochastic General Equilibrium (DSGE) approach specifies that utility maximising agents with rational expectations will behave in a coherent manner, even when policy changes the regime in which they operate. Prices respond to the actions taken by these agents to counteract distortions they encounter. A framework based on utility maximising agents makes it possible to analyse both the overall welfare effects and distributional consequences of different policies while taking into account indirect effects and feedback mechanisms. According to Angeloni (2014) the goal of macroprudential regulation is to protect the financial system as a whole from systemic risk. Since many of the externalities that trigger systemic risk arise from the financial sector our model includes a banking sector that is integrated with the real side of the economy. In Chapter 2, we emphasise endogenous mortgage default in the housing sector. Chapter 3 introduces heterogeneity in the risks attached to some assets held by the banking sector. Lastly, in Chapter 4, we examine the impact of the different levels of capital regulation in a model with occasionally-binding constraints in the nominal interest rate.

Financial stability definition. The Financial Stability Board (FSB), International Monetary Fund (IMF), and Bank for International Settlements (BIS) define macroprudential policy as *'a policy that uses primarily prudential tools to limit systemic or system-wide financial risk, thereby limiting the incidence of disruptions in the provision of key financial services that can have serious consequences for the real economy.'*[1] This definition highlights how macroprudential policy limits *systemic risk* as opposed to microprudential policy, which is designed to ensure the safety of specific institutions. Caruana and Cohen (2014) interpret *systemic risk* in two dimensions. First, the *time dimension* addresses the accumulation of financial imbalances over time and the procyclicality of the financial system. Second, the *cross-sectional dimension* addresses the imbalances across firms and markets and linkages across entities and sectors within the financial system at a given moment. In this thesis, we focus on some elements of both the *time dimension* and *cross-sectional dimension.* In Chapter 2, we show how using a reserve ratio as a macroprudential policy tool helps mitigate mortgage defaults in the housing sector that create spillover effect in both the real and banking sector. In Chapter 3, we look at how a risk-weighted capital regulation, the output floor, not only reduces excessive expansion of credit during an economic boom but also has a beneficial effect on time-series volatility. In Chapter 4, we show how a high degree of capital regulation that includes a countercyclical capital buffer can lower the volatility of the ratio of credit-to-GDP, particularly when monetary policy operates at an effective lower bound.

Market failures. De Nicolo, Favara and Ratnovski (2014) identify three externalities that give rise to market failures and require the introduction of macroprudential policy. First, externalities that refer to *strategic complementarities* where financial firms take on excessive or correlated risks during the upturn of a credit cycle, more often than not while operating with too thin capital buffers. Second, externalities related to *fire sales.* During a downturn of a credit cycle, financial firms tend to shrink their balance sheets by shedding assets resulting in a reduction in asset prices that impairs the balance sheet of firms holding similar assets. The result is a credit crunch and asset fire sales. Third, externalities related to the *interconnectedness* of financial networks or systemically important institutions that facilitate the propagation of

[1] Caruana and Cohen (2014).

shocks. This thesis focuses on strategic complementarities and fire sales. In Chapter 2, the cost of enforcing contracts generates financial intermediation frictions and endogenous housing loan defaults. In Chapter 3, we analyse the limitations of the model-based approach to setting capital ratios that may have arisen from both informational and incentive problems faced by banks. This market failure generates the excessive volatility of risk-weighted assets and exacerbates the procyclicality of capital requirements. In Chapter 4, we investigate the problems associated with capital regulation in a low interest rate environment.

Macroprudential policy instruments. Angeloni (2014) classifies macroprudential instruments into three broad categories. First, there are capital-based tools, including countercyclical capital buffers (CCBs), sectoral capital requirements, and leverage ratios. Second, liquidity-based tools such as the liquidity requirements or reserve requirements. Third, asset-based tools such as the loan-to-value (LTV) and loan-to-income (LTI) ratios. This thesis focuses on some elements within each of these three broad categories. In Chapter 2, we consider the use of reserve requirements in a model with housing default. In Chapter 3, we focus on a new capital regulation, the output floor along with some elements of the countercyclical capital buffer and LTV. Lastly, in Chapter 4, we focus on a countercyclical capital buffer with an LTV ratio in a low interest rate environment.

Interaction of macroprudential regulation with monetary policy. Since monetary and macroprudential authorities pursue two distinct objectives, i.e., price stability and financial stability, respectively, it is inevitable that one policy may have unintended effects that may conflict with the objective of the other policy. Monetary policy can affect financial stability, while macroprudential tools can influence the rate of inflation. In Chapter 2 exogenous shocks affect policy rates through the optimised Taylor rule which affects asset prices and therefore the value of the collateral pledged, thereby impacting the net worth of borrowers and lenders. In Chapter 3 macroprudential policies affect the banks' risk-taking behaviour which influences credit growth and aggregate demand. In Chapter 4 we characterise the appropriate level of capital regulation when variations in policy rates influence the risk-taking behaviour of banks. In all the chapters the interaction of monetary and macroprudential policies means that in certain circumstances, policymakers may need to consider trade-offs between different objectives.

The thesis chapters. Evidence in Leamer (2015) and Leamer (2008) suggests that housing is the single most important driver of U.S. business cycles. This motivates Chapter 2, *An Analysis of Monetary and Macroprudential Policies in a DSGE Model with Reserve Requirements and Mortgage Lending*, where we build a DSGE model with a housing sector in addition to a sector producing nondurable consumption. We combine the financial accelerator model in Bernanke, Gertler and Gilchrist (1999) used by Quint and Rabanal (2014) to model endogenous loan defaults in the housing sector and Gertler and Karadi (2011) that introduced a financial intermediation friction via the impact of funds available to banks. This model captures how changes in the balance sheet of borrowers due to house price fluctuations caused by idiosyncratic risk shocks affect the spread between lending and deposit rates. We introduce a reserve requirement that regulates how much of its deposit funds a bank may lend. We use this model to examine how the interaction between monetary policy and reserve requirements affect the credit and business cycle, the distribution of welfare between savers and borrowers, and the aggregate welfare when these policies are optimised together or separately. We find that the optimised reserve ratio rules are effective in reducing sudden booms and busts in credit markets associated with business cycles. We also find there are distributive implications associated with the introduction of reserve requirements. Borrowers gain at the expense of savers and that these welfare gains and losses rise as required reserve ratios increase. Higher reserve ratios increase costs for banks, as only a portion of the available deposits can be used for lending activities. As banks have less funds to lend, they reduce lending to subprime borrowers and hence lower the probability of suffering losses from default. However, overall, less lending means smaller bank profits to remit to savers who own the banks. At the same time, as the probability of default decrease due to higher reserve ratios, worthy borrowers enjoy a more stable flow of credit. In this model, it emerges that coordination between monetary policy makers and macroprudential authorities has no impact on agents' welfare and they can safely set policy independently. This is because the policymakers have the same welfare functions.

Chapter 3, *Dynamics of the Output Floor: A Model-Based Assessment*, centers around the output floor, a new capital regulation introduced as part of the Basel III finalisation package. The output floor is meant to correct the failures of model-based regulation, whose measures proved unable to fully reflect banks' portfolio risk, generating instead excessive volatility of risk-weighted assets (RWA) while exacerbating the procyclicality of capital-to-RWA ratio. We develop a general equilibrium framework to evaluate the effect of output floor on: (i) the variability of risk-weighted assets; (ii) cyclical performance in terms of banks' lending decision and risk-taking; and (iii) achievement of the macroprudential authority's objectives. Following the approach of Gambacorta and Karmakar (2018), our analysis uses a DSGE model with a two-asset banking sector, financial frictions, sticky rates, and bank capital requirements. In the model, the banking system is subject to two regulatory frameworks, the risk-weighted capital framework, and the output floor. Our analysis produces three main results. First, we find that the output floor tends to bind during the expansionary phases of a cycle—after a positive technology shock or monetary policy stimulus. We also find that the output floor is able to reduce the excessive expansion of credit during an economic boom, by tightening banks' capital constraints. These results support the idea that the output floor is able to reduce the cyclicality of capital-to-RWA ratio and lending caused by the excessive responsiveness of internal models to economic and financial conditions. Second, we find that while the overall credit expansion is mitigated by the output floor during an economic boom, it also has asymmetric effects on banks' incentives to supply loans to firms and households. More specifically, during economic booms, the output floor smoothes the increase of mortgages but bolsters the expansion of credit to firms. Third, we find that the output floor is very effective in supporting the financial stability objective. It materially reduces the volatility of RWA across time, and this feeds through to a reduction in the volatility of the credit-to-GDP ratio. This result is largely overlooked in policy discussions. When thinking of the output floor, policymakers have often discussed its benefits in terms of the reduction in cross-sectional RWA variability that the Basel Committee on Banking Supervision (BCBS) set out to mechanically reduce through the output floor —by limiting the extent to which RWA can fall relative to credit risk according to standardised approach (SA), cross-sectionally, RWA will exist within a tighter band. The results also suggest that the output floor can reduce volatility. This result could have consequences for stress-testing and prudential policy, if for example adoption of the output floor means RWAs fluctuate less following the onset of adverse shocks.

Chapter 4, *Capital Regulation in a Low-Interest Environment*, considers the conduct of macroprudential policy in a low interest rate environment, particularly at the zero lower bound (ZLB). Low interest rates are a challenge for policymakers for two reasons. First, they limit the scope for conventional monetary policy to stabilise the economy. Second, low interest rates raise have the potential to exacerbate financial imbalances and risks to financial stability. Building on Gerali et al. (2010), we examine the transmission mechanism of a risk-weighted capital regulation in a standard New Keynesian and examine whether a more aggressive capital regulation is appropriate in a situation where monetary policy is constrained by the ZLB. Our

DSGE framework accommodates a ZLB, a credit constraint in a form of capital regulation, and borrowing constraints in the form of loan-to-value (LTV) regulations for mortgages and non-financial corporation (NFC) loans. The model captures the large nonlinearities that are often missing from macro models. We find that high capital regulation contributes more to the stabilisation of the main macroeconomic and financial variables compared to low capital regulation. Second, comparing the cyclical properties of the model under the two regimes (low and high capital regulations), we find that the high capital regulation reduces excessive expansion of credit during an economic boom by tightening the banks' capital constraints when compared to a regime with low capital regulation. This result suggests that high capital regulation can provide an additional buffer in a low interest environment. Third, we evaluate whether the implementation of the model with high capital regulation in ZLB is consistent with the objectives of the policy authorities. We calculate the monetary and macroprudential authority's loss functions and find that—other things equal—high capital regulation in ZLB reduces the loss of both the monetary and the macroprudential authority. This result suggests that high capital regulation can help regulatory authorities in achieving their objectives, particularly in a ZLB environment.

Chapter 2

An Analysis of Monetary and Macroprudential Policies in a DSGE Model with Reserve Requirements and Mortgage Lending

2.1 Introduction

Innovations to macroeconomic theory often develop in response to crises. The high unemployment and low aggregate output that characterised the Great Depression led Keynes (1936) in his *General Theory*, to emphasise a potential role for government spending in augmenting aggregate demand. Similarly, the concurrence of high inflation and low growth during the 1970's motivated the rebuilding of macroeconomics on micro-founded elements, incorporating both forward looking utility maximising households and profit maximising firms. In these early 'real' models, all markets were assumed to be both perfectly competitive and to clear immediately, obviating any role for monetary policy or indeed the existence of money. By incorporating oligopolistic competition together with staggered pricing, New Keynesian DSGE models developed in the early 2000's by Erceg and Levin (2003), Smets and Wouters (2003) and Christiano, Eichenbaum and Evans (2005) created a potential role for central banks to mitigate the welfare-reducing effects of stochastic shocks by adjusting short-term interest rates.

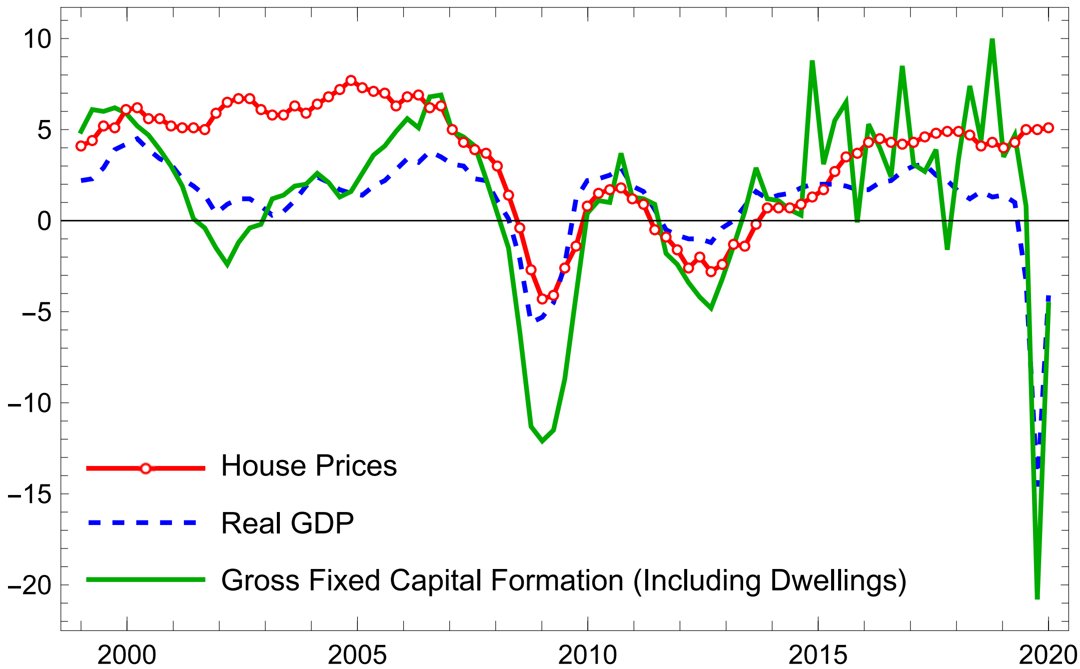
In those models, there is no financial sector. They cannot explain the existence of credit cycles or the way shocks in the financial sector can directly impact the real economy or amplify other shocks. To remedy this, Bernanke, Gertler and Gilchrist (1999) construct a model where asymmetric information between borrowers and lenders generate credit frictions. Christensen and Dib (2008) and others then incorporate financial accelerators into the full-scale NK DSGE model with monetary policy.

Institutionally, the era of relatively high inflation during the 1970's inspired a shift towards greater central bank independence and the adoption of inflation targeting as the main policy framework (Briault, Haldane and King (1996)). Following the general election of 1997 in the UK, the new Labour government opted to grant the Bank of England (BoE) instrument independence in achieving its goal of low and stable inflation. Though formally, the Bank of England Act of 1998 also gave it responsibility for ensuring the stability of the UK's financial system, the global financial crisis (GFC) in 2008 demonstrated how few (intellectual and policy) tools central banks, including the BoE, had possessed in the intervening years to prevent financial institutions from engaging in behaviour that might generate systemic risk across the sector and ultimately impact the entire economy.

The GFC inspired governments and international bodies to develop tools for stabilising the economy that extend beyond traditional monetary policy and emphasise the stability of the financial system. These new macroprudential tools generally mean not just tighter capital requirements and lower loan-to-value (LTV) ratios but developing rules to alter these in response to changes in macroeconomic variables. Studies by Agenor, Alper and Da Silva (2018), Angeloni and Faia (2013), Benes and Kumhof (2015), Collard et al. (2017), Christensen, Meh and Moran (2011), Silvo (2019), and Paries, Sørensen and Rodriguez-Palenzuela (2018) all analyse the interaction of monetary policy and capital regulations. Rubio and Carrasco-Gallego (2014), Beau, Clerc and Mojon (2012), and Lambertini, Mendicino and Punzi (2013) evaluate the interaction of monetary policy and loan-to-value (LTV). Angelini, Neri and Panetta (2014), Brzoza-Brzezina, Kolasa and Makarski (2015), and Suh (2012) consider the interaction of monetary policy, capital regulations, and LTV ratio. De Paoli and Paustian (2017) investigate the interaction between monetary policy, LTV ratios with taxes on both borrowing and deposits and Gelain, Lansing and Mendicino (2012) with loan-to-income (LTI) ratios. Bailliu, Meh and Zhang (2015), Kannan, Rabanal and Scott (2012), Ozkan and Unsal (2013), Quint and Rabanal (2014), Suh (2014), and Unsal (2013) interact monetary policy with a short cut representation of macroprudential policy. Generally, these studies all find that augmenting monetary policy with macroprudential tools can be sufficient for ensuring both economic and financial stability. At the same time, though the reserve ratio is an important element of macroprudential policy, only a few studies, such as Medina and Roldós (2018), and Tavman (2015), have analysed how it interacts with monetary policy.

Moreover, while some DSGE models do incorporate financial accelerators, in these models, loans are extended to entrepreneurs to finance investment rather than mortgage borrowing by households. This despite the strong empirical evidence for its importance in Leamer (2008) provocatively titled "Housing IS the Business Cycle." Leamer (2015) states that the experience of the GFC further confirms that "Housing is the single most critical part of the U.S. business cycle, certainly in a predictive sense and, I believe, also in a causal sense." We observe similar patterns in the Euro area in Figure 2.1. Furthermore, in the US, government-sponsored enterprises (GSEs), Fannie Mae and Freddie Mac provided implicit government guarantees before 2008 and have provided explicit ones since, which facilitate the securitisation of mortgages.[1] In Europe and elsewhere, these government entities do not exist and so the securitisation of mortgages is far less extensive, leaving nearly all mortgages on bank balance sheets.

Fig. 2.1 Residential Investment, House Prices and Real GDP in the Euro Area (% change, y-o-y)



Source: Federal Reserves Economic Data (FRED), St. Louis Fed.

[1] Mortgage backed securities by Fannie Mae, Freddie Mac or the U.S. government agency Ginnie Mae accounted for 66.6 percent of total mortgage debt in December 2021. See *Housing Finance at a Glance*, Urban Institute, December 2021.

This motivates our development of a general equilibrium framework in which a reserve requirement rule operates alongside conventional monetary policy in a model with a housing sector in addition to the sector that produces nondurable consumption. We combine a version of the financial accelerator model in Bernanke, Gertler and Gilchrist (1999) used by Quint and Rabanal (2014) to model endogenous loan defaults in the housing sector with the model of Gertler and Karadi (2011) who introduced a financial intermediation friction via the impact of funds available to banks.[2] We then augment the model by introducing a reserve requirement that regulates how much of its deposit funds a bank can allocate to lending. We calibrate our model using euro area data.[3]

The reserve ratio has been introduced as early as 1820 when banks in New York and New England agreed to redeem each other's notes provided the issuing bank maintained a sufficient deposit of specie (gold or its equivalent) on account with the redeeming bank (Feinman (1993)). The first legal requirements were introduced in the US by the states of Virginia, Georgia, and New York following the Panic of 1837 (Carlson (2018)), implemented nationwide in 1863 with passage of the National Bank Act and incorporated within the 1913 Federal Reserve Act (Goodfriend and Hargraves (1983)). Given this history, it is notable that alongside the growing emphasis on macroprudential policy in emerging market economies (as shown in Table 2.1), advanced economies have increasing lowered or eliminated the reserve requirements. In the euro area the required reserve ratio was set at two percent from 1999 until its reduction to one percent in 2012. In the UK, the Bank of England no longer uses required reserve ratios as a policy tool. On 26 March 2020, two centuries after they were introduced, the United States Federal Reserve Board eliminated the reserve requirements for all depository institutions.[4] Our results suggest that these changes may have been ill-advised, and that the reintroduction of reserve requirements may ultimately be warranted.

We use this model to examine how the interaction between monetary policy and reserve requirements affect: (i) the credit and business cycle; (ii) the distribution of welfare between savers and borrowers; and (iii) the aggregate welfare when these policies are optimised together or separately. Our model is closely based on Quint and Rabanal (2014), but our explicit use of

[2] Quint and Rabanal (2014) captures how changes in the balance sheet of borrowers due to house price fluctuations caused by idiosyncratic risk shock affects the spread between lending and deposit rates, and the credit market.

[3] As in Angelini, Neri and Panetta (2014) and Beau, Clerc and Mojon (2012), we do not distinguish between different countries within the euro area, but rather treat the euro area as a single economy.

[4] *Reserves Administration Frequently Asked Questions*; https://www.federalreserve.gov/monetarypolicy/reservereq.htm.

the reserve ratio and addition of a formal banking sector in the model enable us to compare our results with the former.

Table 2.1 Required Reserve Ratio for Selected Economies

Country	Central Bank	Ratio (%)
	Advanced Economies	
Czech Republic	Czech National Bank	2.0
Denmark	National Bank of Denmark	2.0
Euro Area	European Central Bank	1.0
Iceland	Central Bank of Iceland	0.00
Israel	Bank of Israel	6.0
United States	Federal Reserve	0.0
Switzerland	Swiss National Bank	2.50
	Emerging Market, Middle- and Low-Income Economies	
Albania	Bank of Albania	10.0
Angola	National Bank of Angola	22.0
Argentina	Central Bank of Argentina	44.0
Brazil	Central Bank of Brazil	17.0
Bulgaria	Bulgarian National Bank	10.0
Cape Verde	Bank of Cape Verde	10.0
China	People's Bank of China	10.0
Costa Rica	Central Bank of Costa Rica	12.0
Croatia	Croatian National Bank	12.0
Curacao and St. Maarten	Central Bank of Curacao and St. Maarten	19.0
Egypt	Central Bank of Egypt	14.0
Ethiopia	National Bank of Ethiopia	10.0
Fiji	Reserve Bank of Fiji	10.0
Gambia	Central Bank of The Gambia	13.0
Guatemala	Bank of Guatemala	14.6
Liberia	Central Bank of Liberia	25.0
Moldova	National Bank of Moldova	28.0
Mozambique	Bank of Mozambique	10.5
Nicaragua	Central Bank of Nicaragua	10.0
Nigeria	Central Bank of Nigeria	27.0
Philippines	Bangko Sentral ng Pilipinas	12.0
Seychelles	Central Bank of Seychelles	10.0
South Sudan	Bank of South Sudan	15.0
Suriname	Centrale Bank van Suriname	35.0
Taiwan, China	Central Bank of the Rep. of China (Taiwan)	10.75
Tonga	Reserve Bank of Tonga	10.0
Trinidad & Tobago	Central Bank of Trinidad & Tobago	14.0
Uruguay	Central Bank of Uruguay	25.0
Venezuela	Central Bank of Venezuela	19.0
Zimbabwe	Reserve Bank of Zimbabwe	10.0

Source: Individual central banks as compiled by Central Bank News as of 20 January 2022.

This analysis produces five main results. First, we considered the model with only monetary policy as the benchmark and show the distributive implications of operating the different levels of static reserve ratio in stochastic model and deterministic model. We find that there is a welfare trade-off between borrowers and savers. In both cases, we find that there is an increase in borrowers' welfare as reserve ratio increases. By contrast, savers welfare decreases as the level of reserve ratio increases. In aggregate, total household welfare exhibits a minimal gain given that the gains by borrowers offset the losses by savers. These results underscore that a higher reserve ratio increases costs for banks as only a portion of the available deposits can be used for lending activities. As banks have fewer funds to lend, they also reduce excessive risk-taking. By doing so, they are able to eliminate extending loans to subprime borrowers and thereby reduce the probability of default. However, banks accumulate less profits in the process which are then remitted to savers as owners of banks. Savers also earn lower returns on deposits as lower funds are intermediated. Meanwhile, worthy borrowers enjoy a stable flow of credit as probability of default decreases with higher reserve ratio. This narrative reflects why savers experience welfare losses and borrowers experience welfare gains when the reserve ratio increases.

Second, we look at whether situations might arise where two different agencies, a central bank setting monetary policy and a macroprudential policy agency might cooperate, or given the different tools at their disposal, operate independently without any cooperation in a way that might be detrimental to stability or welfare. We compute the parameters associated with both the monetary and macroprudential policy rules that optimise total welfare. We use the consumer welfare as a goal rather than the stabilisation objectives of the monetary authority and macroprudential regulator. Since both agencies are maximising consumer welfare, what emerges is a cooperative solution, so that the optimal parameters for both cases are the same. This contrasts with Angelini, Neri and Panetta (2014) where the optimal parameters in the cooperative and noncooperative cases differ because the objective functions of the two policymakers are different.

Third, we use the optimised parameters to generate the impulse response functions (IRFs) in response to the two of three shocks associated with the housing sector that together account for 43% of the variance in real GDP and nearly all the variance in loans. We demonstrate that macroprudential policy, even if it operates completely on its own, stabilises the economy when negative risk shock hits, by dampening the financial accelerator mechanism. Macroprudential policy, either on its own or when combined with monetary policy, stabilises the economy and more generally generates a small welfare benefit to borrowers at the expense of savers. This differential impact increases as the ratio shifts higher. Meanwhile, the response of the economy to a negative shock to the housing preference parameter is similar to the impact from the risk shock, but GDP carries on declining for another quarter. Neither macroprudential policy nor monetary policy when operating in the absence of the other are able to do much to mitigate the impact of the demand shock. Only when they operate in tandem that there is a discernible impact on the economy—particularly in reducing the drop in total loans. Turning to the nondurable goods sector, we find that neither macroprudential policy nor monetary policy, when operating in the absence of the other, are able to do much to mitigate the impact of a nondurable technology shock. We also consider the impact of a negative demand shock in the non-durable sector. The negative impact on consumption for savers and borrowers is roughly similar though the latter do recover more quickly. Unlike the case for the technology shock, the demand shock on nondurable inflation generates countercyclical declines in both the policy rate and the reserve ratio.

Fourth, we also analyse the welfare effects of the different regimes compared to a baseline model with no policy. We find that monetary policy, when analysed in New Keynesian models, is generally found to mitigate but only to a small degree, the negative impacts on agents' welfare generated by stochastic shocks to the economy. We also find that at the baseline steady state reserve requirement of 10%, the total impact on welfare of macroprudential policy, either on its own, or in conjunction with monetary policy, reaches consumption equivalents of 0.003% or 0.006% respectively. If the steady state reserve requirement is set as high as 30% the consumption equivalents are 0.014% and 0.017%, well over an order of magnitude higher than the impact of monetary policy alone. These are still small numbers, but they demonstrate that once we incorporate housing and banks into our model, macroprudential policy is more effective than monetary policy in mitigating the welfare effects of shocks.

Lastly, we demonstrate how much can these different regimes reduce the volatility of key macroeconomic and financial variables. We find that the reduction in the loss function is largest when monetary and macroprudential policy operate together and the reserve ratio is highest. Monetary policy, combined with macroprudential policy implemented with the low steady state reserve requirement we observe in the Eurozone, achieves a reduction in the loss function nearly as large as macroprudential policy when it operates on its own with the much higher reserve requirement.

We proceed as follows. In Section 2.2 we provide a brief description of the model and in Section 2.3 we discuss the calibration of its structural and stochastic parameters. In Section 2.4 we analyse the behaviour of the model and consider the welfare implications of different policy choices. Section 2.5 concludes.

2.2 The Model

Consider a closed economy DSGE model that combines a balance sheet constraint from Quint and Rabanal (2014) with financial frictions modelled by Gertler and Karadi (2011). Figure

2.2 provides a description of the feedback mechanism of the model by showing the flow of transactions among the agents. The model has two sectors, non-durable consumption and housing, and heterogeneous households, the savers and borrowers in equilibrium with discount factor of β and β^B, respectively, where $\beta > \beta^B$. Merging the two models allows us to understand the role of banks that intermediate funds from savers to borrowers (with reserve ratio that regulate the supply of credit) and face balance sheet constraints. These constraints originate with the endogenous loan defaults of borrowers caused by idiosyncratic shocks to their housing collateral. The two final goods in this economy, non-durables and housing are produced in perfectly competitive markets, by combining different sets of intermediate goods. The intermediate goods are produced by two different sets of monopolistically competitive firms associated with each sector. Private banks too, are monopolistically competitive and there are also collection agencies, that banks engage for a fee, to recover a portion of any loans in default. The central bank conducts monetary policy according to a Taylor rule and sets the reserve ratio for banks. We abstract from fiscal policy.

2.2.1 Savers

Savers indexed by $j \in [0, \lambda]$ maximize expected utility by choosing non-durable consumption, housing, and labour hours:

$$\max_{C_t^j, D_t^j, L_t^j} E_0 \left\{ \sum_{t=0}^{\infty} \beta^t \left[\gamma \xi_t^C log(C_t^j - \varepsilon C_{t-1}) + (1-\gamma) \xi_t^D log(D_t^j) - \frac{(L_t^j)^{1+\varphi}}{1+\varphi} \right] \right\}, \tag{2.1}$$

where the parameter ε measures the external habit on past total non-durable goods consumption while β, γ, and φ stand for the discount factor, the share of non-durable goods in the utility function, and the inverse elasticity of labour, respectively. There is also a preference shock ξ^k, where $k = C, D$, where C and D refer to consumption and housing, respectively, which follow an AR(1) process with zero mean.

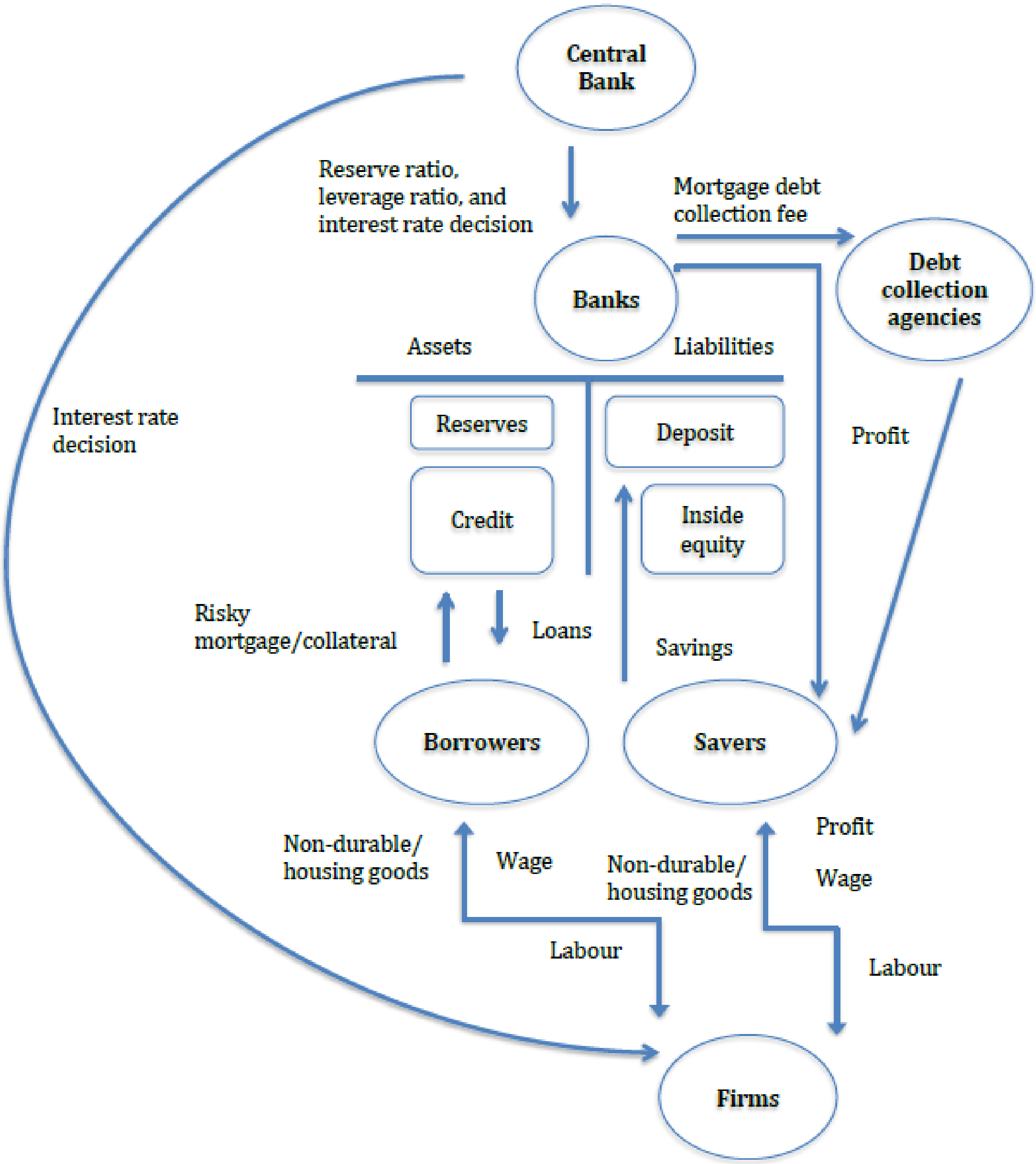
The labour disutility index consists of hours worked:

$$L_t^j = \left[\alpha^{-\iota_L} (L_t^{C,j})^{1+\iota_L} + (1-\alpha)^{-\iota_L} (L_t^{D,j})^{1+\iota_L} \right]^{\frac{1}{1+\iota_L}}, \tag{2.2}$$

where $L_t^{C,j}$ denotes non-durable sector and $L_t^{D,j}$ housing sector, with α as share of employment in the non-durable sector. Reallocating labour across sectors is costly and is governed by parameters ι_L.

Saver households face a budget constraint which we express in real terms:

Fig. 2.2 Model Interactions



Source: Authors' own construction.

$$C_t^j + S_t^j + Q_t I_t^j = W_t^C L_t^{C,j} + W_t^D L_t^{D,j} + \frac{R_{t-1} S_{t-1}^j}{\Pi_t^C} + \Psi_t^j, \tag{2.3}$$

where $Q_t = \frac{P_t^D}{P_t^C}$ is the price of housing relative to the non-durable final consumption good. Real wages paid in the two sectors are denoted by W_t^C and W_t^D. Savers allocate their expenditures between real non-durable consumption C_t^j and housing investment I_t^j. They can save by holding deposits in the financial system S_t^j, which pay a gross nominal deposit interest rate R_t, converted to a real rate by dividing by the non-durable consumption inflation Π_t^C. In addition, savers also receive profits Ψ_t^j from intermediate goods producers in the housing and non-durable sectors, from the banks they manage, and from debt-collection agencies that collect fees from banks to recover defaulting loans.

The housing stock D_t^j, accumulates through housing investment I_t^j by savers:

$$D_t^j = (1-\delta)D_{t-1}^j + \left[1 - f\left(\frac{I_{t-1}^j}{I_{t-2}^j}\right)\right] I_{t-1}^j, \tag{2.4}$$

where δ denotes the rate of depreciation for the housing stock and $f(\cdot)$ is an adjustment cost function. Following Christiano, Eichenbaum and Evans (2005), $f(\cdot)$ is a convex function, which in steady state satisfies: $\bar{f} = \bar{f}' = 0$ and $\bar{f}'' > 0$.[5]

Defining the stochastic discount factor as $\mathrm{P}_{t,t+1} \equiv \beta \frac{\mathrm{P}_{t+1}}{\mathrm{P}_t}$, the first order conditions (FOCs) for the savers' optimisation problem are as follows:

Euler consumption

$$1 = \beta R_t E_t \Big[\frac{C_t - \varepsilon C_{t-1}}{C_{t+1} - \varepsilon C_t} \frac{\xi_{t+1}^C}{\xi_t^C} \Pi_{t+1}^C\Big] \tag{2.5}$$

Stochastic discount factor

$$\mathrm{P}_{t,t+1} \equiv \beta \frac{\mathrm{P}_{t+1}}{\mathrm{P}_t} = \beta \frac{\gamma \xi_{t+1}^C C_t - \varepsilon C_{t-1}}{\gamma \xi_t^C C_{t+1} - \varepsilon C_t} \tag{2.6}$$

Labour supply

$$\alpha^{-\iota_L} L_{t+s}^{\varphi - \iota_L} (L_{t+s}^C)^{\iota_L} = \frac{\xi_t^C W_t^C}{C_t - \varepsilon C_{t-1}} \tag{2.7}$$

$$(1-\alpha)^{-\iota_L} L_{t+s}^{\varphi - \iota_L} (L_{t+s}^D)^{\iota_L} = \frac{\xi_t^C W_t^D}{C_t - \varepsilon C_{t-1}} \tag{2.8}$$

Investment

$$\begin{aligned} \frac{\gamma \xi_t^C Q_t}{C_t - \varepsilon C_{t-1}} = \beta E_t \varrho_{t+1} \Big[1 - f\Big(\frac{I_t}{I_{t-1}}\Big) - f'\Big(\frac{I_t}{I_{t-1}}\Big)\frac{I_t}{I_{t-1}}\Big] \\ + \beta^2 E_t \Big[\varrho_{t+2} f'\Big(\frac{I_{t+1}}{I_t}\Big)\Big(\frac{I_{t+1}}{I_t}\Big)^2\Big] \end{aligned} \tag{2.9}$$

[5]The cost function is important to replicate hump-shaped responses of residential investment to shock and reduce residential investment volatiliy.

2.2.2 Borrowers

The borrowers in this economy, indexed by $j \in [\lambda, 1]$, also maximise their expected utility with respect to non-durable consumption, housing and labour hours:

$$\max_{C_t^{B,j}, D_t^{B,j}, L_t^{B,j}} E_0 \left\{ \sum_{t=0}^{\infty} \beta^{B,t} \left[\gamma \xi_t^C log(C_t^{B,j} - \varepsilon^B C_{t-1}^B) + (1-\gamma) \xi_t^D log(D_t^{B,j}) - \frac{(L_t^{B,j})^{1+\varphi}}{1+\varphi} \right] \right\} \quad (2.10)$$

We define $F(\bar{\omega}, \bar{\sigma}_\omega)$ as the cumulative distribution function (CDF) of the idiosyncratic shock to the quality of the housing stock. Hence, the budget constraint, in real terms, aggregated across all borrowers, incorporates both the fraction $F(\bar{\omega}, \bar{\sigma}_\omega) = \int_0^{\bar{\omega}} dF(\omega, \sigma_\omega) d\omega$ of households that receive shocks to the quality of their housing below the threshold $\bar{\omega}$ and default on their loans, and the fraction $1 - F(\bar{\omega}, \bar{\sigma}_\omega) = \int_{\bar{\omega}}^{\infty} dF(\omega, \sigma_\omega) d\omega$ that receive shocks above the threshold and pay their loans:

$$C_t^B + Q_t I_t^B + \left[R_t^D + (1 - F(\bar{\omega}, \sigma_\omega)) R_{t-1}^L \right] S_{t-1}^B = S_t^B + W_t^C L_t^{B,C} + W_t^D L_t^{B,D}. \quad (2.11)$$

where $R_t^D = G(\bar{\omega}, \bar{\sigma}_\omega) \frac{Q_t D_t^B}{S_{t-1}^B}$ is the rate that is paid to banks after a debt-collection agency intervenes. Borrowers receive no income from profits.

Defining the stochastic discount factor as $\text{P}_{t,t+1}^B \equiv \beta \frac{\text{P}_{t+1}^B}{\text{P}_t^B}$, FOCs for this optimisation problem are as follows:

Euler consumption

$$1 = \beta^B E_t \left[R_{t+1}^D + (1 - F(\bar{\omega}, \bar{\sigma}_\omega)) R_t^L \right] \left[\frac{C_t^B - \varepsilon C_{t-1}^B}{C_{t+1}^B - \varepsilon^B C_t} \frac{\xi_{t+1}^C}{\xi_t^C} \Pi_{t+1}^C \right] \quad (2.12)$$

Stochastic discount factor

$$\text{P}_{t,t+1}^B \equiv \beta^B \frac{\text{P}_{t+1}^B}{\text{P}_t^B} = \beta^B \frac{\gamma \xi_{t+1}^C C_t^B - \varepsilon^B C_{t-1}^B}{\gamma \xi_t^C C_{t+1}^B - \varepsilon^B C_t^B} \quad (2.13)$$

Labour supply

$$\alpha^{-\iota_L} L_{t+s}^{\varphi - \iota_L} (L_{t+s}^{B,D})^{\iota_L} = \frac{\xi_t^C W_t^C}{C_t^B - \varepsilon^B C_{t-1}^B} \quad (2.14)$$

$$(1-\alpha)^{-\iota_L} L_{t+s}^{\varphi-\iota_L} (L_{t+s}^{B,D})^{\iota_L} = \frac{\xi_t^C W_t^D}{C_t^B - \varepsilon^B C_{t-1}^B} \tag{2.15}$$

Investment

$$\frac{\gamma \xi_{t+s}^C Q_t}{C_{t+s}^B - \varepsilon^B C_{t+s-1}^B} = \beta E_t \varrho_{t+1}^B \Big[1 - f\Big(\frac{I_t^B}{I_{t-1}^B}\Big) - f'\Big(\frac{I_t^B}{I_{t-1}^B}\Big)\frac{I_t^B}{I_{t-1}^B}\Big] + \beta^2 E_t \Big[\varrho_{t+2}^B f'\Big(\frac{I_{t+1}^B}{I_t^B}\Big)\Big(\frac{I_{t+1}^B}{I_t^B}\Big)^2\Big] \tag{2.16}$$

An endogenous default risk is introduced in the model similar with Quint and Rabanal (2014), which was originally introduced by Bernanke, Gertler and Gilchrist (1999). The risk is introduced in the credit and housing market by assuming an idiosyncratic quality shock to value of the housing stock of each borrower household, which is use as collateral for their loans. However, similar with the former, we do not model asymmetric information or agency problems. Borrowers will only default if they are hit by a shock that would make the value of their housing stock lower than their outstanding debts.

This idiosyncratic shock is log-normally distributed: $\log(\omega_t^j) \sim N(\mu_\omega, \sigma_{\omega,t}^2)$ where setting $\mu_\omega = -\frac{1}{2}\sigma_{\omega,t}^2$ ensures that $E(\omega_t^j)$=1. That means the cumulative distribution of the shocks is $F(\omega, \sigma_\omega)$=$\Phi(\frac{ln\omega + \frac{1}{2}\sigma_\omega^2}{\bar{\sigma}_\omega})$ where $\Phi(x) = \int_{-\infty}^{x} \frac{1}{\sqrt{2\pi}} e^{\frac{-t^2}{2}} dt$.

The standard deviation of the housing quality shock $\sigma_{\omega,t}$ follows is an AR(1) process in logs:

$$log(\sigma_{\omega,t}) = (1-\rho_{\sigma_\omega}) log(\bar{\sigma}_\omega) + \rho_{\sigma_\omega} log(\sigma_{\omega,t-1}) + u_{\omega,t} \tag{2.17}$$

where $u_{\omega,t} \sim (0, \sigma_{u_\omega})$ follows the log normal distribution on the support (0,∞), so ω_t^j is always positive. Any rise in $\sigma_{\omega,t}$ is mean-preserving and only increases the skewness of the distribution, resulting in more of the mass of the distribution concentrated on the left and lower values for ω_t^j. As a result, the probability of mortgage default increases, necessitating banks to charge higher spreads.

The shock ω_t^j equals the ex-ante threshold default value $\bar{\omega}_t^a$ if the expected value of the housing stock exactly matches the gross interest payment on the loan. We defined D_t^B as the real value of the housing stock held by borrowers and writing S_t^B as the real value of the loan, it follows that:

$$\bar{\omega}_t^a E_t[Q_{t+1} \Pi_{t+1}^C D_{t+1}^B] = R_t^L S_t^B \tag{2.18}$$

For borrowers, the ex-post threshold value $\bar{\omega}^p_{t-1}$ where a borrower still repays its loan is:

$$\bar{\omega}^p_{t-1} Q_t \Pi^C_t D^B_t = R^L_{t-1} S^B_{t-1} \tag{2.19}$$

As in Quint and Rabanal (2014), the one-period lending rate R^L_{t-1} is pre-determined and not a function of the state of the economy and since investment increases the housing stock with a lag, D^B_t is also a predetermined variable. Therefore the housing risk, ex-ante $\bar{\omega}^a_t$ and ex-post $\bar{\omega}^p_t$, can differ even though when the loan contract is signed, $\bar{\omega}^a_t = E_t \bar{\omega}^p_t$. Ex-post, borrowers hit by shocks above and below the the threshold $\bar{\omega}^p_{t-1}$ face different budget constraints. High realisation of ω^j_t leads to borrowers paying in full:

$$\bar{\omega}^p_{t-1} Q_t D^B_t \geq \frac{R^L_{t-1} S^B_{t-1}}{\Pi^C_t} \tag{2.20}$$

However, low realisation of ω^j_t leads to borrowers defaulting:

$$\bar{\omega}^p_{t-1} Q_t D^B_t < \frac{R^L_{t-1} S^B_{t-1}}{\Pi^C_t} \tag{2.21}$$

The fraction of loans that banks expect to default in period $t+1$, equals the CDF of the quality shock:

$$F(\bar{\omega}, \bar{\sigma}_\omega) = \int_0^{\bar{\omega}} dF(\omega) = \int_0^{\bar{\omega}} \frac{1}{\omega \bar{\sigma}_\omega \sqrt{2\pi}} e^{-\frac{(ln\omega + \frac{1}{2}\bar{\sigma}^2_\omega)^2}{2\bar{\sigma}^2_\omega}} d\omega \tag{2.22}$$

where the log-normal distribution of ω_t implies that the steady state of the mean is $\bar{\mu}_\omega = -\frac{1}{2}\bar{\sigma}^2_\omega$.[6] Since the expected value of the quality shock conditional on being less than the threshold $\bar{\omega}^p_{t-1}$ is $G = 1 - \Phi\Big(\frac{\frac{1}{2}\bar{\sigma}^2_\omega - ln\bar{\omega}}{\bar{\sigma}_\omega}\Big)$, the value of the housing stock recovered by debt collection agencies in each period is:

$$R^D_t S^B_{t-1} = G Q_t D^B_t. \tag{2.23}$$

2.2.3 Banks

The banking sector in this model closely follows that of Gertler and Kiyotaki (2010) but embeds the New Keynesian (NK) model of sticky prices similar to Gertler and Karadi (2011). Specifically, banks in our model face costs associated with enforcing contracts in an environment where financial frictions also limit the funds available to banks from savers. To these two

[6] See Quint and Rabanal (2014) Appendix for the complete derivation.

elements, we add an additional friction in the form of a reserve ratio, which rations the funds available for banks to purchase state-contingent securities.

Banks operate in a monopolistically competitive environment where they adjust the deposit and lending rates in response to shocks or the cyclical conditions of the economy. Banks pay depositors a gross interest rate R_t and extend loans to borrowers at a gross rate R_t^L against the future value of their housing collateral. Banks introduce a wedge between the cost of deposits from savers R_t, and the average interest rate banks receive for the loans they choose to make $R_t^D + (1-F)R_{t-1}^L$, subject to the required reserve ratio, rr_t. Banks will tend to increase the loanable amount they issue in a credit boom environment while decreasing it when times are uncertain. The reserve ratio limits riskier credit activity during booms.

The activity of banks can be summarised in two phases. First, banks raise deposits, an average of S_t, from each saver at a deposit rate R_{t+1} over the interval $[t, t+1]$. These deposits and the internal equity n_t they raise from households serve as the banks' liabilities. Banks retain a certain amount of unremunerated reserves rr_t from the deposits they receive from households. In the second phase, banks use these liabilities to make loans averaging S_t^B to each borrower. The house borrowers purchase serves as collateral.

The total amount of assets against which the loans are obtained is the end-of-period housing stock D_t in (2.3). The lending rate for those who fully repay is known in advance and is a contractual obligation, while the average return on those loans that default is only known at time t. A bank's balance sheet is summarised by:

$$(1-\lambda)S_t^B \le n_t + \lambda(1-rr_t)S_t, \tag{2.24}$$

while the net worth of the banks accumulates according to:

$$n_{t+1} = (1-\lambda)\Big[(1-\mu)R_{t+1}^D + (1-F)R_t^L\Big]S_t^B - \lambda(R_{t+1} - rr_t)S_t. \tag{2.25}$$

The interest rate on the loans that are recovered in full is:

$$R_{t-1}^L = \frac{1}{\beta^B}\left\{\frac{1}{1-F+G/\bar{\omega}_{t-1}^p}\right\}, \tag{2.26}$$

and the return on the assets recovered from those who default is:

$$R_t^D = \frac{Q_t G D_t^B}{S_{t-1}^B}. \tag{2.27}$$

If default occurs, banks call in debt-collection agencies which return the fraction $(1-\mu)$ of the realised value of borrower j's housing stock and retain the fraction μ in fees, which is distributed as profits to savers. Banks each face an exit probability $1-\sigma_B$ each period and therefore exit in the i^{th} period with probability $(1-\sigma_B)\sigma_B^{i-1}$. As banks only pay dividends when they exit, the bankers' objective function maximises expected discounted terminal wealth:[7]

$$V_t = E_t \sum_{i=0}^{\infty} (1-\sigma_B)\sigma_B^{i-1} \mathrm{P}_{t,t+i} n_{t+i}, \tag{2.28}$$

where $\mathrm{P}_{t,t+i} = \beta^i \frac{\mathrm{P}_{C,t+i}}{\mathrm{P}_{C,t}}$ is the stochastic discount factor, subject to an incentive constraint for savers to be willing to supply funds to the banks.

Assume (2.24) holds with equality, solving for S_t and substituting into (2.25) yields:

$$n_{t+1} = E_t \left\{ (1-\lambda)\Big[(1-\mu)R_{t+1}^D + (1-F)R_t^L - \frac{R_{t+1} - rr_t}{1-rrt}\Big] S_t^B + \frac{R_{t+1} - rr_t}{1-rr_t} n_t \right\} \tag{2.29}$$

We assume that after a bank obtains funds and complies with the required reserve ratio, the bank's owner may transfer a fraction Θ of the assets not held as reserves to his family, causing the bank to default on its debts and shut down. In recognition of the possibility that as much as $\Theta(1-\lambda)S_t^B$ of the bank's assets could be diverted for personal gain—leaving only $(1-\Theta)(1-\lambda)S_t^B$ to be reclaimed by creditors—households limit the funds they lend to banks. To ensure that banks do not divert funds, a bank's franchise value V_t must be at least as large as its gain from diverting funds:

$$V_t \geq \Theta(1-\lambda)S_t^B. \tag{2.30}$$

The right-hand side of this incentive constraint is what the bank's owner gains by diverting a fraction of assets and the left-hand side is what is lost from diverting funds. The optimisation problem for the bank is to choose a path for loans $\{S_{t+i}^B\}$ which maximises V_t subject to (2.24), (2.25) and (2.30). The solution is assumed to take the form:

$$V_t = E_t \Omega_{t+1} \mathrm{P}_{t,t+1} n_{t+1}. \tag{2.31}$$

[7] A simpler solution in Pearlman (2015) is to assume that $V_t = \Omega_t E_t[P_{t,t+1} n_{t+1}]$.

The value of the bank at the end of period $t-1$ satisfies the Bellman equation:

$$V_{t-1} = E_{t-1}\mathrm{P}_{t-1,t}[(1-\sigma_B)n_t + \sigma_B V_t]. \tag{2.32}$$

Substituting (2.29) and (2.31), into (2.30) and (2.32) yields the dynamic programming problem:

$$\begin{aligned} V_{t-1} = E_{t-1}\mathrm{P}_{t-1,t}[(1-\sigma_B)n_t + \sigma_B E_t\Omega_{t+1}\mathrm{P}_{t,t+1}\Big\{(1-\lambda)\Big[(1-\mu)R^D_{t+1} \\ +(1-F)R^L_t - \frac{R_{t+1}-rr_t}{1-rr_t}\Big]S^B_t + \frac{R_{t+1}-rr_t}{1-rr_t}n_t\Big\}, \end{aligned} \tag{2.33}$$

subject to the constraint:

$$\begin{aligned} E_t\Omega_{t+1}\mathrm{P}_{t,t+1}\Big\{(1-\lambda)\Big[(1-\mu)R^D_{t+1} + (1-F)R^L_t - \frac{R_{t+1}-rr_t}{1-rrt}\Big]S^B_t \\ +\frac{R_{t+1}-rr_t}{1-rr_t}n_t\Big\} \geq \Theta(1-\lambda)S^B_t. \end{aligned} \tag{2.34}$$

If $E_t\Omega_{t+1}\mathrm{P}_{t+1}\Big[(1-\mu)R^D_{t+1} + (1-F)R^L_t - \frac{R_{t+1}-rr_t}{1-rr_t}\Big] \geq \Theta$, then the constraint (2.34) does not bind and the (assets to equity) leverage ratio, defined as $\phi_t \equiv \frac{(1-\lambda)S^B_t}{n_t}$, is indeterminate. Assume instead that the constraint does bind, the value function is then[8]:

$$V_{t-1} = E_{t-1}\mathrm{P}_{t-1,t}n_t\Big[(1-\sigma_B) + \sigma_B\Theta\frac{(1-\lambda)S^B_t}{n_t}\Big] \tag{2.35}$$

where $\Theta = E_t\Omega_{t+1}\mathrm{P}_{t,t+1}\left\{\frac{R_{t+1}-rr_t}{(1-rr_t)(1-\lambda)S^B_t}n_t + \Big[(1-\mu)R^D_{t+1} + (1-F)R^L_t - \frac{R_{t+1}-rr_t}{1-rr_t}\Big]\right\}$.

Aggregating (2.24), the balance sheet for the banking sector as a whole is:

$$(1-\lambda)S^B_t = N_t + \lambda(1-rr_t)S_t, \tag{2.36}$$

and its leverage ratio is:

$$\phi_t = \frac{(1-\lambda)S^B_t}{N_t}. \tag{2.37}$$

The net worth of all the banks founded before time t and survive to period t is $N_{0,t}$ and it equals the earnings on all the assets S^B_{t-1} of all the banks that operated in the previous period, after subtracting the cost of deposit finance and complying with the reserve ratio requirement,

[8] Our derivation of this result arises from solving what is in effect a simple linear programming problem; it eliminates the Lagrangian utilised by Gertler and Kiyotaki (2010).

multiplied by the survival probability σ_B:

$$N_{0,t} = \sigma_B \Big\{ (1-\lambda) \Big[(1-\mu) R_t^D + (1-F) R_{t-1}^L \Big] S_{t-1}^B - \lambda (R_t - rr_{t-1}) S_{t-1} \Big\} \tag{2.38}$$

The new banks, those founded in period t, raise equity from households in an amount equal to the fraction $\xi_B/(1-\sigma_B)$ of the total value of assets held by banks that exited at the end of period $t-1$, which amounts to the fraction ξ_B of the total value of bank assets in $t-1$:

$$N_{n,t} = \xi_B \Big\{ (1-\lambda) \Big[(1-\mu) R_t^D + (1-F) R_{t-1}^L \Big] S_{t-1}^B \Big\} \tag{2.39}$$

Summing (2.38) and (2.39) yields the net worth of the banking sector:

$$N_t = (\xi_B + \sigma_B) \Big\{ (1-\lambda) \Big[(1-\mu) R_t^D + (1-F) R_{t-1}^L \Big] S_{t-1}^B \Big\} - \sigma_B \lambda (R_t - rr_{t-1}) S_{t-1} \tag{2.40}$$

2.2.4 Firms

Firms in both the homogeneous non-durable final consumption sector and the housing sector operate in perfectly competitive markets with flexible prices. Producers in each sector purchase sector-specific intermediate goods that exist in a continuum and are imperfect substitutes and produce them using a Dixit-Stiglitz aggregator:

$$Y_t^k = \left[\int_0^1 (Y_t(i)^k)^{\frac{\sigma_k - 1}{\sigma_k}} di \right]^{\frac{\sigma_k}{\sigma_k - 1}}, \ k = C, D \tag{2.41}$$

where $\sigma_k > 1$ represents the price elasticity of substitution between intermediate goods.

The final goods firm chooses $Y_t(i)$ to minimize its costs and so the demand function for intermediate good i is:

$$Y_t(i)^k = \left(\frac{P_t(i)^k}{P_t^k} \right)^{-\sigma_k} Y_t^k, \ k = C, D \tag{2.42}$$

and the price index is:

$$P_t^k = \left[\int_0^1 (P_t(i)^k)^{1-\sigma_k} di \right]^{\frac{1}{\sigma_k - 1}}, \ k = C, D \tag{2.43}$$

The two markets for intermediate goods are monopolistically competitive and price setting is staggered as in Calvo (1983). In each period only a fraction $1 - \theta_C$ $(1 - \theta_D)$ of intermediate goods producers in the non-durable (housing) sector receive a signal to re-optimize their price. For the remaining fraction θ_C (θ_D), their prices are partially indexed to lagged sector-specific inflation (with a coefficient ϕ_C, ϕ_D in each sector). In both sectors, intermediate goods are produced solely with labour and subject to sector-specific stationary technology shocks Z_t^C and Z_t^D, each of which follows a zero-mean $AR(1)$ process in logs:

$$Y_t^k = Z_t^k L_t^k, \; k = C, D \tag{2.44}$$

Cost minimization implies that real marginal costs in both sectors are:

$$MC_t^C = \frac{W_t^C}{Z_t^C} \tag{2.45}$$

$$MC_t^D = \frac{W_t^D}{Q_t Z_t^D} \tag{2.46}$$

Each intermediate goods producers solves a standard Calvo model profit-maximization problem with indexation described by three equations:

$$J_t^C - \beta\theta^C E_t\left[\left(\frac{\Pi_{t+1}}{\Pi_t^{\phi^C}}\right)^{\sigma} J_{t+1}^C\right] = \frac{MC_t^C Y_t^C}{C_t - \varepsilon C_{t-1}} \tag{2.47}$$

$$H_t^C - \beta\theta^C E_t\left[\left(\frac{\Pi_{t+1}}{\Pi_t^{\phi^C}}\right)^{\sigma-1} H_{t+1}^C\right] = \left(1 - \frac{1}{\sigma}\right)\frac{Y_t^C}{C_t - \varepsilon C_{t-1}} \tag{2.48}$$

$$J_t^D - \beta\theta^D E_t\left[\left(\frac{\Pi_{t+1}}{\Pi_t^{\phi^D}}\right)^{\sigma} J_{t+1}^D\right] = \frac{MC_t^D Y_t^D}{D_t} \tag{2.49}$$

$$H_t^D - \beta\theta^D E_t\left[\left(\frac{\Pi_{t+1}}{\Pi_t^{\phi^D}}\right)^{\sigma-1} H_{t+1}^D\right] = \left(1 - \frac{1}{\sigma}\right)\frac{Y_t^D}{D_t} \tag{2.50}$$

$$1 = (1-\theta^k)\left(\frac{J_t^k}{H_t^k}\right)^{1-\sigma} + \theta^k\left(\frac{\Pi_t}{\Pi_{t-1}^{\phi^k}}\right)^{\sigma-1}, \; k = C, D \tag{2.51}$$

Producers of the intermediate good used in the production of the nondurable consumption good solve (2.47), (2.48) and (2.51) and their counterparts in the intermediate goods sector that supplies the housing sector (2.49), (2.50) and (2.51).

2.2.5 Monetary and Macroprudential Policy

The monetary authority sets the nominal interest rate by operating a Taylor-type rule:

$$log\Big(\frac{R_t}{\bar{R}}\Big) = \rho_r log\Big(\frac{R_{t-1}}{\bar{R}}\Big) + (1-\rho_r)\Big(\rho_{r\pi} log\Big(\frac{\Pi_t}{\bar{\Pi}}\Big) + \rho_{ry} log\Big(\frac{Y_t}{\bar{Y}}\Big)\Big) + \epsilon_{M,t} \tag{2.52}$$

Similarly, there is a separate macroprudential authority that imposes a required reserve ratio rr_t to limit the ability of banks to engage in risky lending. Traditionally, required reserve ratios have been imposed as a floor on bank reserves, but in recent years, with the introduction of negative interest rates on excess reserves they also represent a type of ceiling. Reflecting this, the reserve requirement is a target relative to a steady state reserve ratio $\bar{rr}$ set to 10% – according to Gray (2011) this is the average required reserve ratio for most countries that use a reserve ratio as a policy instrument. We also follow Rubio and Carrasco-Gallego (2015) in setting the macroprudential policy rule to include credit growth SB_t, relative house prices Q_t, and output Y_t to reduce systemic risk and promote macroeconomic stability:

$$log\Big(\frac{rr_t}{\bar{rr}}\Big) = \phi_{rry} log\Big(\frac{Y_t}{\bar{Y}}\Big) + \phi_{rrsb} log\Big(\frac{SB_t}{\bar{SB}}\Big) + \phi_{rrq} log\Big(\frac{Q_t}{\bar{Q}}\Big) + \epsilon_{rr,t} \tag{2.53}$$

2.2.6 Market Clearing Conditions

In the non-durable sector, production is equal to demand by savers C_t and borrowers C_t^B:

$$Y_t^C = \lambda C_t + (1-\lambda)C_t^B. \tag{2.54}$$

Production in the housing goods sector is equal to the residential investments of savers and borrowers:

$$Y_t^D = \lambda I_t + (1-\lambda)I_t^B. \tag{2.55}$$

Total output is:

$$Y_t = Y_t^C + Q_t Y_t^D \tag{2.56}$$

and the total hours worked in each sector equals the aggregate supply of labour:

$$\int_0^1 L_t^k dk = \lambda \int_0^1 L_t^{k,j} dj + (1-\lambda)\int_0^n L^{B,k,j} dj,\ k = C, D \tag{2.57}$$

2.3 Calibration

2.3.1 Structural Parameters

Table 2.2 Calibrated Structural Parameters

Parameters	Value	Definition
		Households
β	0.99	Discount rate for savers
β^B	0.96	Discount rate for borrowers
γ	0.7368	Share of non-durable consumption in utility
ε	0.72	External habit formation for savers
ε^B	0.46	External habit formation for borrowers
φ	0.37	Inverse elasticity of labour supply
ι_L	0.72	Cost of reallocating labour across sector
δ	0.0125	Depreciation rate
ψ	1.75	Investment adjustment cost
α	0.94	Size of non-durable sector in GDP
λ	0.61	Fraction of savers in total population
		Firms
θ_C	0.62	Calvo lottery non-durables goods
θ_D	0.64	Calvo lottery housing goods
ϕ_C	0.15	Indexation non-durables goods
ϕ_D	0.25	Indexation housing goods
σ_C	10	Elasticity of substitution non-durable goods
σ_D	10	Elasticity of substitution housing goods
		Banks
μ	0.2	Share of housing value paid to debt-collection agency
σ_B	0.9688	Proportion of bankers that survive
ξ_B	0.0026	Transfers to new bankers
Θ	0.3841	Proportion of divertable assets
		Monetary and Macroprudential
$\bar{rr}$	0.1	Steady-state reserve ratio
ϕ	4.0	Steady state leverage ratio
$spread$	0.0025	Interest spread target
ρ_r	0.8	Interest rate smoothing in Taylor rule
ϕ_π	1.56	Response to inflation in Taylor rule
ϕ_y	0.2	Response to output growth in Taylor rule

Table 2.2 lists the calibrated values of the 27 structural parameters in the model. Mostly, the parameter values match the quarterly data estimates in Quint and Rabanal (2014) for the core members of the euro area.[9] Parameters for the banking sector are calibrated using Gertler and Kiyotaki (2010). The probability σ_B is chosen so that the banks survive on average eight

[9]Except for β^B which is adopted from Pearlman (2015).

years (32 quarters). Parameters for divertable assets and transfers to new banks, Θ and ξ_B, respectively, are computed to match an economy-wide leverage ratio of four, an average credit spread of 100 basis points per year, and as mentioned above, a reserve ratio of ten percent.[10]

2.3.2 Stochastic Parameters

Table 2.3 Calibrated Stochastic Shocks

Parameters	Value	Description
ρ_{ZD}	0.86	Productivity shock housing-autocorrelation
ρ_{ZC}	0.79	Productivity shock non-durable-autocorrelation
ρ_{ξ^D}	0.98	Preference shock housing-autocorrelation
ρ_{ξ^C}	0.66	Preference shock non-durable-autocorrelation
ρ_ω	0.84	Idiosyncratic housing quality shock-autocorrelation
σ_{ZD}	0.0162	Productivity shock housing-standard deviation
σ_{ZC}	0.0062	Productivity shock non-durable-standard deviation
σ_{ξ^D}	0.0309	Preference shock housing-standard deviation
σ_{ξ^C}	0.0187	Preference shock non-durable-standard deviation
σ_ω	0.1179	Idiosyncratic housing quality shock-standard deviation
σ_M	0.0012	Monetary shock-standard deviation

The business cycle movements in this model are driven by seven stochastic shocks to: non-durable and housing preferences, non-durable and housing technology, housing risk,[11] monetary policy, and the reserve ratio. All follow an AR(1) process in logs.[12] The shock processes are calibrated using the estimates in Quint and Rabanal (2014) to match the standard moments of the euro area data and presented in Table 2.3.

2.3.3 Variance Decomposition

To analyse the behaviour of the model, we start by decomposing the contribution of each of the six stochastic shocks to the variance of the model's most salient variables as presented in Table 2.4.[13] There are four shocks out of the six that generate nearly all the variance in real GDP, with 67% resulting from the two demand shocks (nondurable goods and housing preferences).

[10] The choice of a 10 percent reserve ratio matches the lowest required reserve ratios in emerging, middle- and low-income economies as shown in Table 2.1. We also consider a 30 percent reserve ratio to represent the required reserve ratios from 20 to 44 percent that prevail in Angola, Argentina, Liberia, Moldova, Nigeria, Suriname and Uruguay (also in Table 2.1).

[11] The same as Piazzesi and Schneider (2016) housing quality shock is used to highlight the properties of house prices and returns which could be connected to asset prices movement. Housing thus played an implicit role as part of payoffs and risk adjustment.

[12] The monetary policy shock is assumed to be white noise.

[13] Historically, central banks do not change reserve ratios frequently. Hence, when calculating the variance decomposition, we set it to a constant steady state value of 10% and exclude the macroprudentential rule (2.53).

In terms of the shocks associated with the housing sector, the demand shock for housing is the second most important, accounting for 30.99% of the variance, the shock to housing quality 11.55%, while productivity in that sector accounts for only 1.59%. Taken together, the three shocks associated with housing account for nearly half (44.35%) the variance associated with the business cycle, matching the observations made in Leamer (2008) and Leamer (2015).

Shocks to the demand for housing generate 79.93% of the variance in credit and together with the shock to housing quality drive nearly 100% of the credit cycle. Housing investment as a whole is largely driven by shocks to the demand for housing (81.60%) and then sector supply shocks (18.68%), but not by quality shocks. These results are also consistent with estimates by Musso, Neri and Stracca (2011), and Brzoza-Brzezina, Kolasa and Makarski (2015), which find that changes in monetary policy have little effect on housing investment whereas, shocks to housing quality generate more than half the variance in the policy interest rate. Indeed, outside of their direct impact on the policy rate, monetary shocks have little effect on the economy beyond their impact on the inflation rate for nondurable consumption. At the same time, the quality shocks account for nearly all the variance in the net worth of banks (82.44%) and the interest rate they charge borrowers (93.57%).

2.3.4 Static Reserve Requirements

Figure 2.3 shows the distributive implications of operating the different levels of static reserve ratio in stochastic model. A similar result for the steady state of the model is shown analytically in Appendix A.4, for a plausible range of parameters (for the case of no banking constraints, for simplicity). We now consider the model with a benchmark of monetary policy alone. We show that there is a welfare trade-off between borrowers and savers. In both cases, borrowers tend to enjoy welfare gains as reserve ratio increases. By contrast, savers tend to experience lower welfare as the level of reserve ratio increases. In aggregate, total household welfare exhibits a minimal gain given that the gains by borrowers offset the losses by savers. These results underscore that a higher reserve ratio increases costs for banks as only a portion of the available deposits can be used for lending activities. As banks have less funds to lend, they also reduce excessive risk-taking. From doing so, banks are able to eliminate extending loans to subprime borrowers and reduce the probability of default as shown in Figure 2.4. However, banks accumulate less profits in the process which are then remitted to savers as owners of banks. Savers also earn lower returns on deposits as fewer funds are intermediated. Meanwhile, worthy borrowers enjoy a stable flow of credit as probability of default decrease with higher

Table 2.4 Variance Decomposition

	Contribution of each shock (in percent)					
	Nondurable goods productivity	Housing productivity	Nondurable goods preference	Housing preference	Housing risk	Monetary policy
Real GDP	18.76	1.81	35.94	30.99	11.55	0.96
Total loans	0.04	0.09	0.05	79.93	19.88	0.01
House prices	1.52	4.05	0.52	93.82	0.07	0.02
Total consumption	25.15	0.04	55.04	2.53	16.00	1.24
Total investment	0.02	18.61	0.05	80.83	0.44	0.04
House price inflation	5.99	27.29	2.93	55.82	6.61	1.36
Nondurable goods inflation	37.56	0.37	2.78	8.97	39.62	10.69
Lending rate	0.89	0.34	0.27	4.81	93.57	0.12
Policy rate	10.92	0.29	12.18	13.94	36.94	25.73
Reserve ratio	0.80	0.38	0.03	88.49	10.25	0.04
Banks net worth	0.40	0.57	0.11	16.43	82.44	0.06
Savers consumption	29.49	0.02	64.90	2.78	2.40	0.41
Borrowers consumption	5.69	0.07	12.96	9.36	70.47	1.44
Savers investment	0.08	29.99	0.18	67.48	2.22	0.04
Borrowers investment	0.05	5.47	0.04	88.11	6.13	0.20

Fig. 2.3 Welfare in Consumption Equivalent in Stochastic Model

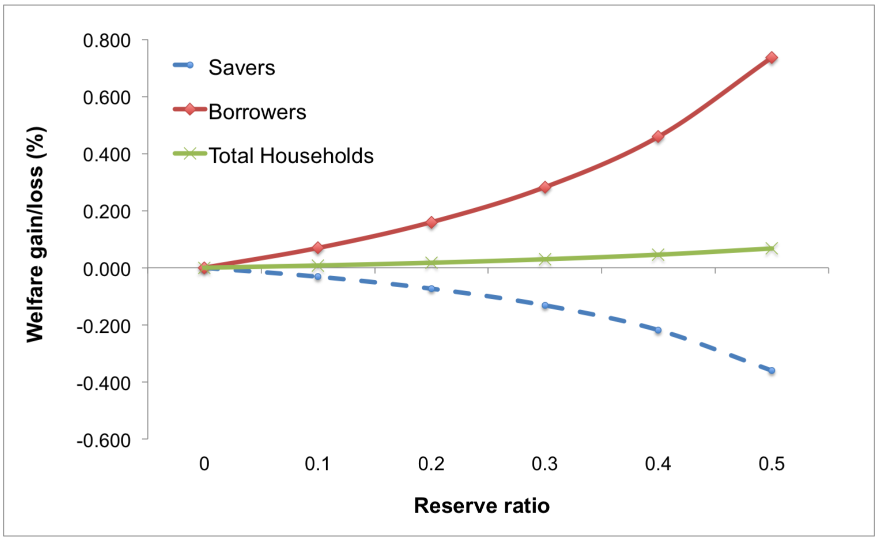
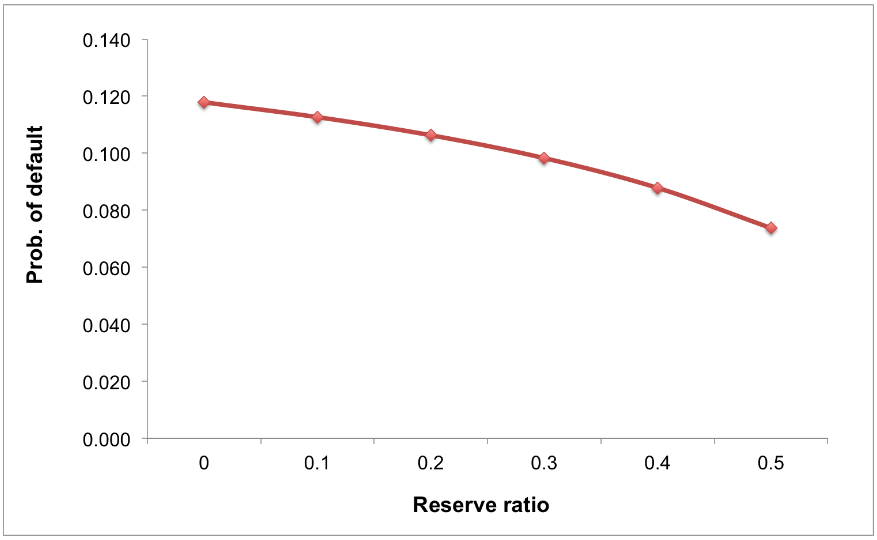


Fig. 2.4 Probability of Default at Different Levels of Reserve Ratio



reserve ratio. This narrative reflects why savers experience welfare losses and borrowers increase welfare gains when the reserve ratio increases.

2.4 Model Analysis

2.4.1 Optimal Policy

What criterion should policy makers use to determine the parameter values in both (2.52) and (2.53)? One option is to follow Angelini, Neri and Panetta (2014) and make stabilisation of the economy the goal of monetary and macroprudential policy. Instead we opt for a policy that maximises a population-weighted aggregate measure of welfare across the two types of agents and then consider the distributive welfare impact these policies generate.

First, we solve the benchmark version of the model—where neither monetary policy or macroprudential policy is employed—using second-order approximations, and then calculate individual utility measures for savers and borrowers:

$$\Omega_t^S \equiv E_t\left\{\sum_{\tau=0}^{\infty}\beta^{\tau}\left[\gamma\xi_{t+\tau}^{C} log(C_{t+\tau}^{j} - \varepsilon C_{t-1+\tau}) + (1-\gamma)\xi_t^{D} log(D_{t+\tau}^{j}) - \frac{(L_{t+\tau}^{j})^{1+\varphi}}{1+\varphi}\right]\right\}, \quad (2.58)$$

$$\Omega_t^B \equiv E_t\left\{\sum_{\tau=0}^{\infty}\beta^{B,\tau}\left[\gamma\xi_{t+\tau}^{C} log(C_{t+\tau}^{B,j} - \varepsilon^B C_{t-1+\tau}^{B}) + (1-\gamma)\xi_{t+\tau}^{D} log(D_{t+\tau}^{B,j}) - \frac{(L_{t+\tau}^{B,j})^{1+\varphi}}{1+\varphi}\right]\right\}. \quad (2.59)$$

This process is then repeated again, with the macroprudential policy using the reserve ratio activated, to generate the utility measures $\Omega^{i,RR}$, $i = B, S$.

To calculate the welfare impact of implementing monetary (MP), or macroprudential policy (RR), or both (MPRR), in terms of consumption equivalents, we follow Ascari and Ropele (2012) and Rubio and Carrasco-Gallego (2014) to derive consumption equivalents—the constant fraction of consumption, each type of agent would sacrifice in order to obtain the benefits of the policy:

$$CE^B = exp\Big[(1-\beta^B)(\Omega^{B,j} - \Omega^B)\Big] - 1, \; j \in \{MP, RR, MPRR\} \quad (2.60)$$

$$CE^S = exp\Big[(1-\beta)(\Omega^{S,j} - \Omega^S)\Big] - 1, \; j \in \{MP, RR, MPRR\} \quad (2.61)$$

and the total welfare effect, which is the population weighted sum of the two:

$$CE = (1-\lambda)CE^B + \lambda CE^S. \quad (2.62)$$

Historically, central banks set both policy interest rates and required reserve ratios. However, in the wake of the 2008 financial crisis, as governments have looked for tools beyond traditional monetary policy to help stabilise the economy with special emphasis on the financial system. In the UK, these macroprudential tools are situated within the monetary authority—both the Financial Policy Committee and the Prudential Regulation Authority operate under the aegis of the Bank of England. By contrast, the Financial Stability Oversight Council in the US is chaired by the Secretary of the Treasury and of the ten voting members only the Chairman of the Federal Reserve represents the central bank. The European Systemic Risk Board occupies a middle ground. It is independent of the European Central Bank but is chaired by its President. The vice president of the ECB is a voting member of the board, as are the governors of the Eurozone national central banks alongside a representative of the EU and several other European institutions. We therefore follow Angelini, Neri and Panetta (2014) and consider whether situations might arise where two different agencies, a central bank setting monetary policy and a macroprudential policy agency might cooperate, or given the different tools at their disposal, operate independently without any cooperation in a way that might be detrimental to stability or welfare.

We compute the parameters associated with both the monetary (2.52) and macroprudential policy rules (2.53) that optimise total welfare (2.62) as in Quint and Rabanal (2014). Under *cooperation*:

$$(\rho_r^{c*}, \phi_\pi^{c*}, \phi_y^{c*}, \phi_{rry}^{c*}, \phi_{rrsb}^{c*}, \phi_{rrq}^{c*}) = arg\ max\ CE(\rho_r, \phi_\pi, \phi_y, \phi_{rry}, \phi_{rrsb}, \phi_{rrq}), \tag{2.63}$$

the two sets of parameters are optimised jointly and under *noncooperation* we assume each agency optimises the relevant parameters of either (2.52) or (2.53) independently:

$$(\rho_r^{n*}, \phi_\pi^{n*}, \phi_y^{n*}) = arg\ max\ CE(\rho_r, \phi_\pi, \phi_y; \phi_{rry}^{n*}, \phi_{rrsb}^{n*}, \phi_{rrq}^{n*}), \tag{2.64}$$

$$(\phi_{rry}^{n*}, \phi_{rrsb}^{n*}, \phi_{rrq}^{n*}) = arg\ max\ CE(\phi_{rry}, \phi_{rrsb}, \phi_{rrq}; \rho_r^{n*}, \phi_\pi^{n*}, \phi_y^{n*}). \tag{2.65}$$

Table 2.5 Optimising Parameters

	Policy rule coefficients					
	ρ_r	ϕ_π	ϕ_y	ϕ_{rry}	ϕ_{rrsb}	ϕ_{rrq}
NP baseline	0	1.0001	0	0	0	0
MP	0.466	1.054	0.069	0	0	0
MP(10%)	0.466	1.054	0.069	0	0	0
MP(30%)	0.466	1.054	0.069	0	0	0
RR(10%)	0	1.0001	0	0.634	0.496	1.092
RR(30%)	0	1.0001	0	0.634	0.496	1.092
MPRR(10%)	0.653	1.736	0.171	0.370	0.257	0.326
MPRR(30%)	0.646	1.742	0.181	0.359	0.246	0.318

NP means no policy (policy rate is fixed at a constant real value). MP means monetary policy only. RR means only reserve ratio rule operates. MPRR means monetary policy plus reserve ratio rule.

Several things emerge from the results in Table 2.5. In Angelini, Neri and Panetta (2014), stabilisation rather than consumer welfare is the goal and in the noncooperative case each agency minimizes its own loss function; the parameters in the cooperative and noncooperative cases differ. Here since both agencies are maximising consumer welfare, what emerges is that the parameters for both cases are the same.[14] This means it does not matter whether the two policies fall within the remit of the central bank as in the UK, or macroprudential policy is managed by an independent agency as in the US or the EU. Moreover, the parameters associated with optimal monetary policy remain the same whether or not this type of macroprudential policy is operating or not.

It is no surprise that when macroprudential policy operates on its own (RR(10%) and RR(30%)), in the absence of active monetary policy, the parameters associated with this policy, ϕ_{rry}, ϕ_{rrsb} and ϕ_{rrq} in (2.53) are larger than when macroprudential policy accompanies monetary policy (MPRR(10%) and MPRR(30%)). This is particularly the case for ϕ_{rrq}, which determines the response of the reserve ratio to deviations from steady state house prices. By contrast, the parameters associated with the Taylor rule (2.52), ρ_r, ϕ_π and ϕ_y, appear larger

[14]The cooperative and noncooperative solutions are the same due to the noncooperative solution just being a team solution as both policymakers have identical welfare functions to maximise. If there were a high probability of violating the ZLB (which we do not have in this model), then we would have introduced a cost in the central bank's objective function that would have penalised deviations from steady state interest rate, and likewise for macroprudential - penalising deviations from steady state reserve ratio. Then their objective functions would have been distinct.

when monetary policy operates alone (MP) rather than together with macroprudential policy.[15] However, the response of the central bank to inflation is nearly identical across the three regimes (MP, RR(10%) and RR(30%)) once we consider the impact of the higher rate of interest rate smoothing in the presence of macroprudential policy. However, the central bank should behave more aggressively when setting policy in response to deviations in output when it can do so in tandem with macroprudential policy.

2.4.2 Impulse Response Functions

We use the parameters in Table 2.5 to generate impulse response functions (IRFs) in response to the two of three shocks associated with the housing sector that together account for 43% of the variance in real GDP and nearly all the variance in loans in Table 2.4. We view these two variables (housing risk shock in Figures 2.5 and 2.6 and housing demand shock in Figures 2.7 and 2.8) as the main proxies for credit cycles. We also generate IRFs for shocks to technology and demand in the nondurable goods sector in Figures 2.9 to 2.12 as they together account for 54.7% of the variance in GDP. In each case we consider how output, consumption, prices, loan activity, investment, interest rates and banks' net worth vary, differentiating between the impact of policy on the behaviour of borrowers and savers when monetary policy operates alone (MP), macroprudential policy operates on its own with steady state reserve requirements of 10% (RR(10%) and 30% (RR(30%)), and where monetary policy and macroprudential operate in tandem with steady state reserve requirements of 10% (MPRR(10%) and 30% (MPRR(30%)). All are juxtaposed against a baseline case of no policy (NP) where there is no macroprudential policy or required reserve ratio and the policy rate is fixed at a constant real value.[16]

Figures 2.5 and 2.6 show what happens when the standard deviation of housing quality in (2.17) temporarily increases due to a shock equivalent to 11.79% (one standard deviation in the shock process). The distribution of housing quality becomes more skewed to the left, prompting more borrowers to default on their loans. Banks' net worth declines, and their balance sheets deteriorate. As their leverage ratios increase, banks offer fewer new loans and charge higher interest rates. Though savers take advantage of the decline in house prices and invest in more housing, this is not enough to compensate for the decline in borrowers' investment and overall,

[15]The response of policy to output and inflation shocks is larger given that the relevant coefficients are multiplied by 1-ρ_r.

[16]For the case of no policy (NP) and macroprudential policy alone (RR(10%) and (RR(30%), we set the coefficients in (2.52): ρ_r=0, ϕ_y=0 and ϕ_π=1.0001, keeping the real policy rate nearly fixed while ensuring saddle path stability of the economy. The IRFs in Figures 2.5 to 2.12 are calculated for 20 quarters. The IRFs for 100 quarters, Figures A.1, A.2 and A.5 to A.8, and 200 quarters, Figures A.3 and A.4 can be found in the Appendix, Section A.5.

fewer houses are built.[17] Output drops and so does inflation, prompting a decline in the policy rate and further increasing the interest spread.

When monetary policy operates alone, the high coefficient on inflation and low coefficient on output in the optimised rule Table 2.5 means that the central bank immediately lowers the policy rate by 5.4 basis points and keeps it there for an additional period in the second period in response to the 0.08% drop in nondurable goods inflation. By contrast, if the policy rate is kept fixed at its steady state real value, the drop in inflation is greater and so is the initial response. However, the policy rate recovers more quickly whereas when the Taylor rule operates, the policy rate remains low for longer.

Figure 2.5 also demonstrates that macroprudential policy, even if it operates completely on its own, stabilises the economy by dampening the financial accelerator mechanism thus performing a role similar to monetary policy. However, the negative risk shock has a differential impact on savers and borrowers; despite the decline in output, the consumption of the former increases on impact and remains high for six quarters while borrowers' consumption bears the full impact of the downturn. A policy that relies on macroprudential policy only to stabilise the economy slightly ameliorates this effect. Macroprudential policy, either on its own, where the reserve requirement drops on impact from 10% to 9.92% or from 30% to 29.78%, or when combined with monetary policy (MPRR(10%) and MPRR(30%)) in Figure 2.6, where the reserve requirement drops on impact from 10% to 9.96% or from 30% to 29.89%, stabilises the economy and more generally, as we shall see in Section 2.4.3, also generates a small overall welfare benefit to borrowers at the expense of savers. This differential impact accelerates as the ratio shifts higher from 10% to 20% to 30% as it does when reserve ratios are static in Figure 2.3.

Figures 2.7 and 2.8 show the response of the economy to a negative one standard deviation shock to the housing preference parameter. The initial impact on GDP is similar to the impact from the risk shock, but GDP carries on declining for another quarter. Overall, the impact of the demand shock lasts for a very long time, far longer than the impact from the risk shock and so the recovery is much slower (see Figures A.3 and A.4). Total investment drops on impact by 0.1% and then continues to decline for another three quarters before slowly recovering. Total loans decline on impact and then carry on declining for 21 quarters before they begin to recover, but even after 100 quarters are still 1.06% below their steady state level and bank's net worth still only three-quarters of the way recovered from their lowest point in quarter 30.

[17] Figures A.1 and A.2 show that over the course of the first decade, investment by borrowers and particularly savers, oscillate around their steady state values in response to the risk shock.

Fig. 2.5 IRFs with Housing Risk Shock (Deviations from Steady State)

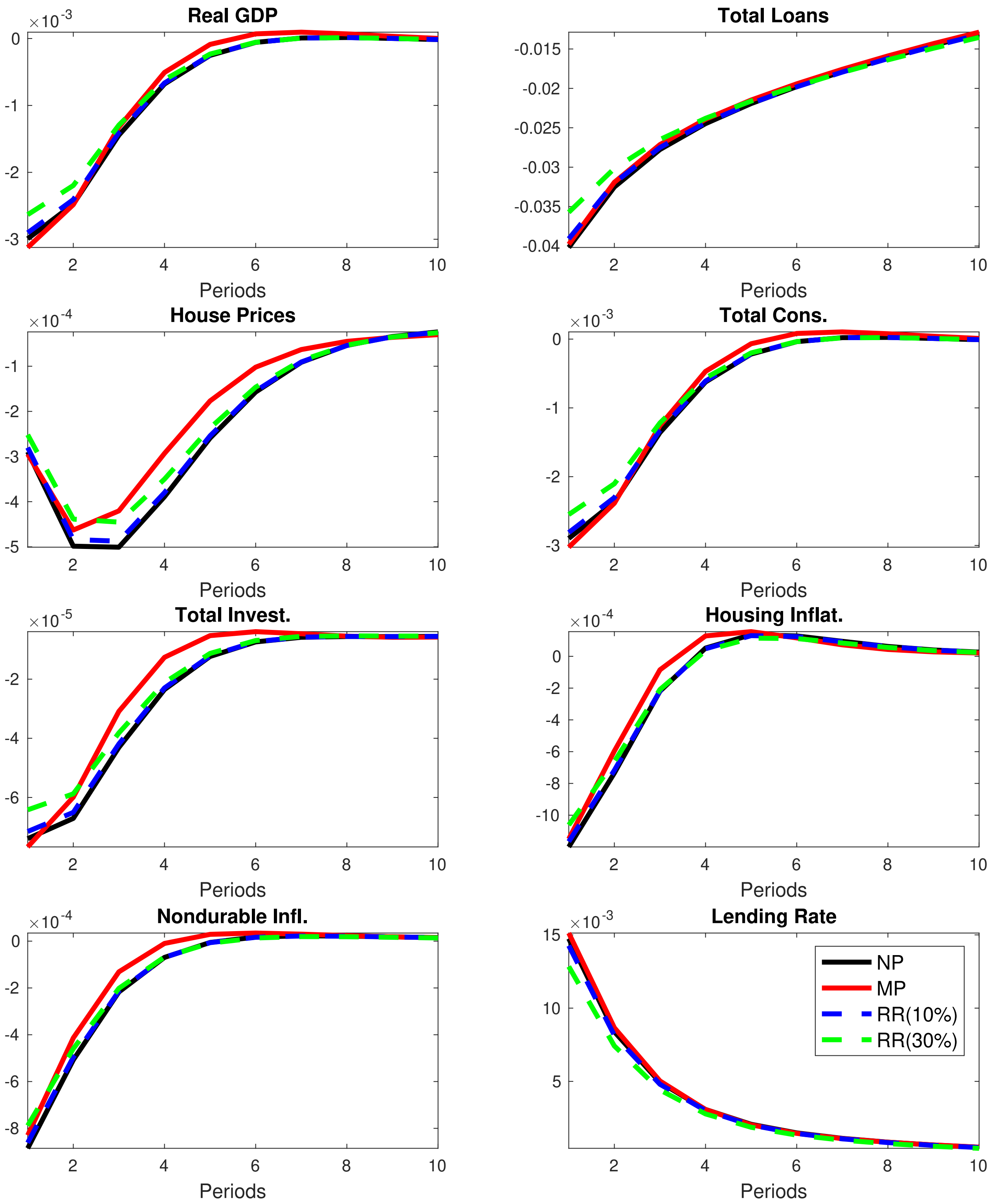


Fig. 2.5 (Continued) IRFs with Housing Risk Shock (Deviations from Steady State)

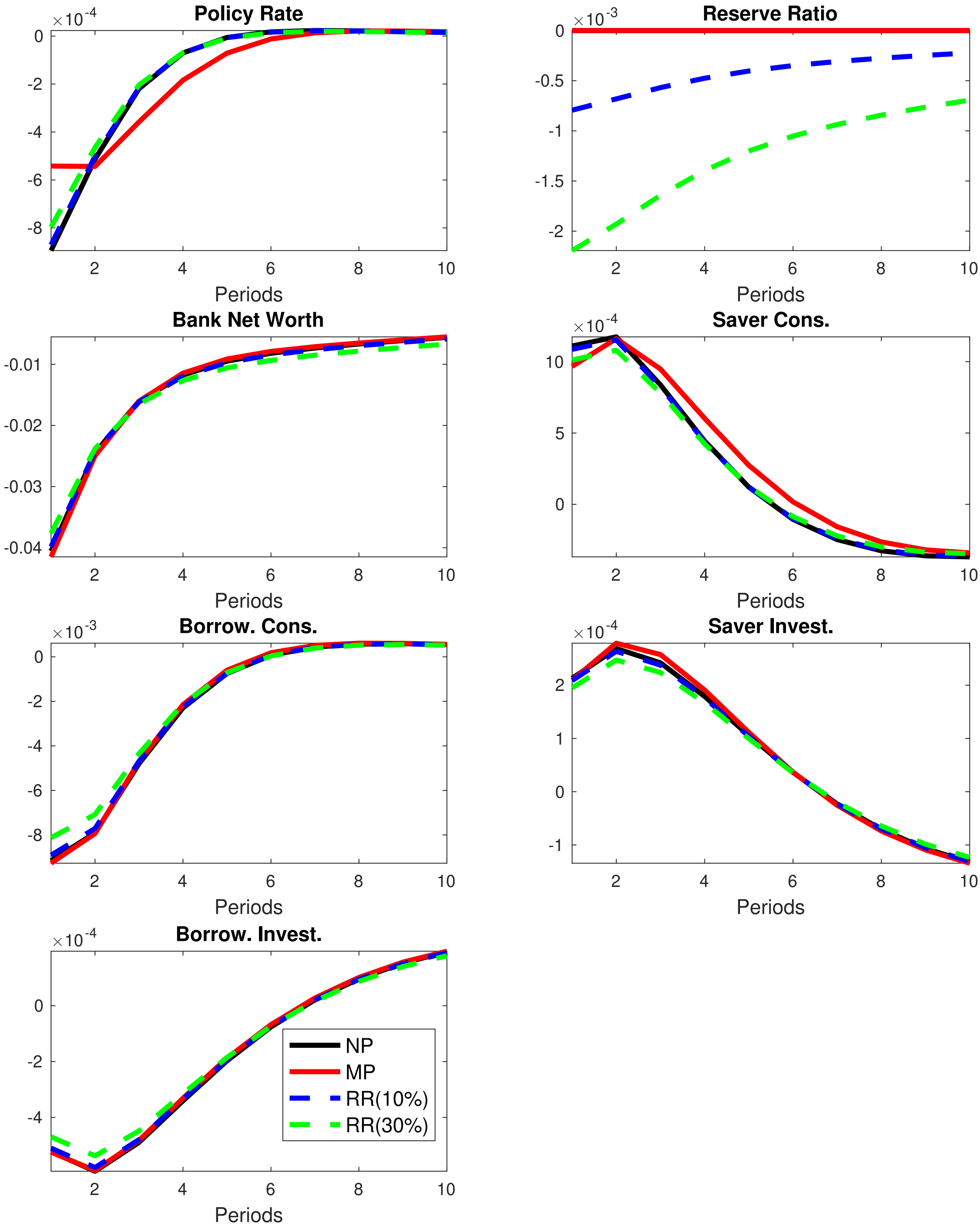


Fig. 2.6 IRFs with Housing Risk Shock (Deviations from Steady State)

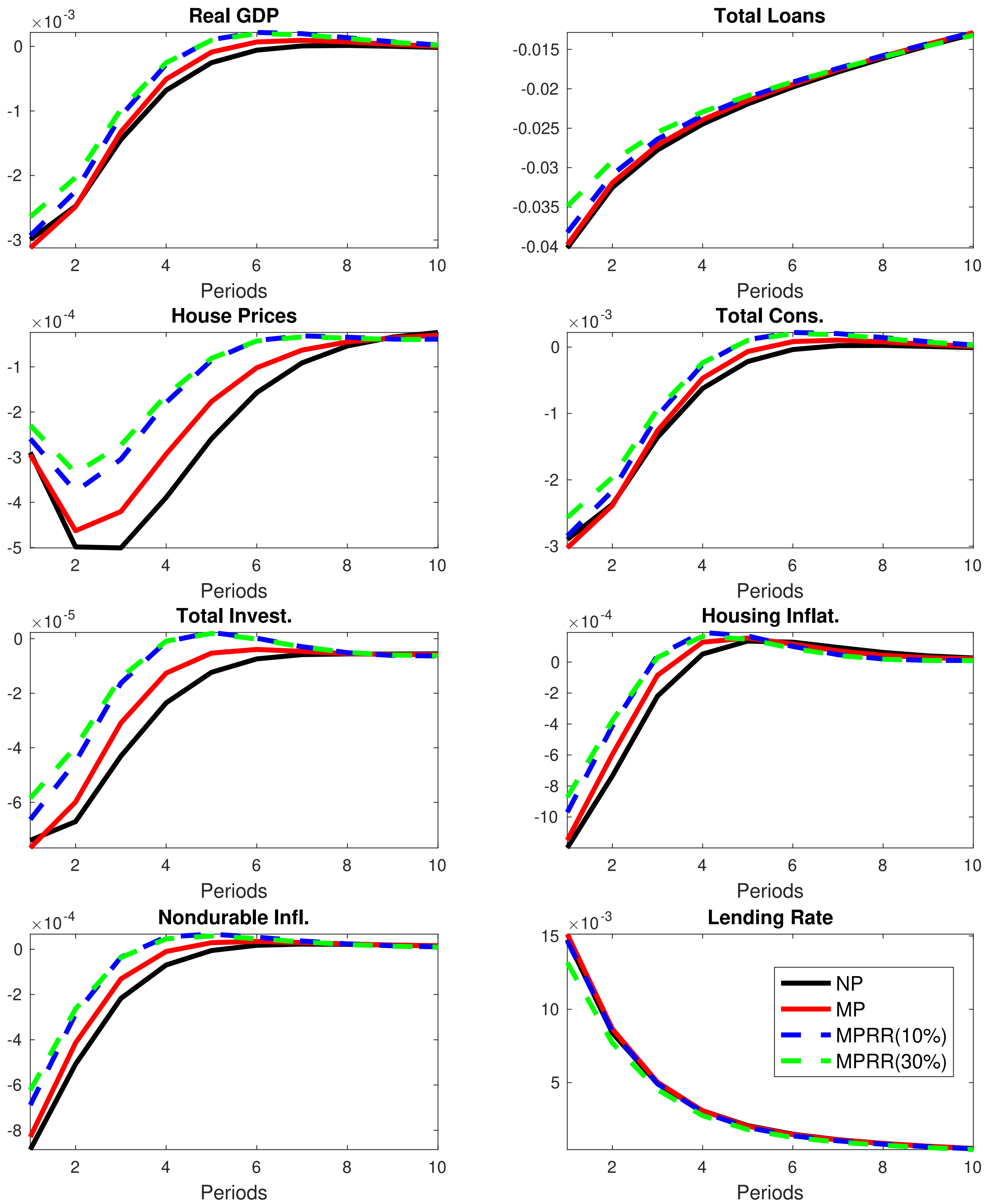


Fig. 2.6 (Continued) IRFs with Housing Risk Shock (Deviations from Steady State)

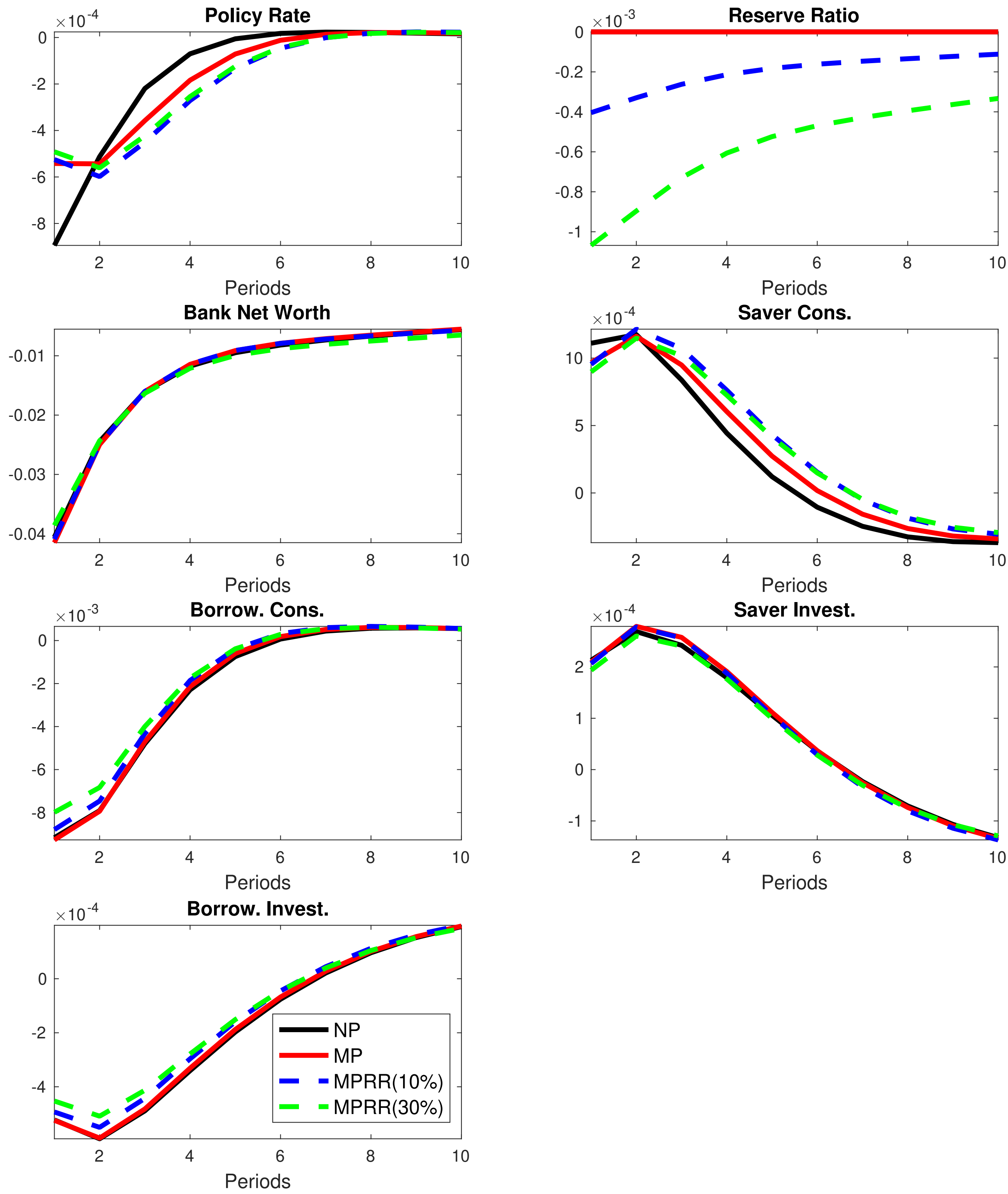


Fig. 2.7 IRFs with Housing Demand Shock (Deviations from Steady State)

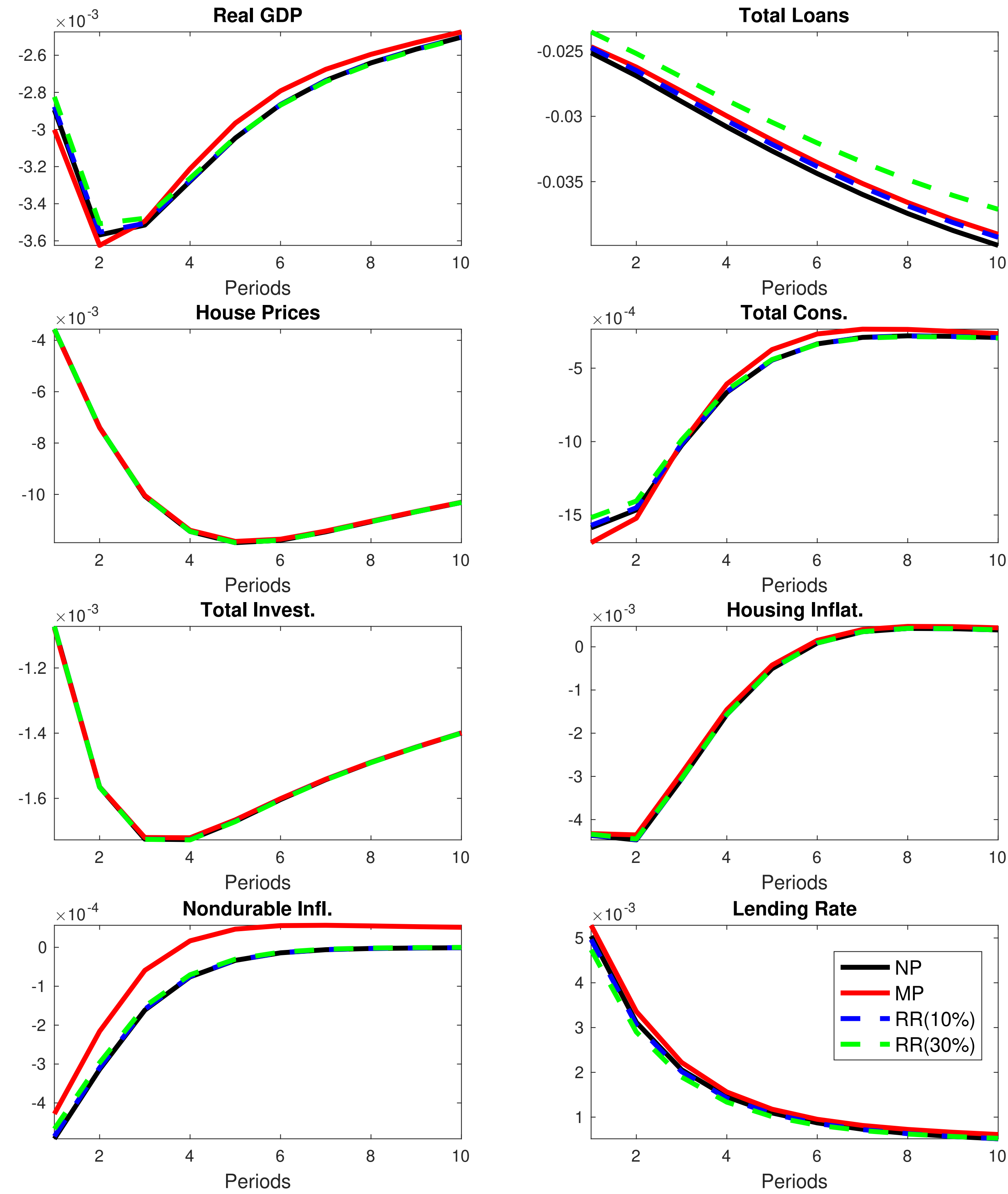


Fig. 2.7 (Continued) IRFs with Housing Demand Shock (Deviations from Steady State)

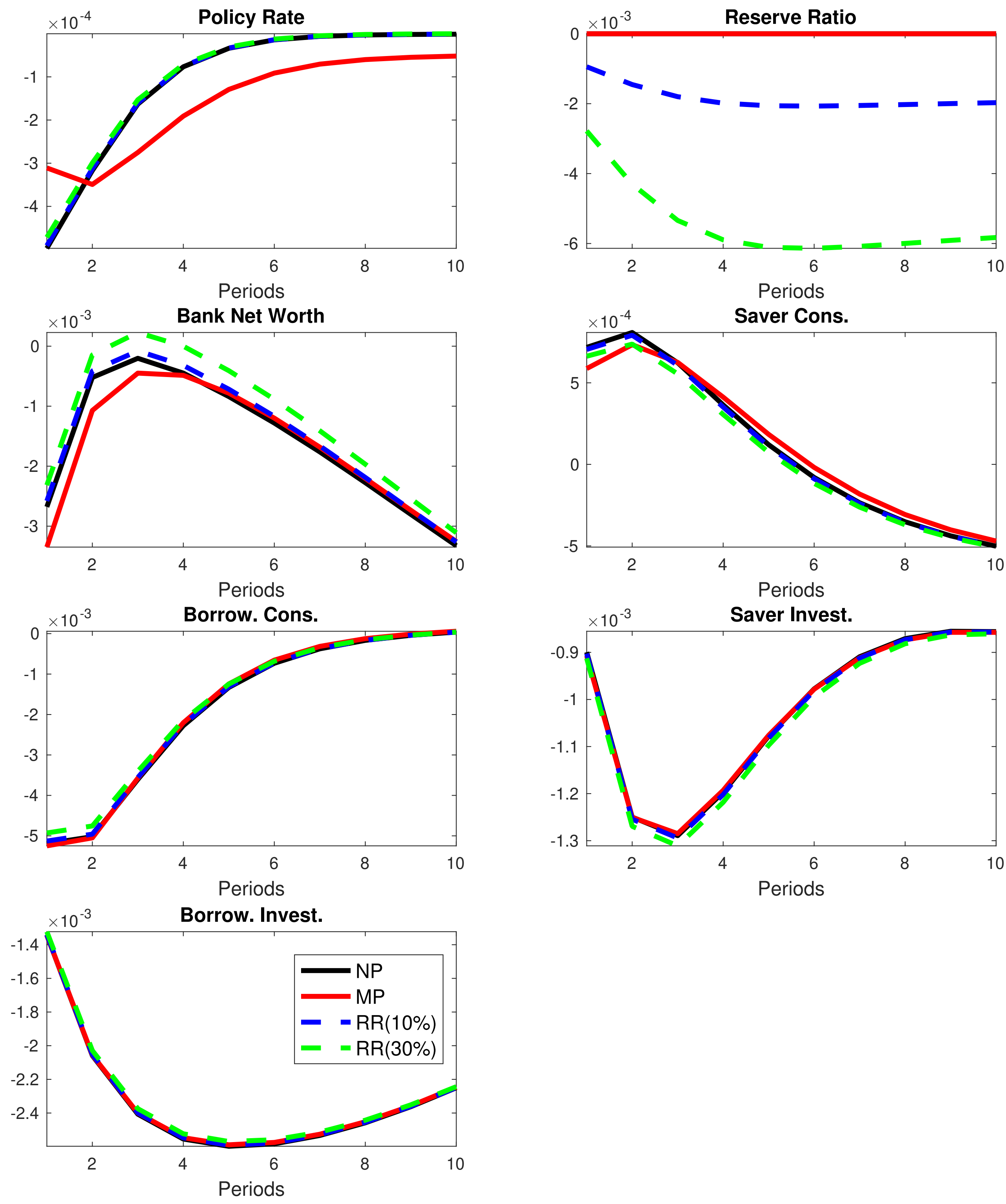


Fig. 2.8 IRFs with Housing Demand Shock (Deviations from Steady State)

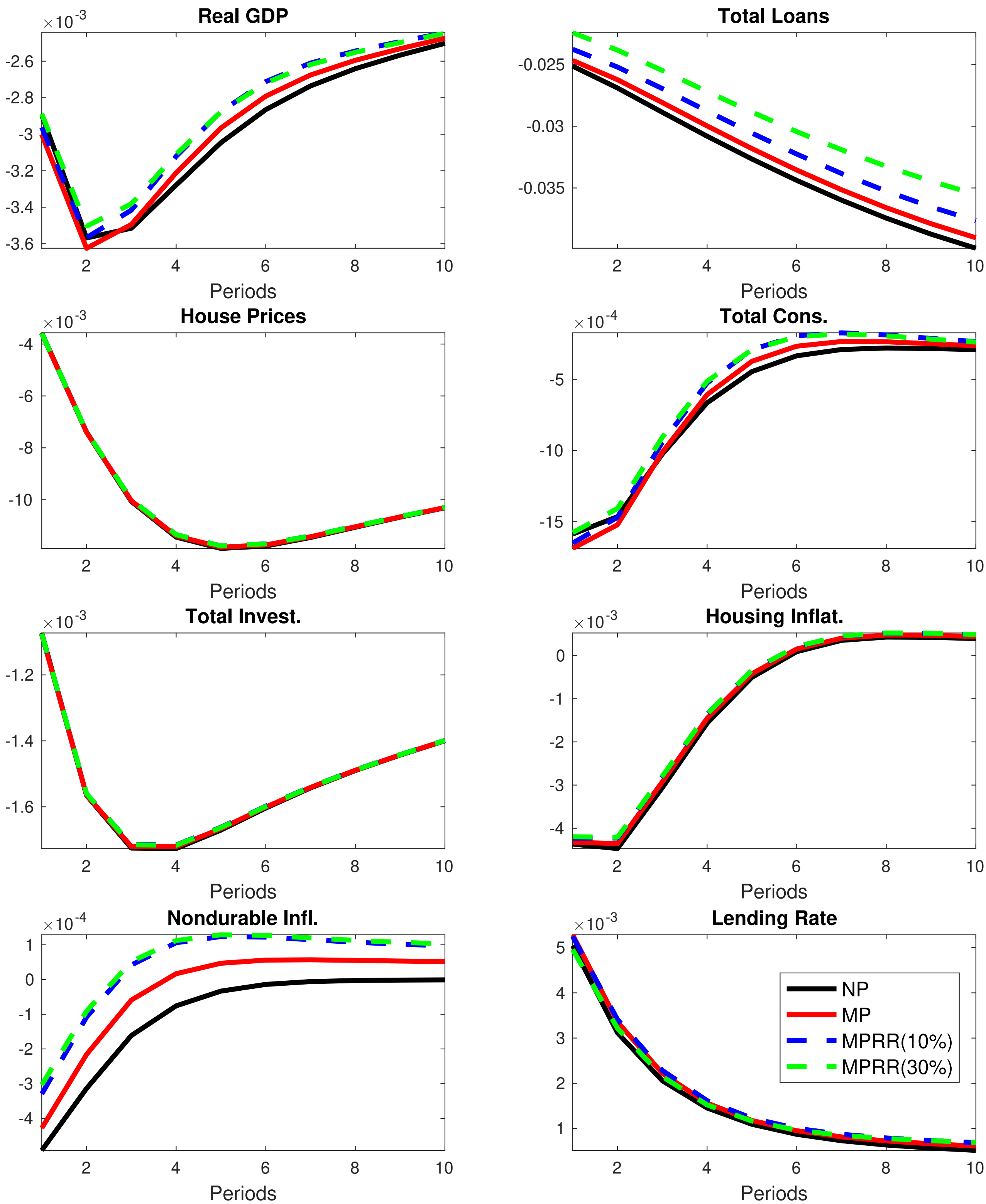


Fig. 2.8 (Continued) IRFs with Housing Demand Shock (Deviations from Steady State)

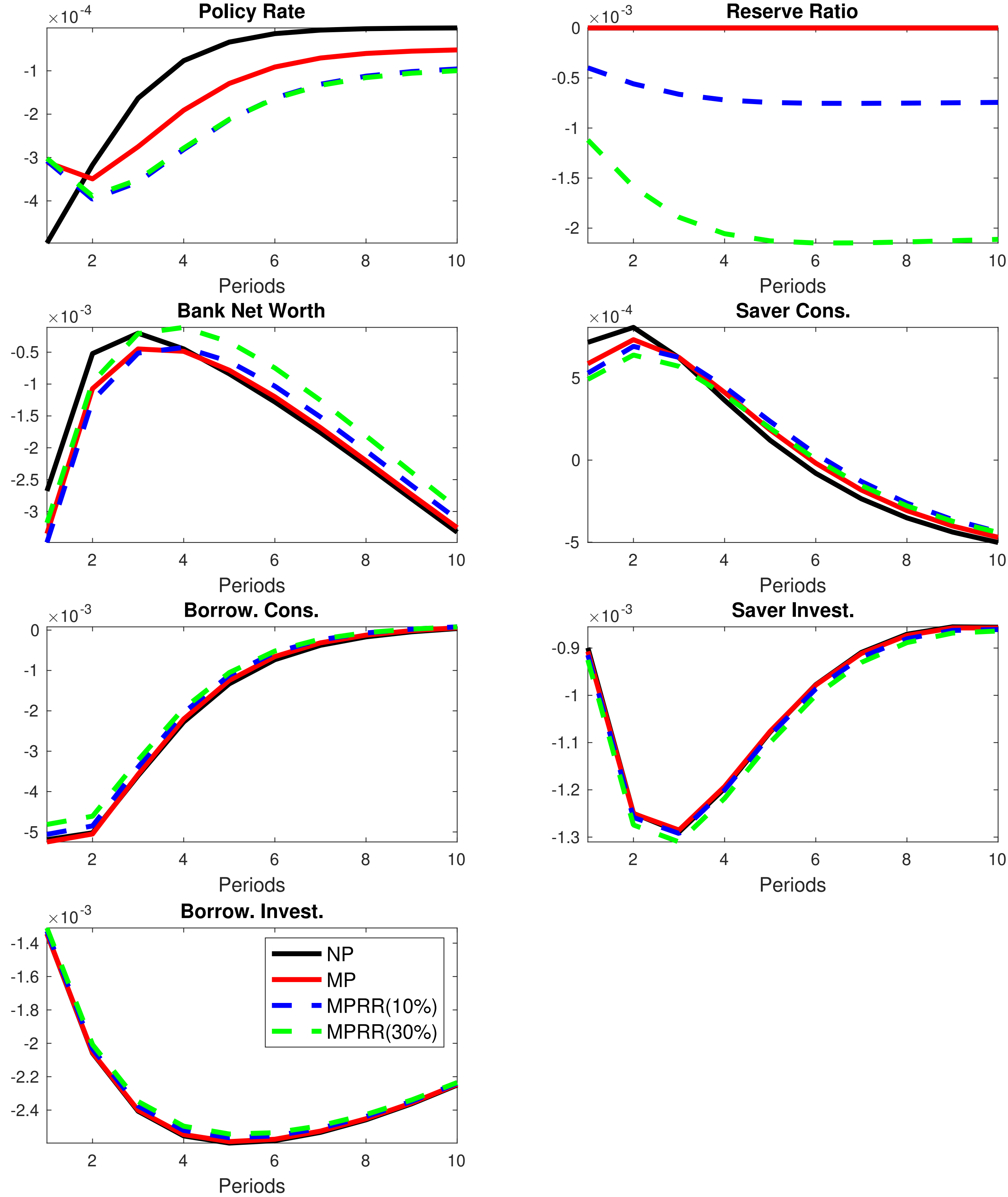


Fig. 2.9 IRFs with Non-Durable Technology Shock (Deviations from Steady State)

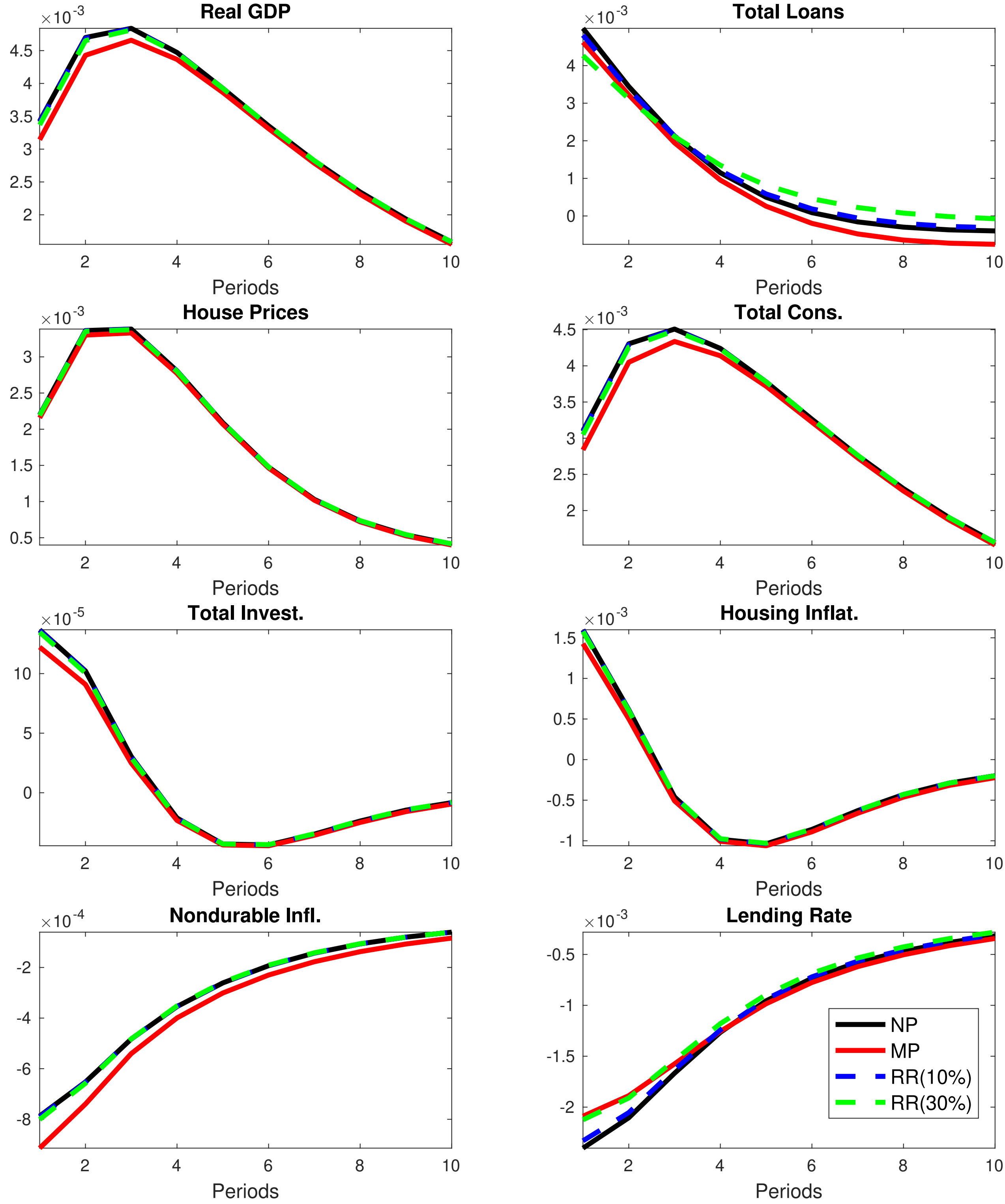


Fig. 2.9 (Continued) IRFs with Non-Durable Technology Shock (Deviations from Steady State)

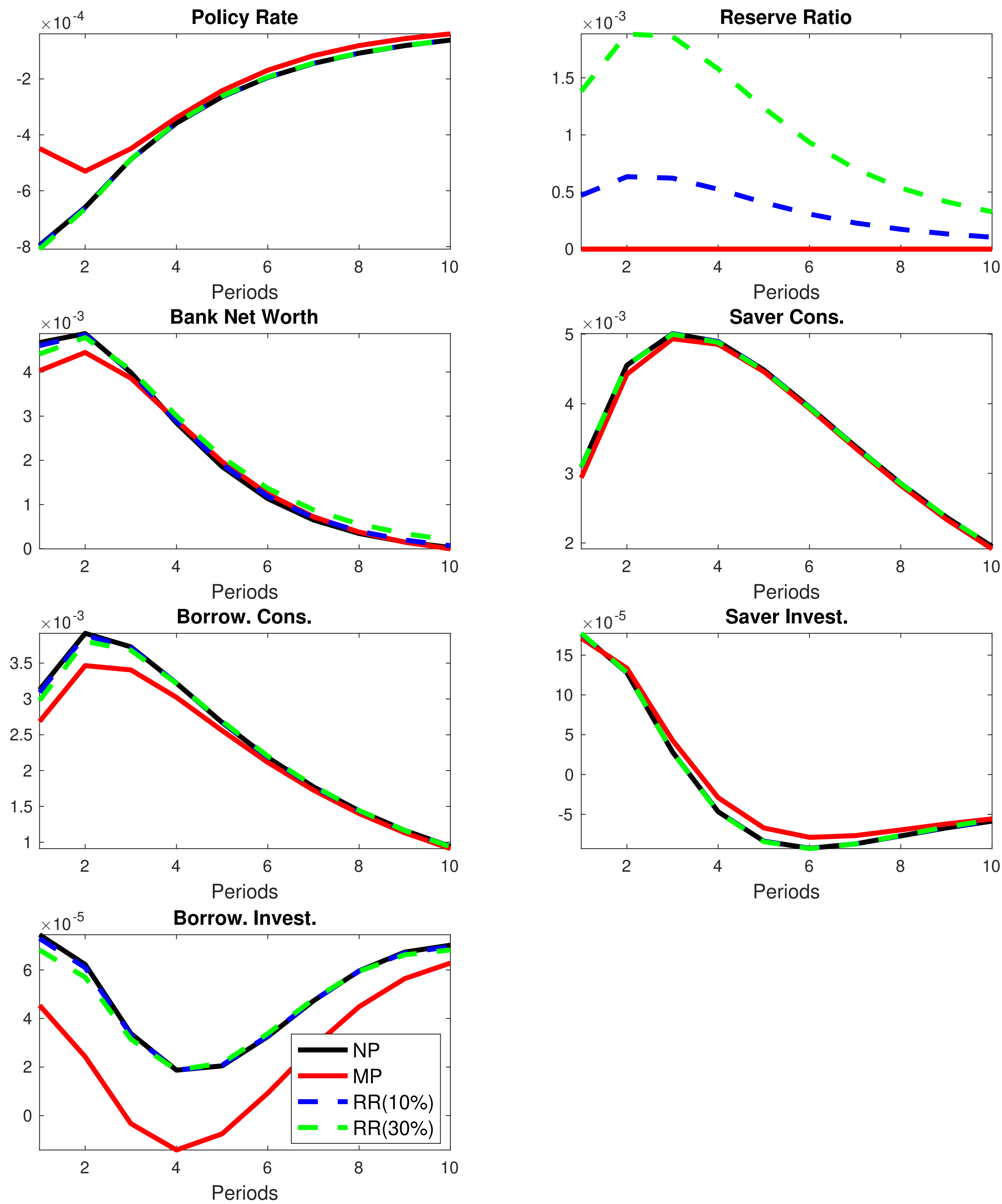


Fig. 2.10 IRFs with Non-Durable Technology Shock (Deviations from Steady State)

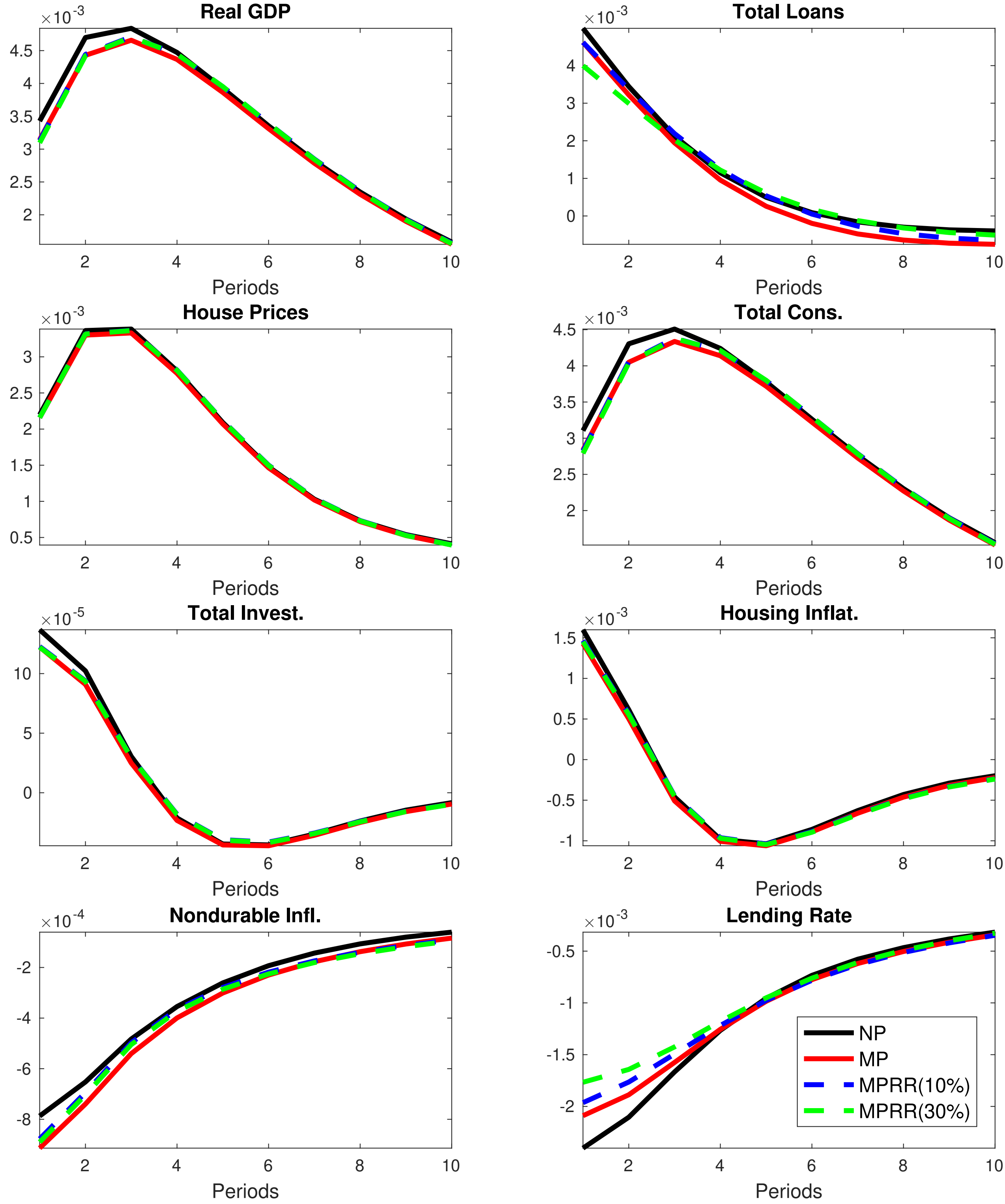


Fig. 2.10 (Continued) IRFs with Non-Durable Technology Shock (Deviations from Steady State)

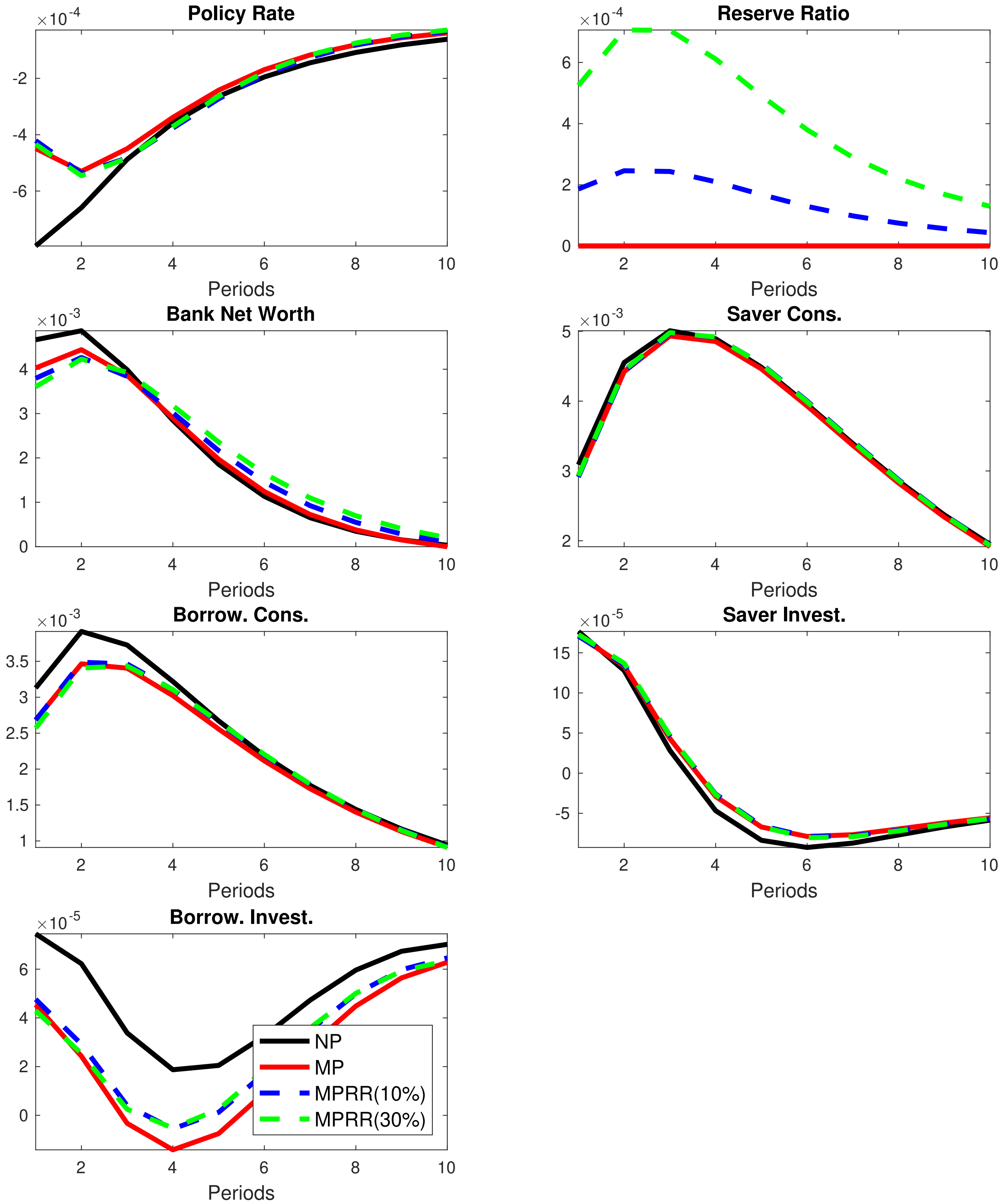


Fig. 2.11 IRFs with Non-Durable Demand Shock (Deviations from Steady State)

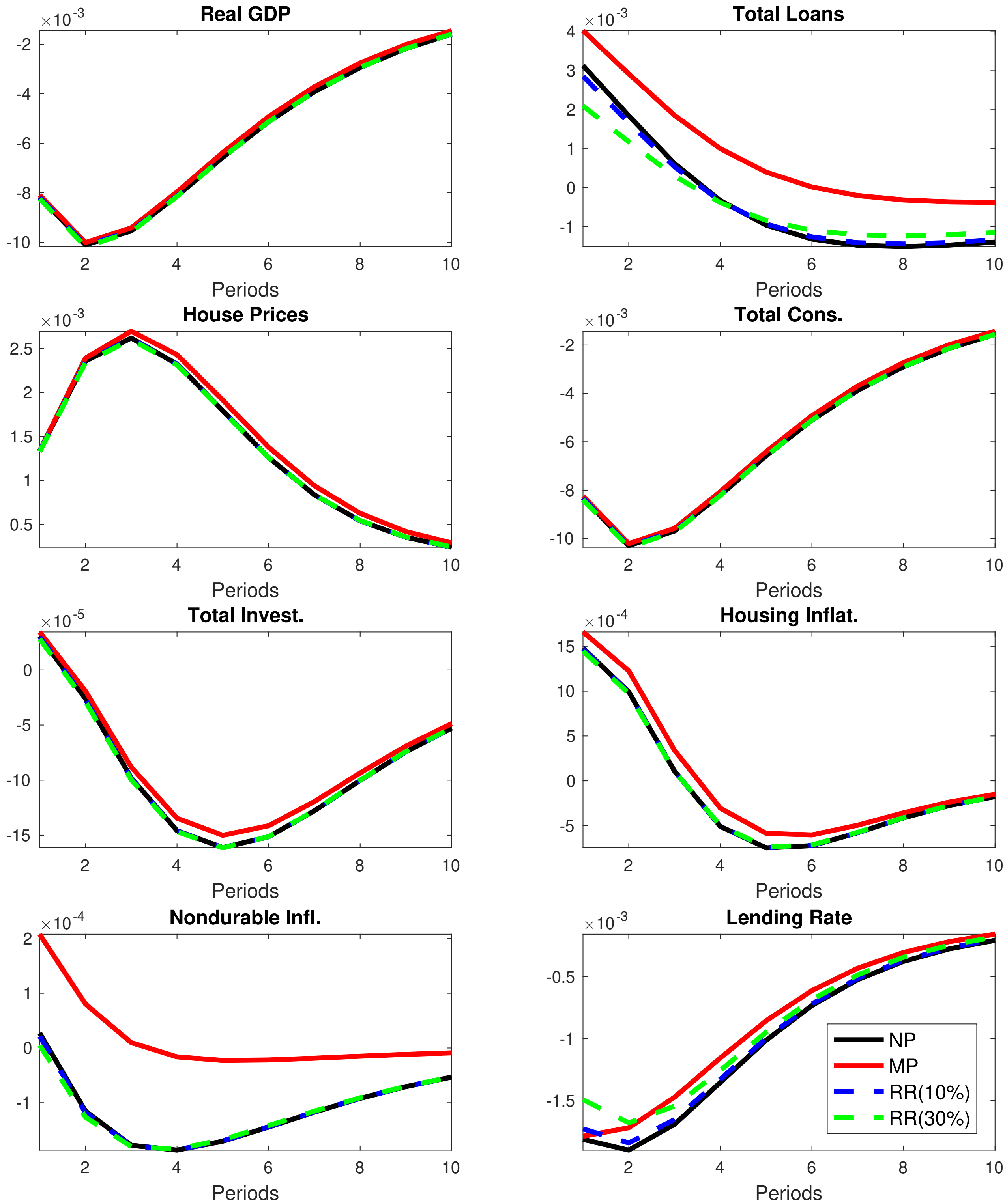


Fig. 2.11 (Continued) IRFs with Non-Durable Demand Shock (Deviations from Steady State)

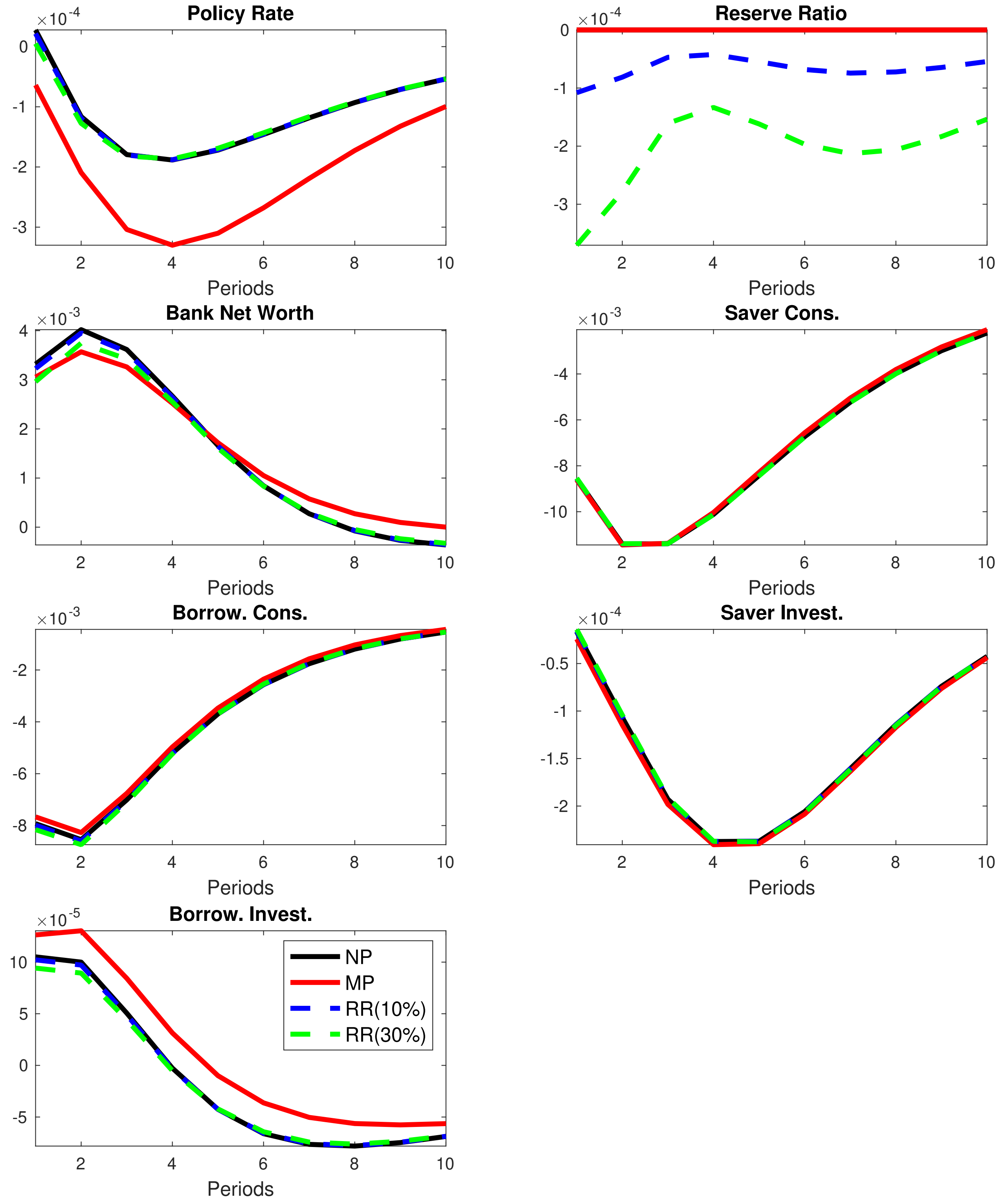


Fig. 2.12 IRFs with Non-Durable Demand Shock (Deviations from Steady State)

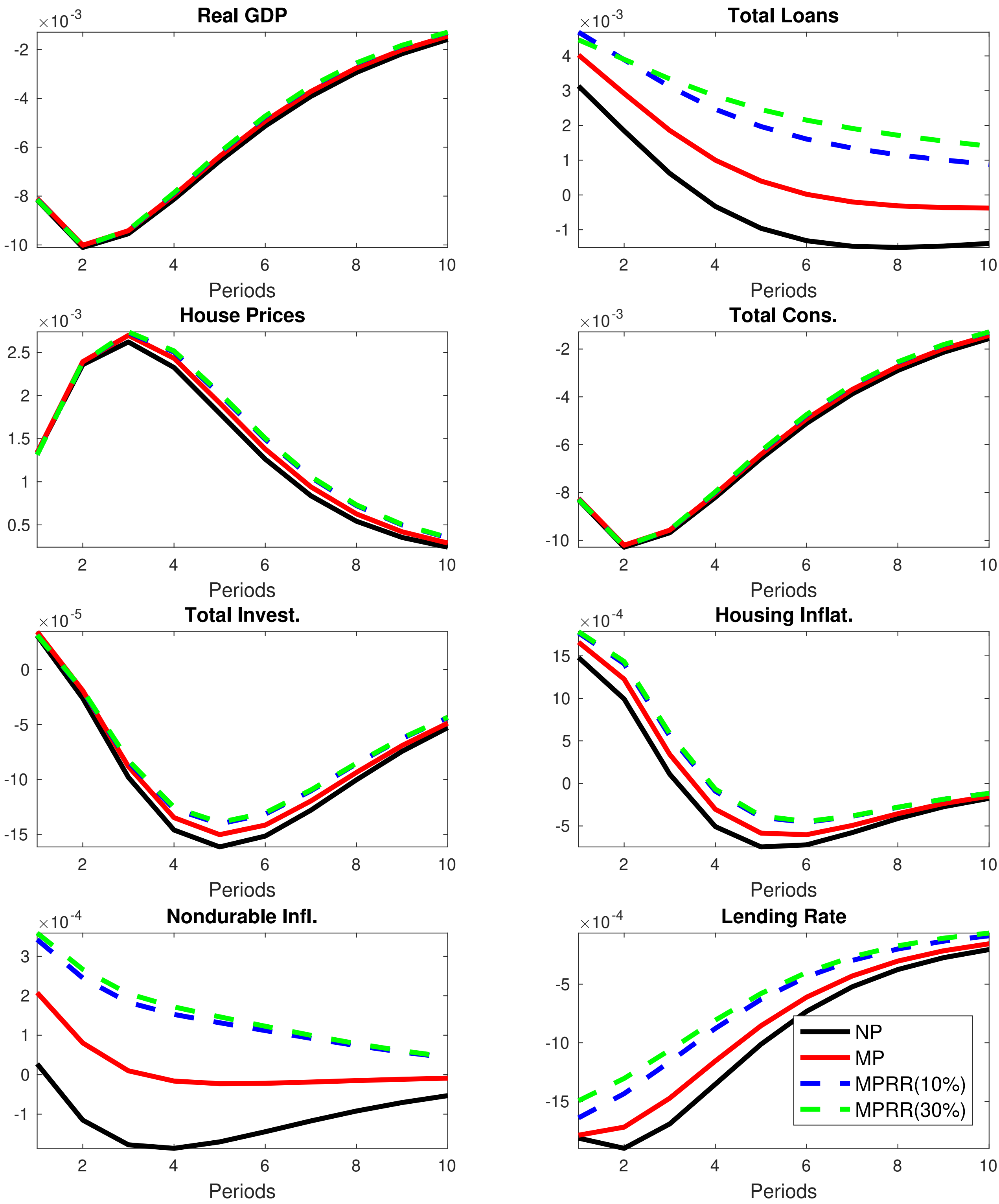
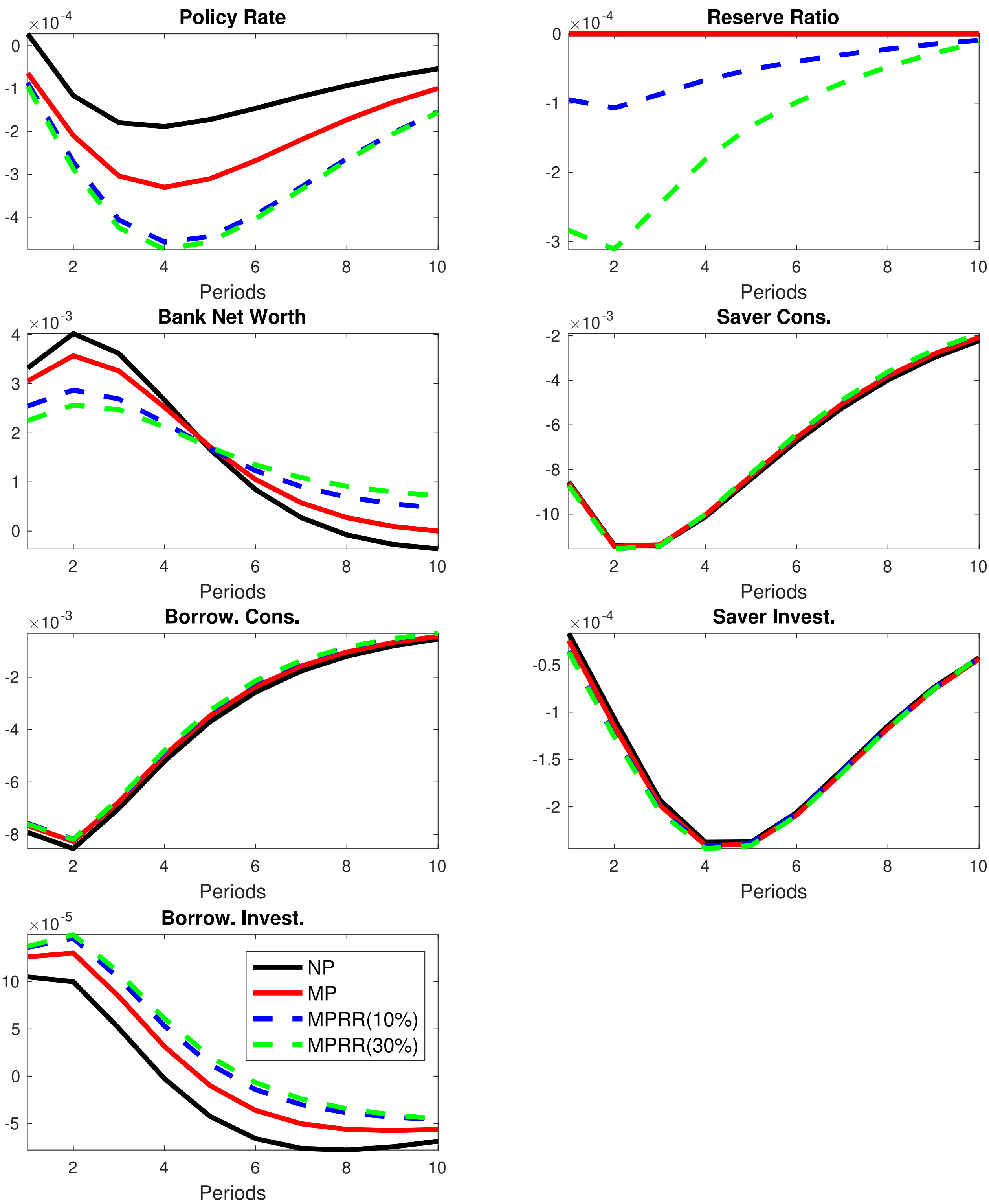


Fig. 2.12 (Continued) IRFs with Non-Durable Demand Shock (Deviations from Steady State)



House prices drop, causing the value of collateral to decline. This triggers a higher default probability, immediately decreasing banks' net worth. However, the countervailing impact of the sharp 50 basis points increase in the lending rate means that initially, net worth recovers during the first four quarters, before declining once again for another 23 quarters before beginning to recover. As is the case for the risk shock, the demand shock on investment causes investment in housing, disaggregated between savers and borrowers to oscillate for years to come. On impact, investment by savers declines by 0.1%, declines still further for two more periods, reaching 0.13% below its steady state value. It then recovers so that by the tenth quarter it is 0.86% below steady state and then declines once again for a further 19 quarters (Figures A.3 and A.4) before finally converging back to steady state.

The long-lasting impact of the demand shock on the housing and banking sectors means that whereas the monetary authority will respond with a sharp but short-lived drop in policy rate, the response of macroprudential policy will leave reserve requirements below their steady state values for decades. When macroprudential policy operates alone, the reserve ratio requirement drops on impact from 10% to 9.9% or from 30% to 29.7% and then declines still further for another three quarters till it reaches 9.8% (RR(10%)) or 29.4% (RR(30%)). Even after 40 quarters the reserve requirements are still 9.9% and 29.7%, respectively.

Neither macroprudential policy nor monetary policy when operating in the absence of the other are able to do much to mitigate the impact of the demand shock. Only when they operate in tandem in Figure 2.8 is there a discernible impact on the economy—particularly in reducing the drop in total loans. This happens because though the reserve requirements drop less than when macroprudential policy operates without monetary policy, the presence of macroprudential policy prompts the central bank to lower its policy rate more aggressively and for longer than it would choose to do if it were operating alone. While the impact of the demand shock on house prices is an order of magnitude larger than the impact generated by a risk shock, macroprudential policy is only effective in mitigating the latter.

Turning to the nondurable goods sector, Figures 2.9 and 2.10 show the response of the economy to a positive one standard deviation shock to nondurable technology. As is the case for other models with habit persistence in consumption (Christiano, Eichenbaum and Evans (2005), Smets and Wouters (2007) and Leith, Moldovan and Rossi (2012)), the shock produces the hump-shaped rise in output that resembles that generated by VAR models.

Nondurable inflation falls on impact due to the decline in real marginal costs, while the relative price of house increases. The distribution of housing quality becomes less skewed to the left prompting fewer borrowers to default on their loans. Banks' net worth increases, and their balance sheets improve. As their leverage ratios decrease, banks offer more loans and charge lower interest rates. Both savers and borrowers increase consumption and investment. In the case of the latter, the shock generates particularly long-lasting oscillations in investment as seen in Figures A.5 and A.6.

As with demand shocks, neither macroprudential policy nor monetary policy, when operating in the absence of the other, are able to do much to mitigate the impact of a nondurable technology shock in Figure 2.9. Note in particular that the response of monetary policy to the positive shock is expansionary—though output increases the central bank responds more aggressively to the drop in inflation and lowers policy rate by 4.5 basis points. As house prices, credit and output all increase, the macroprudential authority does implement countercyclical policy, by raising the reserve ratio to 10.05% (RR(10%)) or 30.14% (RR(30%)) in the absence of monetary policy and 10.02% (MPRR(10%)) or 30.05% (MPRR(30%)), moderating somewhat, the impact of the shock on banks' net worth, the lending rate and the total amount of lending.

Finally, in Figures 2.11 and 2.12 we consider the impact of a negative demand shock in the non-durable sector. The negative impact on consumption for savers and borrowers is roughly similar though the latter do recover more quickly. House prices increase on impact by 0.13% and increase further till the fourth quarter, when they reach 0.24% above their steady state value. Rather than substitute from nondurable consumption to housing in response to the shock, the higher prices are enough to deter savers from investing in housing— they choose more leisure instead. At the same time the lending rate declines by 18 basis points—enough to induce borrowers to invest in what are temporarily more expensive homes.

Unlike the case for the technology shock, here the demand shock on nondurable inflation generates countercyclical declines in both the policy rate and the reserve ratio in Figure 2.11. Furthermore, particularly in the case of monetary policy, the two appear to reinforce each other. Hence, by the fourth quarter the policy interest rate drops by 3 basis points if monetary policy operates in isolation and 5 basis points if macroprudential policy is activated as well. This effect compounds the increase in total loans and nondurable inflation but smooths the impact of the shock on banks' net worth and borrowers' investment.

2.4.3 Welfare

Monetary policy, when analysed in New Keynesian models, is generally found to mitigate, but only to a small degree, the negative impacts on agents' welfare generated by stochastic shocks to the economy (Rubio and Carrasco-Gallego (2015), Gertler, Kiyotaki and Queralto (2012), Cantore et al. (2019), Tayler and Zilberman (2016), Levine, McAdam and Pearlman (2012)). Here, the limited efficacy of monetary policy is even more acute—in Table 2.6 implementation of the optimised Taylor rule (2.52) yields an overall welfare benefit equivalent to only a 0.001% permanent increase in consumption for both types of agents. Why so small? In steady state, savers spend 47% and borrowers 52% of their incomes on nondurable goods and the rest is invested in housing. Nonetheless, we assume the central bank's optimal Taylor rule only responds to the rate of nondurable goods inflation, as this is the closest analog to rates of change in the traditional consumer price index. Under these circumstances, introducing a housing sector lessens the scope for traditional monetary policy tools to improve welfare.

Adding a fixed reserve requirement alongside monetary policy generates a larger effect on total welfare and a significant differential impact on borrowers and savers. The consumption equivalent welfare gain to borrowers is 0.075% at the expense of a 0.04% loss to savers if the reserve requirement is fixed at 10% (MP(10%)) and a 0.301% gain for borrowers at the expense of a 0.167% loss if fixed at 30% (MP(30%)). At the baseline steady state reserve requirement of 10%, the total impact on welfare of macroprudential policy, either on its own (RR(10%)), or in conjunction with monetary policy (MPRR(10%)), reaches consumption equivalents of 0.003% or 0.006% respectively. If the steady state reserve requirement is set as high as 30%, the consumption equivalents are 0.014% and 0.017%, well over an order of magnitude higher than the impact of monetary policy alone. Moreover, these are the net effects from aggregating across our two types of agents and obscures the policy's differential impact. The small total welfare effects are the residual gains that accrue to the economy's borrowers from macroprudential policy, after the losses suffered by the economy's savers are accounted for. Macroprudential policy alone generates a benefit to borrowers equivalent to 0.073% (0.301%) of permanent consumption at the expense of savers who suffer a loss equivalent to 0.041% (0.170%) for RR(10%) (RR(30%)). The addition of monetary policy improves these welfare effects to only a marginal degree. These are still small numbers, but they demonstrate that once we incorporate housing and banks into our model, macroprudential policy alone is more effective than monetary policy in mitigating the welfare effects of shocks and combining monetary policy with either a fixed reserve ratio, or better still, macroprudential policy is best in terms of total welfare.

Table 2.6 Interaction of Monetary Policy and Macroprudential Regulation

Model	Consumption equivalent welfare(%)		
	Savers	Borrowers	Total
MP	0.001	0.001	0.001
MP(10%)	-0.040	0.075	0.005
MP(30%)	-0.167	0.301	0.015
RR(10%)	-0.041	0.073	0.003
RR(30%)	-0.170	0.301	0.014
MPRR(10%)	-0.040	0.078	0.006
MPRR(30%)	-0.168	0.307	0.017

2.4.4 The Loss Functions of Policy Authorities

Beyond welfare, how much can these different regimes reduce the volatility of key macroeconomic and financial variables? In Table 2.7, total loans volatility reduces from 28.3% in the no policy case to 27.7% when monetary policy is introduced. Meanwhile, introducing a fixed reserve requirement in addition to monetary policy with no macroprudential policy being activated reduces total loans volatility to 27.5% and 26.6% in MP(10%) and MP(30%), respectively. Macroprudential policy applied on its own, reduces this to 28.0% (26.8%) in RR(10%) (RR(30%)). When the two policies are combined the volatility of total loans reduces to 26.9% (25.8%) in MPRR(10%) (MPRR(30%)). Monetary policy alone, also reduces volatility of output and house prices and reduces it further if combined with macroprudential policy. However, these policies also exacerbate the volatility of inflation.

To better understand these trade-offs, we compute the loss functions for monetary and macroprudential policy as in Angelini, Neri and Panetta (2014). The macroprudential policymaker minimises the volatility of credit growth, output and to maintain consistency with (2.53), house prices as well:

$$L^{MaP} = \sigma^2_{SB} + \sigma^2_{Q} + \kappa_{Y,MaP}\sigma^2_{Y} + \kappa_{rr}\sigma^2_{\Delta_{rr}} \tag{2.66}$$

where σ^2_i represents the asymptotic variance of the target variables $i = SB, Q, Y$, and Δ_{rr} or credit growth, relative house price, real GDP, and change in reserve ratio, respectively. While parameter $\kappa_{Y,MaP} \geq 0$ characterises the policymaker's preferences over output. As in Angelini, Neri and Panetta (2014), we set κ_{rr}=0.1— they demonstrate it must be strictly positive to ensure that the policy instrument rr is not too volatile. The monetary policy loss function is:

$$L^{MP} = \sigma_{\pi}^{2} + \kappa_{Y,MP}\sigma_{Y}^{2} + \kappa_{R}\sigma_{\Delta R}^{2} \tag{2.67}$$

where σ_{π}^{2} and $\sigma_{\Delta_R}^{2}$ represent the asymptotic variance of inflation and the change in the policy rate, respectively. As in Angelini, Neri and Panetta (2014), we set $\kappa_{Y,MP}$=0.5 and κ_R=0.1 to ensure that the policy rate R is not too volatile.

Table 2.7 Loss Functions

Model	Volatility (%)						Loss Functions		
	π	Y	ΔR	SB	Q	Δrr	MP	MaP $\kappa_{Y,MaP}=0$	MaP $\kappa_{Y,MaP}=0.25$
NP	0.179	3.053	0.203	28.295	5.461	0.000	4.696	830.409	832.739
MP	0.190	3.000	0.186	27.739	5.454	0.000	4.539	799.198	801.448
MP(10%)	0.189	3.000	0.186	27.476	5.453	0.000	4.538	784.683	786.933
MP(30%)	0.185	3.000	0.183	26.625	5.452	0.000	4.537	738.640	740.889
RR(10%)	0.178	3.054	0.201	27.976	5.461	1.118	4.698	812.592	814.923
RR(30%)	0.173	3.056	0.197	26.849	5.460	3.311	4.702	751.761	754.095
MPRR(10%)	0.191	2.982	0.213	26.937	5.448	0.440	4.487	755.311	757.534
MPRR(30%)	0.192	2.974	0.213	25.795	5.447	1.252	4.462	695.193	697.403

Note: The volatility of the select variables are computed from a 1000-period simulation having all shocks active.

In Table 2.7 we see how the reduction in the loss function is largest when monetary and macroprudential policy operate together and the reserve ratio is highest. Whether it is feasible to impose a reserve requirement as high as 30% is beyond the scope of our analysis. Yet it is encouraging to note that when combined with monetary policy, macroprudential policy with a low steady state reserve requirement MPRR(10%)—similar to the observed reserve ratio in the Eurozone—achieves a reduction in the loss function nearly as large as macroprudential policy when it operates on its own with the much higher reserve requirement RR(30%).

2.5 Conclusions

The GFC demonstrated the role financial markets can play as both sources and propagators of shocks to the aggregate economy. It also demonstrated how vulnerable the financial sector can be to downturns in one particular sector—housing. Researchers have responded by building models that explicitly incorporate the unique role of banks as financial intermediaries and distinguishing between nondurable consumption and investment in housing, that must be financed by mortgage borrowing. For policy makers, particularly central bankers, the GFC demonstrated that standard monetary policy tools may be inadequate to stabilise an economy if they cannot keep the banking system solvent. A variety of new macroprudential policy tools have been developed to overcome this problem. Required reserve ratios were designed for the narrow purpose of preventing bank runs, but as we demonstrate, can also be deployed as a macroprudential tool.

Our DSGE framework combines housing default with reserve requirements. We use this model to examine how the interaction between monetary policy and reserve requirements affect: (i) the credit and business cycle; (ii) the distribution of welfare between savers and borrowers; and (iii) aggregate welfare when these policies are optimised together or separately.

Our results show there are potential distributive implications surrounding the imposition of different levels of required reserve ratios—borrowers gain at the expense of savers. These results suggest that a higher reserve ratio increases costs for banks, inducing them to restrict loans to subprime borrowers to reduce the losses they from defaults. Less financial intermediation means that savers earn lower returns on deposits, while eligible borrowers enjoy a stable flow of credit—the probability of default is inversely related to the reserve ratio. We also show that a central bank setting both monetary and macroprudential policy agency need not coordinate—they can operate independently without any detriment to stability or welfare. Furthermore, we demonstrate that macroprudential policy, even if it operates completely on its own, stabilises the economy in response to a negative risk shock, by dampening the financial accelerator mechanism. At the same time, neither macroprudential policy nor monetary policy when operating in isolation, can ameliorate the impact of a demand shock in the nondurable sector. Only when the two operate in tandem do we observe a discernible effect on the economy—particularly in mitigating the drop in lending. While the welfare effects of introducing macroprudential policy, either on its own, or in conjunction with monetary policy, is generally small, it is still more effective than monetary policy alone in mitigating welfare losses from shocks. The highest welfare gains are achieved by combining monetary policy with a macroprudential policy that sets a high required reserve ratio.

While the results show that the reserve ratio can influence credit and real economic activity, the magnitude of that impact will depend on the specific characteristics of the economy. Future work should incorporate occasionally binding constraints to model the implications of an effective lower bound on nominal interest rates. At the same time, this work suggests that policy makers might want to rethink eliminating required reserve requirements and instead retain them as a macroprudential policy tool.

Chapter 3

Dynamics of the Output Floor: A Model-Based Assessment

3.1 Introduction

The Basel III framework is centered around the concept of risk-weighted regulation, namely banks' capital requirements are calculated as the ratio between banks' capital and risk-weighted assets (RWA). In this framework, the different classes of assets held by banks carry different risk weights. In doing this, different asset categories are adjusted by their level of risk, making capital charges more risk sensitive and allowing banks to discount low-risk assets. Moreover, the Basel III framework allows banks, after the approval of the national regulatory/supervisory authorities, to calculate the risk weights using their internal models (IMs). Many of the largest banks are now using internal models to determine capital requirements.[1]

This model-based regulation generates some clear benefits. First of all, by tying capital charges to actual asset risk, banks are no longer penalized for holding very safe assets on their balance sheets, so that the distortion in the allocation of credit is minimised. In addition, banks are supposed to be closer to the sources of risks, hence able to estimate the risk measures more efficiently. Nevertheless, the global financial crisis has shown significant limitations of the model-based approach. The risk weights applied to asset categories have failed to fully reflect banks' portfolio risk, generated an excessive volatility of risk-weighted assets and exacerbated the procyclicality of capital requirements (Repullo and Suarez (2016)). If the risk weights are excessively responsive to economic conditions – i.e. improve during booms and deteriorate

[1]For instance, all the major UK banks are allowed to use internal models.

during busts – capital requirements become more procyclical. This might also have an impact on the cyclical properties of lending (Behn, Haselmann and Wachtel (2016)) and generate increases in systemic risk (Acharya, Engle and Pierret (2014), Hellwig (2010), and Vallascas and Hagendorff (2013)).

The inability of the model-based regulation to capture fully the riskiness of the underlining assets can be explained by several factors. Behn, Haselmann and Vig (2016) argue that banks' internal risk models may suffer from both informational and incentive problems. First, there is a limited information problem that constrains the ability of internal models to properly assess financial cycle momentum. Second, for some classes of banks' exposures, the lack of historical data makes the estimation of the assets' riskiness very challenging (BCBS (2013)). Third, banks might have the incentive to underrate the riskiness of the assets in order to gain a capital requirements discount (Dautovic (2019) and Santos et al. (2020)).

Although the debate on the limits of the model-based regulation is still ongoing, the Basel Committee on Banking Supervision (BCBS) has recognised that these limits can generate a loss of confidence in the regulatory framework. BCBS (2017) argued that *"at the peak of the global financial crisis, a wide range of stakeholders - including academics, analysts and market participants - lost faith in banks' reported risk-weighted capital ratios"*. To tackle this issue, BCBS first introduced in 2014 a minimum leverage ratio, defined as a bank's capital over an exposure measure, which is independent of risk assessment (Gambacorta and Karmakar (2018) and BCBS (2014*a*)). Although the leverage ratio introduces an independent, risk-neutral guard against the understatement and non-capture of assets' risks, it does not directly restore the investors' confidence in the risk-weighted capital requirements. On the contrary, BCBS (2017) has stated that *"banks' reported risk-weighted capital ratios should be sufficiently transparent and comparable to permit stakeholders to assess their risk profile"*.

Accordingly, in 2017 the BCBS introduced a set of new reforms, known as the Basel III finalisation package (BCBS (2017)), with the explicit aim to restore credibility in the calculation of RWA. Among the several reforms introduced, the Basel III finalisation package included a new floor requirement that is applied to risk-weighted assets, the so called *output floor*. This new constraint requires banks' calculations of RWAs generated by internal models cannot, in aggregate, fall below 72.5% of the risk-weighted assets computed by the standardised approaches. The main aim of the output floor is to reduce the excessive RWA's variability and dispersion across banks with similar risks profile generated by the understatement and non-capture of assets' risks by the internal models.

Policy institutions have started to assess the effects of the output floor (EBA (2019*b*), EBA (2019*a*) and Santos et al. (2020), among others). These studies conclude that the introduction of the output floor is expected to materially reduce the variability of RWA and improve the risk-weighted capital framework. However, they also highlight possible unintended behavioural reactions by banks in response to the floor. In particular, banks may be incentivised to change their portfolio composition, risking up or de-risking for moderately and low risky portfolios respectively. Indeed, the gap between the risk weights calculated under the IMs and SA is usually larger for low-risk assets, such as residential mortgages.

However, from a research perspective, an assessment of the macroeconomic consequences of the output floor has not yet been performed. This paper aims to fill this gap. In particular, we develop a general equilibrium framework to evaluate the effect of the output floor on: (i) the variability of risk-weighted assets; (ii) the cyclical performance of the output floor in terms of banks' lending decisions and risk-taking; and, (iii) the contribution to the achievement of the macroprudential authority's objectives. To the best of our knowledge, this paper is the first to provide a structural model assessment of how the output floor can help in addressing the existing concerns of the model-based regulatory framework.

Following the approach of Gambacorta and Karmakar (2018), our analysis uses a dynamic stochastic general equilibrium model with two-asset banking sector, financial frictions, sticky rates and banks' capital requirements. In the model, the banking system is subject to two regulatory frameworks - the risk-weighted capital framework and the output floor. In order to account for the non-linearities of the output floor - it embodies a max function - the model where the banking system is subject to both frameworks is solved using the approach developed by Holden (2016). First, we estimate the DSGE model using UK data and assess the main drivers of the UK credit cycle. In this regard, we find that in the run up to the 2007-2008 global financial crisis, the credit boom was mainly driven by technology, households' loans spreads, firms' LTV ratios and housing preferences. By contrast, when the crisis hit, credit-to-GDP started to fall due to the decline in the housing preference shock and the tightening of the firms' LTV limits. This is consistent with the findings of Barnett and Thomas (2014) for the UK which underscore the importance of credit supply shocks as the drivers of credit fluctuation. Second, we compare the cyclical properties of the estimated model under the two regulatory regimes. Finally, we evaluate how the implementation of the output floor affects the ability of the monetary and macroprudential authority to achieve their objectives.

Our analysis produces three main results. First, comparing the cyclical properties of the model under the two prudential regimes, we find that the output floor tends to bind during the expansionary phases of the cycle - e.g. after a positive technology shock or monetary policy stimulus. In these cases, the pro-cyclicality of risk weights generates downward pressures on the modelled RWA that declines below the 72.5% of its standardised value. We also find that the output floor is able to reduce the excessive expansion of credit during an economic boom (i.e. after a positive technology shock), by tightening banks' capital constraints compared to the case in which the output floor is not in place. Indeed, without the output floor, the decline of modelled RWA provides space for banks to further increase lending to households and firms. These results support the idea that the output floor is able to reduce the cyclicality of capital-to-RWA ratio and lending caused by the excessive responsiveness of internal models to economic and financial conditions. Therefore, our analysis supports the introduction of the output floor in the policy toolkit as an effective instrument to deal with the limitations of the model-based regulation.

Second, we evaluate whether the output floor can trigger the type of portfolio shifting by banks highlighted in the policy reports (see EBA (2019*b*) among others). This kind of banks' behavioural reactions to risk-insensitive requirements, such as the leverage ratio, has been already documented also by the empirical literature (see Acosta-Smith, Grill and Lang (2021) among others). One way in which the output floor could trigger portfolio shifting is if its impact on bank capital requirements depends on the composition of assets that banks supply. Indeed, we find that while the overall credit expansion is mitigated by the output floor during an economic boom, it also has asymmetric effects on banks' incentives to supply loans to firms and households. More specifically, during economic booms the output floor smoothes the increase of mortgages but makes stronger the expansion of credit to firms. That occurs in our model because after the implementation of the output floor, banks have an incentive to prefer assets characterised by a lower gap between internally-modelled, and standardised, risk weights - corporate loans in our model - than those with a larger gap, like mortgages. The average internally modelled risk weight typically applied to corporate loans in the UK means that the 72.5% discount factor applied by the output floor to the aggregate RWAs calculated under the standardised approach[2] makes corporate loans less expensive in terms of capital requirements relative to mortgages which have internally-modelled risk weights that are on average lower than 72.5% of their standardised counterparts. A stylised explanation of this mechanism is

[2]The standardised approach sets risk weights according to the recommendations of Basel 3, hence they are fixed and not exposed to the cyclical variation of risks.

provided in Section 3.2. These results suggest that prudential authorities, when introducing the output floor, need to consider its distributional consequences on credit to the real economy and the potential effects on the banks' risk profile.

Third, we evaluate whether the implementation of the output floor is consistent with the wider financial and price stability objectives of the macroprudential and monetary authorities. Moreover, we calculate the monetary and macroprudential authority's loss functions (Angelini, Neri and Panetta (2014)) under the two regulatory regimes. We find that – other things equal – the output floor is very effective in supporting the financial stability objective. It is able, indeed, to materially reduce the volatility of RWA across time, and this feeds through into a reduction in volatility of the credit-to-GDP. The effect of the output floor on the monetary policy objectives, instead, depends on the type of shocks and the authority's preference on the volatility of the real GDP. If the monetary authority focuses only on inflation volatility the output floor always supports its objective. By contrast, the output floor might increase the volatility of the real GDP over the business cycle and then require a stronger monetary intervention to stabilise it. The finding that the output floor reduces the volatility of RWA across time, and this feeds through into a reduction in volatility of other macro and financial variables, has so far been an overlooked area of consideration in policy discussions. When thinking of the output floor, policymakers have often discussed its benefits in terms of the reduction in cross-sectional RWA variability that the BCBS set out to mechanically reduce through the output floor – by limiting the extent to which RWA can fall relative to the SA, cross-sectionally (i.e., across banks' assets), RWA will exist within a tighter band – but our results also suggest that the output floor can have a beneficial effect on time-series volatility, with a reduction in such variability. This is a novel result and has potential consequences for stress-testing and prudential policy, for example if RWAs fluctuate by less following the onset of adverse shocks.

Literature Review. To the best of our knowledge, there are no existing academic papers on the output floor. However, several papers have evaluated the challenges of the model-based regulations and assessed the benefits of alternative instruments. Gambacorta and Karmakar (2018) find that the procyclicality of internal model risk weights fails to fully reflect banks' portfolio risk, potentially causing an increase in systemic risk. The authors underscore that given the existing limitations of the internal models, introducing a risk-insensitive leverage ratio could generate substantial net benefits. Hodbod, Huber and Vasilev (2018) propose a macroprudential approach for sectoral risk weights with the aim to reduce the capital requirements procyclicality.

They stress that countercylical adjustments of risk-weights outperform the leverage ratio in taming the cycle.

Other seminal papers have highlighted the procyclicality of the Basel framework. For instance, Angeloni and Faia (2013) argue that the internal model risk-based capital ratio amplifies the cycle and is detrimental to welfare, hence, they supported the introduction of the countercyclical capital buffer. Angelini, Neri and Panetta (2014) introduce in the Gerali et al. (2010) the risk-weighted capital requirements and provide a clear procyclical representation of the risk weights.

Our paper is also related to the vast empirical literature on the shortcomings of the model-based regulation. For instance, Behn, Haselmann and Vig (2016); Goodhart, Hofmann and Segoviano (2014); Kashyap and Stein (2004) highlight the procyclical effects and the gaming that arise from the use of internal model risk weights. Meanwhile, Santos et al. (2020) examine how banks underestimated the risks weights of their assets, especially during the great financial crisis. These studies represent the empirical justification of our assumptions on the modeled risk weights procyclicality.

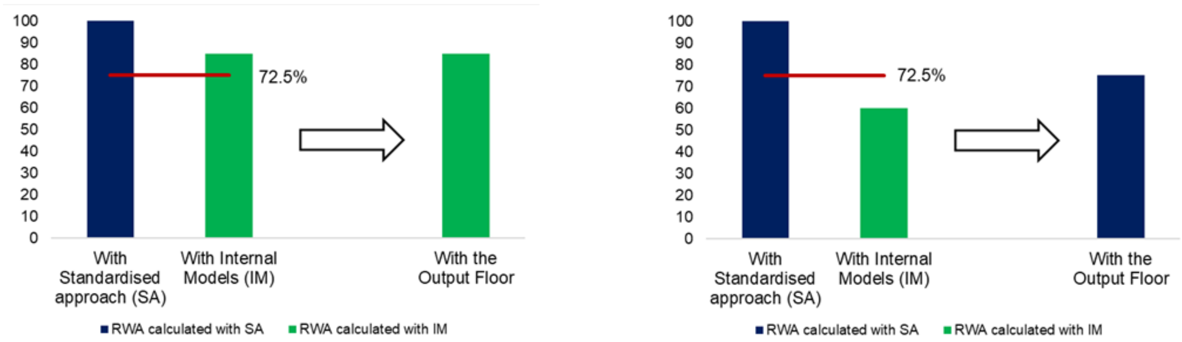
The rest of the section proceeds as follows. Section 3.2 provides a brief discussion on the output floor. Section 3.3 describes the model. Section 3.4 discusses the estimation of the model. Section 3.5 contains the model analysis. Section 3.6 concludes.

3.2 The Output Floor

Ever since the 2007-08 global financial crisis, the BCBS has set to update the Basel framework to further enhance the risk management and supervision of banks. The crisis highlighted many flaws in the existing risk-based capital requirement including inconsistencies amongst banks' RWA, such that a wide range of stakeholders had lost faith in modelled RWA. For example, a post-crisis comprehensive survey amongst investors revealed investor trust in RWA were extraordinarily low, and confidence had fallen sharply following the financial crisis (see Samuels (2013)). The UK Financial Services Authority confirmed these conclusions: when the same hypothetical loan book was given to 13 European banks for them to estimate probabilities of default – a key component in the estimation of RWA – estimates observed across firms exhibited extreme variations (FSA (2010)).[3] In response to these concerns, the BCBS decided to introduce

[3] Vallascas and Hagendorff (2013) also examined the risk sensitivity of capital requirements on an international sample of large banks between 2000 and 2010. They suggest that capital requirements were only loosely related to a market measure of portfolio risk for banks such that even pronounced increases in portfolio risk generated almost negligible increases in capital requirements.

Fig. 3.1 The Output Floor at Work



(a) The output floor does not bind

(b) The output floor binds

a risk-based backstop (i.e. the *"output floor"*) to sit alongside the non-risk based backstop (the leverage ratio), and the other measures introduced as part of the Basel III package.[4]

The output floor was agreed on 7 December 2017 with the publication of the final Basel III reforms (BCBS (2017)). It was agreed that the output floor would be calibrated at 72.5%, but due to its potential impact, the BCBS agreed to implement the output floor over a phased period of five years starting from 50% of standardised capital requirements on 1 January 2022. It will then be increased by 5 percentage points each year until 2026 when it is set at 70%, before increasing by 2.5 percentage points in 2027 to its final calibration of 72.5%.[5] In response to the impact of Covid-19, the Basel Committee delayed its implementation by one year.

According to the output floor, the risk-weighted assets that banks must use to determine compliance with the capital requirements must be derived as the maximum of: 1) the total risk-weighted assets calculated using banks' internal models; and, 2) 72.5% of the total risk weighted assets, calculated using only the standardised approach (SA). The latter assigns standardised risk weights to exposures, which maintain a certain degree of risk sensitivity - i.e. the standardised risk weights vary across asset categories - but do not react to economic conditions (BCBS (2001)).

Figure 3.1 provides a graphical description of how the output floor works. In case (a), the RWA calculated with internal models are larger than the 72.5% of the RWA calculated with the SA, hence the output floor does not bind. The bank's RWA (used to compute capital

[4]In addition to adjustments to the risk-based capital framework – which included adjustments to strengthen and improve both the internal modelled approach itself and the standardised approaches – the Basel III reforms also included two new liquidity requirements: the Liquidity Coverage Ratio (LCR) and the Net Stable Funding Ratio (NSFR). See BCBS (2017) for further details.

[5]During the phase-in period, the agreement also allowed for a transitional cap in which national regulators could limit any increase in RWA to a maximum of 25% relative to a bank's RWA without the output floor.

requirements) remain the ones calculated with internal models. In case (b), the output floor binds because the RWA calculated with internal models are lower than 72.5% of the RWA calculated with the SA. In this case, the relevant bank's RWA are the ones calculated with the SA scaled down to 72.5% of their initial value.

The aim of introducing the output floor was to address three key issues (BCBS (2017)): (1) to address excessive RWA variability and dispersion as discussed above, thereby enforcing greater consistency of RWA; (2) to mitigate model risk and measurement error stemming from internally modelled approaches. The BCBS noted that after the model-based approaches of Basel II were introduced, significant reductions in RWA occurred in a number of jurisdictions, and extremely low levels of internally modelled RWA were observed for some exposure categories; and (3) to ensure a more level playing field between SA banks and those using internal models. In this way, the output floor would enhance the comparability of capital outcomes across banks, and ensure horizontal equity in risk-weighted capital requirements.

Taken together, the output floor aimed to help promote confidence in the regulatory capital framework, and sit in a complementary fashion to the leverage ratio, directly addressing the number of banks who were found to have built up excessive leverage with extremely low internally modelled RWA, despite having apparently maintained strong risk-based capital ratios leading up to the financial crisis (BCBS (2014*b*)). By acting as a floor on internally-modelled RWA, the output floor effectively limits how low internally modelled RWA can fall relative to the SA designed by regulators.

In addition, policy reports on the output floor (see EBA (2019*b*) among others) have highlighted that, if it binds, it might trigger a shift in banks' portfolios. That is because the effects of the output floor on capital requirements will depend on the gaps between internally-modelled and standardised risk weights across assets. Those gaps will differ by asset class so the effect of the output floor will depend on the composition of assets on a bank's balance sheet. For a given category of assets standardised risk weights are usually higher than those calculated with internal models,[6] but the size of the gap between the two might be very different. For those assets with a small risk weights gap, the 72.5% discount factor applied by the output floor to the RWAs calculated under the standardised approach might reduce the marginal costs in terms of capital requirements - i.e. the contribution of a unitary increase of the those specific assets to the calculation of the capital requirements - compared to the case in which the output

[6]There are examples of assets that show standardised risk weights lower than modeled risk weights, such as credit cards. However, for the large part of the banks' balance sheet the standardised risks weights calibration is more conservative than the estimates of internal models.

floor does not bind. The following stylised example of a bank with two assets explains this mechanism.

- The bank holds £500 of Asset 1 and £500 of Asset 2.
- Asset 1 has a modelled risk weight equal to 0.35 and a standardised risk-weight equal to 0.60 - i.e. the modelled risk-weight is 58% of the standardised one and so the gap is large in output floor terms.
- Asset 2 has a modelled risk weight equal to 0.35 and a standardised risk-weight equal to 0.45 - i.e. i.e. the modelled risk-weight is 77% of the standardised one and so the gap is small in output floor terms.
- The bank is subject to a 4.5% (over RWAs) capital requirement and the output floor binds.

Table 3.1 shows that the output floor generates an increase of the total capital requirements (from £15.8 to £17.1). If we look, instead, to the contribution of the two assets to the total requirements, we can see that the effect is asymmetric. Asset 1 displays the larger risk weights gap and its marginal contribution to capital requirements increases when the output floor is in place. The opposite happens for asset 2 with a smaller gap - its marginal contribution to capital requirements is lower because the output floor discount is larger than the risk weights gap. In this situation, everything else equal, the bank might have an incentive to expand their exposures to asset 2 when the output floor binds.

Table 3.1 Behavioral Consequences of the Output Floor

	Total	Contribution of Asset 1	Contribution of Asset 2
Capital Requirements	15.8	7.9	7.9
Capital Requirements (OF)	17.1	9.8	7.3
Capital Requirements	1.3	1.9	-0.6

Total capital requirements are calculated as 0.045(0.35*500 + 0.35*500); contribution of assets as 0.045*(0.35*500); total capital requirements (OF) as 0.045*(0.725*(0.60*500 + 0.45*500)); contribution of Asset 1 (OF) as 0.045*(0.725*(0.60*500)); contribution of asset 2 (OF) as 0.045*(0.725*(0.45*500))*

3.3 The Model

We build on the model by Gerali et al. (2010) and Angelini, Neri and Panetta (2014).[7] The economy is populated by patient households, impatient households and entrepreneurs of measure γ^P, γ^I and γ^E, respectively. The mass of all agents in the economy is normalised to one ($\gamma^P + \gamma^I + \gamma^E = 1$). Households consume, accumulate housing stock and work. The two types of households differ in terms of their degree of impatience. The discount factor of patient households is higher than the one of impatient households ($\beta^P > \beta^I$). Households' heterogeneity generates positive financial flows in equilibrium, as patient households save and impatient ones borrow against the value of their housing stock. Entrepreneurs produce homogeneous intermediate goods using capital and labour. The latter is supplied by both types of households. To finance their capital purchases, entrepreneurs borrow from banks using their capital stock as collateral.

On the production side, workers supply their differentiated labour services through unions, which set wages to maximize members' utility. In addition to entrepreneurs, there are also monopolistically competitive retailers and capital goods producers. The retailers buy intermediate goods from entrepreneurs, differentiate and price them, subject to nominal rigidities. The capital producers are a model device to introduce the price of capital.

The banking sector consists of a wholesale branch and two retail branches. The wholesale branch manages the capital-asset position of the bank as it accumulates bank capital out of retained earnings and pays some quadratic costs whenever it deviates from the capital requirements expressed as the ratio between bank capital and risk-weighted asset (RWA). Banks are subject to different regulatory approaches to calculate the RWA: 1) the internal rating based (IRB) approach; 2) the output floor. Retail branches lend to impatient households and to entrepreneurs, and collect deposits from patient households. They have market power in setting lending and deposit rates.

Finally, there is central bank that set the policy rate according to a standard Taylor-type reaction function and a macroprudential policy authority that controls the capital requirements. The latter have a steady state and a countercyclical component that depends on the credit-to-GDP ratio in the economy. This reflects the current framework in which a countercyclical capital buffer (CCyB) is placed on top of static capital requirements.

[7] They develop a medium-scale DSGE a la Christiano, Eichenbaum and Evans (2005) and Smets and Wouters (2007) enriched by a banking sector an financial frictions. Gambacorta and Karmakar (2018) use a similar model to assess the impact of the leverage ratio.

3.3.1 Households and Entrepreneurs

Patient Households. Each patient household, indexed by i, maximises her expected lifetime utility by choosing consumption c_t^P, housing h_t^P and labour hours l_t^P:

$$E_0 \left\{ \sum_{t=0}^{\infty} (\beta^P)^t \left[(1-a^P)\varepsilon_t^c \log(c_t^P(i) - a^P c_{t-1}^P) + \varepsilon_t^h \log(h_t^P(i)) - \frac{l_t^P(i)^{1+\phi}}{1+\phi} \right] \right\} \tag{3.1}$$

where a^P denotes the degree of habits and ϕ the inverse Frisch elasticity of labour supply. There are two preference shocks ε_t^c and ε_t^h that affect the marginal utility of consumption and housing with an AR(1) representation $\log(\varepsilon_t^j) = \rho_j \log(\varepsilon_{t-1}^j) + \sigma_t^j$, with $j = \{c, h\}$. The household's choices are subject to a budget constraint (in real term):

$$c_t^P(i) + q_t^h \Delta h_t^P(i) + d_t(i) = w_t^P l_t^P(i) + \frac{(1+r_{t-1}^d) d_{t-1}(i)}{\pi_t} + t_t^P(i) \tag{3.2}$$

Households spend their income on current consumption, housing (with q_t^h denoting house prices) and savings through deposits d_t. The income side consists of wage earning $w_t^P l_t^P$ (where w_t^P is the real wage) and gross interest income from deposits $\frac{(1+r_{t-1}^d)d_{t-1}}{\pi_t}$, where $\pi_t = \frac{P_t}{P_{t-1}}$ is gross inflation rate and r_{t-1}^d denotes the interest rate on deposits. In addition, t_t^P is the lump-sum transfer that includes labour union membership net fee, and dividends from firms and banks owned only by patient households.

Impatient Households. Each impatient household maximises her expected lifetime utility:

$$E_0 \left\{ \sum_{t=0}^{\infty} (\beta^I)^t \left[(1-a^I)\varepsilon_t^c \log(c_t^I(i) - a^I c_{t-1}^I) + \varepsilon_t^h \log(h_t^I(i)) - \frac{(l_t^I(i))^{1+\phi}}{1+\phi} \right] \right\} \tag{3.3}$$

subject to a budget constraint:

$$c_t^I(i) + q_t^h \Delta h_t^I(i) + \frac{(1+r_{t-1}^{b,H}) b_{t-1}^I(i)}{\pi_t} = b_t^I(i) + w_t^I l_t^I(i) + t_t^I(i) \tag{3.4}$$

where labour income $w_t^I l_t^I$, new loans b_t^I and net labour union fee t_t^I finance consumption c_t^I, housing h_t^I and payments for previous-period loans $\frac{(1+r_{t-1}^{b,H})b_{t-1}^I}{\pi_t}$. For simplicity, housings have fixed supply, i.e. $h^P + h^I = 1$. Due to their impatience, in equilibrium, impatient households are willing to offer their housing wealth as collateral to obtain loans. In the rest of the paper we will refer to households' loans, b_t^I, also as mortgages.

Impatient households must satisfy also a borrowing constraint, which imposes that the expected value of their housing stock must guarantee repayment of debt and interests:

$$(1 + r_t^{b,H})b_t^I(i) \leq m_t^I E_t[q_{t+1}^h h_t^I(i)\pi_{t+1}] \tag{3.5}$$

where m_t^I denotes the loan-to-value (LTV) ratio for mortgages with an AR(1) representation $\log(m_t^I) = (1 - \rho_{m^I})\bar{m}^I + \rho_{m^I}\log(m_{t-1}^I) + \sigma_t^{m^I}$, where $\bar{m}^I$ is the steady-state LTV ratio.

Entrepreneurs. Entrepreneurs maximise their expected lifetime utility:

$$E_0\left\{\sum_{t=0}^{\infty}(\beta^E)^t\left[\log(c_t^E(i) - a^E c_{t-1}^E)\right]\right\} \tag{3.6}$$

subject to the budget constraint, production function and borrowing constraint. The budget constraint is given by:

$$\begin{aligned} c_t^E(i) + w_t^P l_t^{E,P}(i) + w_t^I l_t^{E,I}(i) + \frac{(1 + r_{t-1}^{b,E})b_{t-1}^E(i)}{\pi_t} + q_t^k k_t^E(i) \\ +\varphi(u_t(i))k_{t-1}^E(i) = \frac{y_t^E(i)}{x_t} + b_t^E(i) + q^k(1-\delta)k_{t-1}^E(i) \end{aligned} \tag{3.7}$$

Entrepreneurs' expenses concerns consumption c_t^E, wage bills for patient $(w_t^P l_t^{E,P})$ and impatient $(w_t^I l_t^{E,I})$ households, previous period loans' repayment $\frac{(1+r_{t-1}^{b,E})b_{t-1}^E}{\pi_t}$ and capital renting expenses $q_t^k k_t^E$ (where q_t^k is the price of capital). They are financed by income from the sale of wholesale goods y_t^E (where $\frac{1}{x_t} = \frac{P_t^W}{p_t}$ corresponds to its relative competitive price) and the revenue from the un-depreciated stock of capital $q^k(1-\delta)k_{t-1}^E$ sold back to capital producers. Moreover, entrepreneurs have to pay the real cost $\varphi(u_t)k_{t-1}^E$ to set the level of capital utilisation rate, u_t. In the rest of the analysis we will refer to entrepreneurs' loans, b_t^E, also as loans to non-financial corporations (NFC).

The wholesale good is produced according to the a standard production function:

$$y_t^E(i) = A_t^E(k_{t-1}^E(i)u_t(i))^\alpha(l_t^E(i))^{1-\alpha} \tag{3.8}$$

where A^E is the stochastic total factor productivity (TFP), which follows an AR(1) process $\log(A_t^E) = \rho_{A^E}\log(A_{t-1}^E) + \sigma_t^{A^E}$. The labour inputs are the sum of patient and impatient household labour supply $l_t^E = (l_t^{E,P})^\mu(l^{E,I})^{1-\mu}$, where μ is the proportion of labour inputs from patient households.

Finally, the amount of funds banks are willing to lend to entrepreneurs are subject to the following borrowing constraint:

$$(1 + r_t^{b,E})b_t^E(i) \leq m_t^E q_{t+1}^k E_t[\pi_{t+1}(1-\delta)k_t^E(i)] \tag{3.9}$$

where m_t^E is the LTV ratio and follows an AR(1) process $\log(m_t^E) = (1-\rho_{m^E})\bar{m}^E + \rho_{m^E}\log(m_{t-1}^E) + \sigma_t^{m^E}$, where $\bar{m}^E$ is the steady-state LTV ratio.

Labour Supply. Patient and impatient households provide differentiated labour types, sold by unions to perfectly competitive labour packers. For each labour type m there are two unions, one for patient households and one for impatient households (indexed by s, where $s = P, I$). Unions set nominal wages $W_t^s(m)$ maximising the utility of their members, where $U_{c_t^s}$ is the stochastic discount factor, subject to the labour packers demand and to a quadratic adjustment cost (parametrised by κ_w). This corresponds to Rotemberg (1982) considerations as opposed to Calvo contracts.

$$E_0 \sum_{t=0}^{\infty} (\beta^s)^t \left\{ U_{c_t^s}(i,m) \left[\frac{W_t^s(m)}{P_t} l_t^s(i,m) - \frac{\kappa_w}{2} \left(\frac{W_t^s(m)}{W_{t-1}^s(m)} - \pi_{t-1}^{\iota_w} \pi^{1-\iota_w} \right)^2 \frac{W_t^s}{P_t} \right] - \frac{l_t^s(i,m)^{1+\phi}}{1+\phi} \right\} \tag{3.10}$$

subject to:

$$l_t^s(i,m) = l_t^s(m) = \left(\frac{W^s(m)}{W_t^s} \right)^{-\varepsilon_t^l} l_t^s \tag{3.11}$$

The wage setting is indexed to a weighted average of lagged and steady-state wage inflation, where ι_w indicates the wedge. The demand from labour packers has a standard CES representation. In a symmetric equilibrium, labour supply for a household of type s is given by:

$$\kappa_w(\pi_t^{w^s} - \pi_{t-1}^{\iota_w}\pi^{1-\iota_w})\pi_t^{w^s} = \beta_t E_t \left[\frac{\lambda_{t+1}^s}{\lambda_t^s} \kappa_w (\pi_{t+1}^{w^s} - \pi_t^{\iota_w}\pi^{1-\iota_w}) \frac{(\pi_{t+1}^{w^s})^2}{\pi_{t+1}} \right] + (1-\varepsilon_t^l) l_t^s + \frac{\varepsilon_t^l l_t^{s1+\phi}}{w_t^s \lambda_t^s} \tag{3.12}$$

where, for each type, w_t^s is the real wage and $\pi_t^{w^s}$ is the nominal wage inflation.

3.3.2 Producers

Capital Producers. New stock of capital is produced and sell to entrepreneurs in a perfectly competitive market. Capital producers use two inputs, the previous-period un-depreciated capital $(1-\delta)K_{t-1}$ bought from entrepreneurs at the nominal price Q_t^k and I_t units of the final consumption good bought from retailers at price P_t. The new stock of effective capital is sold back to entrepreneurs at price Q_t^k. In addition, the transformation of the final good into new capital is subject to adjustment cost κ_i. Capital producers maximization problem is given by:

$$E_0\left\{\sum_{t=0}^{\infty}\Lambda_t^E(\beta^E)^t\left[q_t^k(k_t-(1-\delta)k_{t-1})-I_t\right]\right\} \tag{3.13}$$

subject to the law of motion of capital $k_t=(1-\delta)k_{t-1}+\left[1-\frac{\kappa_i}{2}\left(\frac{\varepsilon_t^{qk}I_t}{I_{t-1}}-1\right)^2\right]I_t$, where $q_t^k\equiv\frac{Q_t^k}{P_t}$ the real price of capital and ε_t^{qk} denotes a shock to investment efficiency with an AR(1) representation $log(\varepsilon_t^{qk})=\rho_{qk}log(\varepsilon_{t-1}^{qk})+\sigma_t^{qk}$. In equilibrium $k_t^E=k_t$.

Retailers. The structure of the retail goods market is monopolistic competition (Bernanke, Gertler and Gilchrist (1999)). Retail prices are sticky and are indexed to a combination of past and steady-state inflation, with relative weight indicated by ι_p. Whenever retailers want to change prices beyond this indexation allowance, they face a quadratic adjustment cost parameterised by κ_p. Retailer i chooses $P_t(i)$ subject to the consumers' demand function.

$$E_0\left\{\sum_{t=0}^{\infty}\Delta_{0,t}^P\left[\left(P_t(i)y_t(i)-P_t^Wy_t(i)-\frac{\kappa_p}{2}\left(\frac{P_t(i)}{P_{t-1}(i)}-\pi_{t-1}^{i_p}\pi^{1-i_p}\right)^2P_ty_t\right)\right]\right\} \tag{3.14}$$

where the CES demand function is given by $y_t(i)=\left(\frac{P_t(i)}{P_t}\right)^{-\varepsilon_t^y}y_t$ where π denotes the steady state inflation, and ε_t^y the stochastic demand price elasticity, which follows an AR(1) process $log(\varepsilon_t^y)=(1-\rho_y)\bar{\varepsilon}^y+\rho_ylog(\varepsilon_{t-1}^y)+\sigma_t^y$ (where $\bar{\varepsilon}^y$ denotes the steady-state markup in the goods market).

3.3.3 Banks

Each bank consists of a wholesale branch and two retail branches. The wholesale branch manages the capital-assets position of the bank subject to capital requirements imposed by the macroprudential authority. Retail branches lend to impatient households, lend to entrepreneurs and collect deposits from patient households.

Wholesale Branch. Each wholesale bank, indexed by j, operates in a perfectly competitive market. On the liabilities side, it combines wholesale deposits D_t with the accumulated bank capital K_t^b, while on the assets side, it issues wholesale loans B_t^H and B_t^E to retail branches.

The two sources of funding, K_t^b and D_t, are perfect substitutes. Bank capital is accumulated through retained earnings only:

$$\pi_t K_t^b(j) = (1-\delta^b)K_{t-1}^b(j) + \Pi_{t-1}(j) \tag{3.15}$$

where δ^b is the costs of managing bank capital, π_t is the current period inflation, and Π_{t-1} denotes the realised overall profits of the bank, namely the profits of the wholesale and the two retail branches ($\Pi_t = \Pi_t^{ws} + \Pi_t^h + \Pi_t^f$).

The wholesale branch is subject to risk-weighted capital requirements, meaning that it occurs in a quadratic cost whenever its capital-to-RWA ratio $\frac{K_t^b(j)}{RWA_t^l(j)}$ deviates from the regulatory ratio ν_t^b. The wholesale branch maximises profits taking into account these quadratic costs:

$$\begin{aligned}\max E_0 \sum_{i=0}^{\infty} \Lambda_{0,t} \Bigg[&(1+R_t^{B,H})B_t^H(j) + (1+R_t^{B,E})B_t^E(j) - (B_{t+1}^H(j) + B_{t+1}^E(j)) \\ &+D_{t+1}(j) - (1+R_t^d)D_t(j) + (K_{t+1}^b(j) - K_t^b(j)) - \frac{\kappa_l}{2}\left(\frac{K_t^b(j)}{RWA_t^l(j)} - \nu_t^b\right)^2 K_t^b \Bigg]\end{aligned} \tag{3.16}$$

where κ_l measures the intensity of the quadratic costs, while the index $l \in \{IRB, OF\}$ identifies the prudential approach to calculate the RWA (see below). The above profit maximisation is subject to a balance sheet constraint in the form $B_t^H(j)+B_t^E(j) = K_t^b(j)+D_t(j)$.

Prudential approaches to calculate the RWA. The risk-weighted assets are defined as the weighted sum of the bank's assets (i.e. B_t^H and B_t^E), where the weights, are a measure of the implicit riskiness of the different assets, the so called *risk weights*. In our model, banks can be subject to two different prudential approaches to calculate the RWA.

1. *Internal Rating Based (IRB) Approach.*[8] Under this regime, the risk-weighted assets are defined as following:

$$RWA_t^{IRB}(j) = (w_t^{H,IRB}B_t^H(j) + w_t^{E,IRB}B_t^E(j)) \tag{3.17}$$

   where $w_t^{H,IRB}, w_t^{E,IRB}$ are the risk weights associated to mortgages and NFC loans, respectively. According to the IRB approach, banks use internal models to estimate the weights, following the Basel III recommendation. In particular, IRB models' main

[8] We refer specifically to IRB rater than IM, because the model considers only the credit risk component of the RWA.

components are probability of default (PD) of borrowers, loss given default (LGD), exposure at default (EAD) and the maturity of the assets.

In absence of defaults in the models, we approximate the risk weights using the approach of Angelini et al. (2015). They argue that the main characteristics of the IRB risk weights are captured by the following equation:

$$w_t^{k,IRB} = (1-\rho_i)\bar{w}^{k,IRB} + (1-\rho^i)\chi^i\Big(logy_t - logy_{t-4}\Big) + \rho^i w_{t-1}^k \qquad \text{with} \qquad k = \in \{H, E\} \tag{3.18}$$

where $w_t^{k,IRB}$ corresponds to the steady-state risk weight, while $\chi^i < 0$ describes the cyclical response of the risk weights. According to this definition, risk weights tend to be low during booms and high during recessions. More details on the IRB risk weights will be given in the estimation section.

2. *Output Floor (OF).* The output floor imposes that the bank's RWA calculated according to the IRB approach cannot go below the 72.5% of the RWA calculated according to the standardised approach:

$$RWA_t^{OF}(j) = max\{RWA_t^{IRB}(j), 0.725 * RWA_t^{SA}(j)\} \tag{3.19}$$

where the RWA calculated under the standardised approach are defined as $RWA_t^{SA} = (w^{H,SA}B_t^H + w^{E,SA}B_t^E)$. Standardised risk weights are calibrated according to the recommendations of Basel 3, hence they are fixed and not exposed to the cyclical variation of risks.

Optimal Wholesale Rates Setting. The wholesale branch's optimal problem produces a relationship between the capital position of the bank and the spread between the wholesale lending and deposit rates:

$$R_t^{B,k} - r_t = -\kappa_l\left(\frac{K_t^b}{RWA_t^l} - \nu_t^b\right)\left(\frac{K_t^b}{RWA^l}\right)^2 w_t^{k,l} \qquad \text{with } k \in \{H, E\},\ l \in \{IRB, OF\} \tag{3.20}$$

where for the output floor $w_t^{k,OF} = max\{w_t^{k,IRB}B^k, 0.725 * (w^{k,SA}B^k)\}$ indicates a sort of adjusted risk weight that comes from the definition of the RWA in equation 3.19.

The left-hand side of the above equations represent the marginal benefit from increasing lending of type j (an increase in profit equal to the increase in interest rate spread), while the right-hand side represents the marginal cost of doing so (an increase in the costs for deviating from ν_t^b). Therefore, the wholesale branch chooses a level of each type of lending j which, at the margin, equalises the costs and benefits of changing the capital asset ratios.

Retail Branches. Retail banks, indexed by j, are Dixit-Stiglitz monopolistic competitors on both the loan and the deposit markets. The retail branches take the loan and deposit demand schedules as given and then chooses the level of interest rates to maximise profits. Hence, each bank sets a different interest rate. The loan and deposit demand schedules facing bank j are defined as:

$$b_t^s(j) = \Big(\frac{r_t^{bs}(j)}{r_t^{bs}}\Big)^{-\varepsilon_t^{bs}} b_t^s, \qquad d_t^P(j) = \Big(\frac{r_t^d(j)}{r_t^d}\Big)^{-\varepsilon_t^d} d_t \qquad \text{with} \qquad s \in \{H, E\} \tag{3.21}$$

where ε_t^{bs} and ε_t^d, where $s = H, E$ elasticities of loan and deposit demand. Elasticities are stochastic and their innovations can be interpreted as innovations to bank spreads arising independently of monetary policy.

The loans' retailers maximise their profits subject to the loan demand schedule:

$$\begin{aligned} \max_{r_t^{B,H}, r_t^{B,E}} E_0 \sum_{i=0}^{\infty} \Lambda_{0,t} \Bigg[& r_t^{B,H}(j) b_t^H(j) + r_t^{B,E}(j) b_t^E(j) - (R_t^{B,H} B_t^H(j) + R_t^{B,E} B_t^E(j)) \\ & - \frac{\kappa_{bH}}{2} \left(\frac{r_t^{bH}(j)}{r_{t-1}^{bH}(j)} - 1 \right)^2 r_t^{bH} b_t^H - \frac{\kappa_{bE}}{2} \left(\frac{r_t^{bE}(j)}{r_{t-1}^{bE}(j)} - 1 \right)^2 r_t^{bE} b_t^E \Bigg] \end{aligned} \tag{3.22}$$

Maximising this generates equations for both types of loans and interest rates for bank j. The first two terms are the returns from lending to households and entrepreneurs. The next term reflects the cost of remunerating funds received from the wholesale branch. The last two terms are the costs of adjusting the interest rates. After imposing a symmetric equilibrium, the first-order conditions for interest rate yields:

$$1 - \varepsilon_t^{bs} + \varepsilon_t^{bs} \frac{R_t^{bs}}{r_t^{bs}} - \kappa_{bs} \left(\frac{r_t^{bs}}{r_{t-1}^{bs}} - 1 \right) \frac{r_t^{bs}}{r_{t-1}^{bs}} + E_t \left[\Lambda_{t+1}^P \kappa_{bs} \Big(\frac{r_{t+1}^{bs}}{r_t^{bs}} - 1 \Big) \left(\frac{r_{t+1}^{bs}}{r_t^{bs}} - 1 \right)^2 \frac{B_{t+1}^s}{B_t^s} \right] = 0 \tag{3.23}$$

The discount factor is equal to that of the patient households because they own the banks. It can be seen that the retail rates depend on the markup and the wholesale rate (the marginal cost for the banks), which in turn depends on the bank's capital position and the policy rate.

A similar equation can be derived for the deposit retail branch:

$$-1-\varepsilon_t^d+\varepsilon_t^d\frac{r_t}{r_t^d}-\kappa_d\Big(\frac{r_t^d}{r_{t-1}^d}-1\Big)\frac{r_t^d}{r_{t-1}^d}+E_t\left[\Lambda_{t+1}^P\kappa_d\Big(\frac{r_{t+1}^d}{r_t^d}-1\Big)\left(\frac{r_{t+1}^d}{r_t^d}-1\right)^2\frac{d_{t+1}}{d_t}\right]=0 \quad (3.24)$$

Finally, the total profits of the banking group, j, can be written as follows:

$$\Pi_t=r_t^{BH}b_t^H+r_t^{BE}b_t^E-r_t^dd_t-\frac{\kappa_l}{2}\left(\nu_t^b-\frac{K_t^b}{RWA_t^l}\right)^2K_t^b- \\ \frac{\kappa_{bH}}{2}\left(\frac{r_t^{bH}(j)}{r_{t-1}^{bH}(j)}-1\right)^2r_t^{bH}b_t^H-\frac{\kappa_{bE}}{2}\left(\frac{r_t^{bE}(j)}{r_{t-1}^{bE}(j)}-1\right)^2r_t^{bE}b_t^E \quad (3.25)$$

3.3.4 Monetary and Macroprudential Policy

Monetary Policy. The central bank sets the policy rate r_t according to a standard Taylor rule

$$R_t=(1-\rho_R)R+\rho_RR_{t-1}+(1-\rho_R)\left[\phi_\pi\left(\frac{\pi_t}{\pi}\right)+\phi_y\left(\frac{Y_t}{Y}\right)\right]+\varepsilon_t^r \quad (3.26)$$

where $R_t=(1+r_t)$ and ϕ_π and ϕ_y denote the weights of inflation and output, respectively. R is the steady state policy rate, ρ_R represents the persistence of the policy rate, and ε_t^r as the monetary policy shock.

Macroprudentential Policy. The risk-weighted capital requirements follow the definition of Angelini et al. (2015) and Gambacorta and Karmakar (2018):

$$\nu_t^b=(1-\rho_\nu)\bar{\nu}+\rho_\nu\nu_{t-1}^b+(1-\rho_\nu)\Big[\chi_\nu\Big(\frac{B_t}{Y_t}-\frac{\bar{B}}{\bar{Y}}\Big)\Big] \quad (3.27)$$

where where $\bar{\nu}$ is the steady level, which corresponds to the fixed capital requirements. $\frac{B_t}{Y_t}$, with $B_t=B_t^H+B_t^E$ denotes the credit-to-GDP ratio and $\chi_\nu>0$ implies the presence of a countercyclical capital buffer on top of the minimum requirements. The objective of having such time-varying capital requirement is to increase bank capital when the credit-to-GDP is above its steady-state level so that the extra capital can be used to expand credit during bad periods.

3.3.5 Market Clearing and Shock Processes

The aggregate output in the economy is divided into consumption, accumulation of physical and bank capital, and the various adjustment costs:

$$Y_t = C_t + I_t + \delta^b \frac{K^b_{t+1}}{\pi_t} + Adj_t \tag{3.28}$$

where $C_t = c^P_t + c^I_t + c^E_t$ is the aggregate consumption, I_t is aggregate investment undertaken, and K^b_{t+1} is the aggregate bank capital. The $Adjt$ includes all adjustment costs.

3.4 Estimation

The baseline model, which assumes the IRB approach for the calculation of the RWA, is estimated using Bayesian methods. We use 11 observables for the UK covering the periods 1991Q1-2019Q3 at quarterly frequency. These include the real consumption, real investment, real house prices, real loans to households and firms, the policy rate, interest rates on deposits, loans to firms and households, real wage, and consumer price inflation rates. Section B.1 in the annex contains a detailed description of the data.

3.4.1 Calibrated Parameters

As common in literature, a subset of parameters is calibrated. Table 3.2 summarises the calibration exercise.

The discount factor of patient households β^P is set at 0.9943 to pin down a 2.5% quarterly steady state shadow policy rate.[9] Meanwhile, the discount factors for impatient households and entrepreneurs, β^I and β^E, are set in line with the literature.[10]

The calibration of the inverse Frisch elasticity, capital share in the production function, and depreciation rate follows the literature (see Gambacorta and Karmakar (2018) among many others). The steady-state loan-to-value (LTV) for households loans of 0.70 reflects the UK LTV ratio limit. For the entrepreneurs loans, instead, the values 0.35 is taken from the literature (Gambacorta and Karmakar (2018)).

The parameters controlling the markups in different markets are calibrated following Gerali et al. (2010). The markup in the goods market is 20 percent (i.e. we set ϵ^y to 6), while in

[9] The shadow rate is based on the computation generated by Wu and Xia (2016).

[10] See Iacoviello (2005), Gerali et al. (2010), Angelini, Neri and Panetta (2014), Hodbod, Huber and Vasilev (2018), and Gambacorta and Karmakar (2018).

Table 3.2 Calibrated Parameters

Parameter	Value	Definition	Source
β^P	0.9943	Patient households' discount factor	Steady-state $R = 2.5\%$
β^I	0.975	Impatient households' discount factor	Iacoviello (2005)
β^E	0.975	Entrepreneurs' discount factor	Iacoviello (2005)
ϕ	1.00	Inverse of the Frisch elasticity	Gerali et al. (2010)
ε^y	6.00	Markup in the goods market $\left(\frac{\varepsilon^y}{\varepsilon^y-1}\right)$	Gerali et al. (2010)
ε^l	5.00	Markup in the goods market $(\frac{\varepsilon^l}{\varepsilon^l-1})$	Gerali et al. (2010)
ϵ^d	-1.46	Markdown in the deposits market $(\frac{\varepsilon^d}{\varepsilon^d-1})$	Gerali et al. (2010)
$\epsilon^{b,H}$	2.79	Markup on loans to households $(\frac{\epsilon^{b,H}}{\epsilon^{b,H}-1})$	Steady-state $\frac{B^H}{B} = 30\%$
$\epsilon^{b,E}$	3.12	Markup on loans to entrepreneurs $(\frac{\epsilon^{b,E}}{\epsilon^{b,E}-1})$	Steady-state $\frac{B^E}{B} = 70\%$
α	0.25	Capital share in the production function	Gerali et al. (2010)
γ^P	0.50	Share of patient household	Brzoza-Brzezina, Kolasa and Makarski (2013)
γ^I	0.25	Share of impatient household	Brzoza-Brzezina, Kolasa and Makarski (2013)
γ^E	0.25	Share of entrepreneurs	$1 - \gamma^P - \gamma^I$
δ	0.025	Capital depreciation rate	Gerali et al. (2010)
m^I	0.70	LTV ratio for impatient households	calibrated on UK data
m^E	0.35	LTV ratio for entrepreneurs	Gerali et al. (2010)
δ^b	0.25	Cost of managing bank capital	Steady-state $\frac{K^b}{B} = 4\%$
ν^b	0.09	Steady-state capital requirements	Basel III & UK regulation
κ_{IM}	15	Cost of deviating from capital requirements	Steady-state $\frac{K^b}{RWA^{IM}} = 9\%$
κ_{OF}	10	Cost of deviating from capital requirements	Steady-state $\frac{K^b}{RWA^{OF}} = 9\%$

the labour market is 15% (i.e. we set ϵ^l to 5). Markdown for deposits is set at 60% (i.e. $\epsilon^d = -1.46$). The markups for loans to households and firms are calibrated in order to pin-down the proportion of UK households and non-financial corporate loans in UK, which are around 30% and 70%, respectively.[11]

The parameters of Table 3.2 concern the prudential regimes. They are mainly calibrated to match the Basel III recommendation[12] and the current UK regulation[13] The cost of managing bank capital δ^b is calibrated to pin down a leverage ratio $\frac{K^b}{B}$ of 4%. The steady state capital requirements ν^b is set equal to 9%, which is the average value of the (fixed) capital requirements for UK banks.[14]. The cost of deviating from the capital requirements under the IRB approach (κ_{IRB}) and the output floor (κ_{OF}) is calibrated to pin down a steady state level of capital-to-RWA ratio equal to the steady state requirements.

[11] The proportion of households and non-financial corporate loans are based on a quarterly average for the period 1991Q1-2019Q3.

[12] Refer to *Basel III: A global regulatory framework for more resilient banks and banking systems*; https://www.bis.org/publ/bcbs189.htm.

[13] Refer to *Supplement to the December 2015 Financial Stability Report: The framework of capital requirements for UK banks*; https://www.bankofengland.co.uk/-/media/boe/files/financial-stability-report/2015/supplement-december-2015.pdf.

[14] The value of 9% considers the minimum capital requirements (4.5%) plus the Pillar 2A requirements and capital buffers, in CET1 capital space

Table 3.3 Prior and Posterior Distributions of the Structural Parameters

Parameter		Prior Distributions			Posterior Distributions			
		Type	Mean	Std dev.	Mean	2.5%	Median	97.5%
		Structural Parameters						
κ_{bH}	Mortgages rate adjustment cost	$\mathcal{G}$	6.00	2.50	6.75	3.11	6.43	11.06
κ_{bE}	NFC loans rate adjustment cost	$\mathcal{G}$	3.00	2.50	11.83	7.64	11.57	16.35
κ_d	Deposits rate adjustment cost	$\mathcal{G}$	10.00	2.50	4.88	2.63	4.60	7.80
κ_y	Degree of price stickiness	$\mathcal{G}$	100.00	20.000	108.40	65.40	107.53	153.98
κ_l	Degree of wage stickiness	$\mathcal{G}$	100.00	20.00	143.81	97.23	139.25	197.92
ι_y	Price indexation	$\mathcal{B}$	0.50	0.15	0.09	0.021	0.09	0.17
ι_l	Wage indexation	$\mathcal{B}$	0.20	0.15	0.031	0.00	0.03	0.08
κ_i	Investment adjustment cost	$\mathcal{G}$	50.00	5.00	47.94	38.63	47.84	56.82
ρ_R	Policy rate stickiness	$\mathcal{B}$	0.50	0.15	0.87	0.83	0.87	0.90
ϕ_π	Monetary policy response to π	$\mathcal{G}$	2.00	0.50	2.07	1.68	2.03	2.55
ϕ_Y	Monetary Policy response to y	$\mathcal{N}$	0.10	0.15	0.27	0.00	0.27	0.53
a^i	Habit coefficients	$\mathcal{B}$	0.70	0.20	0.94	0.92	0.94	0.97
χ_{ν^b}	Sensitivity of capital requirements	$\mathcal{N}$	2.50	0.50	2.19	1.20	2.18	3.17
ρ_{ν^b}	Persistence of capital requirements	$\mathcal{B}$	0.80	0.10	0.987	0.973	0.988	0.998
		Shocks' Persistence						
ρ_A	TFP	$\mathcal{B}$	0.80	0.10	0.954	0.895	0.972	0.996
ρ_c	Consumption preference	$\mathcal{B}$	0.80	0.10	0.443	0.288	0.445	0.598
ρ_h	Housing preference	$\mathcal{B}$	0.80	0.10	0.911	0.860	0.912	0.954
ρ_{mH}	LTV on mortgages	$\mathcal{B}$	0.80	0.10	0.979	0.953	0.982	0.998
ρ_{mE}	LTV on loans to NFC	$\mathcal{B}$	0.80	0.10	0.984	0.969	0.985	0.997
ρ_{bH}	Mortgages mark-up	$\mathcal{B}$	0.80	0.10	0.860	0.768	0.864	0.941
ρ_{bE}	Loans to NFC mark-up	$\mathcal{B}$	0.80	0.10	0.742	0.552	0.744	0.938
ρ_d	Deposits mark-down	$\mathcal{B}$	0.80	0.10	0.782	0.685	0.789	0.858
ρ_{qk}	Investment efficiency	$\mathcal{B}$	0.80	0.10	0.193	0.105	0.199	0.275
ρ_y	Price mark-up	$\mathcal{B}$	0.80	0.10	0.223	0.106	0.221	0.331
ρ_l	Wage mark-up	$\mathcal{B}$	0.80	0.10	0.660	0.489	0.674	0.801
ρ_{Kb}	Bank capital	$\mathcal{B}$	0.80	0.10	0.955	0.891	0.962	0.997

3.4.2 Posterior Estimates

Tables 3.3 reports the prior and posterior distributions of the structural parameters and the shocks' persistence. Section B.3 in annex contains the results for the shocks' standard deviation. Posterior distributions are obtained using the Metropolis-Hastings algorithm. The estimates are based on two chains of 100,000 draws with acceptance ratio of 21.13% and 28.38%. Convergence checks are displayed in section B.3 in the annex.

While we mostly use the priors in Gerali et al. (2010), our posteriors show differences from previous studies. This highlights the characteristics of the UK economy distinct from that of the Euro Area. For instance, most of the exogenous processes have higher persistence in the UK than the Euro Area. These results are broadly consistent with previous DSGE estimates conducted for the UK economy by DiCecio and Nelson (2007), Harrison and Oomen (2010) and Villa and Yang (2012). Specifically, the technology shock is very persistent compared to the one of Euro area (0.97 versus 0.94 in the Euro Area).[15] Also the parameter measuring the degree of consumption habits are estimated to be higher in UK (0.94) than in Euro Area (0.86). Concerning the nominal rigidities, we find that wage rigidities is stronger than price stickiness, consistent with Gerali et al. (2010).

For the monetary policy rule, we estimate the response to inflation at 2.03 and the policy rate persistent equal to 0.87. Both values are in line with the findings of DiCecio and Nelson (2007). Meanwhile, we estimate the coefficient measuring the response to output growth equal to 0.27, which is slightly higher than the previous estimates of DiCecio and Nelson (2007) and Harrison and Oomen (2010) that estimated the output growth coefficient at 0.05 and 0.12, respectively.

Regarding the financial variables, we find results similar to those of Gerali et al. (2010). In particular, we find that the degree of stickiness of UK loans rates (determined by κ_{bH} and κ_{bE}) are similar to those of the Euro Area. Moreover, the estimation shows that deposits rates adjust more rapidly than the rates on loans to the changes in policy rate in the UK.

3.4.3 The Risk Weights

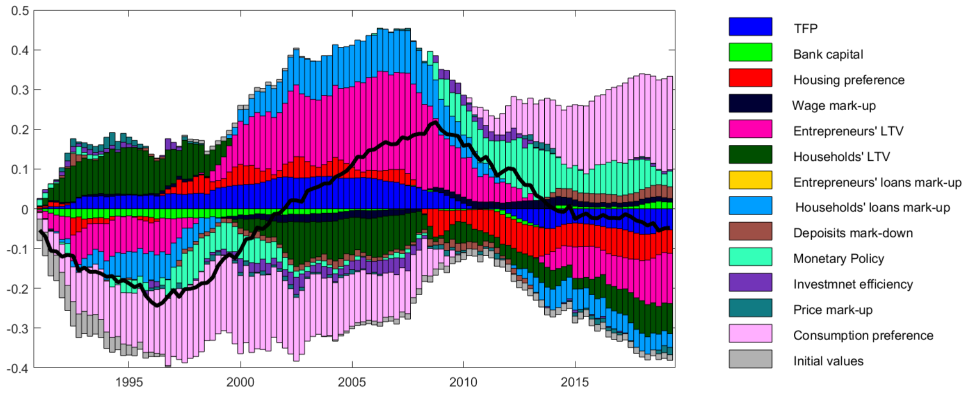
The equations for the IRB risk weights and the values of the SA risk weights are crucial to understand how the output floor differs from the IRB approach. Table 3.4 summarises the calibration/estimation of the risk weights functions. The values of the SA risk weights follow the Basel recommendations. Finally, the steady state value of the IRB risk weights are calibrated using confidential data on UK banks. The sensitivity and persistence of IRB risk weights, instead, are estimated.

Table 3.4 Risk Weights

Parameter	Value	Definition	Source
$w^{H,SA}$	0.30	SA risk weight on mortgages	Basel III principles
$w^{E,SA}$	0.70	SA risk weight on NFC loans	Basel III principles
$w^{H,IRB}$	0.16	Steady-state IRB risk weight on mortgages	Calibrated on UK data
$w^{E,IRB}$	0.57	Steady-state IRB risk weight on NFC loans	Calibrated on UK data
$\chi_{w^{H,IRB}}$	-9.94	Sensitivity of IRB risk weights (HH)	Model-based estimation
$\chi_{w^{H,IRB}}$	-14.99	Sensitivity of IRB risk weights (NFC)	Model-based estimation
$\chi_{w^{H,IRB}}$	0.85	Persistence of IRB risk weights (HH)	Model-based estimation
$\chi_{w^{H,IRB}}$	0.89	Persistence of IRB risk weights (HH)	Model-based estimation

[15] Villa and Yang (2012) estimated a persistence of technology shock for the UK at 0.98 while Harrison and Harrison and Oomen (2010) estimated it at 0.99.

Fig. 3.2 Historical Shock Decomposition: Credit-to-GDP



The estimated equations describe the static and dynamic properties of the risk weights. First, in the steady state, the risk weight of NFC loans is higher than the mortgages risk weight (0.57 vs 0.16), reflecting a higher implicit riskiness of former compared to the latter. The gap between the risk weights means also that mortgages have lower costs for banks in terms of capital requirements. Second, the risk weights have different cyclical properties and, in particular, the NFC loans risk weights react more to changes in the economic conditions. In particular, after an economic expansion, NFC loans risk weights decrease more than mortgages risk weights.

Finally, Table 3.4 shows that in steady state mortgages have a larger gap between IRB and SA risk weights compared to loans to NFC. The modelled risk-weight for mortgages is 53.3% of the standardised one. Instead, the modelled risk-weight for loans to NFC is 81.4% of the standardised one. According to what we discussed in Section 3.2, we can expect that when the output floor is binding, banks might have an incentive to prefer NFC loans with respect to mortgages. The dynamics of the risk weights, instead, gaps depend also on the reactions of the internally-modelled risk weights to the GDP fluctuations (see equation 3.18). We will come back to this point later in section 3.5.

3.4.4 Variance Decomposition

We use the estimated model to understand what are the main forces driving the fluctuations of the endogenous variables of the model. In doing this, we compute the variance decomposition, which measures the contribution of each shock to the variability of the cycles of aggregate variables. We focus on credit-to-GDP given its importance for the macroprudential authority decisions, which are the main focus of the paper.

The posterior mean variance decomposition shows that the total factor productivity (TFP) and the banking sector shocks are the main drivers for its fluctuations. TFP drives around 18% of its fluctuations while shocks to firms LTV ratio, households LTV ratio and households loans spread contribute to around 29%, 5% 15%, respectively. In addition, consumption preference, investment efficiency, and housing preference contribute around 12%, 8%, and 3%, respectively (See Table B.2 in annex B.3). This is consistent with the findings of Barnett and Thomas (2014) for the UK which underscore the importance of credit supply shock as the driver of credit fluctuation. Similarly, Gerali et al. (2010) highlights the importance of banking sector shocks in the fluctuation of credit supply in the Euro Area.

We turn to the historical shock decomposition, which describes the contribution of each shock to the deviations of the cycles of the aggregate variables from their steady state. Figure 3.2 shows the historical shock decomposition of credit-to-GDP between 1991Q1 and 2019Q3 in the UK. The black line represents the deviation of the smoothed values of the observed data from its steady state while the coloured bar graphs represent the contribution of different shocks.

In the run up to the 2007-2008 global financial crisis, it shows that the credit boom is driven by technology, households' loans spread, firms' LTV ratio and housing preferences. When the crisis hit, credit-to-GDP started to fall caused mainly by the decline in the housing preference shock and the tightening of the firms' LTV ratio. This period coincides with the decline in both housing prices and households loans growth (see Figures B.3 and B.4 in the annex B.3 for more details).

3.5 Model Analysis

In this section, we compare the dynamics of the model with the IRB approach and the model with the output floor. In both cases, we use the calibrated and estimated parameters described above.[16] More importantly, the model with the output floor contains non-differentiable function in the definition of the RWA. Accordingly the model is solved using the method of Holden (2016). This solution method allows us to have an output floor that binds only in case the RWA calculated under the IRB approach is lower than the 72.5% of the standardised one. Additional details on the solution methods can be found in Annex B.2.

[16] We use the median of the posterior distributions as suggested by Gerali et al. (2010).

3.5.1 Evolution of RWA and Credit-to-GDP

We start the model analysis by looking at how the output floor affects the dynamics of the RWA and the credit-to-GDP over the cycle. More specifically, we evaluate the path of those variable over a long simulated path (350 quarters) of TFP shocks – one of the main drivers of the model's cyclical fluctuations.

Fig. 3.3 Simulation of RWA and Real GDP

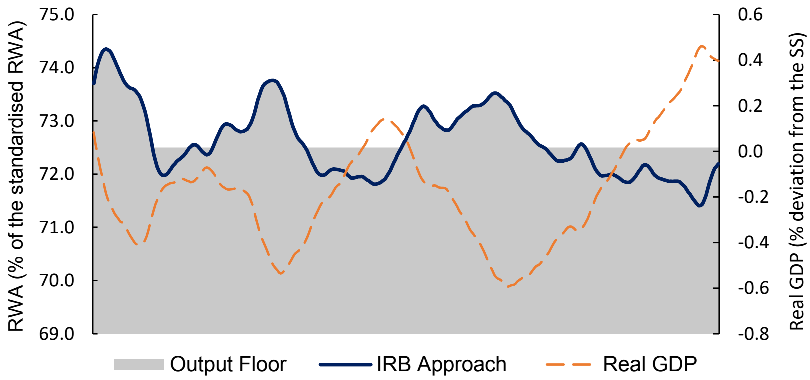
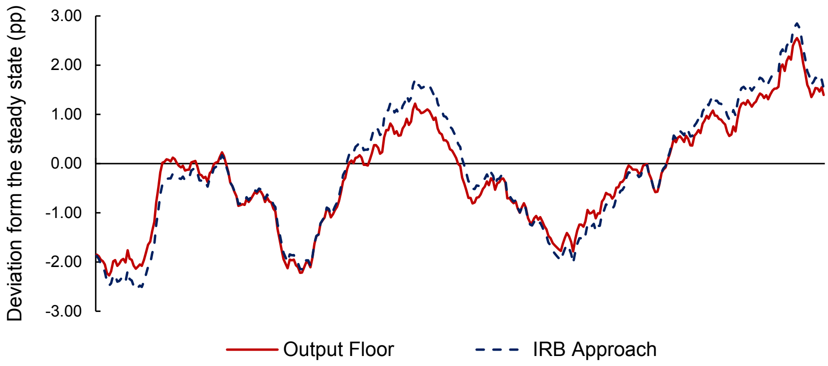


Figure 3.3 shows the evolution of the modelled RWA (IRB) (blue line) and the RWA calculated under the output floor (grey area) in terms of their standardised value. The figure contains also the percentage deviation of the real GDP from its steady state (orange dotted line), which allows us to identify the boom and bust phases of the cycle. As expected, the output floor is likely to be binding during the expansionary phases and during the recoveries from crises. The intuition behind this result is that the economic expansions (positive real GDP deviations) trigger a reduction of the risk weights, and in turn, a downward pressure to the modelled RWA. The output floor prevents these downward pressures, by setting a floor to the reduction of RWAs.

Figure 3.4 displays the simulated path of the credit-to-GDP under the two prudential approaches considered - the IRB approach (blue dotted line) and the output floor (red line). The output floor makes the fluctuations of the credit-to-GDP smoother compared to the case the IRB approach. This is because the output floor prevents the downward pressures on the RWA generated by modelled risk weights and, in turn, constraints the ability of banks to expand their balance sheet. The next section discusses more in detail these mechanisms.

Fig. 3.4 Simulation of Credit-to-GDP



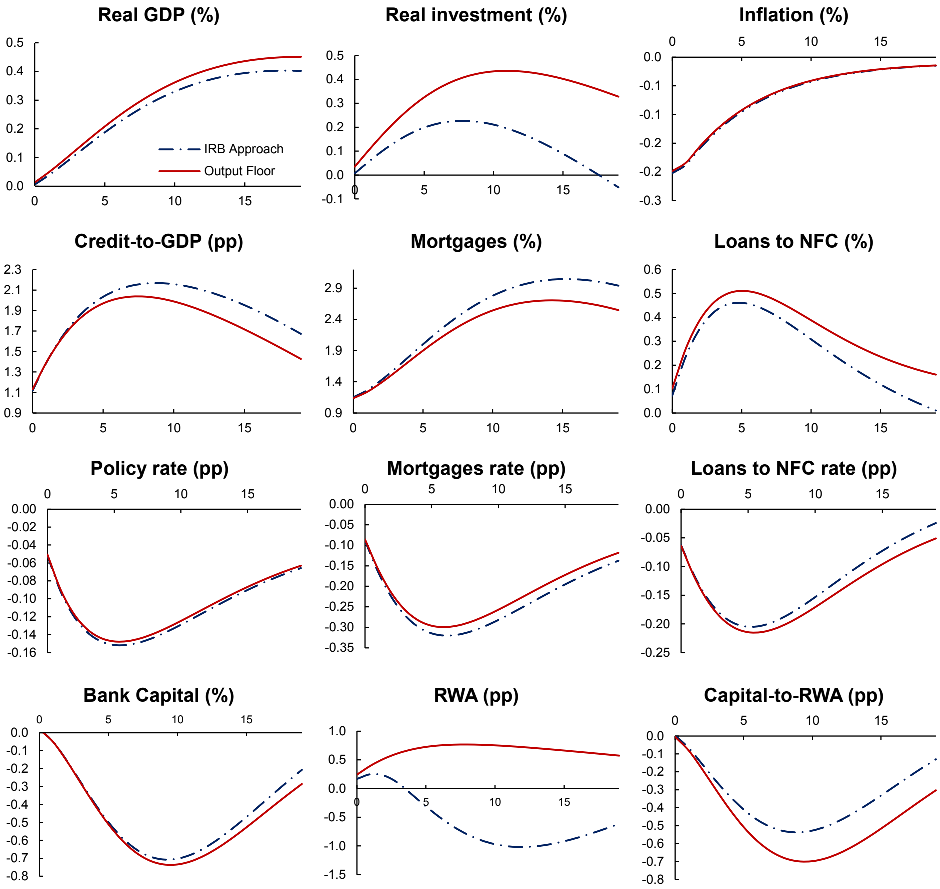
3.5.2 Impulse Response Functions

To explain the above results, this section focuses on the impulse response functions (IRFs). We have selected two shocks that important for the model dynamics and the analysis we want to perform. First, we consider the IRFs to a total factor productivity shock, which is commonly used to simulate business cycle fluctuations. Moreover, the historical shock decomposition analysis has documented the importance of this shock during the build-up of the credit-to-GDP before the crisis. Second, we simulate a negative monetary policy shock to see how the two prudential regimes perform in response to a monetary policy intervention.

Impulse response functions to a positive technology (TFP) shock. Figure 3.5 shows the IRFs to a positive shock to the TFP. An increase in the TFP generates an economic boom (real GDP, real consumption and investment increase) which fuels a credit expansion (credit-to-GDP increases and interest rates decline). The prudential policies in place aim at mitigating the build-up of credit. However, the effectiveness of the two prudential regimes - the IRB approach (blue dotted lines) and the output floor (red lines) - is different.

During the boom, lending to households and entrepreneurs increases while interest rates go down. These effects, in turn, reduce the bank's capital-to-RWA ratio. In the model, banks' capital - the numerator of the capital-to-RWA ratio - is accumulated by retained earnings only and therefore a reduction in the interest rates on mortgages and corporate loans generates a drop in the level of banks' capital. The denominator of the capital-to-RWA, instead, is affected by both banks' lending and the response of risk weights to change in economic conditions. Under the IRB regime, the economic boom also generates a reduction of the risk weights of both mortgages and corporate loans (see 3.5 in Annex B.2) which explains the reduction of the RWA and alleviates the drop of the banks' capital-to-RWA ratio. This implies that banks

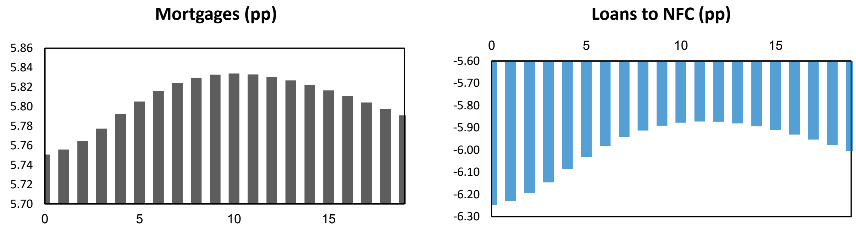
Fig. 3.5 IRFs to a Positive TFP Shock



NOTE: The impulse responses of real GDP, real investment, inflation, loans, bank capital and RWA are in percentage deviations from steady state. The responses of credit-to-GDP, policy rate, loans rate and capital-to-RWA are in absolute deviations from the respective steady state levels and expressed in percentage points.

deviate less from the capital-to-RWA constraint and then can further expand lending to the real economy without paying any costs. The downward pressure on the RWA triggered by the pro-cyclicality of risk weights implies that the modelled RWA declines below the 72.5% of its standardised value and the output floor binds. Figure B.7 in Annex B.2 shows that after the TFP shock the output floor is always binding. When the output floor binds, the risk weights do not respond to the economic conditions and the RWA increase due to the credit expansion. This makes the decline of the capital-to-RWA stronger, namely banks deviate more from the capital requirements. Therefore, banks are forced to limit the credit expansion triggered by the TFP shock in order to reduce the regulatory costs. The output floor is, therefore, able to constrain the excessive increase of the credit-to-GDP during an economic boom.

Fig. 3.6 Marginal Contribution of Assets to RWA: OF vs IRB

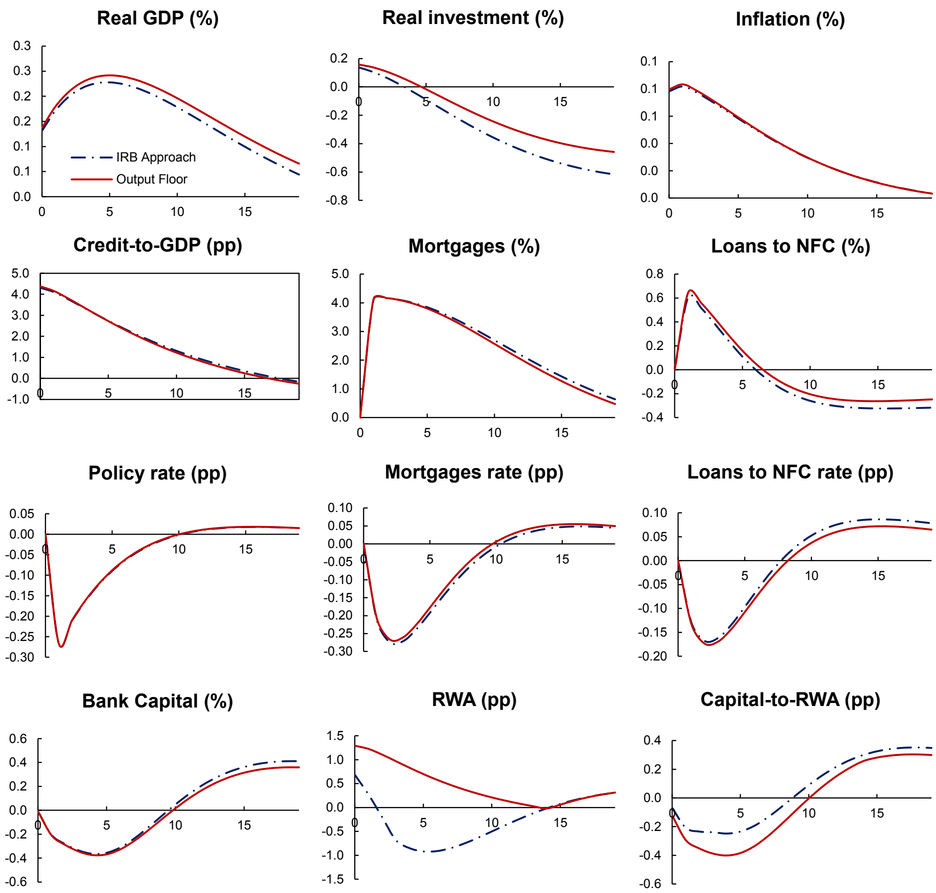


NOTE: The figure reports the difference between the output floor-implied risk weight and the IRB risk weight for both assets - i.e. $\Delta w^k = (0.725 * (w^{k,SA}) - w^{k,IRB}) * 100$ *with* $k \in \{Mortgages,\ Loans\ to\ NFC\}$ *- after a positive TFP shock. The variables are expressed in percentage points.*

Figure 3.5 shows an additional effect of the output floor. Although the overall credit expansion is mitigated, there is an asymmetric response of mortgages and loans to NFC. The output floor moderates the increase of mortgages but makes stronger the expansion of the latter. This asymmetric impact on lending explains the larger expansion of the real investment and real GDP under the output floor regime. As explained in Section 3.2, the intuition of this result can be found looking at the risk weights gap - difference between SA and IRB risk-weights - characterising the two assets. During the 20 periods following the shock, the modelled risk-weight for mortgages is, on average, 53.1% of the standardised one, while the modelled risk-weight for loans to NFC is, on average, 81.1% of the standardised one (Figure B.6 in Annex B.4 shows the gaps over the simulation period). This implies that under the output floor the marginal contribution of mortgages to the aggregate RWA - i.e. the increase of RWA when the bank extends an additional unit of mortgages - is larger compared to the IRB approach, while the opposite happens for the loans to NFC. Figure 3.6 shows the difference between the the output floor-implied risk weights - i.e. $72.5\%(w^{k,SA})$ with $k \in \{H, E\}$ and the IRB risk weights over the simulated period. This shows how the marginal contribution of each asset to the aggregate RWA differs under the two prudential regimes. We can notice that the difference is positive for mortgages but negative for loans to NFC. This means that the output floor makes loans to NFC (mortgages) marginally less (more) expensive in terms of capital requirements. Accordingly, banks have the incentive to prefer more loans to NFC after the implementation of the output floor.

Impulse Response Functions to a negative monetary policy shock. The negative monetary policy shock generates an economic boom and a credit expansion driven by the reduction of the lending rates. During the first 14 periods of the simulation, the output floor is binding (see in Annex B.4). This determines a stronger decline of capital-to-RWA ratio, which in turn forces banks to smooth the credit expansion. However, the difference between the two prudential regimes is tiny in this case. This likely depends on the fact that the credit expansion is mainly driven by the reduction of the policy rate.

Fig. 3.7 IRFs to a Negative Monetary Policy Shock



NOTE: The impulse responses of real GDP, real investment, inflation, loans, bank capital and RWA are in percentage deviations from steady state. The responses of credit-to-GDP, policy rate, loans rate and capital-to-RWA are in absolute deviations from the respective steady state levels and expressed in percentage points.

Interestingly, the IRFs suggest also that the output floor might allow the monetary authority to achieve a higher GDP level for a similar inflation profile. In other words, the output floor might improve the efficiency of the monetary policy. The next section discusses how the output floor can support monetary policy in achieving his objectives.

3.5.3 Monetary and Macroprudential Policy Objectives

Finally, we test how the implementation of the output floor affects the achievement of the monetary and macroprudential authority objectives. Accordingly, we compute the loss function for the monetary and macroprudential authorities, following Angelini, Neri and Panetta (2014). The macroprudential policy aims to minimise the volatility of credit-to-GDP (B/Y) and real GDP (Y):

$$L^{MaP} = \sigma^2_{B/Y} + \kappa_{Y,MaP}\sigma^2_Y + \kappa_{\nu^b}\sigma^2_{\Delta^b_\nu} \tag{3.29}$$

where σ^2_i represents the asymptotic variance of the target variables $i = B/Y$, Y, and Δ_{ν^b} or credit-to-GDP, real GDP, and the change in capital ratio, respectively. Parameter $\kappa_{Y,MaP} \geq 0$ characterises the policymaker's preferences over output. As in Angelini, Neri and Panetta (2014), we set κ_{ν^b}=0.1— a positive κ_{ν^b} is important to check that the policy instrument (ν^b, defined in equation 3.27) is not too volatile.

The monetary policy authority, instead, aims to minimise the volatility of inflation (Π) and real GDP (Y):

$$L^{MP} = \sigma^2_\pi + \kappa_{Y,MP}\sigma^2_Y + \kappa_R\sigma^2_{\Delta R} \tag{3.30}$$

where σ^2_π is the asymptotic variance of inflation, and $\sigma^2_{\Delta R}$ is the asymptotic variance of the change in the policy rate. Meanwhile, $\kappa_{Y,MP}$ and κ_R represent the policymaker's preferences over the volatility of the real GDP and the policy rate (ΔR). Preference parameters are set following Angelini, Neri and Panetta (2014). More specifically, we set the $\kappa_{\nu^b} = \kappa_R = 0.1$ and we consider two scenarios for $\kappa_{Y,MaP} = \{0, 0.5\}$ and $\kappa_{Y,MP} = \{0, 0.5\}$.

Technology (TFP) shocks. We considered technology shock, which can be considered the main driver of the business cycle fluctuations. Table 3.5 summarises the results.

The volatility of all the variables considered, except real GDP, are lower under the output floor. The impact of real GDP is related to the portfolio shifting triggered by the output floor. Indeed, figure 3.5 shows that during the boom the output floor generates a larger expansion of investment and, in turn, real GDP. Notably, the output floor is very effective in reducing the volatility of credit-to-GDP (-12%) and RWA (-20%).

Looking at the impact of the output floor on the authorities' loss functions, we can make the following considerations. First, the output floor contributes in a significant way to the achievement of the macroprudential policy objectives. Independently on the authority's preference on the volatility of real GDP, the loss function is materially lower when the output

Table 3.5 Loss Functions: Technology (TFP) Shocks

Prudential Regimes	Standard deviations (%)					
	Y	B/Y	Π	Δr	$\Delta \nu^b$	RWA
IRB Approach	2.09	4.19	0.41	8.35	2.36	4.48
Output Floor	2.44	3.68	0.40	8.16	2.09	3.57
	Loss Functions					
	Monetary (MP)		Macroprudential (MaP)		Total	
	$\kappa_{MP,Y} = 0$	$\kappa_{MP,Y} = 0.5$	$\kappa_{MaP,Y} = 0$	$\kappa_{MaP,Y} = 0.5$	$\kappa_{i,Y} = 0$	$\kappa_{i,Y} = 0.5$
% change	-4.5	+5.2	-22.9	-6.5	-17.7	-9.7

NOTE: The table reports the standard deviations in percentage points and the difference between the authorities' loss function under the IRB approach and the output floor. The % deviations of the loss functions are calculated as $\left(\frac{L_{IRB}}{L_{OF}} - 1\right) * 100$. *The total loss functions are the sum of the monetary and macroprudential loss functions - i.e.* $L^{MaP} + L^{MP}$. *- under the different regimes.*

floor is in place – -23% when $\kappa_{MaP,Y} = 0$ and -18% when $\kappa_{MaP,Y} = 0.5$. Second, the effect of the output floor on the monetary policy objective depends, instead, on its preferences on the volatility of real GDP. In case $\kappa_{MP,Y} = 0$, the output floor reduces the monetary policy loss functions (-5%). On the contrary, if $\kappa_{MP,Y} = 0.5$, the loss function is higher when the output floor is in place. The results is driven by the higher volatility of output.

All in all, we can conclude that the output floor is very effective is supporting the macroprudential authority to achieve its objectives. It is able to materially reduce the volatility of the credit-to-GDP, by limiting the excessive variability of the RWA. The effect of the monetary policy objectives depends, instead, on the nature of the shock and the preference of the authority on the volatility of the real GDP. If the monetary authority focuses only on inflation, the output floor can support its objectives. By contrast, the output floor might increase the volatility of the real GDP over the business cycle, hence requires a stronger intervention of the monetary authority to stabilise it. All these results must be interpreted with care because they do not consider the optimal policies - i.e. authorities do not optimise their responses to fluctuations of the target variables. It is possible that optimising the policy rules, the authorities would be able to achieve better outcomes. This is, however, beyond the scope of the paper and left for future research.

Finally, the exercise has shown that the output floor can affect the volatility of RWA across time, and this feeds through into a reduction in volatility of other variables. This is a novel result and has potential consequences for stress-testing and prudential policy, for example if RWAs fluctuate (rise) by less following the onset of adverse shocks.

3.6 Conclusions

We propose a DSGE framework with a two-asset banking sector, financial frictions, sticky rates, and multiple regulatory constraints for the macroeconomic evaluation of the introduction of the output floor - a new capital requirement introduced as part of the Basel III finalisation reforms. The main purpose of introducing the output floor is to minimise the variability of risk-weighted assets and thus, ensure a stable level of capital ratio for banks and improve the banking system's ability to absorb negative shocks. We look at the impact of the output floor on: (i) the variability of risk-weighted assets; (ii) banks' lending decision and its tendency to amplify the credit cycle; and (iii) the objectives of the monetary and macroprudential authority.

Our results show that the output floor reduces the variability of risk-weighted assets resulting in a less volatile risk-weighted capital ratio. This reduction in variability over time adds an interesting dimension to the often discussed cross-sectional variability. The results suggest that the output floor can affect not just cross-sectional RWA variability, but it also reduces time-series variability and this will have consequences for stress-testing policy. Indeed, to the extent that stress tests capitalise banks for cyclical variation in modelled RWA, they may need to do so by less for banks constrained by the output floor because their RWA will have less scope to move cyclically over time. The results suggest that this lower volatility stabilises the aggregate supply of loans and attenuates a sudden boom and bust of the supply of credit. However, there is a behavioural consequence from the introduction of the output floor, that is, banks tend to shift their portfolio from assets with a large gap between internally modelled and standardised risk weights (mortgages) to non-financial corporation loans which display a smaller gap.

Some important extensions are left for future research. First, we discussed in the introduction that also the leverage ratio has the aim to create a guard against the understatement and non-capture of assets' risks. Therefore, it would be valuable to include the leverage ratio in the model to study its complementarities with the output floor. Here we have elected not to do so in order to get a tractable model offering a first analysis of the macroeconomic consequences of the output floor. Second, our model shows that the output floor might have a non-negligible impact on the interaction between monetary and macroprudential policy. Finally, the model assumes a well-established function for the risks weights under internal models. However, a more micro-founded justification of their cyclical variation might help to better understand the behavioural consequences of the output floor.

Chapter 4

Capital Regulation in a Low-Interest Environment

4.1 Introduction

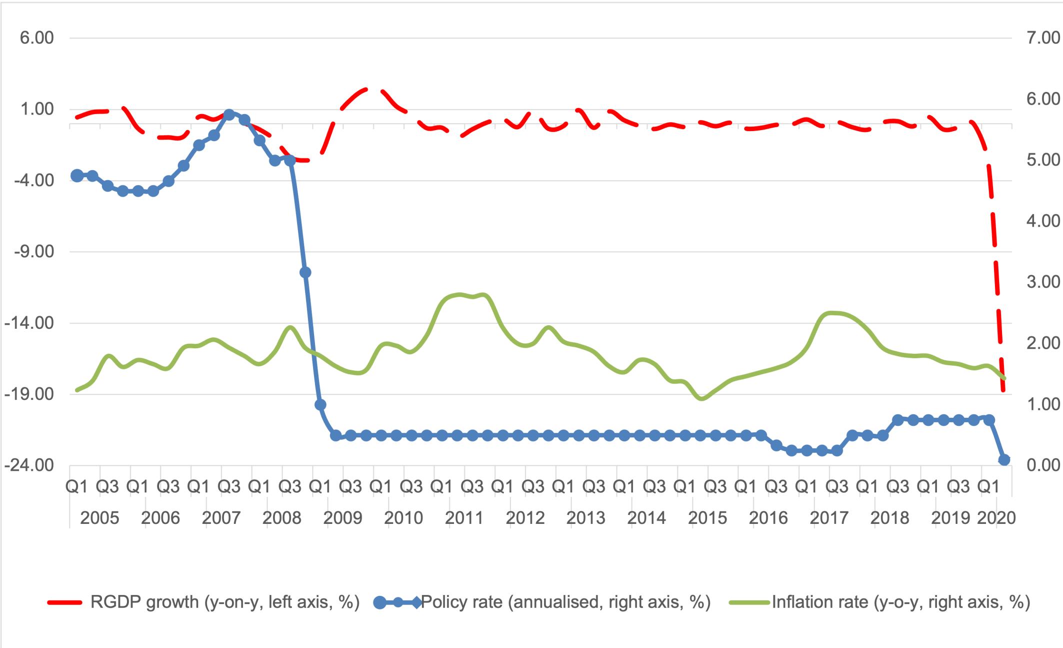
For more than ten years since the global financial crisis (GFC), nominal interest rates in most advanced economies have stayed near their effective lower bound. Laubach and Williams (2016) estimated that long-term neutral rates have declined to much lower levels when compared to the pre-crisis period and furthermore, show no sign of recovery. The current Covid-19 crisis has exacerbated the problem and prompted many central banks to reduce their policy rates still further; the UK being no exception. Figure 1 shows the policy rate, GDP growth and inflation rate of the UK from 2005Q1 to 2020Q2.

Meanwhile, the Basel Committee and Banking Supervision (BCBS) continues to tighten its macroprudential policy framework in response to the limitations of the regulatory framework that the GFC exposed (Ingves (2018)). In 2017, the BCBS released the Basel III package which includes a strengthening of capital regulation by imposing additional buffers.[1] Figure 2 shows the historical risk-weighted capital ratio of the UK, along with the credit-to-GDP ratio, and policy rate from 2005 to 2019.

The current environment of interest rates near the zero lower bound (ZLB) has prompted questions as to how financial stability and the conduct of macroprudential policy should be implemented. First, low interest rates limit the scope of conventional monetary policy to

[1] BCBS, 2015.

Fig. 4.1 Policy rate, GDP growth, and Inflation rate for the UK (2005Q1-2020Q2)



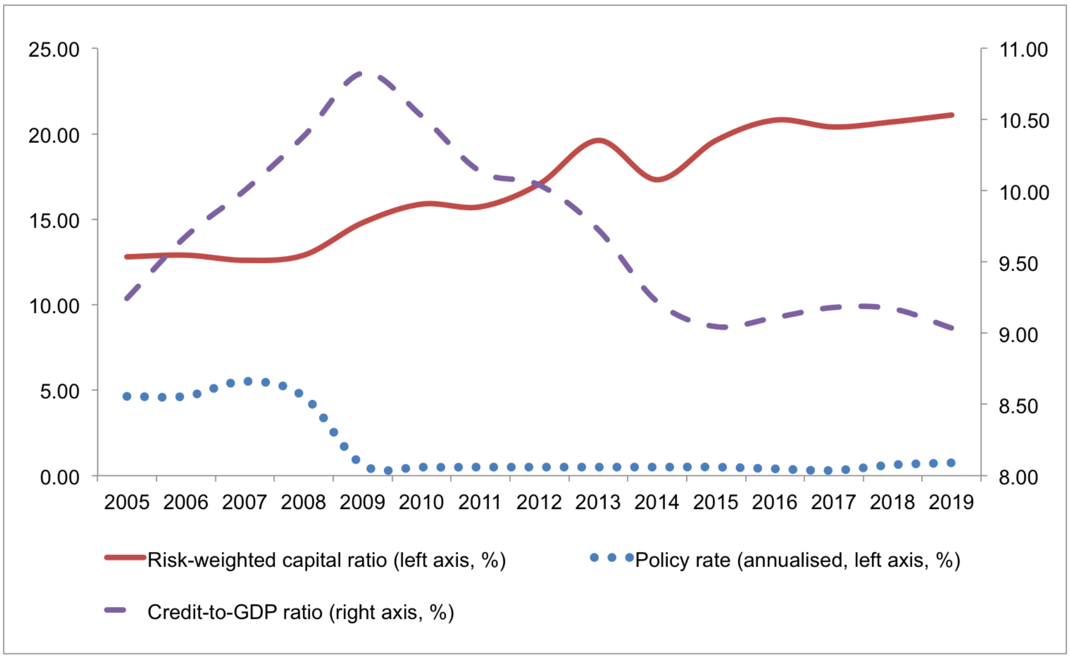
Source: Bank of England database and FRED.

stabilise the economy. Second, low interest rates may themselves lead to financial imbalances and generate risks to financial stability.

On the one hand, the current low interest rate environment decreases banks' profitability and bank capital. This may affect the ability of banks to lend, necessitating an easing of capital regulations (Dottling (2020)). On the other hand, this environment encourages borrowers' indebtedness and banks' excessive risk taking, which would suggest the need for tighter capital regulations (Rubio and Yao (2019), Rubio and Yao (2020)). In this paper, we focus on model-based capital regulation in a low interest environment. In particular, we re-examine the transmission mechanism of a risk-weighted capital regulation when monetary policy is constrained by the ZLB in a standard New Keynesian model that builds on Gerali et al. (2010). We ask whether more aggressive capital regulation is appropriate where monetary policy is constrained by the ZLB.

Rosengren (2019) notes that a low interest rate environment with limited monetary policy buffers could result in more shallow recoveries from future recessions because interest rates cannot be lowered sufficiently. In turn, prolonged periods of relatively poor economic performance imply extended episodes of policy rates stuck at the effective lower bound. What would this do to the stability of the banking system? Many bank stress tests do not capture the effects of

Fig. 4.2 Risk-weighted capital ratio, Policy rate, and Real credit-to-GDP for the UK (2005-2019)



Source: Bank of England database and FRED. Data on real credit-to-GDP is derived using FRED data.

prolonged economic underperformance, as the tests often consider a span of only two years. Hence these tests may indicate a level of capital buffers that prove insufficient to protect banks against severe losses.

A comprehensive assessment of the macroeconomic consequences of the interaction of a capital regulation and ZLB has yet to be performed. This paper aims to fill this gap. In particular, we develop a general equilibrium framework that can accommodate a ZLB, a credit constraint in a form of capital regulation, and borrowing constraints in the form of loan-to-vaue (LTV) regulations for mortgages and non-financial corporation (NFC) loans. The model captures the large nonlinearities that are mostly missing from current macro models.

Following the approach of Gambacorta and Karmakar (2018), the analysis uses a dynamic stochastic general equilibrium model with a two-asset banking sector, financial frictions (i.e. monopolistic competition in retail banks) and sticky interest rates. In the model, the banking system is subject to regulatory constraints such as the the risk-weighted capital framework, and LTV ratios for mortgages and NFC loans. First, we calibrate our model using previous estimates for the UK in Acosta-Smith, Bassanin and Sabuga (2021) that assess the main drivers of the UK credit cycle. They find that in the period preceding the 2007-2008 global financial crisis, the credit boom was mainly driven by technology, households' loans spreads, firms' LTV ratios and housing preferences. As the crisis happened, credit-to-GDP began to decline as a result of negative housing preference shock and the tightening of the firms' LTV limits.[2] For the model to accommodate the effective lower bound, we embed the ZLB in nominal interest rate, using the solutions method formulated by Holden (2019).[3] To analyse the model, we use the technology shock, which is commonly used to simulate the business cycle fluctuations. We then simulate and compare the cyclical properties of the two different regimes, ZLB and no ZLB. After comparing the models with ZLB and no ZLB, we simulate two more models, both with ZLB but now with low and high capital regulations to examine the effectiveness of the different levels of capital regulation in a ZLB environment.

This analysis produces four main results. First, we find that high capital regulation stabilises the main macroeconomic and financial variables far more than low capital regulation. In the ZLB model with a high capital regulation, the volatility of RWAs is lower than in the model with low capital regulation. The lower variability of RWA is also translated into less volatile capital-to-RWA ratio (-76%), credit-to-GDP ratio (-46%) and real GDP (-0.7%).[4]

Second, comparing the cyclical properties of the ZLB models under the two regimes (low and high capital regulations), we find that the high level of capital regulation is able to reduce the excessive expansion of credit during an economic boom (i.e. after a positive technology shock), by tightening banks' capital constraints more when compared to the case of low capital regulation.

Third, we evaluate whether the implementation of the model with high capital regulation at the ZLB is consistent with the objectives of the policy authorities. In doing so, we calculate the monetary and macroprudential authority's loss functions under the two regulatory regimes similar to Angelini, Neri and Panetta (2014). We find that *ceteris paribus*, a high capital regulation model in ZLB reduces the loss of both the monetary and the macroprudential authority. This result suggests that the higher level of capital regulation performs better in helping regulatory authorities achieve their objectives.

[2] Mian and Sufi (2010) use micro-level analysis of the Great Recession highlighting the link between credit and asset prices, the feedback effect from asset prices to the real economy, and the role of household leverage in explaining the downturn.

[3] We perform the numerical computation using the *DynareOBC toolkit*.

[4] Based on a technology shock simulation.

Lastly, we characterise an optimal level of capital requirements that helps stabilise credit. We find that, the model with a ZLB requires a higher capital ratio at 11% to achieve the lowest volatility of credit compared to 9% for a model with no ZLB.

Literature Review. This study complements Rubio and Yao (2019), and Rubio and Yao (2020) by providing a framework for the interaction of a ZLB constraint in the nominal interest rate, capital regulation, and LTV constraints in mortgages and NFC loans. Dottling (2020) models the interaction of capital regulation and ZLB in deposit rates and find that tight capital regulations disproportionately hurt banks franchise values and become less effective in curbing excessive risk-taking. Rubio and Yao (2019) model the interaction of the LTV constraint and ZLB in nominal interest rate and find that the ZLB creates additional scope for macroprudential policy intervention and calls for more policy coordination. Rubio and Yao (2020) model the interaction of a high and low steady state nominal interest rate (but with no ZLB constraint) and find that an aggressive countercyclical buffer should be implemented when the interest rate is low. While the literature that analyses how the ZLB in nominal interest rate affects the implementation of capital regulation remains limited, policy institutions have started to incorporate this issue in their policy discussions (Rosengren (2019)). Other papers such as Bubeck, Maddaloni and Peydró (2020) look at the interaction of a negative nominal interest rate and bank-risk taking behaviour. De Moraes, Montes and Antunes (2016) look at how capital regulation reacts to monetary policy but not in a low interest rate environment. They find that banks react to monetary policy by changing the amount of loan provisions as well as their capital adequacy ratios.

Broader research on the ZLB for the nominal rate began in the mid 1990's, motivated by Japan's experience. This gathered further momentum after the GFC when many advanced economies also experienced near zero nominal interest rates. Many of these papers such Eggertsson (2011), Christiano, Eichenbaum and Rebelo (2011), Cochrane (2017), Moran and Queralto (2018) and Braun and Körber (2011), look at the dynamics generated by New Keynesian models when the nominal interest rate is constrained by the ZLB. Other studies, including Adjemian and Juillard (2011), Fernández-Villaverde et al. (2015), Holden (2019), Holden and Swarbrick (2018) and Guerrieri and Iacoviello (2015), focus on developing numerical solutions that can cope with nonlinearities in models with occasionally binding constraints—including the ZLB. Jung, Teranishi and Watanabe (2005), Eggertsson and Woodford (2003) evaluate optimal monetary policy with a ZLB. Finally, Erceg and Lindé (2014), Mertens and

Ravn (2014), and Cook and Devereux (2011) analyse fiscal policy under the conditions of a liquidity trap.

The rest of the section proceeds as follows. Section 4.2 provides a brief description of the model. Section 4.3 discusses the calibration of the model. Section 4.4 contains the model analysis. Section 4.5 concludes.

4.2 The Model

We use the same model as chapter 3, which is a version of Gerali et al. (2010) and Angelini, Neri and Panetta (2014) but with a modified banking sector to allow for the interaction of ZLB, capital regulation and LTV.[5]

Another modification we introduce in this model is that banks can be subject to different levels of capital regulations: 1) a low capital regulation model set at 8% to reflect the standard capital ratio suggested by Basel II; and 2) a high capital regulation model set at 10.5% to reflect the standard capital regulation of 8% plus an 2.5% maximum countercyclical capital buffer (CCyB) suggested by Basel III.

4.2.1 Households and Entrepreneurs

Patient Households. Each patient household, indexed by i, maximises her expected lifetime utility by choosing consumption c_t^P, housing h_t^P and labour hours l_t^P:

$$E_0 \left\{ \sum_{t=0}^{\infty} (\beta^P)^t \left[(1 - a^P)\varepsilon_t^c \log(c_t^P(i) - a^P c_{t-1}^P) + \varepsilon_t^h \log(h_t^P(i)) - \frac{l_t^P(i)^{1+\phi}}{1+\phi} \right] \right\}, \tag{4.1}$$

where a^P denotes the degree of habit persistence and ϕ the inverse Frisch elasticity of labour supply.[6] There are two preference shocks ε_t^c and ε_t^h that affect the marginal utility of consumption and housing with an AR(1) representation $\log(\varepsilon_t^j) = \rho_j \log(\varepsilon_{t-1}^j) + \sigma_t^j$, with $j = \{c, h\}$. The

[5] They develop a medium-scale DSGE as in Christiano, Eichenbaum and Evans (2005) and Smets and Wouters (2007), but enriched by a banking sector and financial frictions. Gambacorta and Karmakar (2018) use a similar model to assess the impact of the leverage ratio. Acosta-Smith, Bassanin and Sabuga (2021) estimated the same model for UK data and analyse the implications of the new capital regulation called the *output floor*. Hence, the majority of the model's notation is adopted from Acosta-Smith, Bassanin and Sabuga (2021) and can also be found in Chapter 3 of this thesis.

[6] It assumes that there are external and group specific habits in consumption. Premultiplication by one minus habit coefficient a^P offsets their impact on the steady-state marginal utility of consumption.

household's choices are subject to a budget constraint (in real term):

$$c_t^P(i) + q_t^h \Delta h_t^P(i) + d_t(i) = w_t^P l_t^P(i) + \frac{(1+r_{t-1}^d)d_{t-1}(i)}{\pi_t} + t_t^P(i). \tag{4.2}$$

Households spend their income on current consumption, housing (with q_t^h denoting house prices) and savings through deposits d_t. The income side consists of wage earning $w_t^P l_t^P$ (where w_t^P is the real wage) and gross interest income from deposits $\frac{(1+r_{t-1}^d)d_{t-1}}{\pi_t}$, where $\pi_t = \frac{P_t}{P_{t-1}}$ is gross inflation rate and r_{t-1}^d denotes the interest rate on deposits. In addition, t_t^P is the lump-sum transfer that includes labour union membership net fee, and dividends from firms and banks owned only by patient households.

Impatient Households. Each impatient household maximises her expected lifetime utility:

$$E_0 \left\{ \sum_{t=0}^{\infty} (\beta^I)^t \left[(1-a^I)\varepsilon_t^c \log(c_t^I(i) - a^I c_{t-1}^I) + \varepsilon_t^h \log(h_t^I(i)) - \frac{(l_t^I(i))^{1+\phi}}{1+\phi} \right] \right\}, \tag{4.3}$$

subject to a budget constraint:

$$c_t^I(i) + q_t^h \Delta h_t^I(i) + \frac{(1+r_{t-1}^{b,H})b_{t-1}^I(i)}{\pi_t} = b_t^I(i) + w_t^I l_t^I(i) + t_t^I(i), \tag{4.4}$$

where labour income $w_t^I l_t^I$, new loans b_t^I and net labour union fee t_t^I finance consumption c_t^I, housing h_t^I and payments for previous-period loans $\frac{(1+r_{t-1}^{b,H})b_{t-1}^I}{\pi_t}$. For simplicity, housing is in fixed supply, i.e. $h^P + h^I = 1$. Due to their impatience, in equilibrium, impatient households are willing to offer their housing wealth as collateral to obtain loans. In the rest of the paper I will refer to households' loans, b_t^I, also as mortgages.

Impatient households must also satisfy a borrowing constraint, which imposes a condition that the expected value of a household's housing stock is sufficient to guarantee repayment of debt and interests:

$$(1+r_t^{b,H})b_t^I(i) \leq m_t^I E_t[q_{t+1}^h h_t^I(i)\pi_{t+1}], \tag{4.5}$$

where m_t^I denotes the loan-to-value (LTV) ratio for mortgages with an AR(1) representation $\log(m_t^I) = (1-\rho_{m^I})\bar{m}^I + \rho_{m^I}\log(m_{t-1}^I) + \sigma_t^{m^I}$, where $\bar{m}^I$ is the steady-state LTV ratio.

Entrepreneurs. Entrepreneurs maximise their expected lifetime utility:

$$E_0\left\{\sum_{t=0}^{\infty}(\beta^E)^t\left[\log(c_t^E(i)-a^E c_{t-1}^E)\right]\right\}, \tag{4.6}$$

subject to the budget constraint, production function and borrowing constraint. The budget constraint is given by:

$$\begin{aligned} c_t^E(i)+w_t^P l_t^{E,P}(i)+w_t^I l_t^{E,I}(i)+\frac{(1+r_{t-1}^{b,E})b_{t-1}^E(i)}{\pi_t}+q_t^k k_t^E(i) \\ +\varphi(u_t(i))k_{t-1}^E(i)=\frac{y_t^E(i)}{x_t}+b_t^E(i)+q^k(1-\delta)k_{t-1}^E(i). \end{aligned} \tag{4.7}$$

Entrepreneurs' expenses concerns consumption c_t^E, wage bills for patient ($w_t^P l_t^{E,P}$) and impatient ($w_t^I l_t^{E,I}$) households, previous period loans' repayment $\frac{(1+r_{t-1}^{b,E})b_{t-1}^E}{\pi_t}$ and capital renting expenses $q_t^k k_t^E$ (where q_t^k is the price of capital). They are financed by income from the sale of wholesale goods y_t^E (where $\frac{1}{x_t}=\frac{P_t^W}{p_t}$ corresponds to its relative competitive price) and the revenue from the stock of capital $q^k(1-\delta)k_{t-1}^E$ that has not depreciated, sold back to capital producers. Moreover, entrepreneurs must pay the real cost $\varphi(u_t)k_{t-1}^E$ to set the level of capital utilisation rate, u_t. In the rest of the analysis we refer to entrepreneurs' loans, b_t^E, also as loans to non-financial corporations (NFC).

The wholesale good is produced according to a standard production function:

$$y_t^E(i)=A_t^E(k_{t-1}^E(i)u_t(i))^{\alpha}(l_t^E(i))^{1-\alpha}, \tag{4.8}$$

where A^E is the stochastic total factor productivity (TFP), which follows an AR(1) process $\log(A_t^E)=\rho_{A^E}\log(A_{t-1}^E)+\sigma_t^{A^E}$. The labour inputs are the sum of patient and impatient household labour supply $l_t^E=(l_t^{E,P})^{\mu}(l^{E,I})^{1-\mu}$, where μ is the proportion of labour inputs from patient households.

Finally, the amount of funds banks are willing to lend to entrepreneurs are subject to the following borrowing constraint:

$$(1+r_t^{b,E})b_t^E(i)\le m_t^E q_{t+1}^k E_t[\pi_{t+1}(1-\delta)k_t^E(i)], \tag{4.9}$$

where m_t^E is the LTV ratio and follows an AR(1) process $\log(m_t^E)=(1-\rho_{m^E})\bar{m}^E+\rho_{m^E}\log(m_{t-1}^E)+\sigma_t^{m^E}$, where $\bar{m}^E$ is the steady-state LTV ratio.

Labour Supply. We take the same characterization of the labor supply as the one presented in Gerali et al. (2010) where patient and impatient households provide differentiated labour types, sold by unions to perfectly competitive labour packers who assemble them in a CES aggregator. For each labour type m there are two unions, one for patient households and one for impatient households (indexed by s, where $s = P, I$). Unions set nominal wages $W_t^s(m)$ maximising the utility of their members, where $U_{c_t^s}(i,m)$ is the stochastic discount factor:

$$E_0 \sum_{t=0}^{\infty} (\beta^s)^t \left\{ U_{c_t^s}(i,m) \left[\frac{W_t^s(m)}{P_t} l_t^s(i,m) - \frac{\kappa_w}{2} \left(\frac{W_t^s(m)}{W_{t-1}^s(m)} - \pi_{t-1}^{\iota_w} \pi^{1-\iota_w} \right)^2 \frac{W_t^s}{P_t} \right] - \frac{l_t^s(i,m)^{1+\phi}}{1+\phi} \right\}, \tag{4.10}$$

subject to demand from labor packers:

$$l_t^s(i,m) = l_t^s(m) = \left(\frac{W^s(m)}{W_t^s} \right)^{-\varepsilon_t^l} l_t^s, \tag{4.11}$$

and to a quadratic adjustment cost (parametrised by κ_w). The union equally charges each member household lump-sum fees to cover adjustment costs.

The wage setting is indexed to a weighted average of lagged and steady-state wage inflation, where ι_w indicates the wedge. In a symmetric equilibrium, labour supply for a household of type s is given by an ensuing (non-linear) wage-Phillips curve:

$$\kappa_w(\pi_t^{w^s} - \pi_{t-1}^{\iota_w} \pi^{1-\iota_w})\pi_t^{w^s} = \beta_t E_t \left[\frac{\lambda_{t+1}^s}{\lambda_t^s} \kappa_w (\pi_{t+1}^{w^s} - \pi_t^{\iota_w} \pi^{1-\iota_w}) \frac{(\pi_{t+1}^{w^s})^2}{\pi_{t+1}} \right] + (1 - \varepsilon_t^l) l_t^s + \frac{\varepsilon_t^l l_t^{s1+\phi}}{w_t^s \lambda_t^s}. \tag{4.12}$$

where, for each type, w_t^s is the real wage and $\pi_t^{w^s}$ is the nominal wage inflation.

4.2.2 Producers

Capital Producers. New stock of capital is produced and sold to entrepreneurs in a perfectly competitive market. Capital producers use two inputs, the previous-period un-depreciated capital $(1-\delta)K_{t-1}$ bought from entrepreneurs at the nominal price Q_t^k and I_t units of the final consumption good bought from retailers at price P_t. The new stock of effective capital is sold back to entrepreneurs at price Q_t^k. In addition, the transformation of the final good into new capital is subject to adjustment cost κ_i. Capital producers maximization problem is given by:

$$E_0 \left\{ \sum_{t=0}^{\infty} \Lambda_t^E (\beta^E)^t \left[q_t^k (k_t - (1-\delta)k_{t-1}) - I_t \right] \right\}, \tag{4.13}$$

subject to the law of motion of capital $k_t = (1-\delta)k_{t-1} + \left[1 - \frac{\kappa_i}{2}\left(\frac{\varepsilon_t^{qk} I_t}{I_{t-1}} - 1\right)^2\right] I_t$, where $q_t^k \equiv \frac{Q_t^k}{P_t}$ the real price of capital and ε_t^{qk} denotes a shock to investment efficiency with an AR(1) representation $log(\varepsilon_t^{qk}) = \rho_{qk} log(\varepsilon_{t-1}^{qk}) + \sigma_t^{qk}$. In equilibrium $k_t^E = k_t$.

Retailers. The structure of the retail goods market is monopolistic competition (Bernanke, Gertler and Gilchrist (1999)). Retail prices are sticky and are indexed to a combination of past and steady-state inflation, with relative weight indicated by ι_p. Whenever retailers want to change prices beyond this indexation allowance, they face a quadratic adjustment cost parameterised by κ_p. Retailer i chooses $P_t(i)$ subject to the consumers' demand function:

$$E_0\left\{\sum_{t=0}^{\infty} \Lambda_{0,t}^P \left[\left(P_t(i)y_t(i) - P_t^W y_t(i) - \frac{\kappa_p}{2}\left(\frac{P_t(i)}{P_{t-1}(i)} - \pi_{t-1}^{i_p}\pi^{1-i_p}\right)^2 P_t y_t\right)\right]\right\}, \tag{4.14}$$

where the CES demand function is given by $y_t(i) = \left(\frac{P_t(i)}{P_t}\right)^{-\varepsilon_t^y} y_t$ where π denotes the steady state inflation, and ε_t^y the stochastic demand price elasticity, which follows an AR(1) process $log(\varepsilon_t^y) = (1-\rho_y)\bar{\varepsilon}^y + \rho_y log(\varepsilon_{t-1}^y) + \sigma_t^y$ (where $\bar{\varepsilon}^y$ denotes the steady-state markup in the goods market).

Differentiating with respect to $P_t(i)$ and imposing $P_t(i) = P_t$ results in:

$$\begin{aligned} \Lambda_t^P &\left[-\varepsilon_t^y y_t + \frac{\varepsilon_t^y y_t}{X_t} + y_t - \kappa_p(\pi_t - \pi_{t-1}^{i_p}\pi^{1-i_p})P_t y_t \frac{1}{P_{t-1}(i)}\right] \\ &+\Lambda_{t+1}^P \beta^P \left[\kappa_p(\pi_{t+1} - \pi_t^{i_p}\pi^{1-i_p})P_{t+1}y_{t+1}\frac{P_{t+1}(i)}{P_t^2(i)}\right] \end{aligned} \tag{4.15}$$

Dividing by y_t and Λ_t^P:

$$1 - \varepsilon_t^y + \frac{\varepsilon_t^y}{X_t} - \kappa_p(\pi_t - \pi_{t-1}^{i_p}\pi^{1-i_p})\pi_t + \frac{\Lambda_{t+1}^P \beta^P}{\Lambda_t^P}\kappa_p(\pi_{t+1} - \pi_t^{i_p}\pi^{1-i_p})\frac{y_{t+1}}{y_t}\pi_{t+1}^2 = 0 \tag{4.16}$$

where $\frac{1}{X_t} = \frac{P_t^W}{P_t}$ and $\pi_t = \frac{P_t}{P_{t-1}}$.

4.2.3 Banks

For the banking sector, we adopted the framework from Gerali et al. (2010). Each bank consists of a wholesale branch and two retail branches. The wholesale branch manages the capital-assets position of the bank subject to capital requirements imposed by the macroprudential authority. Retail branches lend to impatient households, lend to entrepreneurs and collect deposits from patient households.

Wholesale Branch. Each wholesale bank, indexed by j, operates in a perfectly competitive market. On the liabilities side, it combines wholesale deposits D_t with the accumulated bank capital K_t^b, while on the assets side, it issues wholesale loans B_t^H and B_t^E to retail branches. The two sources of funding, K_t^b and D_t, are perfect substitutes. Bank capital is accumulated through retained earnings only:

$$\pi_t K_t^b(j) = (1-\delta^b)K_{t-1}^b(j) + \Pi_{t-1}(j), \tag{4.17}$$

where δ^b is the costs of managing bank capital and Π_{t-1} denotes the realised overall profits of the bank, namely the profits of the wholesale and the two retail branches ($\Pi_t = \Pi_t^{ws} + \Pi_t^h + \Pi_t^f$).

The wholesale branch is subject to risk-weighted capital requirements, meaning that it occurs in a quadratic cost whenever its capital-to-RWA ratio $\frac{K_t^b(j)}{RWA_t^l(j)}$ deviates from the regulatory ratio ν_t^b where $b \in \{l,h\}$, which stand for low and high capital regulations. The wholesale branch maximises profits taking into account these quadratic costs:

$$\begin{aligned}\max E_0 \sum_{i=0}^{\infty} \Lambda_{0,t} \Bigg[&(1+R_t^{B,H})B_t^H(j) + (1+R_t^{B,E})B_t^E(j) - (B_{t+1}^H(j) + B_{t+1}^E(j)) \\ &+D_{t+1}(j) - (1+R_t^d)D_t(j) + (K_{t+1}^b(j) - K_t^b(j)) - \frac{\kappa_b}{2}\left(\frac{K_t^b(j)}{RWA_t(j)} - \nu_t^b\right)^2 K_t^b\Bigg]\end{aligned} \tag{4.18}$$

where κ_b, $b \in \{l,h\}$ measures the intensity of the quadratic costs. The above profit maximisation is subject to a balance sheet constraint in the form $B_t^H(j) + B_t^E(j) = K_t^b(j) + D_t(j)$.

Calculation of the RWA. The risk-weighted assets are defined as the weighted sum of the bank's assets (i.e. B_t^H and B_t^E), where the weights, are a measure of the implicit riskiness of the different assets, the so called *risk weights*. The risk-weighted assets are defined as following:

$$RWA_t(j) = (w_t^{H,IRB} B_t^H(j) + w_t^{E,IRB} B_t^E(j)) \tag{4.19}$$

where $w_t^{H,IRB}$, $w_t^{E,IRB}$ are the risk weights associated to mortgages and NFC loans, respectively. According to the IRB approach, banks use internal models to estimate the weights, following the Basel III recommendation. In particular, IRB models' main components are probability of default (PD) of borrowers, loss given default (LGD), exposure at default (EAD) and the maturity of the assets.

In absence of defaults in the models, we approximate the risk weights using the approach of Angelini et al. (2015). They argue that the main characteristics of the IRB risk weights are captured by the following equation:

$$w_t^k = (1-\rho_i)\bar{w}^k + (1-\rho^i)\chi^i\Big(logy_t - logy_{t-4}\Big) + \rho^i w_{t-1}^k \qquad \text{with} \qquad k =\in \{H, E\} \tag{4.20}$$

where w_t^k corresponds to the steady-state risk weight, while $\chi^i < 0$ describes the cyclical response of the risk weights. According to this definition, risk weights tend to be low during booms and high during recessions.

Optimal wholesale rates setting. The wholesale branch's optimal problem produces a relationship between the capital position of the bank and the spread between the wholesale lending and deposit rates:

$$R_t^{B,k} - r_t = -\kappa_l\left(\nu_t^b - \frac{K_t^b}{RWA_t^l}\right)\left(\frac{K_t^b}{RWA^l}\right)^2 w_t^{k,l} \qquad \text{with } k \in \{H, E\} \tag{4.21}$$

The left-hand side of the above equation represents the marginal benefit from increasing lending of type j (an increase in profit equal to the increase in interest rate spread), while the right-hand side represents its marginal cost (an increase in the cost of deviating from ν_t^b with $b =\in \{h, l\}$, high or low capital regulation). Therefore, the wholesale branch chooses a level of each type of lending j which, at the margin, equalises the costs and benefits of changing the capital asset ratios.

Retail Branches. Retail banks, indexed by j, are Dixit-Stiglitz monopolistic competitors on both the loan and the deposit markets. The retail branches take the loan and deposit demand schedules as given and then chooses the level of interest rates to maximise profits. The loan and deposit demand schedules facing bank j are defined as:

$$b_t^s(j) = \Big(\frac{r_t^{bs}(j)}{r_t^{bs}}\Big)^{-\varepsilon_t^{bs}} b_t^s, \qquad d_t^P(j) = \Big(\frac{r_t^d(j)}{r_t^d}\Big)^{-\varepsilon_t^d} d_t \qquad \text{with} \qquad s \in \{H, E\} \tag{4.22}$$

where ε_t^{bs} and ε_t^d, where $s = H, E$ elasticities of loan and deposit demand. Elasticities are stochastic and their innovations can be interpreted as innovations to bank spreads arising independently of monetary policy.

The loans' retailers maximise their profits subject to the loan demand schedule:

$$\max_{r_t^{B,H}, r_t^{B,E}} E_0 \sum_{i=0}^{\infty} \Lambda_{0,t} \Bigg[r_t^{B,H}(j) b_t^H(j) + r_t^{B,E}(j) b_t^E(j) - (R_t^{B,H} B_t^H(j) + R_t^{B,E} B_t^E(j)) \\ - \frac{\kappa_{bH}}{2} \left(\frac{r_t^{bH}(j)}{r_{t-1}^{bH}(j)} - 1 \right)^2 r_t^{bH} b_t^H - \frac{\kappa_{bE}}{2} \left(\frac{r_t^{bE}(j)}{r_{t-1}^{bE}(j)} - 1 \right)^2 r_t^{bE} b_t^E \Bigg] \tag{4.23}$$

The first two terms are the returns from lending to households and entrepreneurs. The next term reflects the cost of remunerating funds received from the wholesale branch. The last two terms are the costs of adjusting the interest rates. After imposing a symmetric equilibrium, the first-order conditions for interest rate yields:

$$1 - \varepsilon_t^{bs} + \varepsilon_t^{bs} \frac{R_t^{bs}}{r_t^{bs}} - \kappa_{bs} \left(\frac{r_t^{bs}}{r_{t-1}^{bs}} - 1 \right) \frac{r_t^{bs}}{r_{t-1}^{bs}} + E_t \left[\Lambda_{t+1}^P \kappa_{bs} \Big(\frac{r_{t+1}^{bs}}{r_t^{bs}} - 1 \Big) \left(\frac{r_{t+1}^{bs}}{r_t^{bs}} - 1 \right)^2 \frac{B_{t+1}^s}{B_t^s} \right] = 0. \tag{4.24}$$

Patient households own the banks and so the two share the same discount factor. Retail rates depend on the markup and the wholesale rate (the marginal cost for the banks), which in turn depends on the bank's capital position and the policy rate.

A similar equation can be derived for the deposit retail branch:

$$-1 - \varepsilon_t^d + \varepsilon_t^d \frac{r_t}{r_t^d} - \kappa_d \Big(\frac{r_t^d}{r_{t-1}^d} - 1 \Big) \frac{r_t^d}{r_{t-1}^d} + E_t \left[\Lambda_{t+1}^P \kappa_d \Big(\frac{r_{t+1}^d}{r_t^d} - 1 \Big) \left(\frac{r_{t+1}^d}{r_t^d} - 1 \right)^2 \frac{d_{t+1}}{d_t} \right] = 0. \tag{4.25}$$

Finally, the total profits of the banking group, j, can be written as follows:

$$\Pi_t = r_t^{BH} b_t^H + r_t^{BE} b_t^E - r_t^d d_t - \frac{\kappa_l}{2} \left(\nu_t^b - \frac{K_t^b}{RWA_t^l} \right)^2 K_t^b - \\ \frac{\kappa_{bH}}{2} \left(\frac{r_t^{bH}(j)}{r_{t-1}^{bH}(j)} - 1 \right)^2 r_t^{bH} b_t^H - \frac{\kappa_{bE}}{2} \left(\frac{r_t^{bE}(j)}{r_{t-1}^{bE}(j)} - 1 \right)^2 r_t^{bE} b_t^E. \tag{4.26}$$

4.2.4 Monetary and Macroprudential Policy

Monetary Policy. Unlike the standard setting of monetary policy used by Gerali et al. (2010), Angelini, Neri and Panetta (2014), Gambacorta and Karmakar (2018), and Acosta-Smith, Bassanin and Sabuga (2021), the central bank sets the policy rate r_t according to a Taylor rule that allows for the nominal interest rate to occasionally bind at the ZLB.[7]

$$\begin{aligned} log(1+r_t) = max\{0, (1-\rho_R)log(1+r_{ss}) + \rho_R log(1+r_{t-1}) \\ +(1-\rho_R)\left[\phi_\pi log\left(\pi_t - \pi\right) + \phi_y log\left(Y_t - Y\right)\right] + \varepsilon_t^r\}, \end{aligned} \tag{4.27}$$

where $R_t = (1+r_t)$ and ϕ_π and ϕ_y denote the weights of inflation and output, respectively. The steady state policy rate is $R = (1+r_{ss})$, ρ_R represents the persistence of the policy rate, and ε_t^r is the monetary policy shock.

Macroprudential Policy. The risk-weighted capital requirements follow the definition of Angelini et al. (2015), Gambacorta and Karmakar (2018) and Acosta-Smith, Bassanin and Sabuga (2021):

$$\nu_t^b = (1-\rho_\nu)\bar{\nu} + \rho_\nu \nu_{t-1}^b + (1-\rho_\nu)\Big[\chi_\nu\Big(\frac{B_t}{Y_t} - \frac{\bar{B}}{\bar{Y}}\Big)\Big], \tag{4.28}$$

where $\bar{\nu}$ is the steady level, which corresponds to the fixed capital requirements. The credit-to-GDP ratio is $\frac{B_t}{Y_t}$, with $B_t = B_t^H + B_t^E$ denotes and $\chi_\nu > 0$ implies the presence of a countercyclical capital buffer on top of the minimum requirements. The objective of including a time-varying capital requirement is to increase bank capital when the credit-to-GDP is above its steady-state level.

4.2.5 Market Clearing and Shock Processes

Aggregate output is divided into consumption, accumulation of physical and bank capital, and various adjustment costs:

$$Y_t = C_t + I_t + \delta^b \frac{K_{t+1}^b}{\pi_t} + Adj_t, \tag{4.29}$$

where $C_t = c_t^P + c_t^I + c_t^E$ is the aggregate consumption, I_t is aggregate investment undertaken, and K_{t+1}^b is the aggregate bank capital. The term $Adjt$ includes all adjustment costs (wages and prices).

Table 4.1 Calibrated Parameters

Parameter	Value	Definition	Source
β^P	0.9943	Patient households' discount factor	Steady-state $R = 2.5\%$
β^I	0.975	Impatient households' discount factor	Iacoviello (2005)
β^E	0.975	Entrepreneurs' discount factor	Iacoviello (2005)
ϕ	1.00	Inverse of the Frisch elasticity	Gerali et al. (2010)
ε^y	6.00	Markup in the goods market $\left(\frac{\varepsilon^y}{\varepsilon^y-1}\right)$	Gerali et al. (2010)
ε^l	5.00	Markup in the goods market $(\frac{\varepsilon^l}{\varepsilon^l-1})$	Gerali et al. (2010)
ϵ^d	-1.46	Markdown in the deposits market $(\frac{\varepsilon^d}{\varepsilon^d-1})$	Gerali et al. (2010)
$\epsilon^{b,H}$	2.79	Markup on loans to households $(\frac{\epsilon^{b,H}}{\epsilon^{b,H}-1})$	Steady-state $\frac{B^H}{B} = 30\%$
$\epsilon^{b,E}$	3.12	Markup on loans to entrepreneurs $(\frac{\epsilon^{b,E}}{\epsilon^{b,E}-1})$	Steady-state $\frac{B^E}{B} = 70\%$
α	0.25	Capital share in the production function	Gerali et al. (2010)
γ^P	0.50	Share of patient household	Brzoza-Brzezina, Kolasa and Makarski (2013)
γ^I	0.25	Share of impatient household	Brzoza-Brzezina, Kolasa and Makarski (2013)
γ^E	0.25	Share of entrepreneurs	$1 - \gamma^P - \gamma^I$
δ	0.025	Capital depreciation rate	Gerali et al. (2010)
m^I	0.70	LTV ratio for impatient households	calibrated on UK data
m^E	0.35	LTV ratio for entrepreneurs	Gerali et al. (2010)
ν^l	0.08	Steady-state capital requirements	standard capital ratio under Basel II
ν^h	0.105	Steady-state capital requirements	standard capital ratio+CCyB under Basel III
κ_l	15	Cost of deviating from capital requirements	Steady-state $\frac{K^b}{RWA^{IM}} = 8\%$
κ_h	20	Cost of deviating from capital requirements	Steady-state $\frac{K^b}{RWA^{IM}} = 10.5\%$

4.3 Calibration

The structural parameters are calibrated using the sources shown in Table 4.1. The discount factor for patient households β^P is set at 0.9943, equivalent to a 2.5% quarterly steady state shadow policy rate.[8] The discount factors for impatient households and entrepreneurs, β^I and β^E, are set in line with the literature.[9] The calibration of the inverse Frisch elasticity, capital share in the production function, and depreciation rate follows the literature (see Gambacorta and Karmakar (2018) among many others). The steady-state loan-to-value (LTV) for households loans of 0.70 reflects the UK LTV ratio limit. For the entrepreneurs loans, instead, the values 0.35 is taken from the literature (Gambacorta and Karmakar (2018)).

The parameters controlling the markups in different markets are calibrated following Gerali et al. (2010). The markup in the goods market is 20% (i.e. ϵ^y set to 6), and in the labour market is 15% (i.e. ϵ^l is set to 5). Markdown for deposits is set at 60% (i.e. $\epsilon^d = -1.46$). The markups for loans to households and firms are calibrated in order to match the proportion

[7] We use the solutions method introduced by Holden (2016) and Holden (2019).

[8] The shadow rate is based on the computation generated by Wu and Xia (2016).

[9] See Iacoviello (2005), Gerali et al. (2010), Angelini, Neri and Panetta (2014), Hodbod, Huber and Vasilev (2018), and Gambacorta and Karmakar (2018).

Table 4.2 Prior and Posterior Distributions of the Structural Parameters

Parameter		Prior Distributions			Posterior Distributions			
		Type	Mean	Std dev.	Mean	2.5%	Median	97.5%
κ_l	Capital ratio deviation cost	$\mathcal{G}$	10.00	2.50	5.94	2.50	5.75	9.50
κ_{bH}	Mortgages rate adjustment cost	$\mathcal{G}$	6.00	2.50	6.75	3.11	6.43	11.06
κ_{bE}	NFC loans rate adjustment cost	$\mathcal{G}$	3.00	2.50	11.83	7.64	11.57	16.35
κ_d	Deposits rate adjustment cost	$\mathcal{G}$	10.00	2.50	4.88	2.63	4.60	7.80
κ_y	Degree of price stickiness	$\mathcal{G}$	100.00	20.00	108.40	65.40	107.53	153.98
κ_l	Degree of wage stickiness	$\mathcal{G}$	100.00	20.00	143.81	97.23	139.25	197.92
ι_y	Price indexation	$\mathcal{B}$	0.50	0.15	0.09	0.021	0.09	0.17
ι_l	Wage indexation	$\mathcal{B}$	0.20	0.15	0.031	0.00	0.03	0.08
κ_i	Investment adjustment cost	$\mathcal{G}$	50.00	5.00	47.94	38.63	47.84	56.82
ρ_R	Policy rate stickiness	$\mathcal{B}$	0.50	0.15	0.87	0.83	0.87	0.90
ϕ_π	Monetary policy response to π	$\mathcal{G}$	2.00	0.50	2.07	1.68	2.03	2.55
ϕ_Y	Monetary Policy response to y	$\mathcal{N}$	0.10	0.15	0.27	0.00	0.27	0.53
a^i	Habit coefficients	$\mathcal{B}$	0.70	0.20	0.94	0.92	0.94	0.97
χ_{ν^b}	Sensitivity of capital requirements	$\mathcal{N}$	2.50	0.50	2.19	1.20	2.18	3.17
ρ_{ν^b}	Persistence of capital requirements	$\mathcal{B}$	0.80	0.10	0.987	0.973	0.988	0.998
$\chi_{w^{H,IRB}}$	Sensitivity of IRB risk weights (HH)	$\mathcal{N}$	-10.00	0.50	-9.94	-10.99	-9.94	-8.87
$\chi_{w^{E,IRB}}$	Sensitivity of IRB risk weights (NFC)	$\mathcal{N}$	-15.00	0.50	-14.99	-15.93	-14.99	-14.02
ρ_{rw_H}	Persistence of IRB risk weights (HH)	$\mathcal{B}$	0.80	0.10	0.84	0.65	0.85	0.98
ρ_{rw_E}	Persistence of IRB risk weights (NFC)	$\mathcal{B}$	0.80	0.10	0.88	0.76	0.89	0.98

of UK households and non-financial corporate loans in UK, which are around 30% and 70%, respectively.[10]

The parameters concerning the prudential regimes are mainly calibrated to match the Basel II and Basel III recommendation.[11] For simplicity, we calibrate $w_t^{H,IRB}$ and $w_t^{E,IRB}$ equal to 1. The cost of managing bank capital is calibrated from Gerali et al. (2010) as $\delta^b = \left(\frac{r_{ss}}{\nu^b}\right)\frac{\epsilon^d-\epsilon^b+\nu^b(\epsilon^d)(\epsilon^b-1)}{(\epsilon^b-1)(\epsilon^d-1)}$, where $\epsilon^b = \frac{\epsilon^{b,H}+\epsilon^{b,E}}{2}$ and ν^b, $b \in \{l, h\}$.

Other structural parameters are mainly calibrated from the estimates by Acosta-Smith, Bassanin and Sabuga (2021) for the UK data using Bayesian methods. The estimates use 11 observables for the UK covering the periods 1991Q1-2019Q3 at quarterly frequency. These include the real consumption, real investment, real house prices, real loans to households and firms, the policy rate, interest rates on deposits, loans to firms and households, real wage, and consumer price inflation rates.

Tables 4.2 and 4.3 report median estimates of the structural parameters and the coefficients controlling the shocks' persistence, respectively, conducted by Acosta-Smith, Bassanin and Sabuga (2021) for the UK data.

[10] The proportion of households and non-financial corporate loans are based on a quarterly average for the period 1991Q1-2019Q3.

[11] Refer to *Basel III: A global regulatory framework for more resilient banks and banking systems.*

Table 4.3 Prior and Posterior Distributions of the Shocks Persistence

Parameter		Prior Distributions			Posterior Distributions			
		Type	Mean	Std dev.	Mean	2.5%	Median	97.5%
ρ_A	TFP	$\mathcal{B}$	0.80	0.10	0.954	0.895	0.972	0.996
ρ_c	Consumption preference	$\mathcal{B}$	0.80	0.10	0.443	0.288	0.445	0.598
ρ_h	Housing preference	$\mathcal{B}$	0.80	0.10	0.911	0.860	0.912	0.954
ρ_{mH}	LTV on mortgages	$\mathcal{B}$	0.80	0.10	0.979	0.953	0.982	0.998
ρ_{mE}	LTV on loans to NFC	$\mathcal{B}$	0.80	0.10	0.984	0.969	0.985	0.997
ρ_{bH}	Mortgages mark-up	$\mathcal{B}$	0.80	0.10	0.860	0.768	0.864	0.941
ρ_{bE}	Loans to NFC mark-up	$\mathcal{B}$	0.80	0.10	0.742	0.552	0.744	0.938
ρ_d	Deposits mark-down	$\mathcal{B}$	0.80	0.10	0.782	0.685	0.789	0.858
ρ_{qk}	Investment efficiency	$\mathcal{B}$	0.80	0.10	0.193	0.105	0.199	0.275
ρ_y	Price mark-up	$\mathcal{B}$	0.80	0.10	0.223	0.106	0.221	0.331
ρ_l	Wage mark-up	$\mathcal{B}$	0.80	0.10	0.660	0.489	0.674	0.801
ρ_{Kb}	Bank capital	$\mathcal{B}$	0.80	0.10	0.955	0.891	0.962	0.997

4.4 Model Analysis

In this section, we perform a model analysis comparing the model with ZLB and no ZLB and the model with low and high capital regulation in ZLB. In both cases, we use the calibrated parameters described above. More importantly, the model with the ZLB is solved using the solutions method proposed by Holden (2019).[12]

4.4.1 Impulse Response Functions

We consider the impulse response functions to a positive total factor productivity shock, which is commonly used to simulate business cycle fluctuations.

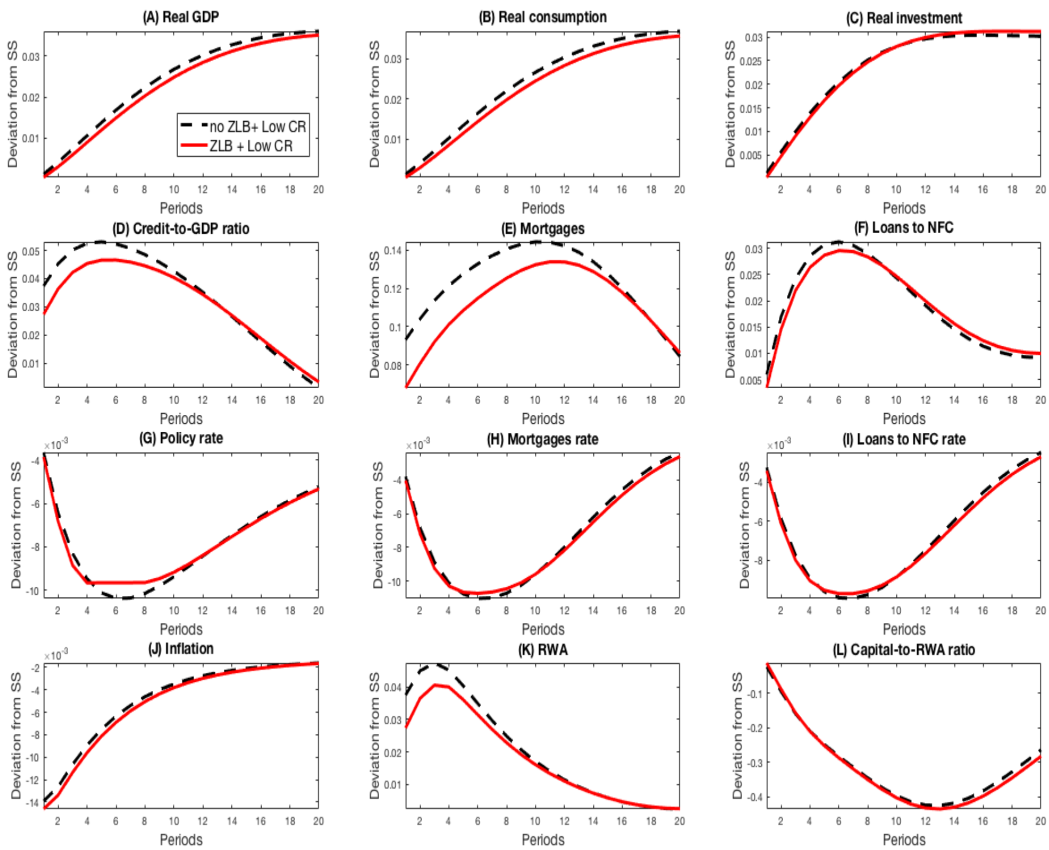
ZLB versus No ZLB Model

The first part of the model analysis shows the different model dynamics when the ZLB constraint in nominal interest rate is included. These results emphasise the importance of evaluating capital regulation when the ZLB binds, given its different dynamics.

Impulse response functions to a positive technology (TFP) shock. Figure 4.3 shows the impulse response functions to a 6% positive shock to TFP.[13] An increase in the TFP generates an economic expansion (real GDP, real consumption and investment increase) which fuels a credit expansion (credit-to-GDP increases and interest rates decline). The purpose of risk-weighted capital regulation is to mitigate the expansion of credit. However, the model

[12] Additional details on the solution methods in Annex C.1.
[13] The 6% shock is used to push the interest rate to bind.

Fig. 4.3 IRFs to a positive TFP shock



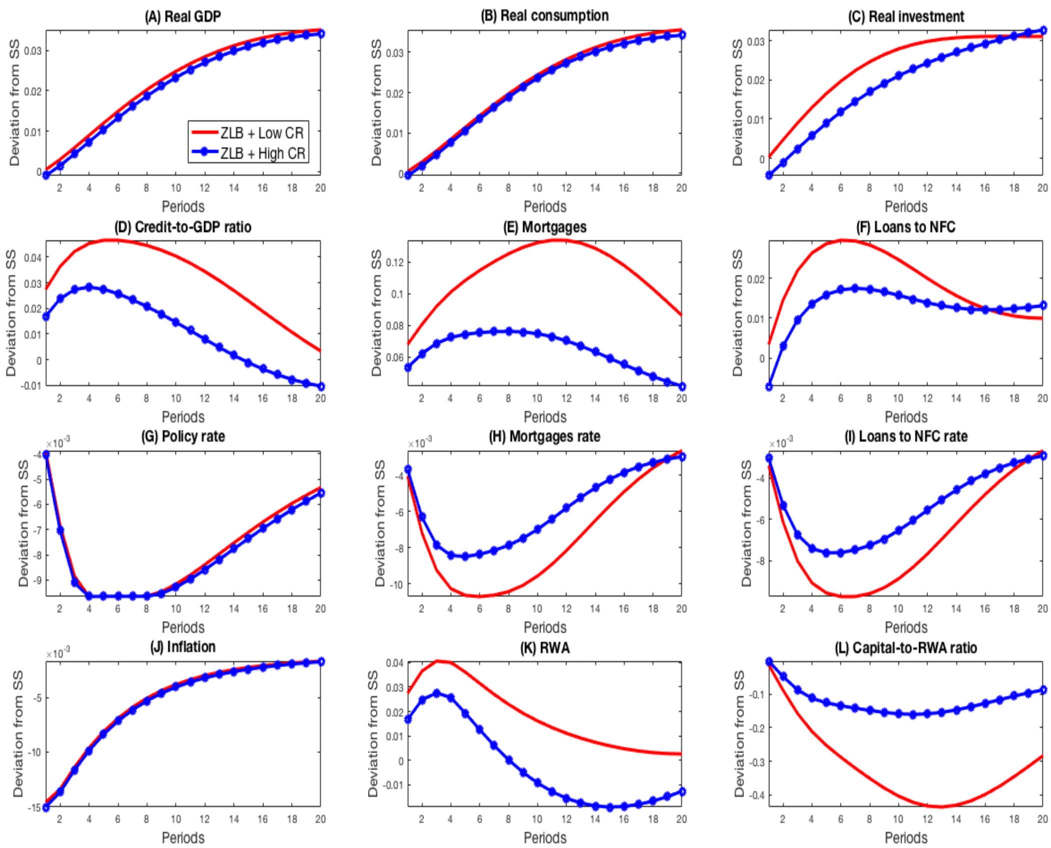
dynamics vary between two regimes, the no ZLB (black-dashed lines) and the with ZLB (red lines).

During the expansion, lending to households and entrepreneurs increases. The model with ZLB exhibits lower credit expansion compared to the no ZLB model as the monetary authority cannot lower the interest rate further making credit more expensive (see panels H and I). As such, the higher loan rates impact real consumption (see panel B), real investment (see panel C), and real GDP (see panel A). This impact on real GDP also determines the reduction of the bank capital-to-RWA ratio (panel K).

High versus Low Capital Regulation with ZLB

The second part of the results compares the effectiveness of low (8%) versus high (10.5%) capital regulation in ZLB models. We again simulate the two shocks identified above but this time only allowing for the nominal interest rate to bind at ZLB. This is a more appropriate framework in evaluating the capital regulation in the UK as interest rates are not allowed to drop in the negative territory. These results help illustrate whether a more aggressive capital regulation is more appropriate in a situation where monetary policy is constrained by the ZLB. An important highlight of this result show that the higher capital regulation can help mitigate the decline in lending under ZLB regime especially when a shock hits the economy that triggers a sudden bust.

Fig. 4.4 IRFs to a positive TFP shock



Impulse response functions to a positive technology (TFP) shock. Figure 4.4 shows the impulse response functions to a 6% positive shock to TFP but this time only comparing ZLB models with low versus high capital regulation.[14] An increase in the TFP generates an economic boom (real GDP, real consumption and investment increase) which fuels a credit

[14] The 6% shock is used to push the interest rate to bind.

expansion (credit-to-GDP increases and interest rates decline). The decline in the interest rates is limited given that the policy rate is stuck at ZLB. The model with the higher capital regulation (blue-dotted lines) imposes an additional cost for banks resulting in a much higher loan rate compared to the model with low capital regulation (red lines). These result in a lower investment (see panel C) and output (see panel A). These findings are similar with Mendicino et al. (2020) which highlights how a higher capital regulation can mitigate an excessive increase in lending exacerbated by the lower interest rate environment.

4.4.2 Volatility Analysis

From the previous section we see that having a high capital regulation can help stabilise the flow of credit. The next section tries to evaluate the impact of the different levels of capital regulation under ZLB on the volatility of some key macro and financial variables. Table 4.4 summarises the results.

Table 4.4 Volatility of Macro and Financial Variables

	Volatility (in percent)							
Prudential Regime	Y	π	B/Y	B^H	B^E	r^H	r^E	$\frac{K^b}{RWA}$
ZLB + Low CR	3.76	0.491	2.34	9.02	4.30	0.62	0.56	16.33
ZLB + High CR	3.74	0.494	1.60	6.86	4.36	0.54	0.49	9.28
Diff (%)	-0.7%	0.5%	-45.8%	-15.8%	1.5%	-15.6%	-15.8%	-75.9%

Note: The volatility of the select variables are computed from a 1000-period simulation having a TFP shock active.

A high capital regulation regime under the ZLB strongly reduces the volatility of the RWA, by limiting the cyclicality of the risk weights. This corresponds to a reduction of the volatility of RWA. The lower volatility of RWA helps in stabilising also the capital-to-RWA ratio (-76%) and the credit-to-GDP ratio (-45.8%). Finally, the high capital regulation also makes the real GDP slightly less volatile. GDP volatility is equal to 3.76% under the low capital regulation approach, compared to 3.74% under the high capital regulation regime.

4.4.3 The Loss Functions of Policy Authorities

Does the implementation of a low and high capital regulations will help the macroprudential authority in achieving their objectives? To test this we compute the loss function for the monetary and macroprudential authorities, following Angelini, Neri and Panetta (2014). The macroprudential policy minimises the volatility of credit-to-GDP ratio and output:

$$L^{MaP} = \sigma^2_{B/Y} + \kappa_{Y,MaP}\sigma^2_Y + \kappa_{\nu^b}\sigma^2_{\Delta^b_\nu}, \tag{4.30}$$

where σ_i^2 represents the asymptotic variance of the target variables $i = B/Y$, Y, and Δ_{ν^b} or credit-to-GDP, real GDP, and the change in capital ratio, respectively. Parameter $\kappa_{Y,MaP} \geq 0$ characterises the policymaker's preferences over the output. As highlighted by Angelini, Neri and Panetta (2014), a positive κ_{ν^b} is important to ensure that the policy instrument is not too volatile.[15]

We also consider a monetary policy loss function to check that the implementation of capital regulations does not interfere with monetary policy objectives:

$$L^{MP} = \sigma^2_\pi + \kappa_{Y,MP}\sigma^2_Y + \kappa_R\sigma^2_{\Delta R} \tag{4.31}$$

where σ^2_π is the asymptotic variance of inflation, and $\sigma^2_{\Delta R}$ is the asymptotic variance of the change in the policy rate. Meanwhile, parameter $\kappa_{Y,MP} \geq 0$ characterises the policymaker's preferences over the output. As highlighted by Angelini, Neri and Panetta (2014), a positive κ_R is important to ensure that the policy instrument is not too volatile.[16]

Table 4.5 show that implementation of the higher level of capital regulation, *ceteris paribus*, stabilises and reduces the loss of the monetary authority and the macroprudential authority, respectively.

Table 4.5 Loss Functions

Model	Volatility (%)					Loss Functions		
	π	Y	ΔR	B/Y	$\Delta\nu^b$	MP	MaP $\kappa_{Y,MaP} = 0$	MaP $\kappa_{Y,MaP} = 0.25$
ZLB + Low CR	0.49	3.76	9.69	2.34	1.53	16.71	5.70	9.25
ZLB + High CR	0.49	3.74	9.73	1.60	0.80	16.69	2.64	6.13

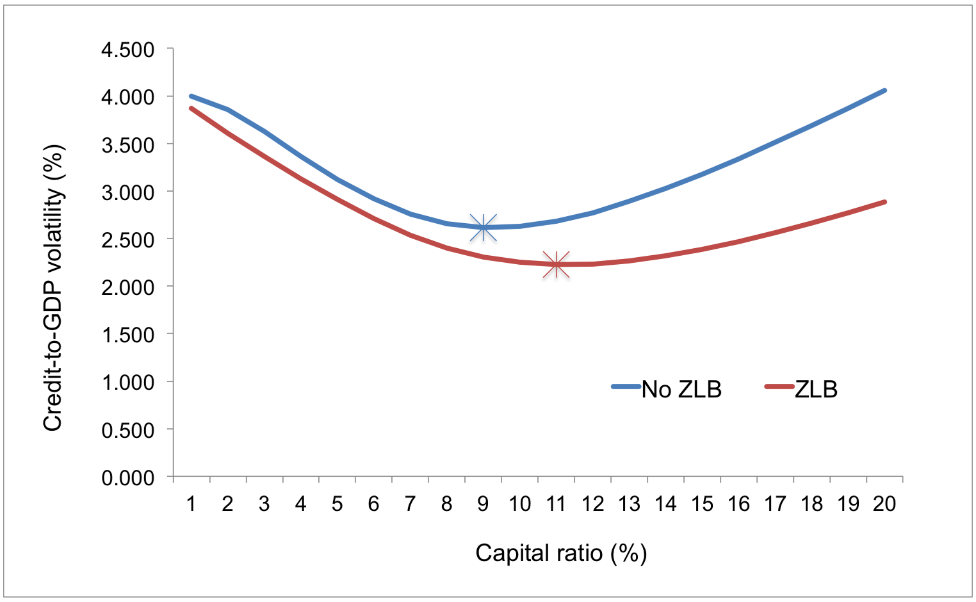
Note: The volatility of the select variables are computed from a 1000-period simulation having a TFP shock active.

[15] Same as Angelini, Neri and Panetta (2014), we set κ_{ν^b}=0.1.
[16] As in Angelini, Neri and Panetta (2014), we set κ_R=0.1 and $\kappa_{Y,MP} = 0.5$.

4.4.4 Financial Stability and Capital Requirements

What then is the optimal level of capital ratio that achieves financial stability? As previously shown by Rubio and Yao (2020), consider how effective the level of capital ratio is in reducing the volatility of credit. We find that, the model with ZLB requires a higher capital ratio at 11% to achieve the lowest volatility of credit, compared to 9% for a model with no ZLB. These results underscore once again that the level of capital regulation that stabilises credit is higher when ZLB binds. In Annex C.2, we also show the different levels of capital requirement and real GDP volatility associated with each.

Fig. 4.5 Volatility of Credit and Capital Requirements



Simulation results having all shocks active. Markers denote the optimal level of capital regulation for each regime.

4.5 Conclusions

The current low interest environment prompted many questions on how financial stability and the conduct of macroprudential policy should be implemented. On the one hand, it leads to a decrease in banks' profitability, bank capital, and eventually bank lending, implying the need for lower capital regulation. On the other hand, this environment encourages more indebtedness of borrowers and banks excessive risk taking, which suggests higher capital regulation is required. We study the consequences of capital regulation when the interest rate is at zero lower bound (ZLB) using DSGE framework and use UK data to calibrate the parameters of the model.

First, we look at the dynamics of the model with capital regulation under the ZLB and no ZLB regimes. We find the model with ZLB has different dynamics when compared to the model with no ZLB. Second, we compare the model with low and high capital regulation to illustrate whether a more aggressive capital regulation regime is appropriate if monetary policy is constrained by the ZLB.

Comparing low and high capital regulation regimes at the ZLB, we find that the higher level of capital regulation helps stabilise the main macro and financial variables. Furthermore, we find that implementation of high capital regulation, *ceteris paribus*, stabilises and reduces the loss function of the monetary authority and the macroprudential authority.

In this chapter, we characterise an optimal level of capital requirements that stabilises credit. We find that, the model with ZLB requires a capital ratio at 11% to achieve the lowest volatility of credit compared to 9% for a model with no ZLB. These results underscore once again that the level of capital regulation that stabilises credit is higher when ZLB binds. While our results suggest what level of capital regulations should be adopted when the ZLB binds, future models should integrate default.

Chapter 5

Thesis Conclusions

This doctoral thesis is a collection of three papers that study the interaction of monetary and macroprudential policies and provides a DSGE framework suitable for analysing the impact of these macroprudential tools for policymaking. We also show that even well-intended policies may produce unintended consequences. Thus, underscoring the importance of a general equilibrium framework for analysing these macroprudential tools.

In Chapter 2, we propose a DSGE framework that highlights the interaction of reserve requirements and a conventional monetary policy in a model that combines an endogenous housing loan defaults and financial intermediation frictions due to the costs of enforcing contracts. We use the model to examine how the interaction of these policies affect (i) the credit and business cycle; (ii) the distribution of welfare between savers and borrowers; and (iii) the overall welfare objectives when monetary and macroprudential policies are optimised together or separately. Our results show there are distributive implications of operating the different levels of reserve ratio where borrowers tend to enjoy an increase in welfare at the expense of savers. These results suggest that a higher reserve ratio increases costs for banks which induces them to restrict loans to subprime borrowers, reducing the probability of default. Less financial intermediation means that savers earn lower returns on deposits, while eligible borrowers enjoy a stable flow of credit as the probability of default is inversely related to the reserve ratio. We also show that a central bank setting monetary policy and a macroprudential policy agency need not coordinate—they can operate independently without any detriment to stability or welfare. Furthermore, we demonstrate that macroprudential policy, even if it operates completely on its own, stabilises the economy when a negative risk shock occurs, by dampening the financial accelerator mechanism. Meanwhile, neither macroprudential policy nor monetary policy when operating in the absence of the other are able to do much to mitigate the impact of a demand shock in the nondurable sector. Only when the two operate in tandem is there a discernible impact on the economy—particularly in reducing the drop in total loans. We also find that the total impact on welfare of macroprudential policy, either on its own, or in conjunction with monetary policy, is generally small but they demonstrate that once we incorporate housing and banks into our model, macroprudential policy is more effective than monetary policy in mitigating the welfare effects of shocks. At the same time, the reduction in the loss function is largest when monetary and macroprudential policy both operate with a high reserve ratio.

In Chapter 3, we propose a DSGE framework with a two-asset banking sector, financial frictions, sticky rates, and multiple regulatory constraints for the macroeconomic evaluation of the introduction of the output floor - a new capital requirement introduced as part of the Basel III finalisation reforms. The main purpose of introducing the output floor is to potentially minimise the variability of risk-weighted assets and thus, ensure a stable level of capital ratio for banks and improve the banking system's ability to absorb negative shocks. We look at the impact of the output floor on: (i) the variability of risk-weighted assets; (ii) banks' lending decision and risk-taking, and its tendency to amplify the credit cycle; and (iii) the objectives of the monetary and macroprudential authority. Our results show that the output floor reduces the variability of risk-weighted assets resulting in a less volatile risk-weighted capital ratio. This reduction in variability over time adds an interesting dimension to the often discussed cross-sectional variability. The results suggest that the output floor can affect not just cross-sectional RWA variability, but it also reduces time-series variability and this will have consequences for stress-testing policy. Indeed, to the extent that stress tests capitalise banks for cyclical variation in modelled RWA, they may need to do so by less for banks constrained by the output floor because their RWA will have less scope to move cyclically over time. The results suggest that this lower volatility stabilises the aggregate supply of loans and attenuates a sudden boom and bust of the supply of credit. However, there is a behavioural consequence from the introduction of the output floor, that is, banks tend to shift their portfolio from assets with a large gap between internally modeled and standardised risk weights (mortgages) to non-financial corporation loans which display a smaller gap.

In Chapter 4, we focus on the current low interest rate environment capital regulation dilemma. On the one hand, this environment leads to a decrease in banks' profitability, bank capital, and eventually bank lending, calling for a lower capital regulation. On the other hand, this environment encourages more indebtedness of borrowers and banks excessive risk taking, calling for a higher capital regulation. We study the consequences of capital regulation when the interest rate is at zero lower bound (ZLB) by developing a DSGE framework that can handle this model nonlinearities. We look at the dynamics of the model with capital regulation under the ZLB and no ZLB regimes. We shows that the model with ZLB has a different dynamics compared to the model with no ZLB and emphasise the importance of evaluating the model when the ZLB binds. Second, we compare the model with low and high capital regulation to illustrate whether a more aggressive capital regulation is appropriate in a situation where a monetary policy is constrained by the ZLB. We also evaluate the trade-off between a low and high capital regulations under the ZLB, we examine the volatility of some key macro and financial variables under two regimes and find that the contributions of having a high capital regulation in the stabilisation of the main macro and financial variables is more compared to a low capital regulation regime. We also draw some conclusions on the normative implications of having a low and high capital regulations by checking how the two regimes help achieve the policy objective of the macroprudential authority. We find that the implementation of the high capital regulation, other things equal, reduce both the loss function of the monetary authority and the macroprudential authority. Lastly, we characterise the optimal level of capital requirements that helps stabilise credit and find that, the model with ZLB requires a higher capital ratio to achieve the lowest volatility of credit compared to a model with no ZLB. These results underscore once again that the level of capital regulation that stabilises credit is higher when ZLB binds.

To conclude, this thesis contributes to the literature that looks at the interaction of monetary and macroprudential policies in several ways. First, we develop model frameworks that make possible the interaction of these policies in different model environments to capture different externalities and test the effectiveness of the existing and new macroprudential tools. These model frameworks allow as to evaluate that some well-intended policies may have unintended consequences. In addition, by modelling nonlinearities, we find that conventional policies may not be appropriate in a new policy environment such as the low interest rate environment. This thesis adds to the academic and policy debate on the state of macroprudential policies and its interaction with monetary policy.

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Appendix A

A.1 Saver's Optimisation Problem

To solve the savers problem we have

$$L = E_0\Big\{\sum_{s=0}^{\infty}\beta^s\Big[\gamma\xi^C_{t+s}log(C_{t+s}-\varepsilon C_{t+s-1})+(1-\gamma)\xi^D_{t+s}log(D_{t+s})-\frac{(L_{t+s})^{1+\varphi}}{1+\varphi}\Big]$$
$$+\varrho_{t+s}\Big\{\frac{R_{t+s-1}S_{t+s-1}}{\Pi^C_{t+s}}+W^C_{t+s}L^C_{t+s}+W^D_{t+s}L^D_{t+s}+\Pi_{t+s}-C_{t+s}-Q_{t+s}I_{t+s}-S_{t+s} \tag{A.1.1}$$
$$+\Big[(1-\delta)D_{t+s-1}+\Big[1-F\Big(\frac{I_{t+s}}{I_{t+s-1}}\Big)\Big]I_{t+s}-D_{t+s}\Big]\Big\}$$

The FOCs with respect to C_{t+s}, S_{t+s-1}, D_{t+s}, I_{t+s} and L_{t+s} are the following:

$$C_{t+s}:E_t\Big[\frac{\gamma\xi^C_{t+s}}{C_{t+s}-\varepsilon C_{t+s-1}}-\beta^s\varrho_{t+s}\Big]=0;s\geq 0 \tag{A.1.2}$$

$$S_{t+s-1}:E_t\Big[\beta^s\varrho_{t+s}\frac{R_{t+s-1}}{\Pi^C_{t+s}}-\beta^{s-1}\varrho_{t+s-1}\Big]=0;s>0;(S_{t-1}\ given) \tag{A.1.3}$$

$$D_{t+s}:E_t\Big[\frac{(1-\gamma)\xi^D_{t+s}}{D_{t+s}}-\beta^s\varrho_{t+s}+\beta^{s+1}\varrho_{t+s+1}(1-\delta)\Big]=0;s\geq 0 \tag{A.1.4}$$

$$I_{t+s}:E_t\Big[-\beta^s\varrho_{t+s}Q_{t+s}+\beta^{s+1}\varrho_{t+s+1}\Big[1-F\Big(\frac{I_{t+s}}{I_{t+s-1}}\Big)-F'\Big(\frac{I_{t+s}}{I_{t+s-1}}\Big)\frac{I_{t+s}}{I_{t+s-1}}\Big]$$
$$+\beta^{s+2}\varrho_{t+s+2}F'\Big(\frac{I_{t+s+1}}{I_{t+s}}\Big)\Big(\frac{I_{t+s+1}}{I_{t+s}}\Big)^2\Big]=0;s\geq 0 \tag{A.1.5}$$

$$L^C_{t+s}:E_t[\alpha^{-\iota_L}L^{\varphi-\iota_L}_{t+s}(L^C_{t+s})^{\iota_L}-\varrho_{t+s}W^C_{t+s}]=0;s\geq 0 \tag{A.1.6}$$

$$L^D_{t+s}:E_t[(1-\alpha)^{-\iota_L}L^{\varphi-\iota_L}_{t+s}(L^D_{t+s})^{\iota_L}-\varrho_{t+s}W^D_{t+s}]=0;s\geq 0 \tag{A.1.7}$$

Putting $s=0$ in (A.1.2), (A.1.4), (A.1.5), (A.1.6), and (A.1.7) and $s=1$ in (A.1.3) and defining the stochastic discount factor as $\mathrm{P}_{t,t+1}\equiv\beta\frac{\mathrm{P}_{t+1}}{\mathrm{P}_t}$ we now have:

Euler consumption

$$1 = \beta R_t E_t\Big[\frac{C_t - \varepsilon C_{t-1}}{C_{t+1} - \varepsilon C_t}\frac{\xi^C_{t+1}}{\xi^C_t}\Pi^C_{t+1}\Big] \tag{A.1.8}$$

Stochastic discount factor

$$\mathrm{P}_{t,t+1} \equiv \beta\frac{\mathrm{P}_{t+1}}{\mathrm{P}_t} = \beta\frac{\gamma\xi^C_{t+1}C_t - \varepsilon C_{t-1}}{\gamma\xi^C_t C_{t+1} - \varepsilon C_t} \tag{A.1.9}$$

Labour supply

$$\alpha^{-\iota_L}L^{\varphi-\iota_L}_{t+s}(L^C_{t+s})^{\iota_L} = \frac{\xi^C_t W^C_t}{C_t - \varepsilon C_{t-1}} \tag{A.1.10}$$

$$(1-\alpha)^{-\iota_L}L^{\varphi-\iota_L}_{t+s}(L^D_{t+s})^{\iota_L} = \frac{\xi^C_t W^D_t}{C_t - \varepsilon C_{t-1}} \tag{A.1.11}$$

Investment

$$\begin{aligned}\frac{\gamma\xi^C_t Q_t}{C_t - \varepsilon C_{t-1}} = \beta E_t\varrho_{t+1}\Big[1 - f\Big(\frac{I_t}{I_{t-1}}\Big) - f'\Big(\frac{I_t}{I_{t-1}}\Big)\frac{I_t}{I_{t-1}}\Big] \\ +\beta^2 E_t\Big[\varrho_{t+2}f'\Big(\frac{I_{t+1}}{I_t}\Big)\Big(\frac{I_{t+1}}{I_t}\Big)^2\Big]\end{aligned} \tag{A.1.12}$$

A.2 Borrower's Optimisation Problem

To solve the borrowers problem we have:

$$\begin{aligned}L = E_0\Big\{\sum_{s=0}^{\infty}\beta^{B,s}\Big[\gamma\xi^C_{t+s}log(C^B_{t+s} - \varepsilon^B C^B_{t+s-1}) + (1-\gamma)\xi^D_{t+s}log(D^B_{t+s}) - \frac{(L^B_{t+s})^{1+\varphi}}{1+\varphi}\Big] \\ +\varrho^B_{t+s}\Big[S^B_t + W^C_t L^{B,C}_t + W^D_t L^{B,D}_t - C^B_{t+s} - Q_{t+s}I^B_{t+s} \\ -\Big\{R^D_{t+s} + \Phi\Big(\frac{-log\bar{\omega}^p_{t-1}}{\sigma_{\omega,t-1}} - \frac{\sigma_{\omega,t-1}}{2}\Big)R^L_{t+s-1}\Big\}S^B_{t+s-1} \\ +\Big[(1-\delta)D^B_{t+s-1} + \Big[1 - f\Big(\frac{I_{t+s}}{I_{t+s-1}}\Big)\Big]I_{t+s} - D^B_{t+s}\Big]\end{aligned} \tag{A.2.1}$$

The FOCs with respect to C^B_{t+s}, S^B_{t+s-1}, D^B_{t+s-1}, I^B_{t+s} and L^B_{t+s} are the following

$$C^B_{t+s} : E_t\Big[\frac{\gamma\xi^C_{t+s}}{C^B_{t+s} - \varepsilon^B C^B_{t+s-1}} - \beta^{B,s}\varrho^B_{t+s}\Big] = 0; s \geq 0 \tag{A.2.2}$$

$$\begin{aligned}S^B_{t+s-1} : E_t\Big[\beta^{B,s}\varrho^B_{t+s} - \beta^{B,s-1}\varrho^B_{t+s-1}\Big[R^D_{t+1} \\ +\Phi\Big(\frac{-log\bar{\omega}^p_{t-1}}{\sigma_{\omega,t-1}} - \frac{\sigma_{\omega,t-1}}{2}\Big)R^L_{t+s-1}\Big] = 0; s > 0; (S_{t-1}\ given)\end{aligned} \tag{A.2.3}$$

$$D^B_{t+s}: E_t\Big[\frac{(1-\gamma)\xi^D_{t+s}}{D_{t+s}} - \beta^s \varrho^B_{t+s} + \beta^{B,s+1}\varrho^B_{t+s+1}(1-\delta)\Big] = 0; s \geq 0 \tag{A.2.4}$$

$$I^B_{t+s}: E_t\Big[-\beta^s \varrho^B_{t+s+1} Q_{t+s} + \beta^{B,s+1}\varrho^B_{t+s}\Big[1 - f\Big(\frac{I^B_{t+s}}{I^B_{t+s-1}}\Big) - f'\Big(\frac{I^B_{t+s}}{I^B_{t+s-1}}\Big)\frac{I^B_{t+s}}{I^B_{t+s-1}}\Big] + \beta^{s+2}\varrho^B_{t+s+2} f'\Big(\frac{I^B_{t+s+1}}{I^B_{t+s}}\Big)\Big(\frac{I^B_{t+s+1}}{I^B_{t+s}}\Big)^2\Big] = 0; s \geq 0 \tag{A.2.5}$$

$$L^{B,C}_{t+s}: E_t[\alpha^{-\iota_L} L^{\varphi-\iota_L}_{t+s}(L^{B,C}_{t+s})^{\iota_L} - \varrho^B_{t+s} W^C_{t+s}] = 0; s \geq 0 \tag{A.2.6}$$

$$L^{B,D}_{t+s}: E_t[(1-\alpha)^{-\iota_L} L^{\varphi-\iota_L}_{t+s}(L^{B,D}_{t+s})^{\iota_L} - \varrho^B_{t+s} W^D_{t+s}] = 0; s \geq 0 \tag{A.2.7}$$

Putting $s = 0$ in (A.2.2), (A.2.4), (A.2.5), (A.2.6), and (A.2.7) and $s = 1$ in (A.2.3) and defining the stochastic discount factor as $\mathrm{P}^B_{t,t+1} \equiv \beta \frac{\mathrm{P}^B_{t+1}}{\mathrm{P}^B_t}$ we now have:

Euler consumption

$$1 = \beta^B E_t\Big[R^D_{t+1} + (1-F)R^L_t\Big]\Big[\frac{C^B_t - \varepsilon C^B_{t-1}}{C^B_{t+1} - \varepsilon^B C_t}\frac{\xi^C_{t+1}}{\xi^C_t}\Pi^C_{t+1}\Big] \tag{A.2.8}$$

where $R^D_t = Q_t G \frac{D^B \Pi^C_t}{S^B_{t-1}}$ and $\omega^p_t Q_t D^B_t = \frac{R^L_{t-1} S^B_{t-1}}{\Pi^C_t}$

Stochastic discount factor

$$\mathrm{P}^B_{t,t+1} \equiv \beta^B \frac{\mathrm{P}^B_{t+1}}{\mathrm{P}^B_t} = \beta^B \frac{\gamma \xi^C_{t+1} C^B_t - \varepsilon^B C^B_{t-1}}{\gamma \xi^C_t C^B_{t+1} - \varepsilon^B C^B_t} \tag{A.2.9}$$

Labour supply

$$\alpha^{-\iota_L} L^{\varphi-\iota_L}_{t+s}(L^{B,D}_{t+s})^{\iota_L} = \frac{\xi^C_t W^C_t}{C^B_t - \varepsilon^B C^B_{t-1}} \tag{A.2.10}$$

$$(1-\alpha)^{-\iota_L} L^{\varphi-\iota_L}_{t+s}(L^{B,D}_{t+s})^{\iota_L} = \frac{\xi^C_t W^D_t}{C^B_t - \varepsilon^B C^B_{t-1}} \tag{A.2.11}$$

Investment

$$\frac{\gamma \xi^C_{t+s} Q_t}{C^B_{t+s} - \varepsilon^B C^B_{t+s-1}} = \beta E_t \varrho^B_{t+1}\Big[1 - f\Big(\frac{I^B_t}{I^B_{t-1}}\Big) - f'\Big(\frac{I^B_t}{I^B_{t-1}}\Big)\frac{I^B_t}{I^B_{t-1}}\Big] + \beta^2 E_t\Big[\varrho^B_{t+2} f'\Big(\frac{I^B_{t+1}}{I^B_t}\Big)\Big(\frac{I^B_{t+1}}{I^B_t}\Big)^2\Big] \tag{A.2.12}$$

A.3 Steady State

$$R = \frac{1}{\beta} \tag{A.3.1}$$

$$R^D = G\frac{R^L}{\bar{\omega}} \tag{A.3.2}$$

$$R^L = \frac{1}{\beta^B(\frac{G}{\bar{\omega}} + 1 - F)} \tag{A.3.3}$$

$$\Gamma^B = \frac{\gamma(1-\beta^B(1-\delta))}{\beta^B(1-\gamma)(1-\varepsilon^B)} \tag{A.3.4}$$

$$\Gamma = \frac{\gamma(1-\beta(1-\delta))}{\beta(1-\gamma)(1-\varepsilon)} \tag{A.3.5}$$

$$L^B = \Big\{\frac{\gamma}{1-\varepsilon^B}\Big(1 + \frac{\delta + G + (1 - F - \frac{1}{R^L}\Big)\bar{\omega}}{\Gamma^B}\Big)\Big\}^{\frac{1}{1+\varphi}} \tag{A.3.6}$$

$$\gamma\Big(1-\frac{1}{\sigma}\Big)\Big(\frac{\lambda}{1-\epsilon} + \frac{1-\lambda}{1-\epsilon^b}\frac{L}{L^B}\Big)\Big(\alpha + (1-\alpha)Q^{1+\frac{1}{\iota_L}}\Big) = \alpha L^{\varphi}((1-\lambda)L^B + \lambda L) \tag{A.3.7}$$

$$(1-\alpha+\alpha Q^{-1-\frac{1}{\iota_L}})\gamma^{\delta}\Big(1-\frac{1}{\sigma}\Big)\Big(\frac{\lambda}{(1-\epsilon)\Gamma} + \frac{\lambda}{(1-\epsilon^b)\Gamma}\Big(\frac{L}{L^B}\Big)\varphi\Big) = (1-\alpha)L^{\varphi}((1-\lambda)L^B + \lambda L) \tag{A.3.8}$$

$$W^D = W^C Q$$

$$C^B = \frac{W^C\gamma}{1-\varepsilon^B}(L^B)^{-\varphi}(\alpha + (1-\alpha)Q^{1+\frac{1}{\iota_L}})^{\frac{\iota_L}{1+\iota_L}} \tag{A.3.9}$$

$$C = \frac{W^C\gamma}{1-\varepsilon}L^{-\varphi}(\alpha + (1-\alpha)Q^{1+\frac{1}{\iota_L}})^{\frac{\iota_L}{1+\iota_L}} \tag{A.3.10}$$

$$D^B = \frac{C^B Q}{\Gamma^B} \tag{A.3.11}$$

$$D = \frac{CQ}{\Gamma^B} \tag{A.3.12}$$

$$I^B = \delta D^B \tag{A.3.13}$$

$$I = \delta D \tag{A.3.14}$$

$$S^B = QG\frac{D^B}{R^D} \tag{A.3.15}$$

$$\varrho = \frac{Q\gamma}{\beta}\frac{C}{(1-\varepsilon)} \tag{A.3.16}$$

$$\varrho^B = \frac{Q\gamma}{\beta^B}\frac{C^B}{(1-\varepsilon^B)} \tag{A.3.17}$$

$$L^D = \alpha L(\alpha + (1-\alpha)Q^{1+\frac{1}{\iota_L}})^{\frac{-1}{1+\iota_L}} \tag{A.3.18}$$

$$L^C = \alpha L(\alpha + (1-\alpha)Q^{1+\frac{1}{\iota_L}})^{\frac{-1}{1+\iota_L}} \tag{A.3.19}$$

$$L^{B,C} = (1-\alpha)L^B Q^{\frac{1}{\iota_L}}(\alpha + (1-\alpha)Q^{1+\frac{1}{\iota_L}})^{\frac{-1}{1+\iota_L}} \tag{A.3.20}$$

$$L^{B,D} = (1-\alpha)L^B Q^{\frac{1}{\iota_L}}(\alpha + (1-\alpha)Q^{1+\frac{1}{\iota_L}})^{\frac{-1}{1+\iota_L}} \tag{A.3.21}$$

$$\omega^a = \omega^p \tag{A.3.22}$$

$$C^{TOTAL} = \lambda C + (1-\lambda)C^B \tag{A.3.23}$$

$$L^{C,TOTAL} = \lambda L^C + (1-\lambda)L^{B,C} \tag{A.3.24}$$

$$L^{D,TOTAL} = \lambda L^D + (1-\lambda)L^{B,D} \tag{A.3.25}$$

$$Y^C = L^{C,TOTAL} \tag{A.3.26}$$

$$Y^D = L^{D,TOTAL} \tag{A.3.27}$$

$$Y = Y^C + QY^D \tag{A.3.28}$$

$$MC^C = W^C \tag{A.3.29}$$

$$MC^D = W^C \tag{A.3.30}$$

$$J^D = \frac{1}{(1-\beta\theta^D)} \frac{Y^D MC^D}{C(1-\varepsilon)} \tag{A.3.31}$$

$$H^D = \frac{1}{(1-\beta\theta^D)} \frac{Y^C W^D}{C(1-\varepsilon)} \tag{A.3.32}$$

$$J^C = \frac{1}{(1-\beta\theta^C)} \frac{Y^C MC^C}{C(1-\varepsilon)} \tag{A.3.33}$$

$$H^C = \frac{1}{(1-\beta\theta^C)} \frac{Y^C W^C}{C(1-\varepsilon)} \tag{A.3.34}$$

$$rr = \bar{rr} \tag{A.3.35}$$

$$\mathrm{P} = \beta \tag{A.3.36}$$

$$N = \frac{(\xi_B + \sigma_B)\Big\{(1-\lambda)\Big[(1-\mu)R^D + (1-F)R^L\Big]S^B\Big\} - (1-\lambda)\sigma\frac{R-rr}{1-rr}S^B}{1-\sigma\lambda\frac{R-rr}{1-rr}} \tag{A.3.37}$$

$$\phi = \frac{(1-\lambda)S^B}{N} \tag{A.3.38}$$

$$\Omega = 1 - \sigma_B + \sigma_B \Theta \phi \tag{A.3.39}$$

A.4 Steady State Effects on Welfare of rr Changes

For simplicity we focus on the case when there are no banking frictions.

A.4.1 Effect on $\bar{\omega}$:

The relationship between rr and $\bar{\omega}$ is given by

$$Z = \frac{\frac{rr\beta^b}{\beta} - 1 + \mu}{\bar{\omega}} \Phi\left(\frac{log\bar{\omega}}{\sigma_\omega} - \frac{\sigma_\omega}{2}\right) + (\frac{rr\beta^b}{\beta} - 1)\Phi\left(-\frac{log\bar{\omega}}{\sigma_\omega} - \frac{\sigma_\omega}{2}\right) = 0 \tag{A.4.1}$$

For later convenience, we define $F = \Phi\left(-\frac{log\bar{\omega}}{\sigma_\omega} - \frac{\sigma_\omega}{2}\right)$, $G = \Phi\left(\frac{log\bar{\omega}}{\sigma_\omega} - \frac{\sigma_\omega}{2}\right)$, where Φ is the cumulative normal distribution.

It follows that $\frac{\partial Z}{\partial rr} = (G/\bar{\omega} + F)\frac{\beta^b}{\beta}$. In addition

$$\frac{\partial Z}{\partial \bar{\omega}} = \frac{\mu}{\sigma_\omega \bar{\omega}^2}\left[\phi(\frac{log\bar{\omega}}{\sigma_\omega} - \frac{\sigma_\omega}{2}) - \sigma_\omega \Phi(\frac{log\bar{\omega}}{\sigma_\omega} - \frac{\sigma_\omega}{2})\right] + \frac{1}{\bar{\omega}^2}(1 - \frac{rr\beta^b}{\beta})\Phi\left(\frac{log\bar{\omega}}{\sigma_\omega} - \frac{\sigma_\omega}{2}\right) \tag{A.4.2}$$

(where ϕ is the normal probability density function, and we have used the result that $\phi(\frac{log\bar{\omega}}{\sigma_\omega} - \frac{\sigma_\omega}{2}) = \bar{\omega}\phi(-\frac{log\bar{\omega}}{\sigma_\omega} - \frac{\sigma_\omega}{2})$).

A reasonable assumption is that the threshold value $\bar{\omega} < 1$; from (A.4.1) it is clear that $\bar{\omega} = 1$ when $\mu = 2(1 - \frac{rr\beta^b}{\beta})$, so it follows that a sufficient condition for $\bar{\omega} < 1$ is that $\mu > 2(1 - \frac{rr\beta^b}{\beta})$. Most calibrations of the agency parameter μ are of the order of 0.1, with $\frac{\beta^b}{\beta} = 0.97$, so that this sufficiency condition holds over the range of rr we investigate. Noting that the term in square brackets is 0 when $\bar{\omega} = 0$ and that its derivative is increasing provided that $(-\frac{log\bar{\omega}}{\sigma_\omega} - \frac{\sigma_\omega}{2}) > 0$, it follows that it must be positive provided that $\bar{\omega} > e^{-\frac{\sigma_\omega^2}{2}}$. Note also that this term is positive at $\bar{\omega} = 1$ provided that $\sigma_\omega < 1.22$. Thus provided that $\mu > 0.08$ and $\sigma_\omega < 1.22$, this term is positive, and therefore $\frac{\partial Z}{\partial \bar{\omega}} > 0$.

It immediately follows that $\frac{d\bar{\omega}}{drr} < 0$.

We can next write $\frac{R}{R^L} = \frac{1}{rr}((1-\mu)\frac{G}{\bar{\omega}} + F) = \frac{\beta^b}{\beta}(\frac{G}{\bar{\omega}} + F)$, where $\beta R = 1$, from which it follows that

$$-\frac{R}{(R^L)^2}\frac{\partial R^L}{\partial \bar{\omega}} = -\frac{\beta^b}{\beta}\frac{G}{\bar{\omega}^2} \tag{A.4.3}$$

and hence $\frac{dR^L}{drr} < 0$.

A.4.2 Effect on Other Variables:

$$R^D = \frac{GR^L}{\bar{\omega}} = \frac{1}{\beta^b}\frac{G/\bar{\omega}}{G/\bar{\omega}+F} \tag{A.4.4}$$

Hence

$$\beta^b\frac{\partial R^D}{\partial\bar{\omega}} = \frac{\frac{F}{\sigma_\omega\bar{\omega}^2}\left[\phi(\frac{log\bar{\omega}}{\sigma_\omega}-\frac{\sigma_\omega}{2})-\sigma_\omega\Phi(\frac{log\bar{\omega}}{\sigma_\omega}-\frac{\sigma_\omega}{2})\right]+\frac{G}{\sigma_\omega\bar{\omega}^2}\phi(-\frac{log\bar{\omega}}{\sigma_\omega}-\frac{\sigma_\omega}{2})}{(G/\bar{\omega}+F)^2} > 0 \tag{A.4.5}$$

and hence $\frac{dR^D}{drr} < 0$.

$$(L^B)^\varphi = \frac{\gamma}{1-\epsilon^B}\left(1+\frac{\delta+G+(F-\frac{1}{R^L})\bar{\omega}}{\Gamma^B}\right) \tag{A.4.6}$$

Thus L^B increases with $G+(F-\frac{1}{R^L})\bar{\omega} = (1-\beta^b)(G+\bar{\omega}F)$; the derivative of this with respect to $\bar{\omega}$ is $(1-\beta^b)F > 0)$, and hence $\frac{dL^B}{drr} < 0$.

The steady state equations for Q and L are given by

$$\gamma\left(1-\frac{1}{\sigma}\right)\left(\frac{\lambda}{1-\epsilon}+\frac{1-\lambda}{1-\epsilon^B}(L/L^B)^\varphi\right)\left(\alpha+(1-\alpha)Q^{1+\frac{1}{\iota_L}}\right) = \alpha L^\varphi((1-\lambda)L^B+\lambda L) \tag{A.4.7}$$

$$\left(1-\alpha+\alpha Q^{-1-\frac{1}{\iota_L}}\right)\gamma\delta\left(1-\frac{1}{\sigma}\right)\left(\frac{\lambda}{(1-\epsilon)\Gamma}+\frac{1-\lambda}{(1-\epsilon^B)\Gamma^B}(L/L^B)^\varphi\right) = (1-\alpha)L^\varphi((1-\lambda)L^B+\lambda L) \tag{A.4.8}$$

where

$$\Gamma = \frac{\gamma(1-\beta(1-\delta))}{\beta(1-\gamma)(1-\epsilon)} \qquad \Gamma^B = \frac{\gamma(1-\beta^B(1-\delta))}{\beta^B(1-\gamma)(1-\epsilon^B)} \tag{A.4.9}$$

One can eliminate Q by multiplying (A.4.8) by $Q^{1+\frac{1}{\iota_L}}$ and then adding to (A.4.7), to obtain

$$\begin{aligned}(1-\lambda)L^B+\lambda L \quad &- \quad \gamma\left(1-\frac{1}{\sigma}\right)\left(\frac{\lambda}{1-\epsilon}L^{-\varphi}+\frac{1-\lambda}{1-\epsilon^B}(L^B)^{-\varphi}\right)\\ &- \quad \gamma\delta\left(1-\frac{1}{\sigma}\right)\left(\frac{\lambda}{(1-\epsilon)\Gamma}L^{-\varphi}+\frac{1-\lambda}{(1-\epsilon^B)\Gamma^B}(L^B)^{-\varphi}\right) = 0\end{aligned} \tag{A.4.10}$$

and it is clear from this that $\frac{dL}{drr} > 0$.

Dividing (A.4.7) by (A.4.8) yields

$$(1-\alpha)\left(\frac{\lambda}{1-\epsilon}+\frac{1-\lambda}{1-\epsilon^B}(L/L^B)^\varphi\right)Q^{1+\frac{1}{\iota_L}} = \alpha\delta\left(\frac{\lambda}{(1-\epsilon)\Gamma}+\frac{1-\lambda}{(1-\epsilon^B)\Gamma^B}(L/L^B)^\varphi\right) \tag{A.4.11}$$

By inspection, we see that if $\Gamma = \Gamma^B$, then Q, the price ratio, is a constant. Noting that

$$\Gamma - \Gamma^B = \frac{\gamma}{1-\gamma}\left(\frac{1/\beta-1+\delta}{1-\epsilon}-\frac{1/\beta^B-1+\delta}{1-\epsilon^B}\right) \tag{A.4.12}$$

and that a lower discount factor β^B is likely to be associated with a smaller habit parameter ϵ^B, the implication is that $\Gamma - \Gamma^B$ is small, and therefore that there is little variation in Q.[1] Treating $\frac{dQ}{drr}$ as negligible, it follows from the equations

$$C^B = W^C \frac{\gamma}{1-\epsilon^B}(L^B)^{-\varphi}(\alpha + (1-\alpha)Q^{1+1/\iota_L})^{\iota_L/(1+\iota_L)} \tag{A.4.13}$$

$$C = W^C \frac{\gamma}{1-\epsilon} L^{-\varphi}(\alpha + (1-\alpha)Q^{1+1/\iota_L})^{\iota_L/(1+\iota_L)} \tag{A.4.14}$$

$$D^B = C^B/\Gamma^B/Q \qquad D = C/\Gamma/Q; \tag{A.4.15}$$

with $W^C = 1 - 1/\sigma$, that C^B and D^B increase with rr, and C, D decrease. With steady state utilities given by

$$U = \gamma log(C - \epsilon C) + (1-\gamma)log(D) - \frac{L^{1+\varphi}}{1+\varphi} \qquad U^B = \gamma log(C^B - \epsilon^B C^B) + (1-\gamma)log(D^B) - \frac{(L^B)^{1+\varphi}}{1+\varphi} \tag{A.4.16}$$

it is evident that the effect of an increase in reserve ratios, as given by rr, is to raise the utility U^B for the borrowers and reduce utility U for the savers.

A.5 Long-Run IRF's and Additional Results

[1] Indeed, the percentage change in Q in the simulations is around 100 times smaller than those of any of the changes in the other variables.

Fig. A.1 IRFs with Housing Risk Shock (Deviations from Steady State)

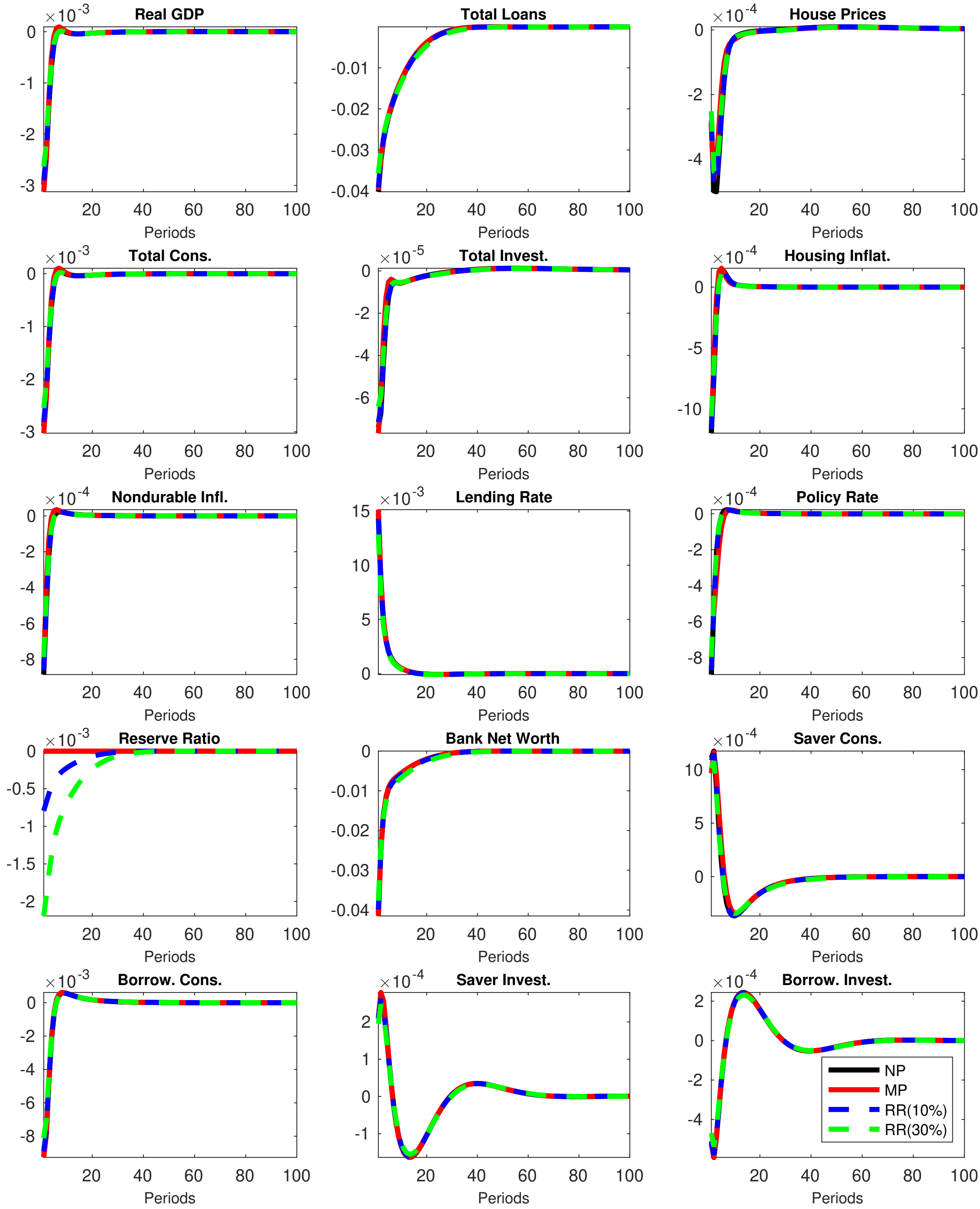


Fig. A.2 IRFs with Housing Risk Shock (Deviations from Steady State)

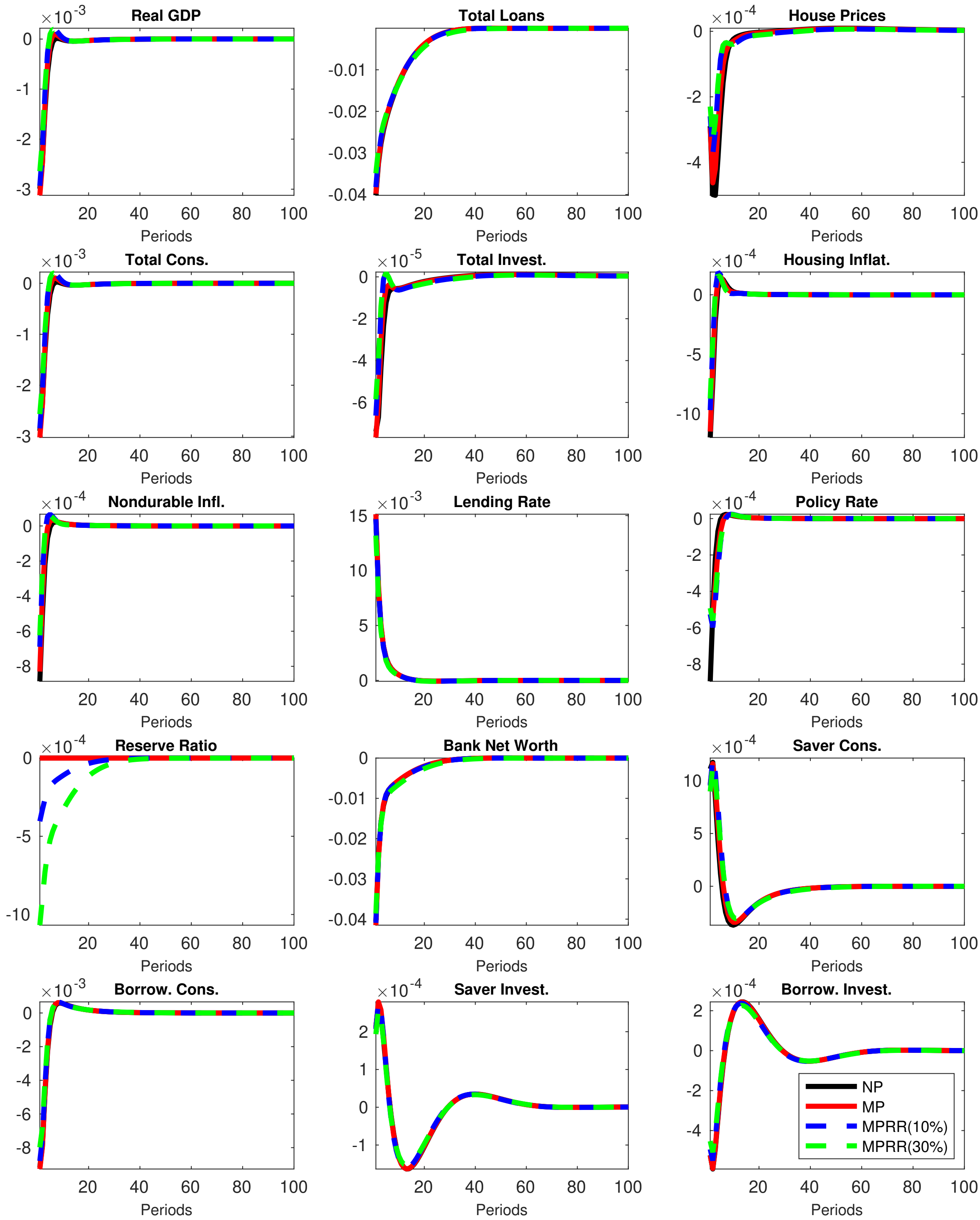


Fig. A.3 IRFs with Housing Demand Shock (Deviations from Steady State)

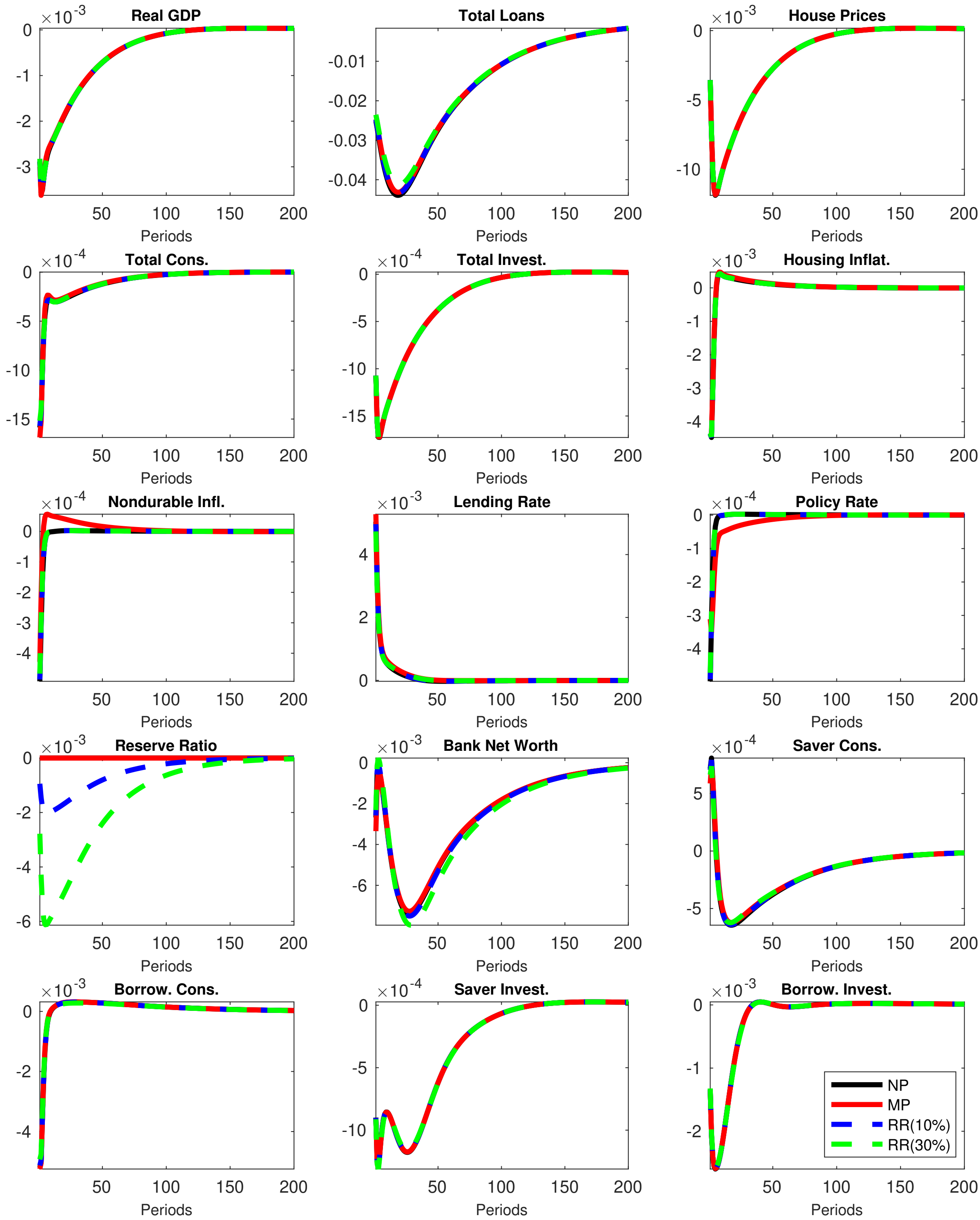


Fig. A.4 IRFs with Housing Demand Shock (Deviations from Steady State)

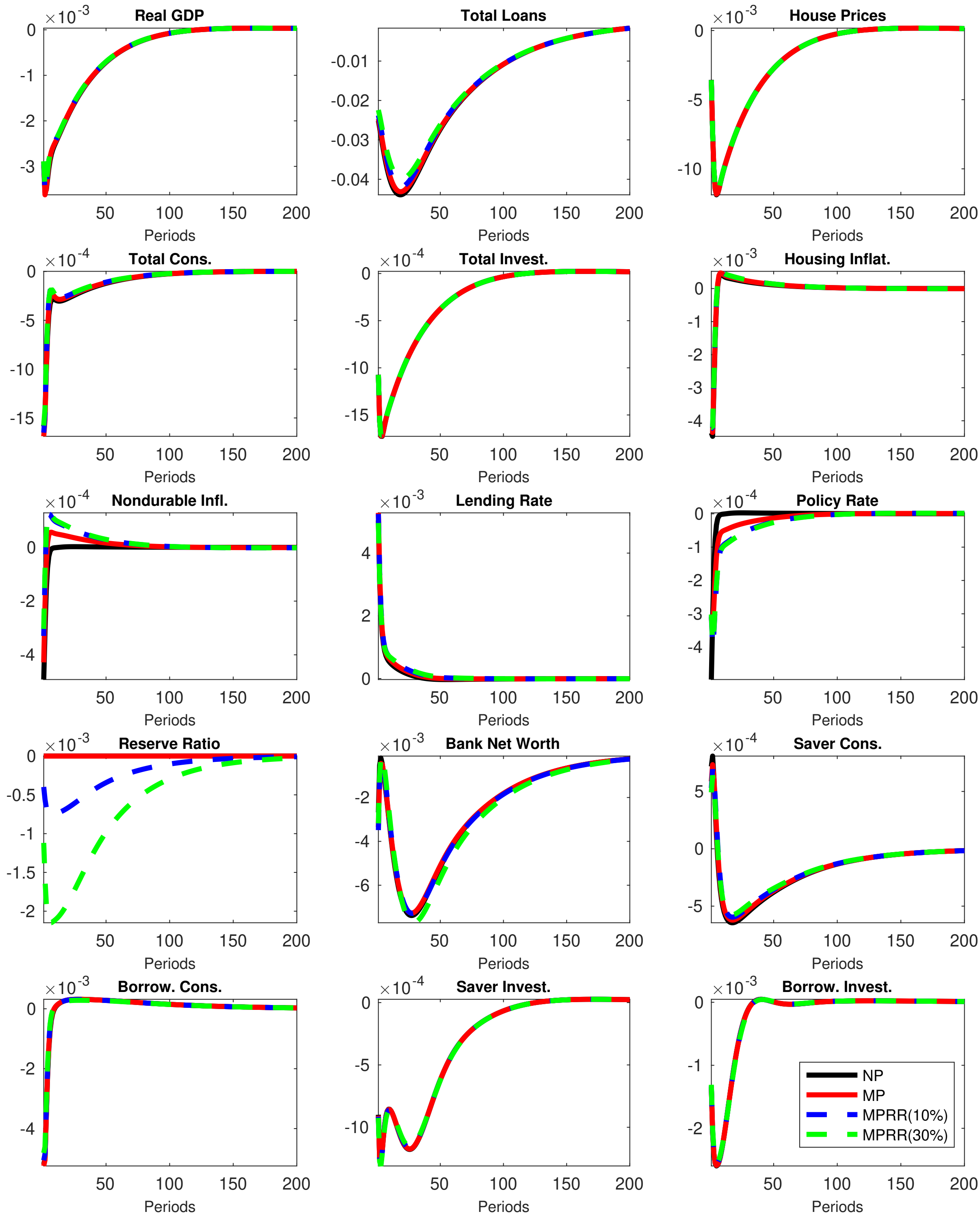


Fig. A.5 IRFs with Non-Durable Technology Shock (Deviations from Steady State)

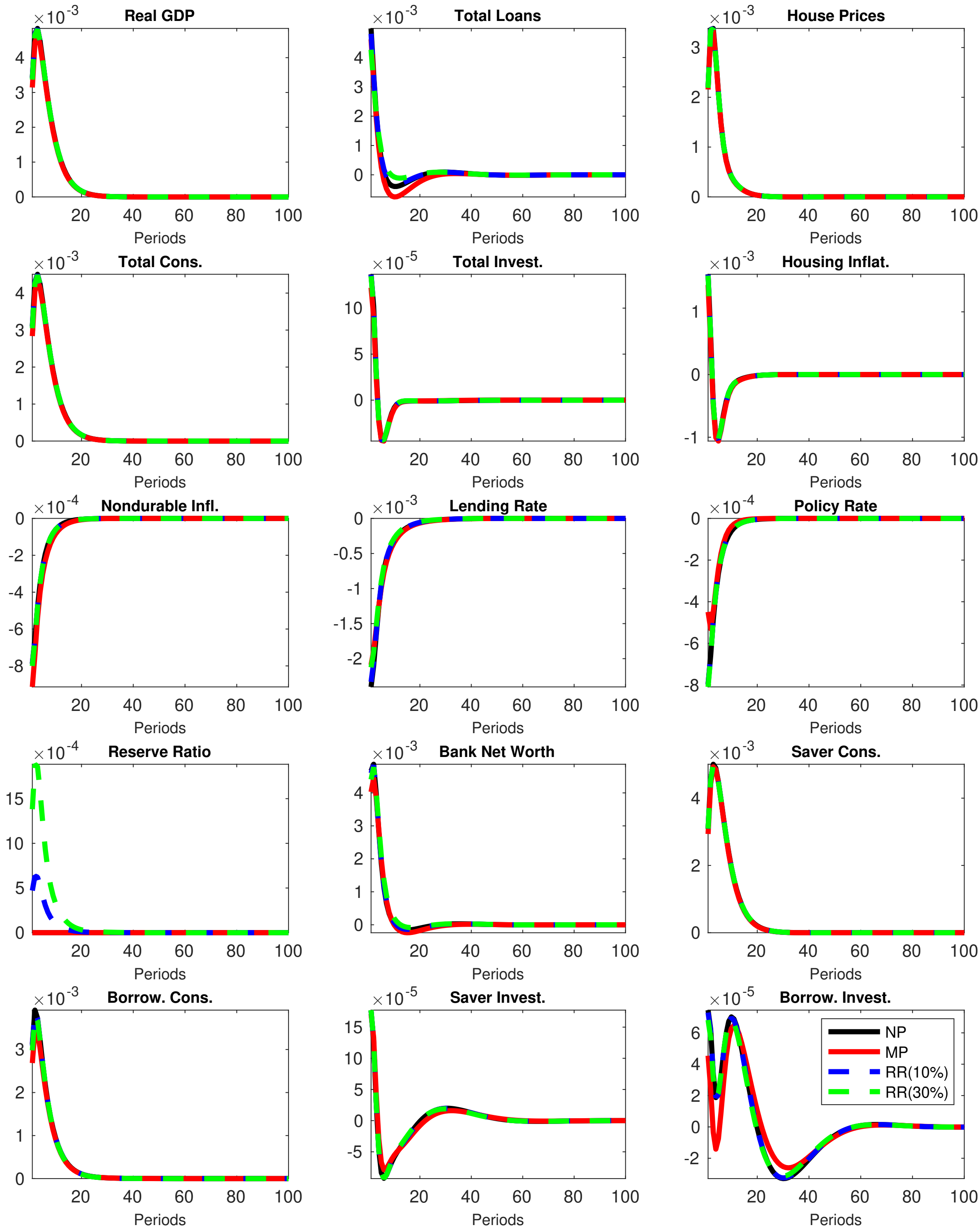


Fig. A.6 IRFs with Non-Durable Technology Shock (Deviations from Steady State)

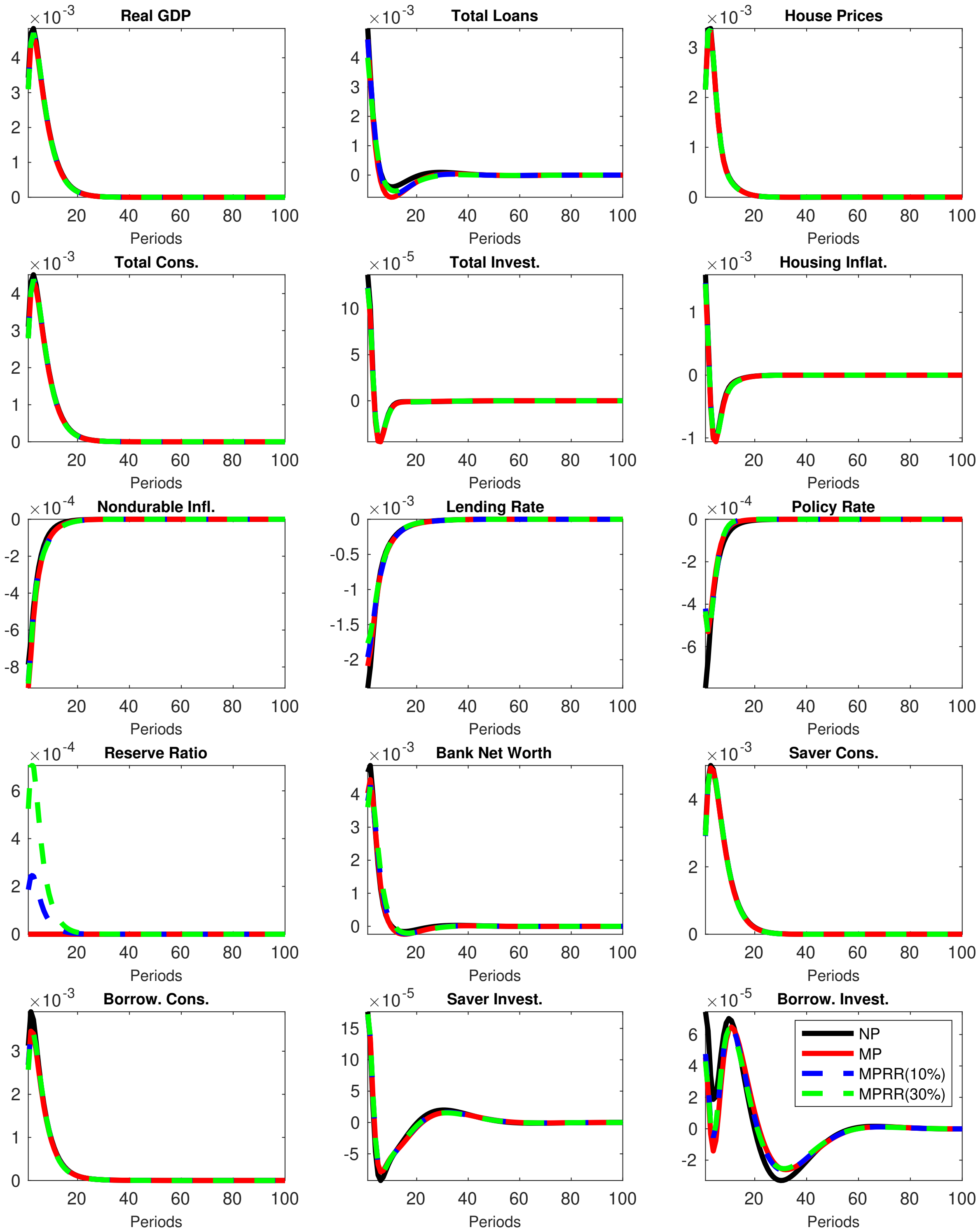


Fig. A.7 IRFs with Non-Durable Demand Shock (Deviations from Steady State)

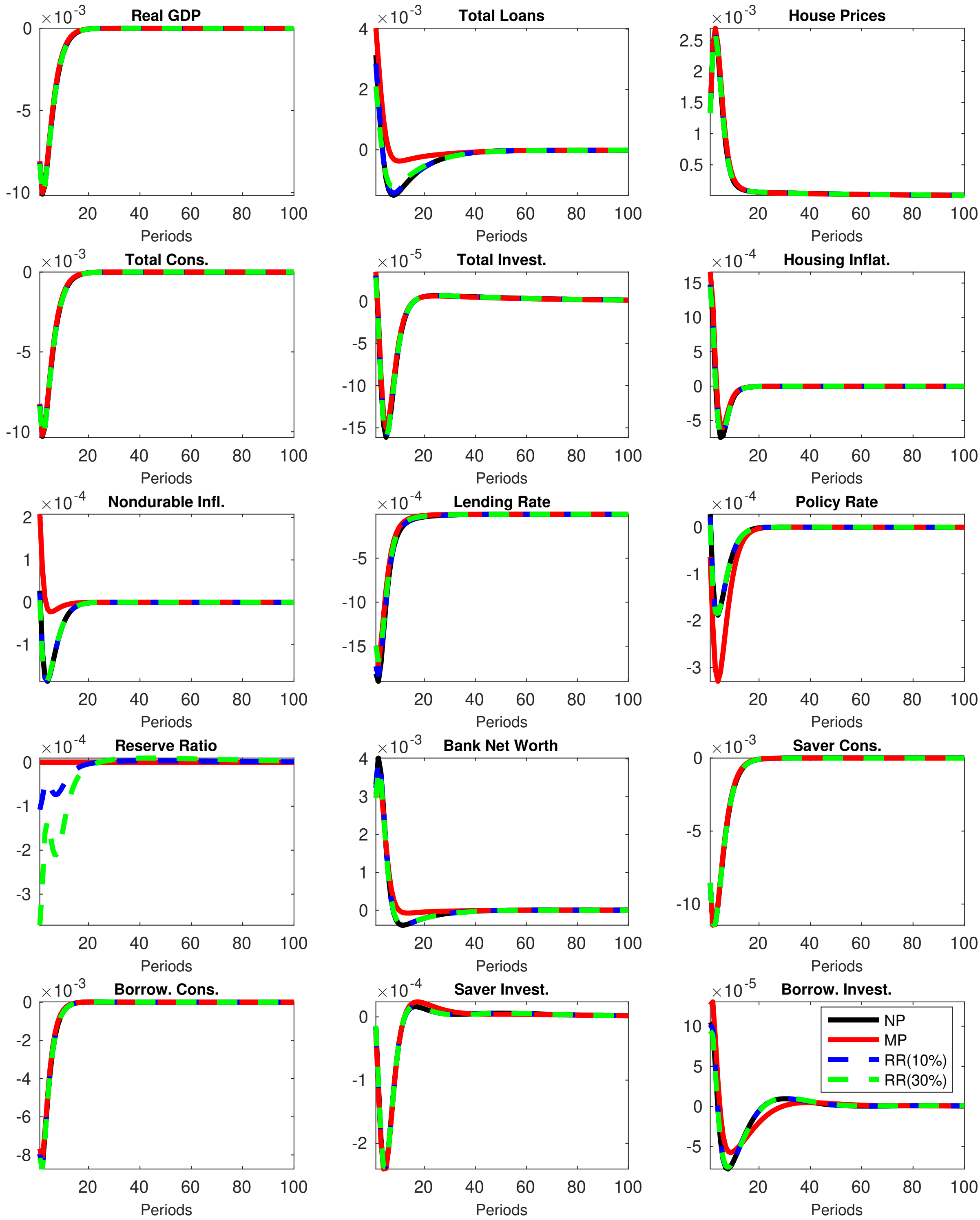


Fig. A.8 IRFs with Non-Durable Demand Shock (Deviations from Steady State)

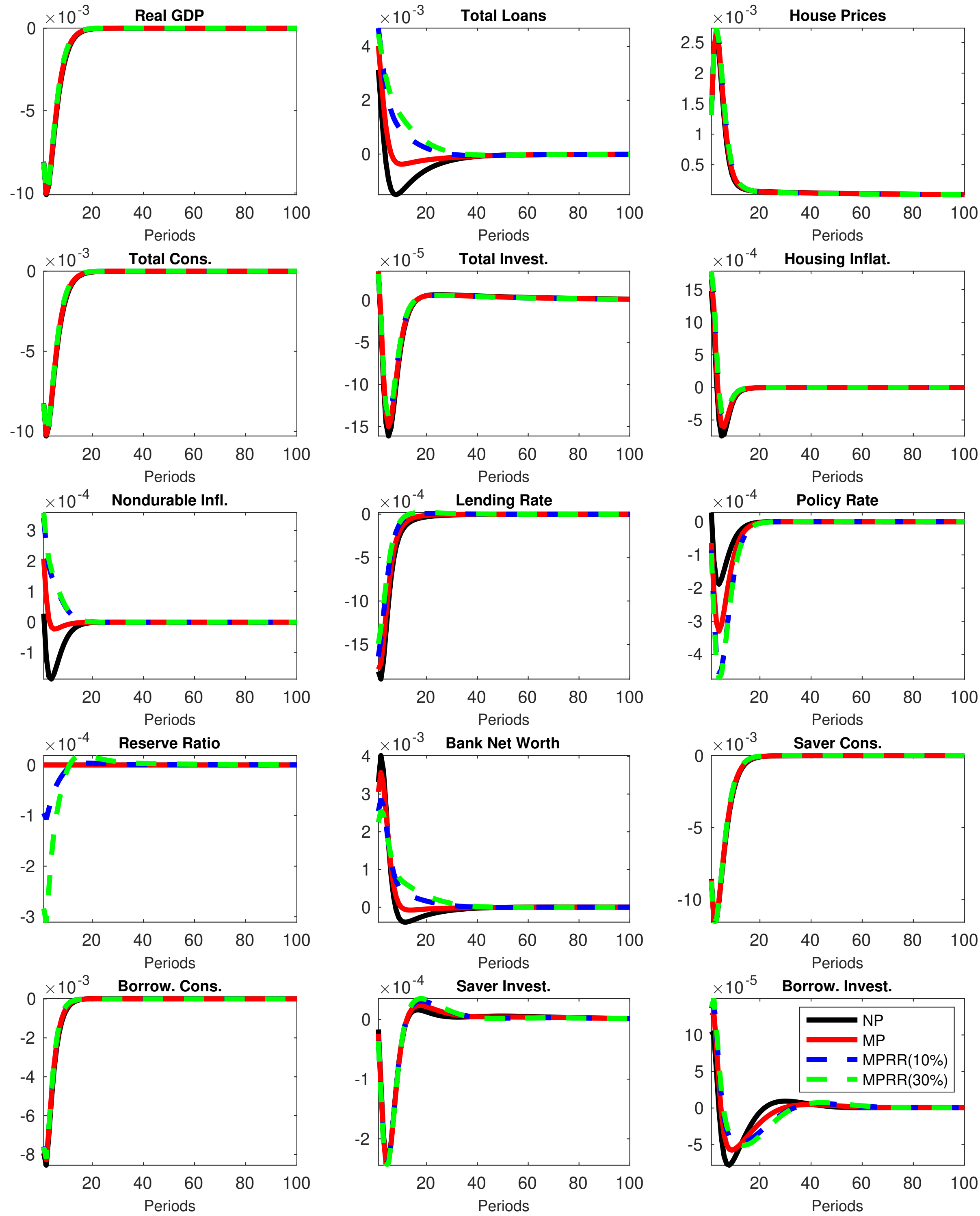
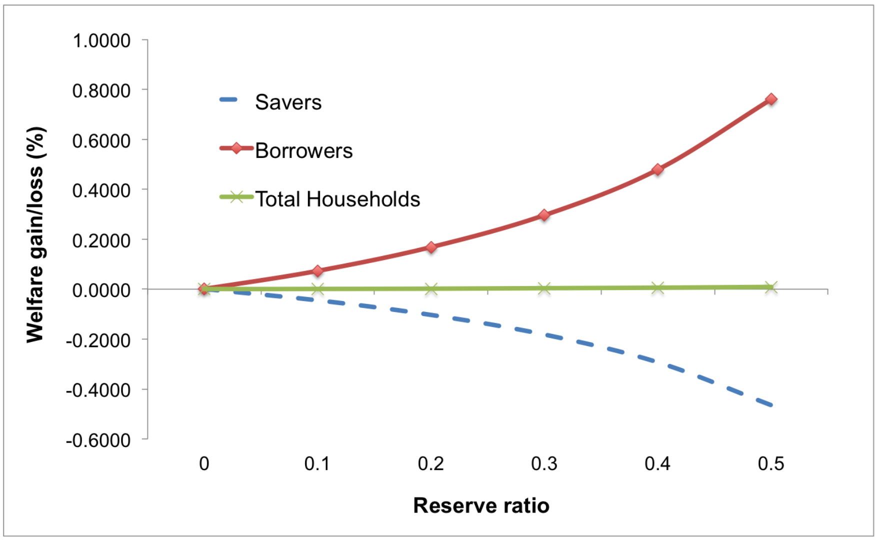


Fig. A.9 Welfare in Consumption Equivalent in Deterministic Model



Appendix B

B.1 Data Definition and Sources

The model is estimated with Bayesian techniques using eleven key macroeconomic quarterly UK time series. All data are seasonally adjusted and demeaned. The original data the relative transformation are summarised below. [1]

- **Consumption.** Data: nominal private final consumption expenditure (in million British Pounds), quarterly, seasonally adjusted. Transformation: deflated by GDP implicit price deflator and divided by population index, first log difference x 100. Source: Federal Reserve Economic Data (FRED).

- **Investment.** Data: gross fixed capital formation (in million British Pound), quarterly, seasonally adjusted. Transformation: deflated by GDP implicit price deflator and divided by population index, first log difference x 100. Source: FRED.

- **House prices.** Data: real residential property prices for the UK (percent per annum), not seasonally adjusted. Transformation: divided by four to convert to quarterly series. Source: FRED.

- **Wages.** Data: unit labour cost, total labour productivity for the UK, index 2015=100, quarterly, seasonally adjusted. Transformation: deflated by GDP deflator, first log difference x 100. Source: FRED.

- **Inflation.** Data: GDP implicit price deflator, index 2015=100, quarterly, seasonally adjusted. Transformation: first log difference x 100. Source: FRED.

[1] For the data transformation we mostly followed Smets and Wouters (2007).

- **Policy rate.** Data: shadow rate for the UK (percent per annum) computed following Wu and Xia (2016). Transformation: divided by four to convert to quarterly series. Source: Wu and Xia (2016).

- **Deposit rate.** Deposit rate in the UK (percent per annum). Transformation: divided by four to convert to quarterly series. Source: FRED.

- **Households borrowing rate.** Data: household personal loan rate in the UK (percent per annum), not seasonally adjusted. Transformation: divided by four to convert to quarterly series. Source: FRED.

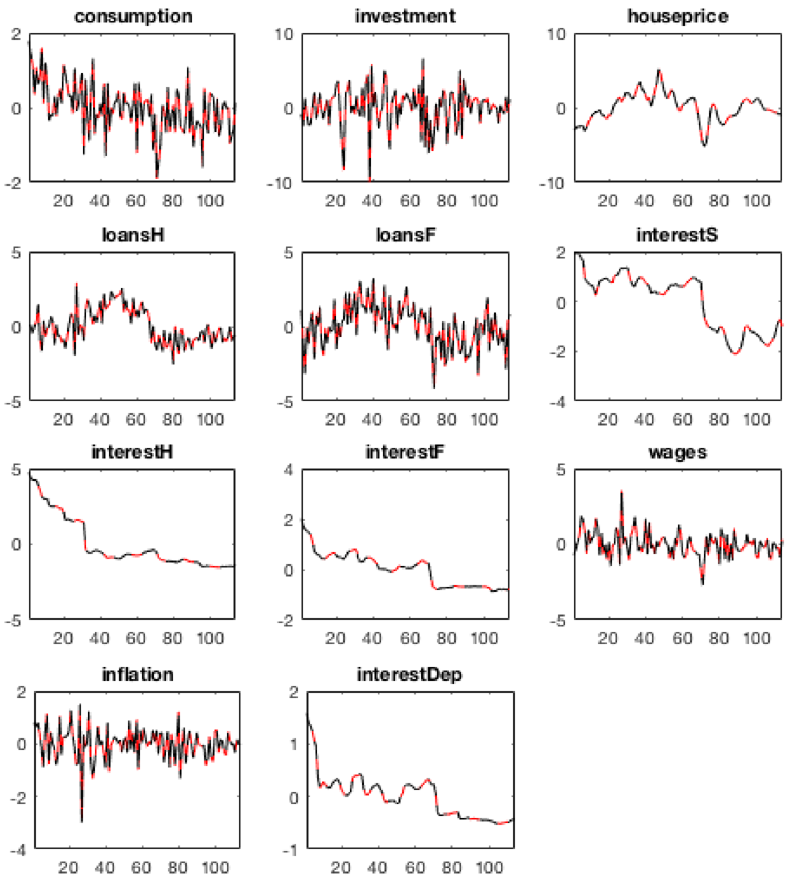
- **Firms borrowing rate.** Data: corporate borrowing rate on loans from banks in the UK (percent per annum), not seasonally adjusted. Transformation: divided by four to convert to quarterly series. Source: FRED.

- **Households borrowing volumes.** Data: quarterly lending secured on dwellings, amount outstanding (in million British Pounds), seasonally adjusted. Transformation: deflated by GDP implicit price deflator, first log difference x 100. Source: Bank of England (BoE) database.

- **Firms borrowing volumes.** Data: quarterly credit to non-financial sector (in million British Pounds), not seasonally adjusted. Transformation: deflated by GDP implicit price deflator, first log difference x 100. Source: Federal Reserve Economic Data (FRED) and Bank for International Settlements (BIS).

Figure B.1 shows the historical and smoothed variables.

Fig. B.1 Historical and Smoothed Variables



B.2 Solutions Method

The baseline model, which features the IRB method for the calculation of the RWA, is solved using algorithm developed in Dynare (Adjemian et al. (2011)).

To solve the model with the output floor which features a non-differentiable function, instead, we adopted the Holden (2016) toolbox or DynareOBC that allows the calculation of a second-order pruned perturbation approximation. While one of the important downsides to the perturbation approximation is an inability to deal with non-differentiatable functions, including those with min and max operators, the DynareOBC toolkit supports both 'max and min' (with two arbitrary arguments) and abs (with one arbitrary argument). There are no restrictions on what is contained within the brackets. You do not have to have a 0 term, and it does not matter which of the arguments of max or min is bigger or smaller in steady state. The only limitation is that the two arguments of max or min cannot be identical in steady state (likewise, the argument of abs cannot be zero in steady state).

Since we have a second-order solution to the underlying model, we can capture the precautionary effects stemming from the model's nonlinearities.[2] The algorithm is applied to the solution of general non-linear models, allowing for future uncertainty. The approach generalises to higher orders that improve accuracy away from the steady-state as well as capturing important risk channels. Below is a summary of the solutions method:[3]

Suppose that $x_0 \in \mathbb{R}^n$ and that $f : \mathbb{R}^n \times \mathbb{R}^n \times \mathbb{R}^n \times \mathbb{R}^c \times \mathbb{R}^m \rightarrow \mathbb{R}^n$, $g, h : \mathbb{R}^n \times \mathbb{R}^n \times \mathbb{R}^n \times \mathbb{R}^c \times \mathbb{R}^m \rightarrow \mathbb{R}^c$ are given continuously $d \in \mathbb{N}^+$ times differentiable functions. Find $x_t \in \mathbb{R}^n$ and $r_t \in \mathbb{R}^c$ for all $t \in \mathbb{N}^+$:

$$0 = E_t f(x_{t-1}, x_t, x_{t+1}, r_t, \varepsilon_t)$$
$$r_t = E_t \ \max\{h(x_{t-1}, x_t, x_{t+1}, r_t, \varepsilon_t), g(x_{t-1}, x_t, x_{t+1}, r_t, \varepsilon_t)\}$$

where $\varepsilon \sim NIID(0, \Sigma)$, where the max operator acts elementwise on vectors, and where the information set is such that for all $t \in \mathbb{N}^+$, $E_{t-1}\varepsilon = 0$ and $E_t\varepsilon_t = \varepsilon_t$.

To deal with non-linearity other than the bounds. In the above problem set up, there exist $\mu_x \in \mathbb{R}^n$ and $\mu_r \in \mathbb{R}^c$ such that:

$$0 = f(\mu_x, \mu_x, \mu_x, \mu_r, 0)$$
$$\mu_r = \max\{h(\mu_x, \mu_x, \mu_x, \mu_r, 0), g(\mu_x, \mu_x, \mu_x, \mu_r, 0)\}$$

and such that for all $\alpha \in \{1, ..., c\}$, $(h(\mu_x, \mu_x, \mu_x, \mu_r, 0))_\alpha \neq (g(\mu_x, \mu_x, \mu_x, \mu_r, 0))_\alpha$.

B.3 Additional Estimation Results

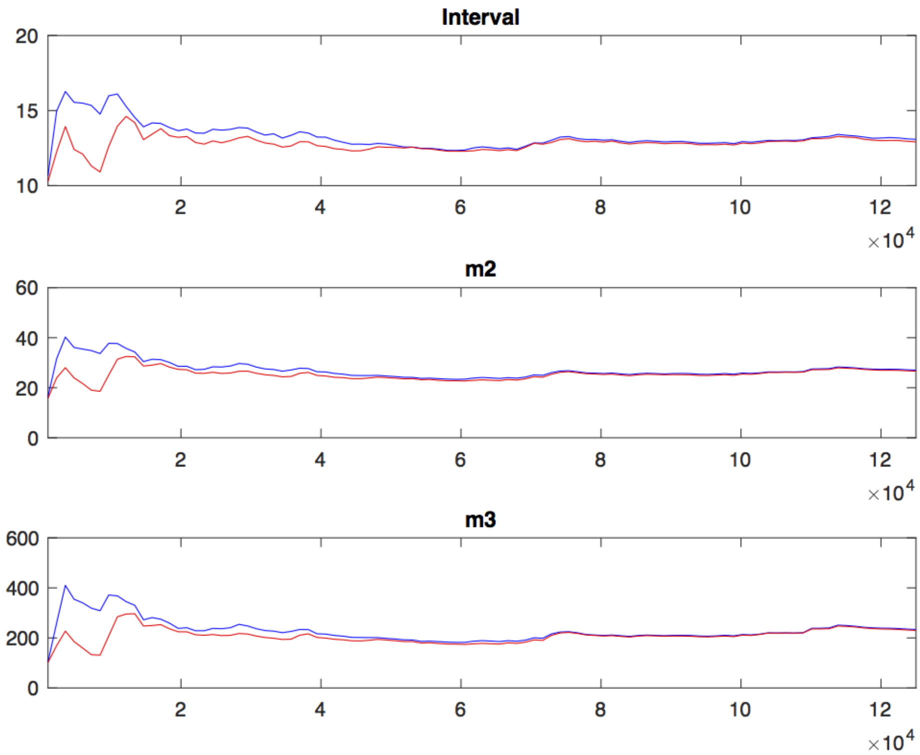
Convergence test. While testing for convergence of the posterior distribution is notoriously difficult, Dynare uses some indicative statistics as recommended by Brooks and Gelman (1998)). Figure B.2 contains three multivariate figures, representing convergence indicators for all

[2]Higher order approximations give a better fit to the non-linearities of the model, but also makes important difference to how risk effects model dynamics. At first order, certainty equivalence holds and there is no risk premium; at second order, risk is constant; and at third order, risk is linear in the state and is the lowest order at which it will be time varying.

[3]The algorithm is implemented in the DynareOBC toolkit, which extends Dynare Adjemian et al. (2011) to solve models featuring inequality constraints. This is available at https://github.com/tholden/dynareOBC. Holden (2016) provides the theoretical foundations for this method.

parameters considered together. The multivariate diagnostics indicate that the chains converge to similar means and distributions, where interval refers to the interval measure, and m2, m3 refer to second and third order multivariate moment measures. As a minimum requirement, the multivariate diagnostics should be seen to converge to the same values.

Fig. B.2 Convergence Test



Additional results. Table B.1 contains the estimation of the shocks standard errors.

Table B.1 Prior and Posterior Distribution of the Structural Parameters-Exogenous Processes

Parameter		Prior Distribution			Posterior Distribution			
		Distib.	Mean	Std dev.	Mean	2.5%	Median	97.5%
Standard deviations								
σ_A	Technology	Inv. Gamma	0.01	2.00	0.011	0.005	0.008	0.021
σ_c	Consumption pref.	Inv. Gamma	0.01	2.00	0.161	0.101	0.157	0.232
σ_h	Housing pref.	Inv. Gamma	0.01	0.05	0.208	0.091	0.201	0.330
σ_{mH}	HHs' LTV	Inv. Gamma	0.01	0.05	0.008	0.007	0.008	0.010
σ_{mE}	Firms' LTV	Inv. Gamma	0.01	0.05	0.008	0.007	0.008	0.010
σ_{bH}	HHs loans markup	Inv. Gamma	0.01	2.00	0.673	0.433	0.642	1.003
σ_{bE}	Firms loans markup	Inv. Gamma	0.01	2.00	0.297	0.002	0.332	0.474
σ_d	Deposits markdown	Inv. Gamma	0.01	2.00	0.169	0.111	0.162	0.243
σ_{qk}	Invest. efficiency	Inv. Gamma	0.01	2.00	0.031	0.027	0.030	0.035
σ_y	p markup	Inv. Gamma	0.01	2.00	4.352	2.865	4.291	6.067
σ_l	w markup	Inv. Gamma	0.01	0.05	2.842	1.677	2.717	4.472
σ_{Kb}	Balance sheet	Inv. Gamma	0.01	0.05	0.034	0.020	0.033	0.052
σ_r	Monetary policy	Inv. Gamma	0.01	0.05	0.003	0.002	0.003	0.003

Table B.2 Posterior Mean Variance Decomposition

	Contribution of each shock (in percent)									
	TFP	Consumption preference	House Price	HH LTV	NFC LTV	HH loans mark-up	Investment efficiency	Price mark-up	Monetary policy	Others
Real GDP	6.1	61.9	0.1	0.1	5.6	1.1	21.4	0.3	1.9	1.5
Consumption	6.2	85.7	0.1	0.0	3.5	0.1	0.8	0.4	1.8	1.0
Investment	1.4	0.3	0.1	0.1	2.9	1.1	92.5	0.0	0.5	1.0
Credit-to-GDP	18.4	12.7	3.2	5.4	29.1	15.4	8.0	1.1	3.1	3.7
HH loans	10.5	1.2	12.6	32.2	3.9	7.1	0.5	2.1	23.5	6.5
NFC loans	11.1	1.2	0.1	0.2	48.3	2.0	9.0	15.2	8.1	4.8
House prices	67.5	6.2	11.2	0.3	1.8	1.0	0.8	3.6	3.4	4.4
Policy rate	72.2	9.5	0.3	0.2	1.0	0.5	0.7	5.6	5.0	5.2
HH loans rate	65.6	8.6	0.2	0.1	0.6	16.5	0.5	1.9	1.8	4.2
NFC loans rate	62.3	5.3	0.7	0.7	7.5	7.4	3.0	2.4	2.3	8.2
Inflation	57.0	4.7	0.2	0.1	0.4	0.3	0.3	30.8	1.5	4.9

Historical shock decomposition. Figures B.3 and B.4 show that historical shock decomposition for the house prices and the households' loans growth, respectively. The historical shock decomposition shows that housing preferences (red bars) and technological shocks (blue bars) played an important role in both the build-up before the global financial crisis and the subsequent bust of the two variable considered.

Fig. B.3 Historical Shock Decomposition: House Prices

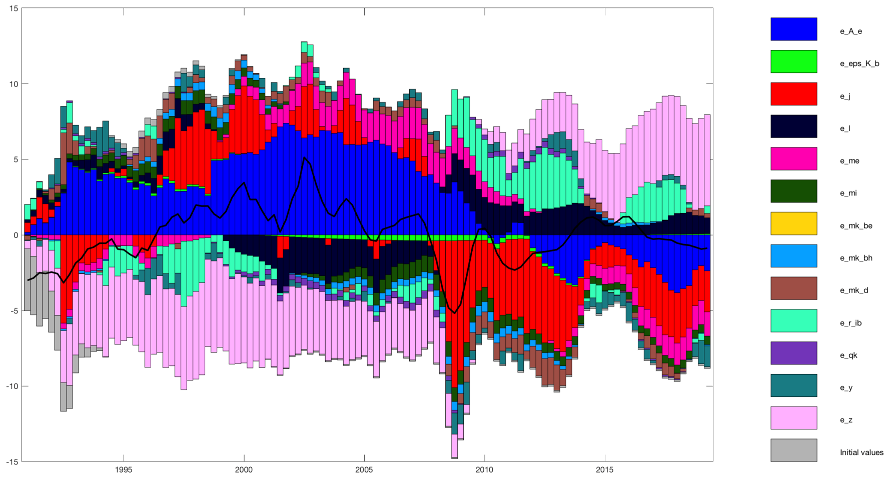
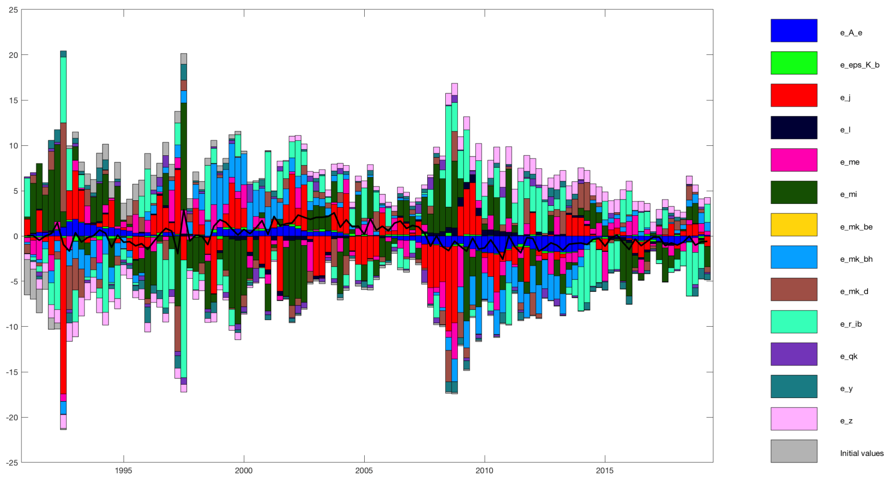


Fig. B.4 Historical Shock Decomposition: Households' Loans Growth



B.4 Additional Results

B.4.1 IRFs to a Positive TFP Shock

Fig. B.5 IRFs to a Positive TFP Shock

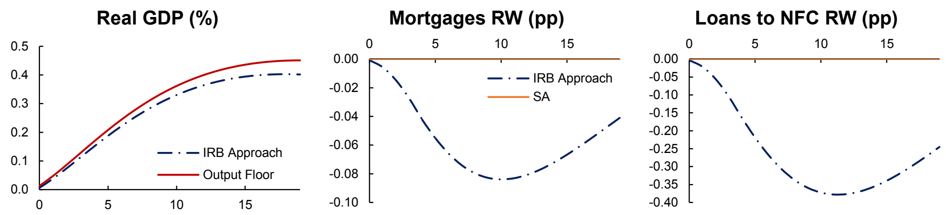


Figure B.5 shows the responses to a positive technology shock of GDP and risk weights. We can notice that under the IRB approach, risk weights decline in response of the increase of the real GDP. This generates downward pressures to the RWA.

Fig. B.6 Risk-Weights Gap (SA vs IRB) During the Positive TFP Shock

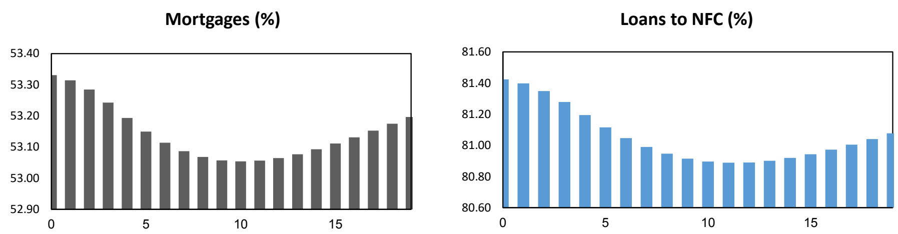


Figure B.6 plots the gap between the IRB and the SA risk weights - $100*\left(\frac{w^{k,IRB}}{w^{k,SA}}\right)$ – with $k \in \{H, E\}$ after the TFP shock. During the simulation period, the modelled risk-weight for mortgages is, on average, 53% of the standardised one, while the modelled risk-weight for loans to NFC is, on average, 81% of the standardised one.

Fig. B.7 RWAs: IRB, SA and the Output Floor

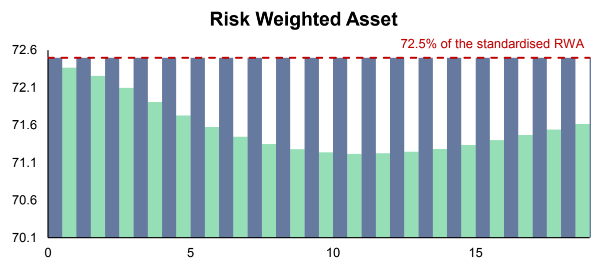


Figure B.7 shows the dynamics of the RWA under the IRB Approach and the Output Floor normalised with respect to the standardised RWA. The Figure shows that the output floor is binding over during the all periods of the simulation.

B.4.2 IRFs to a Negative Monetary Policy Shock

Fig. B.8 IRFs to a Negative Monetary Shock

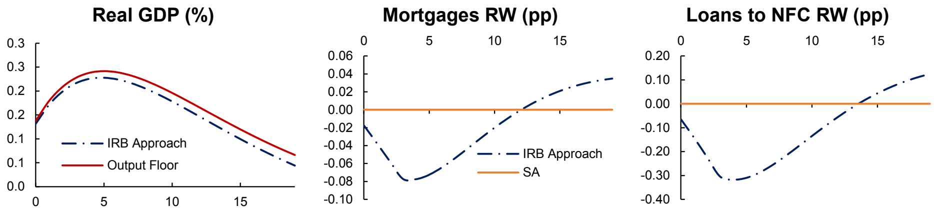


Figure B.8 shows the responses to a negative monetary policy shock of GDP and risk weights. Under the IRB approach, risk weights initially decline in response of the increase of the real GDP, generating a reduction in the RWA. In these initial periods the output floor is binding. Around period 13, the response of the risk weights turns to be positive and the output floor to be slack.

Fig. B.9 RWA Response to MP Shock: IRB, SA and the Output Floor

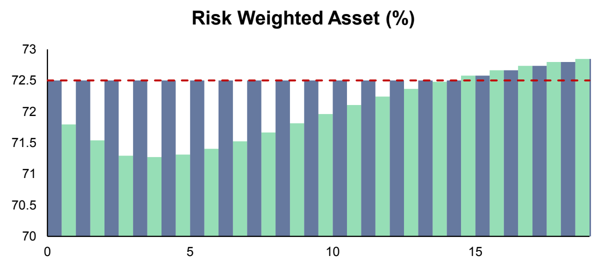


Figure B.9 shows the RWA response to a monetary policy shock under the IRB Approach and the Output Floor. Both RWA values are normalised with respect to the standardised RWA. The Figure shows that the output floor is binding when the monetary policy stimulus is implemented. However, after period 15, the RWA calculated under the IRB Approach starts to be larger than the 72.5% of standardised value and the output floor becomes slack.

Appendix C

C.1 The Holden News Shock Method

The solutions method of a model with ZLB is illustrated as follows:

- The monetary authority sets the gross nominal interest rate $R_t = exp(r_t)$ according to the Taylor-type rule:

$$R_t = R^{1-\rho_r} R_{t-1}^{\rho_r} \left[\left(\frac{\Pi_t}{\Pi} \right)^{\phi_\pi} \left(\frac{Y_t}{Y} \right)^{\phi_y} \right]^{1-\rho_r} m_t \tag{C.1.1}$$

- The ZLB implies that the interest rate $r_t \geq 0$ and C.1.1 can be rewritten as:

$$r_t \equiv \begin{cases} z_t & \text{, when } z_t \geq 0 \text{ zero bound not binding} \\ 0 & \text{, otherwise zero bound binding} \end{cases} \tag{C.1.2}$$

  where $z_t = logZ_t$

$$Z_t = R^{1-\rho_r} R_{t-1}^{\rho_r} \left[\left(\frac{\Pi_t}{\Pi} \right)^{\phi_\pi} \left(\frac{Y_t}{Y} \right)^{\phi_y} \right]^{1-\rho_r} m_t \tag{C.1.3}$$

  where r_t is the nominal interest rate which is set as monetary policy and constrained by the ZLB while z_t represents the shadow interest rate. When monetary authority observes that z_t becomes negative, it will set the nominal interest rate to zero.

- The Holden approach[1] algorithm is based on a fast and well-behaved perfect foresight solver. Although, as a whole, the algorithm is not a perfect foresight one. Such that,

[1] See Holden and Swarbrick (2018) for details.

implementing the ZLB under perfect foresight involves ensuring that $r_t = 0$ during periods when the shadow interest rate z_t falls below and otherwise keeping $r_t = z_t$. Meanwhile, the Holden method endogenously determines when the constraint will bind by introducing an anticipated *news shock* that hit the interest rate when otherwise it would violate the constraint. Hence, pushing the nominal interest rate back to zero.

- To illustrate further, let's consider the basic IRF algorithm with a single bound. Consider a model of variable $x_t = \in \mathbb{R}^n$ with equations all linear except one which is of the form:

$$x_{1,t} = max\{0, \mu_1 + A_1(x_{t-1} - \mu) + B_1(x_t - \mu) + C_1\mathbb{E}_t(x_{t+1} - \mu)\} \tag{C.1.4}$$

where $x_{1,t}$ is the first element of x_t and $\mu = \mathbb{R}^n$ are steady state values and with $\mu_1 > 0$.

- Now, let us consider a shock that causes the bound to be violated.

- Ignoring the bound, we let $q \in \mathbb{R}^T$ be a column vector containing the impulse response of variable x_1 to the shock up to horizon T. $x_0 \in \mathbb{R}^n$ given, assume $x_t \to \mu$ as $t \to \infty$.

  where x_t is an nx1 vector of variables, μ a nx1 vector of steady state values, q is a Tx1 vector with IRF of variable x_1 to the shock up to the horizon T.

- When the constraint is violated, we want an anticipated news shock to return the variable to the bound. We first replace the non-linear condition with one of the form:

$$x_{1,t} = \mu_1 + A_1(x_{t-1} - \mu) + B_1(x_t - \mu) + C_1\mathbb{E}_t(x_{t+1} - \mu) + y_{1,t-1} \tag{C.1.5}$$

$y_{i,t}$ is a news shock known at period i to hit at period $i + t$ that will push the variable $x_{1,t}$ to the bound. The goal of the algorithm is to compute the value of these necessary to impose the bound. $y = [y_{1,1}y_{1,2}...y_{1,T}]'$ is a vector of news shocks up to horizon T.

- We exploit the fact that in a linear model, the IRF to a linear combination of shocks is equal to the same linear combination of each shock's IRF. Let's first compute the path of x_1, t for some arbitrary vector $y_0 \in \mathbb{R}^T$.

- Let $m_k \in \mathbb{R}^T$ be a column vector with impulse response $x_{1,t}$ to a news shock of size 1 at period k with $x_0 = \mu$, and let

$$M \equiv \Big[m_1m_2...m_T\Big] \tag{C.1.6}$$

- It follows that the path of $x_{1,t}$ is given by:

$$My_0 \tag{C.1.7}$$

- The path of $x_{1,t}$ given the original shock with addition of arbitrary news shock vector y_0 is

$$q + My_0 \tag{C.1.8}$$

  where q is a Tx1 vector with IRF of variable x_1 to the shock up to horizon T, $y = [y_{1,1}y_{1,2}...y_{1,T}]'$ is a vector of news shocks up to horizon T,m_k is a Tx1 vector with IRF of $x_{1,t}$ to news shock at period k, $M = \left[m_1 m_2 ... m_T\right]$ is a TxT matrix.

- We want to compute the vector of shocks $y \in \mathbb{R}^T$ to impose the bound:

$$x_1 = q + My \geq 0 \tag{C.1.9}$$

- So that the news shock are only used to imposed the bound:

$$y(q + My) = 0 \tag{C.1.10}$$

$$y \geq 0 \tag{C.1.11}$$

- For a given q and M, the news shock problem is characterised as a linear complementarity problem, $LCP(q, M)$, to find y subject to equations C.1.9, C.1.10, and C.1.11.

- DynareOBC represents $LCP(q, M)$ as a mixed integer linear programming problem. By default, DynareOBC looks for solution with T=0, then a solution with T=1, then T=2, and so on. The terminal condition implies agents believe the economy will return to a given (locally determinate) steady-state. In ZLB model, this is equivalent to assuming that the long-run inflation target is credible.

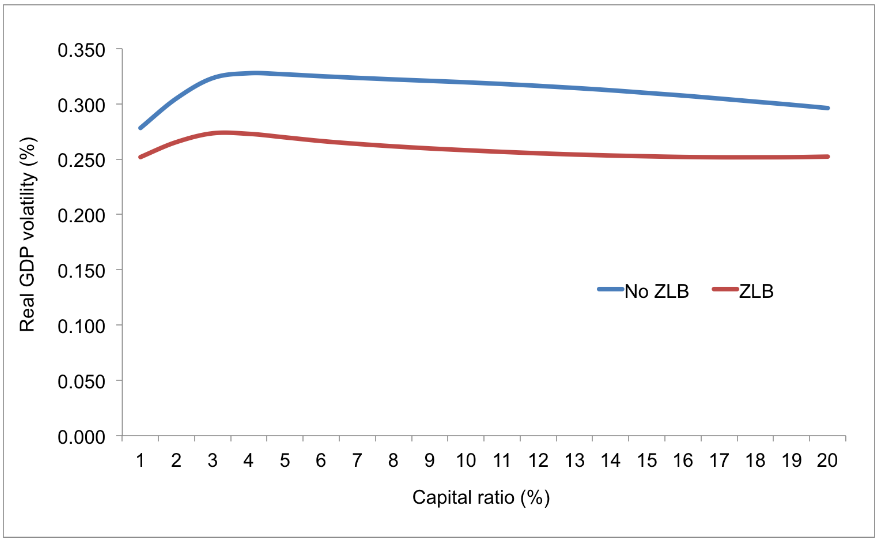
- The approach generalises to higher order pruned perturbation approximation using approach in Lan and Meyer-Gohde (2013) where a d-order pruned perturbation approximation is linear in shocks to power of d, so additive effects of shocks maintain y^d. It also implied closed form covariance matrix which will be useful for integration. The algorithm also extends to an extended-path type simulation. Every period, we solve for the extended future path of the economy ignoring the constraint. This takes place in q.

Under perfect-foresight, we need to find y to impose the bound. To evaluate uncertainty, the algorithm follow the stochastic extended-path method and integrate S periods to determine expected path of the news shocks, y, and bounded variables.

- Now that we are working with a pruned perturbation approximation to the model means that we can make the process of integrating over future uncertainty drastically simpler. In particular, due to some nice properties of pruned perturbation solutions, it is possible to derive a closed-form formula for the covariance of the expected future path of the bounded variables in the absence of the bound. Using this, we can take a Gaussian approximation to the future distribution of the bounded variables in the absence of the bound, and then integrate over this distribution using Gaussian cubature techniques. In this way, we just have to solve the perfect foresight problem a number of times that is polynomial in the periods of uncertainty, independent of the number of shocks.
- This means that we can readily integrate over many periods of uncertainty, with minimal computational cost. Additionally, providing we are taking a higher order perturbation approximation, we are capturing the effects of even long run risk not stemming from the bound for free.

C.2 Additional Results

Fig. C.1 Volatility of Real GDP and Capital Requirements



Simulation results having all shocks active.