Essays on Monetary Economics and Financial Stability

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This dissertation is dedicated to my mother, Cornelia.

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Abstract

This dissertation consists of three chapters related to questions in monetary economics and financial stability. In the first chapter I develop a simple model of financial crises in which the key externalities are overinvestment ex ante and asset price deflation during the crisis. Constrained efficiency can be achieved through a capital tax before the crisis and through a subsidy on asset purchases during the crisis. In the second chapter I study the interaction of macropudential and monetary policy. I develop a New Keynesian DSGE model in which banks can fund their risky investment activities either with non-state-contingent debt or with state-contingent outside equity. In the third chapter, I revisit the effects of monetary policy shocks in the context of a time-varying coefficients VAR model. Conditional on a recursive identification scheme the effects of monetary policy shocks on output and prices have become weaker from around 1980 to 2010.

Resum

Aquesta tesi consta de tres capítols relacionats amb qüestions d'economia monetària i estabilitat financera. En el primer capítol es desenvolupa un model senzill de crisi financera en qual les principals externalitats son la sobreinversiò ex ante i la deflaciò dels preus dels actius durant la crisi. L'eficiència restringida es pot aconseguir a través d'un impost de capital abans de la crisi i a través d'una subvenciò sobre la compra d'actius durant la crisi. En el segon capítol sestudia la interacciò de la politica macroprudencial i monetària. Es desenvolupa un nou model keynesià de DSGE en qual els bancs poden finançar les seves activitats d'inversiò amb risc, ja sigui amb deute o amb capital. En el tercer capítol, es revisen els efectes derivats dels xocs en la poltica monetària en el context d'un model VAR amb variables canviants al llarg del tempss. Els efectes d'un xoc en la política monetària sobre la producciò i els preus s'han tornat mes febles des de 1980 finsa 2010, sota les condicions dun règim d'identificaciò recursiva.

Preface

It is now widely accepted among researchers and policy makers that financial stability considerations and macroprudential regulation should play a bigger role in the economic policy mix. The overarching objective of my research is to contribute to the efforts in macroeconomics to develop and empirically assess models that improve our understanding of how macroprudential policy functions, which externalities it should address and how it may affect the transmission of monetary policy.

Like many others, I believe that we need a greater diversification of macroeconomic models in order to adequately address various policy questions. Future models of macroeconomic fluctuations should still be dynamic (D), stochastic (S), and account for general equilibrium (GE) effects. However, it is important that DSGE models evolve. Among other things, future models have to take into account hysteresis effects; they have to account better for agent heterogeneity; allow for non-rational and myopic alternatives regarding the modelling of expectation formation; move away from the assumption of a unique steady state and allow for multiple equilibria. Moreover, DSGE models of financial crises and macroprudential policy interventions should capture the non-linearities and asymmetries associated with financial crises. In my dissertation I touch upon some of these issues, in particular the last point which is associated with non-linearities, risk and asymmetries. A second leitmotif of this dissertation is the attempt to explicitly model financial externalities that warrant macroprudential policy interventions in order to improve our understanding of existing inefficiencies in the economy and in order to assess potential remedies. Chapter 1 and Chapter 2 were written in this spirit. A third recurring theme in this dissertation is the changing role of monetary transmission and its complex interaction with the recently established field of macroprudential policy. I touch upon these issues in Chapter 2 and in Chapter 3.

In Chapter 1 of this dissertation, I develop a simple model of financial crises in which the key externalities are overinvestment ex ante and asset price deflation during the crisis. I demonstrate that a Pareto planner can achieve constrained efficiency through a capital tax before the crisis and through a subsidy on asset purchases during the crisis. The ex ante intervention can be interpreted as a macroprudential intervention. I then develop a quantitative version of the simple model in which financial crisis events arise endogenously through occasionally binding leverage constraints. I show that non-linear crisis events can occur out of prolonged boom periods and that they can be triggered by moderately adverse shocks.

In Chapter 2 I ask whether the presence of macropudential policy affects how monetary policy should be conducted. To that end, I develop a New Keynesian DSGE model in which banks can fund their risky investment activities either with non-state-contingent debt or with state-contingent outside equity. Macroprudential policy can improve welfare through incentivising banks to increase their equity-to-assets ratio. In the context of this model, I analyse to what extent the presence of macroprudential policy alters the normative prescriptions of monetary policy. I show that monetary policy should stick to inflation stabilisation with a conventional degree of inflation sensitivity. Only in the absence of macroprudential policy and in an environment in which banks are highly leveraged should monetary policy respond to inflation more aggressively.

In Chapter 3 I revisit the effects of monetary policy shocks in the context of a time-varying coefficients version of the canonical structural VAR model in the spirit of Christiano et al. (1999). Conditional on a recursive identification scheme, I confirm the findings that since 1980 monetary policy shocks have had a smaller impact on output and prices. I show that this trend ends around 2010 and that since then the impact of monetary policy shocks has hardly changed. This is interesting to the extent that one might have expected that between 2009 and 2015, when the ZLB was binding and a new comprehensive macroprudential policy framework was established, structural changes in the economy would have altered the impact of monetary policy shocks.

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Chapter 1

OVERINVESTMENT, FINANCIAL CRISES AND POLICY

1.1 Introduction

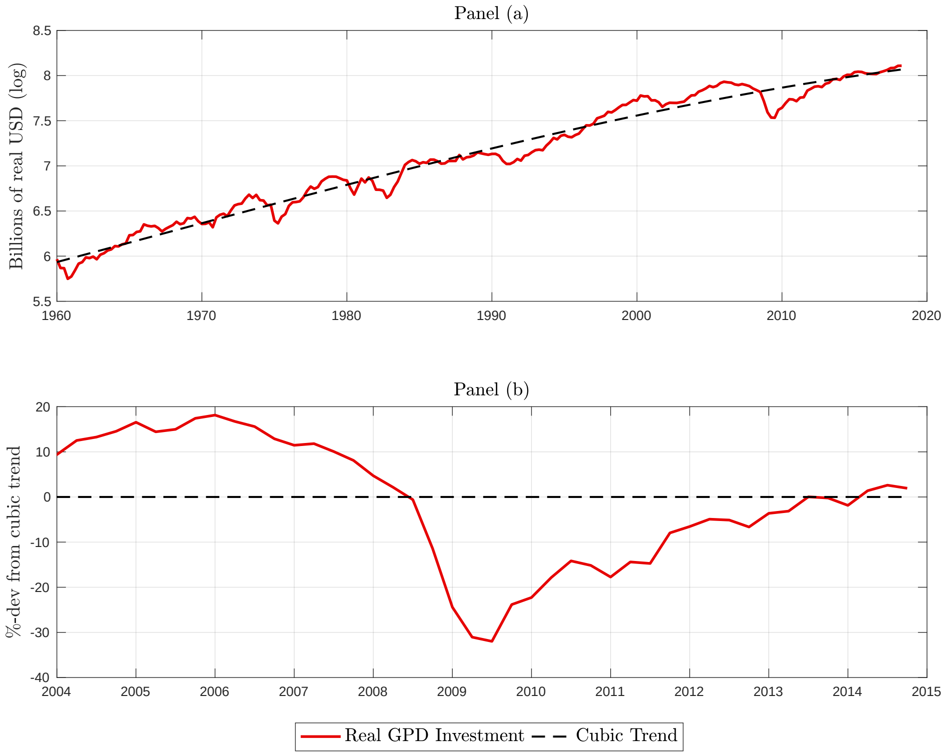
In the aftermath of the financial crisis of 2008, a new consensus regarding the macroeconomic policy mix has emerged among policy makers and academics. It is now widely accepted that the pursuit of price and output stability via monetary policy and the soundness of individual financial institutions via microprudential policies is insufficient to guarantee financial stability. As a consequence, 'macroprudential' policies have been added to the macroeconomic policy frameworks around the world. Macroprudential policy has the explicit and primary aim of stabilising 'the financial system as a whole'. Its purpose is to prevent the build-up and materialisation of systemic risk, to reduce the probability of a financial crisis and mitigate its costs if it occurs.

The key objective of this paper is to contribute to the recent efforts in macroeconomics to develop models that improve our understanding of how macroprudential policy functions, which externalities it should address and how it is related to conventional and unconventional monetary policy. In my paper I put forward a novel framework that relates to these questions. The key insight of my paper is as follows. There is a close relation between investment and collateral since investment affects the stock of capital goods and their price. The value of collateral is crucial since it allows entrepreneurs in the economy to borrow and intermediate funds to the productive sector. Atomistic agents in my model economy ignore the effects of their investment decisions on asset prices and hence on collateral. The resulting pecuniary externality provides a motivation for the regulation of investment and asset purchases ex ante and ex post. Thus, the link between investment and collateral introduces a role for macroprudential policy and crisis interventions.

The key contribution of this paper is twofold. First, I show that standard macro-modelling assumptions on capital adjustment costs and collateral constraints give rise to pecuniary externalities associated with overinvestment before the crisis and a shortfall of investment during the crisis. Second, I embed this mechanism into a non-linear DSGE model and I show that it can replicate empirically observed crisis patterns well.

In the analysis of fluctuations of aggregate economic variables, investment dynamics play an important role. One distinguishing property of investment is the magnitude of its fluctuations and the degree to which it can deviate from its trend. In Figure 1.1 I plot the real US gross private domestic investment series and the corresponding cubic trend. It can be seen that in the years prior to the financial crisis of 2008 investment levels were elevated and deviated by more than 10% from the trend.[1] At the trough of the recession in 2009 investment was more than 30% below the cubic trend and it has since recovered rather slowly.

FIGURE 1.1: US REAL GROSS PRIVATE DOMESTIC INVESTMENT



Source: FRED

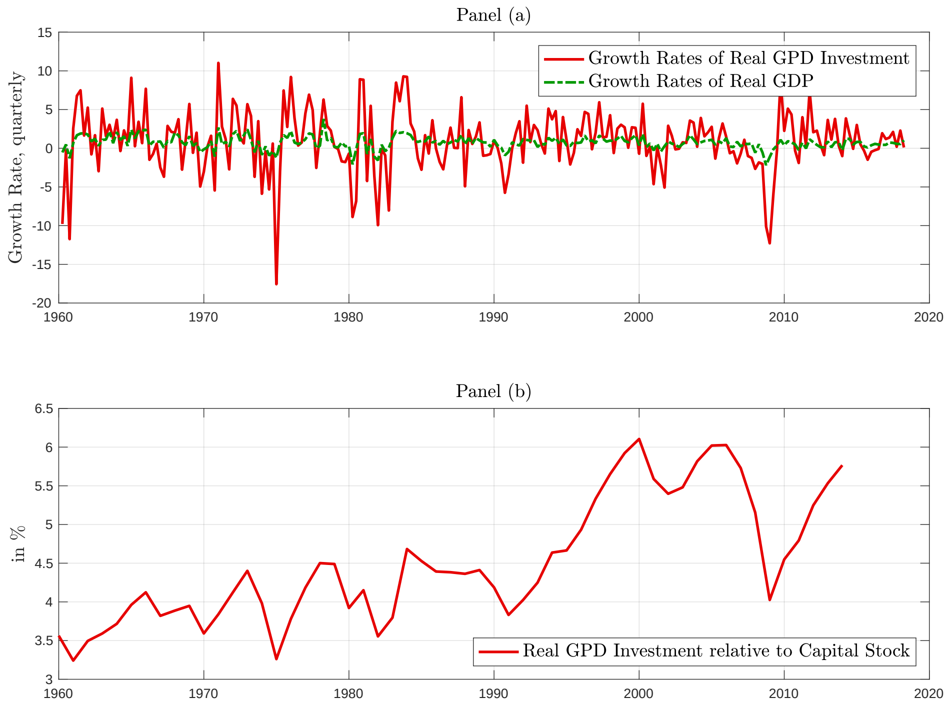
Note: Panel (a) depicts the US real Gross Private Domestic (GPD) Investment series (GPDIC1) in billions of chained dollars, quarterly and seasonally adjusted. Panel (b) depicts the deviation of investment from its cubic trend 20 quarters before and after the trough of the Great Recession in 2009Q2.

Compared to other variables such as consumption and output, investment is highly volatile. In Figure 1.2, in the upper panel, one can see the quarterly growth rates of real gross private domestic investment and real GDP in the US. The volatility of the growth rate of investment significantly exceeds its output growth counterpart. Moreover, as can be inferred from the lower panel in Figure 1.2, investment relative to the capital stock has fluctuated considerably since 1990.

Investment is not only unique due to its comparatively high volatility, but also because of the role it has played in the debate on what drives macroeconomic fluctuations and boom-bust patterns associated with financial crises. Some schools of economic thought have attributed a prominent role to overinvestment in the run-up to recessions. According to this view excessive and inefficient investment activity is fuelled by an environment of abundant

[1] In the Appendix, in Section 1.5.1 I also show the patterns for an alternative measure of investment, the real gross fixed formation of capital. The results are very similar.

FIGURE 1.2: INVESTMENT VOLATILITY RELATIVE TO OUTPUT AND THE CAPITAL STOCK



Source: FRED

Notes: Panel (a) depicts the quarterly growth rates of real GPD Investment and real GDP in the US. Investment is much more volatile than output. Panel (b) depicts real GPD Investment as a share of the capital stock. This ratio has been quite unstable since 1990. It is also noteworthy that investment relative to the capital stock was elevated in the years prior to crisis.

credit and low interest rates and will ultimately trigger a 'necessary correction' and result in a contraction of economic activity. This Hayekian perspective on economic fluctuations would, if anything, warrant a reduction of investment levels. Others have argued that persistent shortfalls of aggregate demand, also in the form of low investment, could harm the productive capacity and the supply side of the economy. Against this background, some policymakers in the industrialised world have called for increasing current levels of investment.

While there have been several recent attempts to explain the empirically observed investment patterns, relatively little attention has been devoted to the normative question on whether the observed investment dynamics are optimal, whether there could be too much or too little investment, and whether the government should intervene. There are very few frameworks that allow us to think about the consequences of investment externalities for asset prices and financial stability. In this paper I put forward one reason why there might be overinvestment ex ante, and a shortfall of investment during a financial crisis and hence why the government would have a role in stabilising investment over the financial cycle in order to promote financial stability.

I study a setting in which conventional macro-modelling assumptions on capital adjustment costs give rise to an asset price that is negatively correlated with previous-period capital. Since this asset price is a component of leverage, and since atomistic agents who are subject to leverage constraints ignore the effects their individual investment decisions have on this asset price, a situation may arise in which the privately optimal level of investment ex ante exceeds the social optimum. Once leverage constraints become binding, entrepreneurs are constrained in their ability to obtain funds and they reduce their investment demand below the social optimum. Thus, a key insight of the model is that there can be overinvestment in periods of loose credit before the crisis breaks out, and a shortfall of investment in periods of tight credit conditions.

I reach this conclusion in the context of a simple model with entrepreneurs and savers. Entrepreneurs raise funds from savers to invest in capital. They are subject to a leverage constraint. Since this constraint is not always binding my model is useful to study both tranquil times and times of financial crises. In the model investment and capital levels affect the price of capital. High levels of ex ante investment tend to depress asset prices ex post and this in turn may tighten the leverage constraint and give rise to a financial crisis. Hence, an investment boom can be followed by low asset prices and a contraction of economic activity. There is room for a policy intervention because atomistic agents do not internalise the effects of their individual investment decisions on asset prices and hence on the leverage constraint. A policy maker can tax and subsidise investment decisions such that the private and social benefits of investment coincide. This will require reducing investment ex ante and increasing it in times of crises.

In my paper, I first develop the above described mechanism in the context of a simple 3-period model. Since such a simplistic and highly stylised model would not be suitable for a comparison with the data and sophisticated policy analyses, I embed the main mechanism into a non-linear New Keynesian DSGE model. I show that this model can match some empirical patterns associated with the recent financial crisis well. The model can generate realistic crisis patterns in a somewhat endogenous manner. A sequence of initially positive and then modestly adverse shocks can trigger highly non-linear boom-bust patterns. The same shock sequence would not trigger a crisis if leverage was lower. In this respect the crisis in the model is endogenous. I then use the New Keynesian DSGE model for policy analysis and show that a simple rule for macroprudential policy and crisis interventions motivated by the findings of the 3-period model is associated with small positive welfare gains.

The remainder of the paper is organised as follows. The next subsection describes the relevant literature and how this paper is related to it. In Section 1.2 I develop a baseline model which illustrates the relevant externalities and policy mechanisms. In Section 2.2 I outline the more realistic dynamic stochastic general equilibrium (DSGE) model and its non-linear properties, its empirical performance and its policy implications in detail. Section 2.4 contains concluding remarks.

1.1.1 Related Literature

My paper is primarily related to two strands of literature. First, there is a recent[2] literature on the role of investment during and after the financial crisis of 2008. Second, there is a literature on modelling financial crises and policy interventions in the context of macro-financial models with pecuniary externalities and collateral constraints.

Beaudry et al. (2018) re-assess the Hayekian hypothesis that recessions often reflect periods of necessary liquidation resulting from past overinvestment. The authors document that in the post-war period US recessions have generally been more severe and longer when they have been preceded by periods of high accumulation of physical capital goods, durable goods and housing. Their model illustrates why liquidations likely cause recessions char-

[2]In this literature review I only focus on the recent strand of literature on investment dynamics. Of course the debate on the nature of investment and its role for business cycle fluctuations dates back to the 1930s and was a key element of the subsequent controversies among Keynesians and Hayekians. Seminal contributions in the literature on investment dynamics were made by Samuelson (1939), Kaldor (1966), Brainard and Tobin (1977), Hayashi (1982) Bernanke (1983), Greenwood et al. (1988), Greenwood and Hercowitz (1991), Blanchard et al. (1993) and Caballero et al. (1995).

acterised by deficient aggregate demand and accordingly suggests that the Keynesian and the Hayekian view of recessions may in fact be closely linked. In Beaudry et al. (2018), aggregate demand affects employment due to a matching friction in the labor market. This study relates to my paper in that it stresses the potential for too much investment ex ante and a shortfall of investment during the crisis. In contrast to my mechanism, their model does not rely on the relation between investment, asset prices and collateral.

In a recent series of papers Gutierrez and Philippon (2016) and Gutierrez and Philippon (2017) conduct an empirical investigation of investment dynamics and analyse private fixed investment in the U.S. over the past 30 years. The authors argue that investment is weak since the early 2000's relative to measures of profitability and valuation, such as Tobin's Q, and that this weakness can be attributed to decreased competition, tightened governance and increased short-termist pressures.

On the other hand, studies such as Rognlie et al. (2018) have argued that there was an investment boom in the US housing market in addition to a price boom, which led to an overbuilding of housing capital by 2005. According to their model the excess build-up of a large capital stock substitutes for new investment so that there will be a shortfall of investment during the crisis. If monetary policy cannot respond sufficiently to this decline of aggregate demand then overbuilding of capital can lead to severe demand-driven recessions. The potential for welfare improvements through the ex ante restriction and ex post stimulation of certain types of investment is a key feature of their paper.

The notion that a policy maker should reduce investment and borrowing ex ante is also a key feature of the seminal paper by Lorenzoni (2008). His paper constitutes an important link between the above described recent strand of literature on investment dynamics and the literature on collateral constraints and pecuniary externalities.[3] While my paper shares this connective property there are also some important differences. Lorenzoni (2008) studies the welfare properties of competitive equilibria in an economy with financial frictions hit by aggregate shocks. The model developed in Lorenzoni (2008) is highly stylised and it is not accompanied by a quantitative version in contrast to my paper. The pecuniary externality in his model is the result of a combination of limited commitment in financial contracts and the fact that asset prices are determined in a spot market. A key difference[4] between the model developed in Lorenzoni (2008) and my model is that the inefficiency in his model is not due to the fact that asset prices affect the collateral value. In Lorenzoni (2008) asset prices matter since they determine the asset side of the entrepreneurs balance sheets, not because of their effects on their capacity to borrow. In accordance with my model, Lorenzoni (2008) makes the case for an ex ante intervention to reduce borrowing and therefore also investment. In contrast to Lorenzoni (2008), my model implies that the ex ante intervention has to be accompanied by a crisis intervention as well.

Early macroeconomic models with financial frictions, such as the models by Bernanke and Gertler (1989) and Kiyotaki and Moore (1997) focused on the quantitative implications of the financial accelerator mechanism by studying how the presence of borrowing and working capital constraints amplifies the local response of the economy to shocks around a deterministic steady state. My paper is related to recent contributions that have stressed the importance of non-linearities in the response of the economy to shocks that affect the balance sheet positions of borrowing constrained agents. Notable examples would be Men-

[3]Other important papers that link these two strands are Shleifer and Vishny (1988), Hart and Zingales (2015) and He and Kondor (2016). There is also a connection to Iacoviello and Pavan (2013) who emphasise the collateral channel by which house price shocks tighten household borrowing constraints.

[4]Moreover, asset prices are introduced in a different manner in Lorenzoni (2008). Whereas asset prices in my model are introduced through capital adjustment costs, Lorenzoni (2008) introduces asset prices through capital demand by households. He assumes that households run a 'firm in the traditional sector'. Thus, in contrast to my model, Lorenzoni (2008) does not assume 'limited market participation'. In crisis situations, when entrepreneurs are financially constrained, they sell capital to households.

doza (2010)[5], Bianchi (2011)[6] and Bianchi and Mendoza (2018)[7]. My paper is different from Mendoza (2010), Bianchi (2011) and Bianchi and Mendoza (2018) in several respects. In my paper I study policy interventions in the context of a closed-economy model with nominal rigidities. The key motivation for an ex ante macroprudential intervention in my model is an overinvestment externality which is not present in the models by Mendoza and Bianchi since they abstract from capital accumulation[8] and capital adjustment costs. Further examples of papers in which non-linearities are explicitly introduced are He and Krishnamurthy (2013)[9], Prestipino (2014)[10], Brunnermeier and Sannikov (2014)[11], Fornaro (2015)[12] and Paul (2017)[13]. Other notable studies in that field are Davila and Korinek (2018), Benigno et al. (2016), Jeanne and Korinek (2016).

1.2 Baseline Model

In this section I develop a baseline 3-period model that illustrates the key messages of the paper. The intuition derived from the simple model can be applied to the dynamic stochastic general equilibrium (DSGE) version developed in Section 2.2 of this paper. The model is populated by representative entrepreneurs and savers. Entrepreneurs consume, run firms and invest in capital. Savers consume and save. The key state variable in the baseline model is the initial level of debt $b_1 < 0$. The initial level of debt of the entrepreneur will be matched by the initial bond-holdings of the saver $b_{1,s} > 0$. If the entrepreneur initially has a high level of debt, then the saver has to have a high level of initial savings, $b_1 = -b_{1,s}$.[14] Time t is discrete and in the baseline model I consider only three periods of time $t \in \{1,2,3\}$. There is

[5]Mendoza (2010) develops a real business cycle model with an occasionally binding collateral constraint that explains financial crashes after a sudden stop as a result of the amplification and asymmetry that the constraint induces in the responses of macro-aggregates to shocks. The Mendoza (2010) model is a small open economy model which primarily tries to account for the business cycle and crisis dynamics in emerging economies.

[6]Bianchi (2011) sets up an open economy model that is similar to Mendoza (2010) with respect to the debt deflation mechanism and the pecuniary externality. Like Mendoza (2010) Bianchi's model is tailored to match emerging economy properties. He compares the competitive with the social planner equilibrium allocation.

[7]Bianchi and Mendoza (2018) develop a real small open-economy model similar to Mendoza (2010). They show that agents in a competitive equilibrium borrow more than a financial regulator who internalises the pecuniary externality. Under commitment the regulator's plans are time-inconsistent, hence Bianchi and Mendoza (2018) focus on studying optimal, time-consistent policy without commitment.

[8]A fixed supply of capital is also assumed in Iacoviello et al. (2016). The paper introduces a 3-period model similar to mine. However, the authors do not establish a connection between investment and collateral since they abstract from capital accumulation and adjustment costs.

[9]He and Krishnamurthy (2013) find that injecting equity capital is the most effective policy intervention to counteract the adverse effects of financial stress because it alleviates the equity capital constraint that drives the model's crises. This finding is similar to the second component of the optimal policy in my model.

[10]Prestipino (2014) develops a real, quantitative, closed-economy model with a simple form of agent heterogeneity and endogenously determined balance sheet constraints on financial intermediaries very much in the spirit of He and Krishnamurthy (2013) and Brunnermeier and Sannikov (2014). Prestipino solves for the constrained efficient allocation and finds that the simple rule for credit market intervention achieves welfare gains that are close to those in the constrained efficient allocation. In Prestipino (2014) the optimal ex ante policy would warrant a subsidy on investment while the optimal crisis intervention would call for a tax. One key difference with regard to my model is that Prestipino (2014) relies on an incentive compatibility constraint instead of a borrowing constraint. One key determinant of this incentive compatibility constraint is the value of autarky that the banker enjoys when diverting funds. Since this value of autarky rises when asset prices are high, the constraint could be relaxed by reducing the asset price in crisis.

[11]Brunnermeier and Sannikov (2014) use continuous-time methodology to sharply characterise the non-linearities of models with occasionally binding constraints. A major contribution of the paper by Brunnermeier and Sannikov is the introduction of the volatility paradox: the idea that the financial system is prone to crises even if exogenous risk is low.

[12]The trade-off between financial stabilisation policies and monetary policy in the form of exchange rate policy is studied in the context of models with occasionally binding constraints by Fornaro (2015) and Ottonello (2015). Fornaro (2015) develops a small open economy model with wage stickiness and occasionally binding collateral constraints in order to study the welfare effects of different policy regimes during a financial crisis. Since he assumes a fixed supply of capital and disregards investment, the nature of the pecuniary externality is different from the one in my paper.

[13]Paul (2017) develops a closed-economy non-linear DSGE model which includes financial intermediation and endogenous financial crises. In his model, financial crises occur out of prolonged boom periods and are initiated by moderately adverse shocks. The mechanism which gives rise to boom-bust episodes around financial crises is based on an interaction between the maturity mismatch of the financial sector and an agency problem which results in pro-cyclical lending. My paper is different from Paul (2017) with regard to the endogenous crisis mechanism and the policy analysis.

[14]Following notational conventions I denote debt with negative values of $b_1 < 0$.

no uncertainty[15] in the baseline model. I will use lower-case letters to denote quantities of goods or debt held by an individual entrepreneurs or saver. Upper-case letters will be used to denote aggregate quantities, prices and interest rates.

1.2.1 Savers

There is a continuum of households who consume, supply labor inelastically ($l = 1$) and save. Henceforth these agents will be referred to as savers and their choice variables will contain a subscript s to distinguish them from entrepreneurial choice variables. In addition to earning a labor income savers start with an initial bond endowment $b_{1,s} > 0$ in period $t = 1$. Thus, their disposable income exceeds the initial consumption desire. Therefore they will attempt to smooth their consumption and save some of their excess resources from period $t = 1$. The only way for them to save is to purchase real non-state-contingent bonds issued by entrepreneurs. Savers maximise life-time utility

$$\max_{c_{1,s},c_{2,s},c_{3,s},b_{2,s},b_{3,s}} \left\{ \log(c_{1,s}) + \beta_s \left(\log(c_{2,s})\right) + \beta_s^2 \left(\log(c_{3,s})\right) \right\}$$

subject to their period budget constraints

$$(\lambda_{t,s}): \qquad c_{t,s} + b_{t+1,s} \quad \leq \quad W_t + R_{t-1} b_{t,s}, \qquad t = \{1,2,3\} \tag{1.2.1}$$

where $c_{t,s}$ denotes the period t level of consumption and $b_{t+1,s} > 0$ denotes the purchased amount of real non-state-contingent bonds. After having purchased an amount of bonds $b_{t,s} > 0$ in period $t-1$, the saver earns a real gross return R_{t-1} in period t on these bonds. In period $t = 3$, the simple model economy ends and there will be no bond purchases $b_{4,s} = 0$. $\lambda_{t,s}$ denotes the Langrange multipliers attached to each period budget constraint. W_t refers to the wage. Solving the optimisation problem of savers delivers the standard Euler equations

$$\frac{1}{c_{t,s}} \quad = \quad \beta_s R_t \left[\frac{1}{c_{t+1,s}} \right], \qquad t = \{1,2\} \tag{1.2.2}$$

which describe the optimal inter-temporal trade-off between deriving utility from consuming in the current period or postponing consumption to save, earn interest and to derive utility from next period's discounted consumption.

1.2.2 Entrepreneurs

There is a continuum of households who consume, run firms and purchase claims on capital. Since they run firms they will henceforth be referred to as entrepreneurs. They enter period $t = 1$ with initial debt $b_1 < 0$, which induces them to borrow in order to consume and conduct their entrepreneurial activities. Another way to interpret the role of entrepreneurs is to think of them as financial intermediaries who have superior monitoring and asset management skills and therefore borrow from savers and channel the funds to the productive sector.[16] Entrepreneurs maximise life-time utility subject to their period $t = \{1,2,3\}$ budget

[15] I focus on analysing policy functions in the state space of the initial debt level b_1. In principle, several different shocks may then cause the model to enter regions of the debt state space in which leverage is high and crisis events may occur. In the baseline model it is not necessary therefore to have shocks and uncertainty.

[16] Limited market participation implies that in the model savers do not have access to capital markets, their only way to transfer resources from one period to another is to deposit their savings at the entrepreneur / lend to the entrepreneur and earn a return R_t. This assumption captures the idea that entrepreneurs serve as intermediaries who have superior skills in lending to the productive sector and specialise in intermediating assets that cannot be absorbed by other agents in the economy. In the 2007/2008 financial crisis many intermediaries were highly exposed to ABS and suffered severe losses as the fire sales of these assets occurred. Households did not step in this market to purchase these ABS.

constraints.

$$\max_{c_{1,e},c_{2,e},c_{3,e},b_2,b_3,k_2,k_3} \left\{ \log(c_{1,e}) + \beta_e \left(\log(c_{2,e})\right) + \beta_e^2 \left(\log(c_{3,e})\right) \right\}$$

s.t. the standard period budget constraints and the collateral constraint in period $t = 2$,

$$(\lambda_t): \quad c_{t,e} + b_{t+1} + Q_t k_{t+1} \leq \left(\mathcal{R}_t^K + \tilde{Q}_t\right) k_t + R_{t-1} b_t, \quad t = \{1,2,3\} \quad (1.2.3)$$

$$(\mu_t): \quad -b_{t+1} \leq \theta Q_t k_{t+1}, \quad t = 2$$

The Lagrange multipliers on the budget and collateral constraints are λ_t and μ_t. The components of the period budget constraints are (i) consumption, (ii) purchases of claims on capital / returns on these purchases and (iii) borrowing. Each period $t = \{1,2,3\}$, entrepreneurs want to consume $c_{t,e}$ over which they derive log-utility. In the periods $t = 1$ and $t = 2$, entrepreneurs may purchase claims on capital k_{t+1} at price Q_t in the capital market and earn a net return $\mathcal{R}_t^K$ next period. At the end of the period, after production has taken place, entrepreneurs sell the (end-of-period) claim on capital at price $\tilde{Q}_t$ to a capital good producing firm who refurbishes it.

In period $t = 1$ and $t = 2$ entrepreneurs may borrow an amount $b_{t+1} < 0$ through issuing real non-state-contingent bonds to the saver. Next period, in period $t = 2$ and $t = 3$, respectively, entrepreneurs have to pay back the principle plus interest, $R_{t-1} b_t$, for the corresponding amount of borrowing. As stated above, the key state variable of the baseline model is initial debt $b_1 < 0$ in period $t = 1$. Since period $t = 3$ is the last period in this simple 3-period economy, there will be no borrowing in period $t = 3$, so that $b_4 = 0$. Likewise, there will be no purchases of assets in period $t = 3$, so that $Q_3 k_4 = 0$.

Entrepreneurs are subject to a collateral constraint which may restrict the amount of funding they can receive from the saver. The constraint states that the leverage ratio, the amount of debt $-b_{t+1}$ relative to the capital stock $Q_t k_{t+1}$, must not exceed a certain ratio θ. One way to interpret this collateral constraint is that the entrepreneur may be tempted to abscond with the assets funded by the saver. The saver would only be able to recover a certain fraction $(1 - \theta)$ of the capital stock and become its owner. Due to this moral hazard problem, the entrepreneur can only obtain funding from the saver up to a fraction θ of the capital stock in period t[17].

The parameter θ therefore represents the degree of 'collateralisability' of the capital stock. Under the parametrisation I am going to use, the collateral constraint will never bind in the first period $t = 1$. The focus of the analysis will be on the effects of the presence of a time $t = 2$ collateral constraint and its implications for policy in period $t = 1$ and period $t = 2$.[18]

[17] Regarding the timing specification of the borrowing constraint I follow papers from the fire sale and sudden stop literature such as Mendoza (2010) and Fornaro (2015) who have assumed that the relevant asset price in the borrowing constraint is Q_t as opposed to Q_{t+1}. This reflects the underlying assumption that the lender cares about the current price of the collateralised asset and not a future (expected) price. Regulatory instruments such as loan-to-value (LTV) ratios also relate the loan volume to the current price of the corresponding asset (or house). The mechanisms I develop in this paper (involving fire sale and overinvestment externalities) would not be valid if one assumes that Q_{t+1} is the relevant price of collateral.

[18] Since one of the main objectives of this paper is to study macroprudential policy, which is an *ex ante* policy intervention, and since there is no period $t = 0$, there is no point in having a collateral constraint and an asset price in period $t = 1$. It would complicate the analysis without adding much, since the intuition behind the crisis intervention in period $t = 2$ would then also hold in period $t = 1$.

The resulting inter-temporal optimality conditions of entrepreneurs are given by

$$\frac{1}{c_{1,e}} = \beta_e R_1 \left[\frac{1}{c_{2,e}}\right] \quad (1.2.4)$$

$$\frac{1}{c_{2,e}} = \beta_e R_2 \left[\frac{1}{c_{3,e}}\right] + \mu_2 \quad (1.2.5)$$

$$\frac{1}{c_{1,e}} = \beta_e R_2^K \left[\frac{1}{c_{2,e}}\right] \quad (1.2.6)$$

$$\frac{1}{c_{2,e}} = \beta_e R_3^K \left[\frac{1}{c_{3,e}}\right] + \theta\mu_2 \quad (1.2.7)$$

$$-b_3 \leq \theta Q_2 k_3 \quad (1.2.8)$$

where (1.2.8) holds with equality if $\mu_2 \geq 0$ and where I have defined the gross rate of return on purchasing a claim on capital as follows

$$R_t^K \equiv \frac{\mathcal{R}_t^K + \tilde{Q}_t}{Q_{t-1}}. \quad (1.2.9)$$

Inspection of Equations (1.2.4) to (1.2.7) shows that if the collateral constraint binds, $\mu_2 > 0$, there will be a spread in period $t = 2$ between the gross rate of return on capital and the gross real rate of interest $R_3^K - R_2 > 0$.

Note that if the collateral constraint is not binding, a higher price of the capital claim Q_{t-1} will be associated with a lower demand for capital claims.[19] The inverse relationship between Q_{t-1} and K_t constitutes the standard case in which higher prices of the capital claim will be associated with a lower demand for capital claims.

Once the collateral constraint becomes binding the capital demand schedule slopes upward, and increases in asset prices will be associated with increases in capital demand. Higher asset prices relax the collateral constraint 1.2.8 and allow the entrepreneur to borrow more and demand more claims on capital. The implications of the downward and upward sloping demand schedules will be discussed in more detail below.

1.2.3 Firms

There are perfectly competitive final good and capital good producers in this economy. Entrepreneurs own and control both of these firms who operate at zero profit.

1.2.3.1 Competitive Final Good Producer

Final good producing firms produce final output y_t. The production inputs are capital and labor. The cost of production are the factor prices of each input factor, the wage W_t and the rental rate $\mathcal{R}_t^K$. The problem of competitive final good producing firms in period $t = \{1,2,3\}$ is given by

$$\max_{k_t} \left\{ y_t(k_t, 1) - \mathcal{R}_t^K k_t - W_t \right\}$$

where the production functions are given by

$$y_t = k_t^\alpha. \quad (1.2.10)$$

[19]Consider that according to (1.2.9), an increase in Q_{t-1} would have to be offset by an increase in $\mathcal{R}_t^K$, all else equal. This implies that the demand for capital claims will be lower.

It follows that the rental rates of capital are given by

$$\mathcal{R}_t^K = \alpha \frac{y_t}{k_t}. \tag{1.2.11}$$

The labor demand schedules imply that the wage is equal to the marginal product of labor

$$W_t = (1-\alpha) y_t. \tag{1.2.12}$$

1.2.3.2 Competitive Capital Good Producer

Each perfectly competitive capital good producer is owned by an entrepreneur and operates at zero profits. It supplies the capital demanded by entrepreneurs. It does this by purchasing the old capital $\tilde{Q}_t k_t$, refurbishing depreciated capital and conducting investment subject to a convex capital adjustment cost. The timing of the decisions of the capital good producer is illustrated by the following example. At the end of period $t = 1$, after production has taken place, capital good producers purchase capital at price $\tilde{Q}_2$. They will use this in the next period $t = 2$, and conduct investment i_2 through combining the purchased old capital stock with final goods to produce capital which is available for production in period $t = 3$ and which is then sold to the entrepreneur at price Q_2.[20] The problem of the competitive capital good producer in period $t = \{1,2\}$ looks as follows

$$\max_{k_t, k_{t+1}} \left\{ Q_t k_{t+1} - i_t - \tilde{Q}_t k_t \right\}$$

where the investment functions in periods $t = \{1,2\}$ are given by

$$i_t = k_{t+1} - (1-\delta) k_t + \frac{a}{2} \left(\frac{k_{t+1} - k_t}{k_t} \right)^2 k_t \tag{1.2.13}$$

This implies the following firm-level[21] supply schedules of capital in period $t = \{1,2\}$

$$Q_t = 1 + a \left(\frac{k_{t+1} - k_t}{k_t} \right). \tag{1.2.14}$$

If an individual firm observes that the price for a claim on capital is high, it will supply a higher quantity of capital. In line with the conventional intuition, this implies an upward-sloping supply schedule of capital. The price $\tilde{Q}_t$ of end-of-period used capital which is bought by the capital good producer from the final good producer is then given by

$$\tilde{Q}_t = Q_t - \delta + \frac{(Q_t - 1)^2}{2a}. \tag{1.2.15}$$

As stated above, atomistic entrepreneurs are subject to collateral constraints that include an asset price Q_t. In my framework I combine atomistic entrepreneurs with a setting in which the relevant asset price is introduced through capital adjustment costs. Since atomistic entrepreneurs (and atomistic capital good producers for that matter) take this asset price Q_t as given, the privately optimal choices for k_{t+1} may deviate from their constrained efficient counterpart, as will be discussed in detail below. Whether the entrepreneur and capital

[20] One can think of the entrepreneur in period $t = 2$ as 'ordering' a certain amount of capital k_3 which is then delivered by the capital good producing firm. The entrepreneur pays the price Q_2 for this order. The 'order' is completed and delivered to the entrepreneur by the end of period 2. At the beginning of period 3, the final goods producing firm then 'purchases' this capital unit for $Q_2 R_3^K$ and uses the associated capital in production in period 3.

[21] In equilibrium, since all capital-good producing firms are symmetrical perfectly competitive price-takers, the supply schedule will be in aggregate terms and the asset price Q_t will depend on aggregate levels of capital K_t, K_{t+1}.

good producer are two separate entities or modelled as one agent[22] does not matter, as long as the entrepreneur is *atomistic* and takes asset prices Q_t as given.

1.2.4 Market Clearing and Aggregation

Aggregate goods markets

$$Y_1 = C_{1,e} + C_{1,s} + I_1 \quad (1.2.16)$$
$$Y_2 = C_{2,e} + C_{2,s} + I_2 \quad (1.2.17)$$
$$Y_3 = C_{3,e} + C_{3,s} - K_3 \quad (1.2.18)$$

and labor markets in period $t = \{1,2,3\}$

$$L = 1 \quad (1.2.19)$$

clear. Bond markets in period $t = \{1,2,3\}$ clear as well

$$B_t = -B_{t,s} \quad (1.2.20)$$

Since both types of representative agents, entrepreneurs and savers, behave symmetrically in equilibrium and lie in continua of unit mass and since both types of firms, final good and capital good producers, operate at zero profit and constant returns to scale technology aggregation implies that individual quantities correspond to aggregate quantities, so that $C_{t,e} = c_{t,e}$, $C_{t,s} = c_{t,s}$, $I_t = i_t$, $B_t = b_t$, $K_t = k_t$, $L = l$ and $Y_t = y_t$.

1.2.5 Competitive Equilibrium

Definition 1 *For a given initial state $\mathcal{S}_1 = \{B_1, K_1\}$ the competitive equilibrium consists of a collection of prices $\{Q_1, Q_2, \tilde{Q}_2, R_2^K, R_3^K, R_1, R_2, W_1, W_2, W_3\}$, and allocations $\{C_{1,s}, C_{2,s}, C_{3,s}, C_{1,e}, C_{2,e}, C_{3,e}, B_{2,s}, B_{3,s}, B_2, B_3, K_2, K_3, I_1, I_2, L_1, L_2, L_3, Y_1, Y_2, Y_3, \mu_2\}$ such that*

1. *Given the pricing functions, the policy functions solve the optimisation problem of savers, entrepreneurs, final good producing firms and capital good producing firms,*
2. *Goods, Labor and Asset markets clear.*

1.2.6 Constrained Efficient Equilibrium

In order to assess the inefficiencies of the model I will now look at the problem of a constrained efficient planner. I study the constrained efficient equilibrium, compare it with the competitive equilibrium and derive the optimal policy from that comparison.

1.2.6.1 Constrained Efficient Planner Problem

The constrained efficient planner maximises saver welfare while making sure that the entrepreneur is not worse off than in the competitive equilibrium. Moreover, the constrained efficient planner internalises the effects of borrowing and investment decisions on relevant asset prices. This implies that the supply schedule of capital (1.2.14) will appear as additional constraint in the constrained efficient planner problem. Since I will consider a Ramsey Planner with available tax instruments on claims of capital, the demand schedule for

[22] It would also be possible to merge the entrepreneur with the capital good producer and assume that the entrepreneur directly conducts physical capital investment. All the results would be unchanged. The setting with the capital good producer is associated with simpler algebra and a simpler interpretation of the optimal taxation scheme.

capital does not show up as additional constraint in the constrained efficient planner problem. Assuming the availability of policy instruments that can stimulate the demand of entrepreneurs for assets/capital claims implies therefore that the constrained efficient planner can shift the demand schedule of capital and that the relevant constraint is capital supply. The constrained efficient allocation is denoted by the superscript $*$. The problem of the constrained efficient planner is as follows

$$\max_{C^*_{1,s},C^*_{2,s},C^*_{3,s},C^*_{1,e},C^*_{2,e},C^*_{3,e},B^*_2,B^*_3,B^*_{2,s},B^*_{3,s},K^*_2,K^*_3} \left\{\log(C^*_{1,s}) + \beta_s \left(\log(C^*_{2,s})\right) + \beta_s^2 \left(\log(C^*_{3,s})\right)\right\}$$

s.t. the aggregate resource constraints of the economy, the collateral constraint and a 'Pareto condition' that ensures that the entrepreneur is not worse off than in the competitive equilibrium

$$\begin{aligned}
\lambda_1^*: &\quad C^*_{1,e} + C^*_{1,s} &\leq&\quad Y_1^* - I_1^* \\
\lambda_2^*: &\quad C^*_{2,e} + C^*_{2,s} &\leq&\quad Y_2^* - I_2^* \\
\lambda_3^*: &\quad C^*_{3,e} + C^*_{3,s} &\leq&\quad Y_3^* + K_3^* \\
\mu_2^*: &\quad -B_3^* &\leq&\quad \theta Q_2^*(K_2^*,K_3^*)K_3^* \\
\xi^*: &\quad V^{e,CompEQ} &\leq&\quad \log(C^*_{1,e}) + \beta_e \log(C^*_{2,e}) + \beta_e^2 \log(C^*_{3,e})
\end{aligned}$$

where

$$\begin{aligned}
I_1^* &= K_2^* - (1-\delta)K_1^* + \frac{a}{2}\left(\frac{K_2^* - K_1^*}{K_1^*}\right)^2 K_1^* \\
I_2^* &= K_3^* - (1-\delta)K_2^* + \frac{a}{2}\left(\frac{K_3^* - K_2^*}{K_2^*}\right)^2 K_2^*
\end{aligned}$$

$$\begin{aligned}
Y_1^* &= (K_1^*)^\alpha \\
Y_2^* &= (K_2^*)^\alpha \\
Y_3^* &= (K_3^*)^\alpha \\
Q_2^*(K_2^*,K_3^*) &= 1 + a\left(\frac{K_3^* - K_2^*}{K_2^*}\right)
\end{aligned}$$

$V^{e,CompEQ}$ is the life-time value of entrepreneurial consumption from the competitive equilibrium, so that the constrained efficient planner will make sure that the entrepreneur is not worse off in the constrained efficient equilibrium. The resulting constrained efficient optimality conditions of the entrepreneur for the inter-temporal decision between consuming and purchasing assets are given by

$$\frac{1}{C^*_{1,e}} = \beta_e R_2^{K,*}\left[\frac{1}{C^*_{2,e}}\right] + \beta_e \frac{\mu_2^*}{\xi^*}\theta\left[\frac{\partial Q_2^*}{\partial K_2^*}\frac{K_3^*}{Q_1^*}\right] \quad (1.2.21)$$

$$\frac{1}{C^*_{2,e}} = \beta_e R_3^{K,*}\left[\frac{1}{C^*_{3,e}}\right] + \frac{\mu_2^*}{\xi^*}\theta\left[\frac{\partial Q_2^*}{\partial K_3^*}\frac{K_3^*}{Q_2^*} + 1\right] \quad (1.2.22)$$

$$-B_3^* \leq \theta Q_2^* K_3^* \quad (1.2.23)$$

$$V^{e,CompEQ} \leq \log(C^*_{1,e}) + \beta_e \log(C^*_{2,e}) + \beta_e^2 \log(C^*_{3,e}) \quad (1.2.24)$$

where I have defined a constrained efficient counterpart for the gross return on capital, $R_t^{K,*}$, in order to facilitate the comparison with the optimality condition from the competitive equilibrium

$$R_t^{K,*} \equiv \frac{\alpha \frac{Y_t^*}{K_t^*} + \tilde{Q}_t^*}{Q_{t-1}^*}, \qquad t = 2,3. \tag{1.2.25}$$

and where (1.2.23) and (1.2.24) hold with equality if $\mu_2^* > 0$ and respectively $\xi^* > 0$.

1.2.6.2 Spreads in the Competitive and in the Constrained Efficient Equilibrium

Recall the Euler equations from the competitive equilibrium and rewrite them so that the implied interest rate spread can be studied

$$\begin{aligned} t=1: \qquad \beta_e\left[\frac{1}{C_{2,e}}\right]\left(R_2^K - R_1\right) &= 0 \\ t=2: \qquad \beta_e\left[\frac{1}{C_{3,e}}\right]\left(R_3^K - R_2\right) &= \mu_2(1-\theta). \end{aligned}$$

The spread in period $t = 1$ is zero, since there is no collateral constraint and the spread in period $t = 2$ is positive if the constraint binds ($\mu_2 > 0$). In the constrained efficient equilibrium the spread in period $t = 1$ will be positive whereas the spread in period $t = 2$ may be zero[23]. In period $t = 1$ in the constrained efficient equilibrium the return on capital investment has to be higher than the gross real interest rate.

$$\begin{aligned} t=1: \qquad \beta_e\left[\frac{1}{C_{2,e}^*}\right]\left(R_2^{K,*} - R_1^*\right) &= -\beta_e\frac{\mu_2^*}{\xi^*}\theta\left[\frac{\partial Q_2^*}{\partial K_2^*}\frac{K_3^*}{Q_1^*}\right] > 0 \\ t=2: \qquad \beta_e\left[\frac{1}{C_{3,e}^*}\right]\left(R_3^{K,*} - R_2^*\right) &= \frac{\mu_2^*}{\xi^*}\left(1-\theta\left[\frac{\partial Q_2^*}{\partial K_3^*}\frac{K_3^*}{Q_2^*}+1\right]\right) \end{aligned}$$

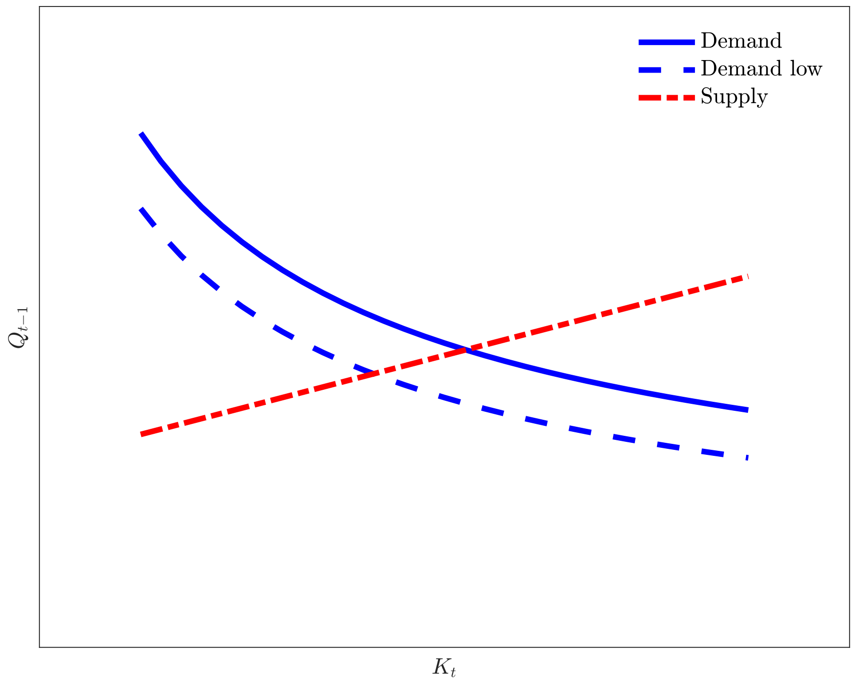
One way to interpret this is that in the constrained efficient equilibrium in period $t = 1$ there is less investment I_1^*, a lower demand for capital K_2^* and thus a lower asset price Q_1^* compared to the competitive equilibrium. Ceteris paribus a decrease in these two variables would be associated with an increase in the real gross return on capital. Therefore, the inefficiency in the competitive equilibrium in period $t = 1$ can be interpreted as 'overinvestment'. In period $t = 2$ the constrained efficient spread is smaller than in the competitive equilibrium which implies that the levels of investment, capital and asset prices are inefficiently low.

1.2.6.3 Sources of sub-optimality

The comparison of the interest rate spreads in the competitive and in the constrained efficient equilibrium allocation highlights the nature of the sub-optimality: too much investment ex ante and too little investment ex post. The source of this sub-optimality is the presence of the asset price Q_t in the collateral constraint (1.2.8) in period $t = 2$. The fact that atomistic entrepreneurs take the asset price Q_t as given as they solve their inter-temporal optimisation problem gives rise to a pecuniary externality. I will briefly highlight the determination of this asset price in the capital market since it is crucial for the understanding of the nature of the pecuniary externality in this model.

[23]Note that if $\theta = 0.5$ and $a = 1$ then $\left(1-\theta\left[a\frac{K_3^*}{K_2^*}\frac{1}{Q_2^*}+1\right]\right) = 1-\theta\left(\frac{aK_3^*}{(1-a)K_2^*+aK_3^*}+1\right) = 0.$

FIGURE 1.3: CAPITAL MARKET EQUILIBRIUM IN PERIOD $t-1$ (UNCONSTRAINED)



Notes: The intersection of the demand and supply schedules of capital claims gives rise to the equilibrium in the capital market before the crisis, ex ante, in time period $t-1$. The demand schedule for claims on capital slopes downward, as is standard. The supply schedule slopes upward. An inward shift of the demand schedule for claims on capital will lead to a lower equilibrium asset price Q_{t-1} and a lower level of capital K_t.

Note that according to the equilibrium supply schedule of capital

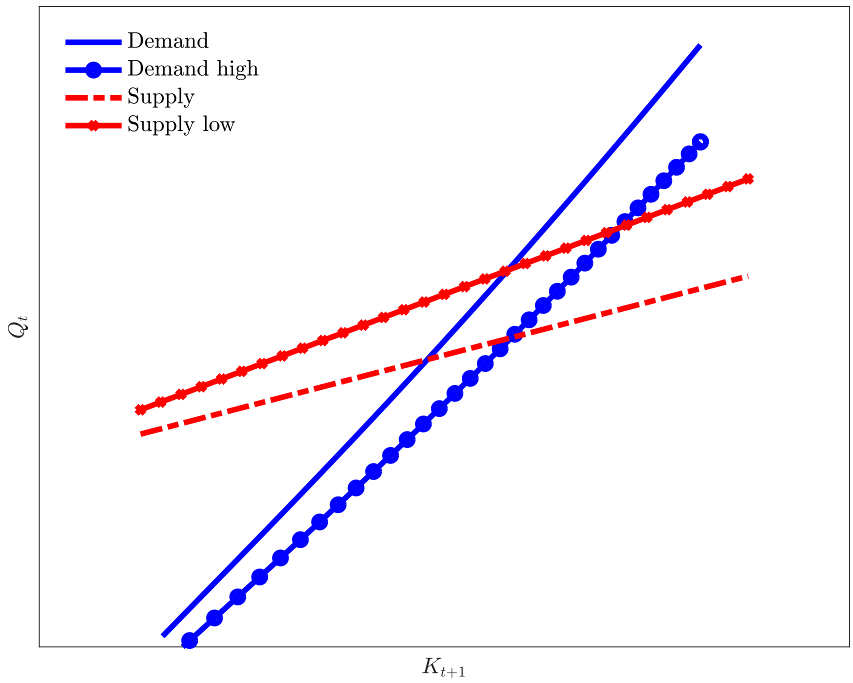
$$Q_t \quad = \quad 1 + a\left(\frac{K_{t+1}}{K_t} - 1\right),$$

it holds that if K_{t+1} is high, then the price of a claim on capital in this period Q_t, will be high as well $\frac{\partial Q_t}{\partial K_{t+1}} > 0$. Also note that if in the same period there is a lot of 'old' capital K_t available, the price of a claim on capital Q_t, will be lower $\frac{\partial Q_t}{\partial K_t} < 0$. One way to interpret this is that if the capital supply K_t was already elevated, there is not much need for a lot of new investment in this period, which is why $\frac{\partial I_t}{\partial K_t} < 0$. And if investment in this period is lower, this in turn has adverse effects on the capital/asset price $\frac{\partial Q_t}{\partial I_t} > 0$.

In Figure 1.3 I illustrate the equilibrium in the capital market in the ex ante period $t = 1$ before the crisis. Recall that a crisis in the baseline model could only occur in period $t = 2$. The demand schedule for purchases of claims on capital slopes downward, as was argued in Section 1.2.2 and which can be inferred from (1.2.9). A higher price for the claim will be associated with a lower demand for it.

Now suppose there is a shift in the demand schedule in the pre-crisis period (depicted

FIGURE 1.4: CAPITAL MARKET EQUILIBRIUM IN PERIOD t (CONSTRAINED)



Notes: During the crisis, in time period t, when the collateral constraint binds, the demand schedule for claims on capital slopes upward. The intuition is that an increase in the asset price Q_t relaxes the collateral constraint, so that the entrepreneur can borrow more and purchase more claims on capital K_{t+1}. A reduction in K_t, as described in Figure 1.3 will lead to an inward shift of the supply schedule. Together with an outward shift in demand for claims on capital this will give rise to a higher equilibrium level of asset prices Q_t and capital K_{t+1}. The new equilibrium will arise at the intersection of the inward-shifted supply schedule and the outward-shifted demand schedule.

in Figure 1.3, from 'demand' to 'demand low'), so that the new equilibrium asset price Q_{t-1} and K_t will be lower. Since K_t is an element of the capital supply schedule next period, this demand shift will therefore also affect the equilibrium allocation next period. In other words, the reduction in demand for claims on capital in the current period will lead to a downward shift of the supply schedule of capital next period. In Figure 1.4 I plot the equilibrium in the capital market in the crisis period $t = 2$. Due to the reduction in demand ex ante, the supply schedule has shifted to the left. Moreover, as discussed above, one consequence of a binding collateral constraint is that the demand for claims on capital now slopes upward. The reason is that an increase in the asset price, will allow the entrepreneur to increase her borrowing. She can consume more and increase her purchases of claims on capital. Suppose there is now an increase in the demand for claims on capital so that the demand schedule shifts to the right. Then the in-crisis equilibrium levels of the asset price Q_t and capital K_{t+1} have increased due to (i) the reduction in demand for capital ex ante, and (ii) the increase of demand for capital during the crisis.

Figures 1.3 and 1.4 therefore illustrate that a high level of previous period capital K_t is associated with an increase in capital supply and will lower the equilibrium asset price

Q_t. Since the asset price Q_t shows up in the collateral constraint (1.2.8) the asset purchase decisions of entrepreneurs will have an impact on whether the constraint binds or not. If the effects of individual asset purchase decisions on the price of capital Q_t are ignored, there will be a pecuniary externality.

In contrast to many existing models which make simplifying assumptions either about the absence of capital adjustment costs or about capital in fixed supply, the equilibrium asset price in my model is not entirely demand determined. The fact that capital supply, introduced via standard convex capital adjustment costs, is a determinant of asset prices will therefore give rise to a second component of the pecuniary externality. In addition to the 'asset price deflation' component my model features ex ante 'overinvestment'.

Thus, the pecuniary externality in my model works in two ways: (i) Excessive accumulation of capital ex ante may depress asset prices in periods of financial stress ($t = 2$) which can cause the collateral constraint to bind and which may result in a severe financial crisis. (ii) When the constraint binds and agents start fire-selling capital[24], they reduce their demand for capital, thereby further depressing the price of capital. The pecuniary externality entails welfare losses and calls for policy interventions as will be discussed in the next section.

1.2.7 Policy Interventions and Welfare Analysis

Based on the comparison of the competitive and the constrained efficient equilibrium allocations I derive the optimal taxation scheme that will let the two allocations coincide.

1.2.7.1 Decentralisation

Consider a planner who maximises the saver life-time utility subject to the relevant budget constraints. Like the constrained efficient planner this planner also respects a Pareto constraint to make sure that the entrepreneur is not worse off than in the competitive equilibrium. In contrast to the constrained efficient planner prices are taken as given. It is assumed that tax instruments for the demand of claims on capital decisions are available[25] to implement the optimal policy. The optimisation problem then looks as follows

$$\max_{c_{1,s},c_{2,s},c_{3,s},c_{1,e},c_{2,e},c_{3,e},b_2,b_3,b_{2,s},b_{3,s},k_2,k_3} \left\{ \log(c_{1,s}) + \beta_s \left(\log(c_{2,s})\right) + \beta_s^2 \left(\log(c_{3,s})\right) \right\}$$

s.t. the aggregate resource constraints of the economy, the collateral constraint and a 'Pareto condition' that ensures that the entrepreneur is not worse off than in the competitive equilibrium

$$\begin{aligned}
(\lambda_{t,s}): \quad & c_{t,s} + b_{t+1,s} &\leq\;& W_t l_s + R_{t-1} b_{t,s}, \qquad t = 1,2,3 \\
(\lambda_{t,e}): \quad & c_{t,e} + b_{t+1} + \left(1 + \tau_{k_{t+1}}\right) Q_t k_{t+1} &\leq\;& \left(\mathcal{R}_t^K + \tilde{Q}_t\right) k_t + R_{t-1} b_t + T_t, \qquad t = 1,2,3 \\
(\mu_t): \quad & -b_{t+1} &\leq\;& \theta Q_t k_{t+1}, \qquad t = 2 \\
(\xi^r): \quad & V^{e,CompEQ} &\leq\;& \log(c_{1,e}) + \beta_e \log(c_{2,e}) + \beta_e^2 \log(c_{3,e})
\end{aligned}$$

The budget constraints of the entrepreneur are not directly altered through the taxation scheme since revenues from taxation/subsidies are rebated to him lump-sum, denoted by

[24] Strictly speaking, the 'fire sale' corresponds to a sharp reduction in the demand for claims on capital in my model. There is no actual sale of capital like in Lorenzoni (2008).

[25] It can easily be shown that tax instruments on borrowing cannot be used to implement the constrained efficient allocation. A comparison of the inter-temporal optimality conditions of the entrepreneur clearly shows that the discrepancy between the competitive and the constrained efficient equilibrium is associated with the optimality conditions for claims on capital 1.2.21 and 1.2.22. I therefore disregard tax instruments on borrowing for the sake of a compact exposition.

$\{T_1, T_2\}$. The inter-temporal optimality conditions of the saver are equivalent to their competitive and constrained efficient equilibrium counterparts. The resulting Euler equations of the entrepreneur associated with the inter-temporal decision between consuming and purchasing claims on capital are given by

$$(1+\tau_{k_2})\frac{1}{c_{1,e}} = \beta_e R_2^K \left[\frac{1}{c_{2,e}}\right] \tag{1.2.26}$$

$$(1+\tau_{k_3})\frac{1}{c_{2,e}} = \beta_e R_3^K \left[\frac{1}{c_{3,e}}\right] + \theta\frac{\mu_2}{\xi} \tag{1.2.27}$$

1.2.7.2 Optimal Policy

A comparison of the entrepreneurs inter-temporal optimality conditions (1.2.26) - (1.2.27) with their constrained efficient equilibrium counterparts (1.2.21) - (1.2.22) allows one to solve for the following optimal tax plan

$$\tau_{k_2}^* = -\beta_e \frac{\mu_2^*}{\xi^*}\theta\left[\frac{\partial Q_2^*}{\partial K_2^*}\frac{K_3^*}{Q_1^*}\right] C_{1,e}^* > 0 \tag{1.2.28}$$

$$\tau_{k_3}^* = -\frac{\mu_2^*}{\xi^*}\theta\left[\frac{\partial Q_2^*}{\partial K_3^*}\frac{K_3^*}{Q_2^*}\right] C_{2,e}^* < 0. \tag{1.2.29}$$

The optimal policy can be implemented via taxing purchases of claims on capital. This does not imply that the amount of borrowing in the competitive equilibrium is constrained efficient. It means that the optimal amount cannot be achieved through taxing debt. Since the inefficiencies in this model originate from ignoring the effects of the demand for claims on capital on asset prices it is intuitive that policy interventions have to target purchasing decisions of capital claims rather than borrowing decisions.

The optimal taxation scheme for capital contains two components, (i) $\tau_{k_2}^* > 0$ and (ii) $\tau_{k_3}^* < 0$. I will refer to the first component as 'macroprudential policy (MPP) intervention' and to the second as 'crisis intervention'.

Macroprudential Policy Macroprudential policies are ex ante policy measures aimed at stabilising the financial system as a whole and mitigating systemic risk. $\tau_{k_2}^* > 0$ can be thought of as macroprudential policy, since it takes place before the crisis and since its role is to stabilise asset prices Q_2 in the potential crisis period $t = 2$. $\tau_{k_2}^* > 0$ implies that under the optimal policy asset purchases before the crisis have to be taxed.

A positive $\tau_{k_2}^*$ increases the price of capital, therefore discourages the entrepreneur to purchase/invest in capital k_2. The reduced capital demand in period $t = 1$ will mitigate the oversupply in period $t = 2$ and will therefore boost asset prices in this period. The tax on capital purchases will create a small spread between the rate of return on capital and the real interest rate.

Crisis Intervention $\tau_{k_3}^* < 0$ can be interpreted as an emergency credit market intervention during the crisis. The policy authority subsidises asset purchases with the objective of increasing asset prices, thus preventing the fire sale and the asset price deflation spiral.

In Figure 1.3 I illustrated how the demand and supply of capital determine capital and asset prices. The optimal policy essentially shifts the capital demand schedule in period $t = 1$ downward. This will then lead to a decline of equilibrium capital K_2 and asset price Q_1. The decline in K_2 will be reflected by a shift of capital supply in period $t = 2$ to the left. Moreover, the optimal policy will boost capital demand in period $t = 2$ which leads to an upward shift of the capital demand schedule. Both, the downward shift of capital supply and the upward shift of capital demand in period $t = 2$ will mitigate the effects of the binding collateral constraint.

1.2.8 Numerical Illustration of the Baseline Model

In order to further shed light on some properties of the baseline model and the inefficiencies associated with the pecuniary externality I provide a simple numerical illustration. The parametrisation here has two important targets: (i) I want to ensure that the gross interest rates R_1, R_2 and the gross rates of return on capital R_2^K, R_3^K are above 1, (ii) investment in period $t = 1$ and $t = 2$ should be positive. I therefore set the initial level of capital to $K_1 = 0.28$.[26] For simplicity the entrepreneur is as patient as the saver; the entrepreneur will borrow ($B_2, B_3 < 0$) due to her low initial endowments $\{B_1, K_1\}$. I set the collateral coefficient $\theta = 0.5$ which implies a maximum leverage of 2. The remaining parameters are set to their standard values: the capital share $\alpha = 0.33$, the depreciation rate $\delta = 0.025$, the capital adjustment parameter $a = 1$ and a fixed labor supply of $l_s = 1$.

In the following figures I plot the policy functions of some key variables, such as leverage, borrowing and investment as a function of the initial debt level B_1. As long as the entrepreneur can obtain the desired amount of funds, variables such as capital, investment, asset prices, output and wages will be constant in the B_1-state-space[27]. In regions of the state space in which the collateral constraint becomes binding the depicted policy functions of the variables will bend downward.

In contrast to most existing models of occasionally binding collateral constraints, the real interest rate in this model is endogenous. As one can see in Figure 1.6 Panel (a), in period $t = 1$ the real rate is flat. In period $t = 2$ it is flat until the point where the constraint becomes binding. In the region where the constraint binds, the real rate R_2 is sharply decreasing.

Recall the entrepreneur and saver Euler equations describing the optimal inter-temporal consumption-borrowing decision between period $t = 2$ and period $t = 3$.

$$\frac{1}{C_{2,e}} = \beta_e R_2 \left[\frac{1}{C_{3,e}}\right] + \mu_2$$

When the constraint binds, $\mu_2 > 0$, the marginal utility of consumption of the entrepreneur in period $t = 2$, $\frac{1}{C_{2,e}}$ has to increase and/or the marginal utility of entrepreneurial consumption in period $t = 3$, $\frac{1}{C_{3,e}}$, has to decrease, and/or the real rate R_2 has to decrease. All of these three things actually happen in equilibrium. The changes in the marginal utilities of consumption of the entrepreneur correspond to a decrease in consumption $C_{2,e}$ in period $t = 2$ and an increase in consumption $C_{3,e}$ in period $t = 3$.

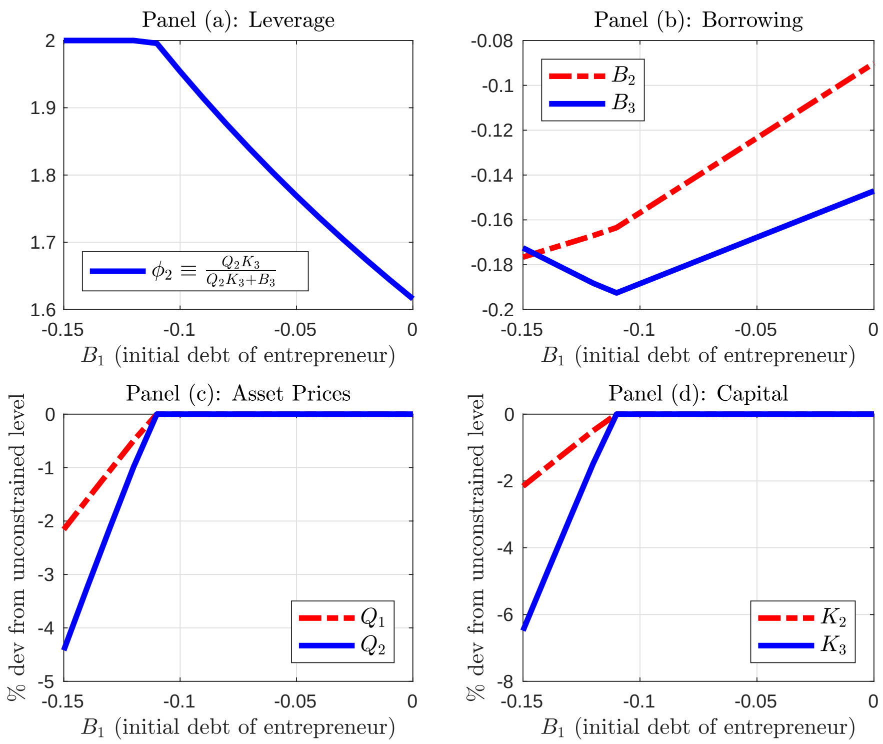
$$\frac{1}{C_{2,s}} = \beta_s R_2 \left[\frac{1}{C_{3,s}}\right]$$

When the real rate R_2 decreases, as argued above, then the marginal utility of consumption of the saver in period $t = 2$, $\frac{1}{C_{2,s}}$, has to decrease and/or the marginal utility of consumption of the saver in period $t = 3$ has increase to counteract the decreasing R_2. These changes in the marginal utilities of consumption of the saver correspond to an increase in consumption $C_{2,s}$ in period $t = 2$ and a decrease of consumption $C_{3,s}$ in period $t = 3$.

[26] I need to let the entrepreneur start with a low initial capital stock, otherwise she would simply 'divest'. This parametrisation does not affect the welfare analysis or any other result of the baseline model.

[27] Note that in this finite horizon economy the variables will not necessarily be constant over time, the desired level of investment in period 1 and in period 2 may not be the same, depending on the calibration. Strictly speaking, there is no 'steady state'. Nevertheless, in the unconstrained region the policy functions are flat, since the time $t = 1$ and time $t = 2$ desired amount of borrowing is available to finance investment and consumption.

FIGURE 1.5: POLICY FUNCTIONS OF KEY VARIABLES IN THE COMPETITIVE EQUILIBRIUM.



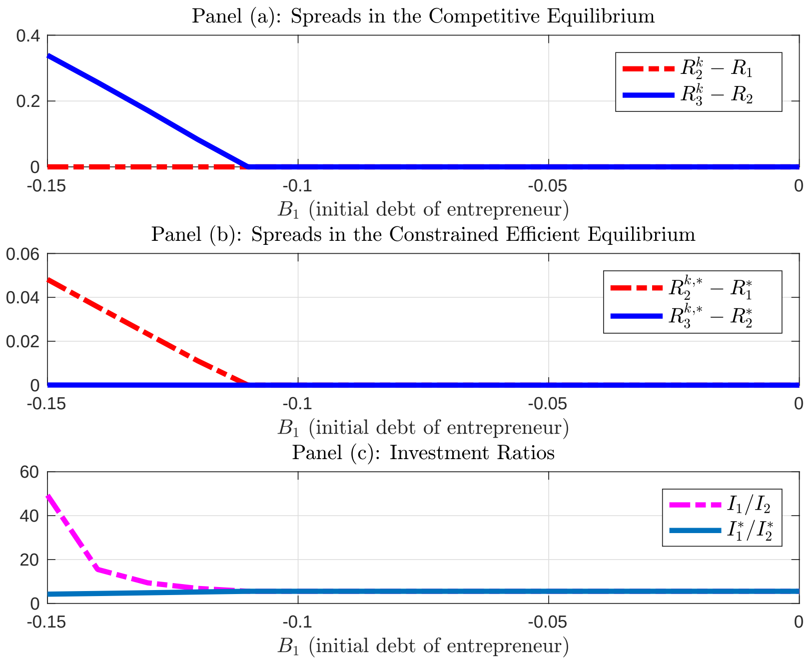
Notes: The higher the entrepreneur's initial debt level (the lower B_1) the higher is the amount the entrepreneur wants to borrow (the lower are B_2 and B_3). The collateral constraint binds at around $B_1 = -0.11$ as can be seen in Panel (a). Panel (b) depicts the corresponding policy functions for borrowing. Note that in regions of the state space with high initial debt ($B_1 < -0.11$) the fact that the borrowing constraint binds in period $t = 2$ will also lead to a reduction in period $t = 1$ borrowing, so B_2 bends upwards. This can be interpreted as a precautionary reduction in borrowing and it causes a kink in the time $t = 1$ policy functions for other variables, such as asset prices and capital as well.

The endogeneity of the real interest rate and the fact that it sharply declines in the crisis region will further affect consumption levels since in period $t = 3$ the price of borrowing (from the perspective of the entrepreneur) / the return on lending (from the perspective of the saver) has sharply dropped.

As discussed above, a key difference between the competitive and the constrained efficient equilibrium allocation are the interest rates spreads. Under the simplistic parametrisation of the baseline model, the constrained efficient spread in period $t = 1$ is positive, whereas it is zero in the competitive equilibrium. Moreover, the constrained efficient spread in period $t = 2$ is zero, whereas it is positive in the competitive equilibrium.

In Figure 1.6 in Panel (c) I show the differences between the competitive and the constrained efficient equilibrium with regard to investment. In the competitive equilibrium there is too much investment ex ante, I_1 is high, and too little investment during the crisis I_2 is low. In regions of the B_1-state space in which the collateral constraint binds the investment ratio in the competitive equilibrium slopes up. The comparison with the constrained efficient equilibrium shows that this is inefficient. Investment ex ante will be lower, investment during the crisis will be higher, so that the ratio is lower in the constrained efficient

Figure 1.6: Spreads and Investment Ratios in the Competitive and Constrained Efficient Equilibrium.



Notes: Behaviour of real gross interest rates, real gross rates of return on capital and the spreads between these interest rates in the competitive equilibrium and in the constrained efficient equilibrium. As can be seen in Panel (b), in the constrained efficient EQ there is no spread at all in the crisis period $t = 2$ (given the parametrisation of $a = 1; \theta = 0.5$), instead there is a spread in the ex ante period $t = 1$. Panel (c) illustrates that there is too much investment ex ante relative to investment in the crisis period in the competitive equilibrium.

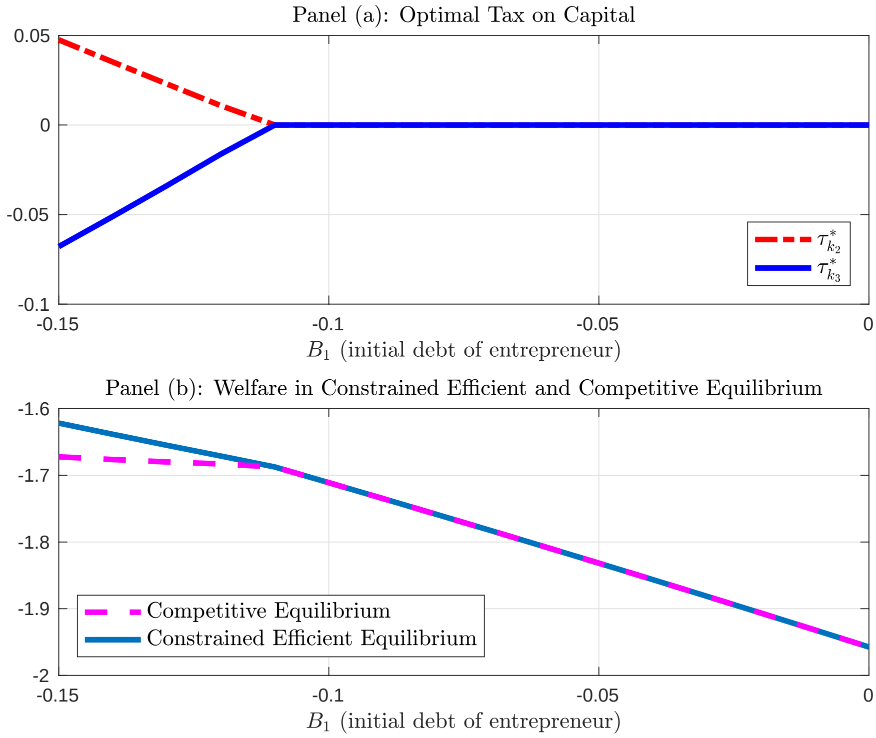
equilibrium.

The different spreads and investment patterns in the competitive equilibrium and the constrained efficient equilibrium can be attributed to the presence of the pecuniary externality. The presence of this externality warrants policy interventions in the form of a tax on asset purchases ex ante ($\tau_{k_2}^* > 0$) and a subsidy on asset purchases during the crisis ($\tau_{k_3}^* < 0$). The optimal tax rates and the associated welfare gains are depicted in Figure 1.7. The depicted welfare gain shows the distance between saver life-time utility in the constrained efficient and in the competitive equilibrium. Implementing constrained efficiency via optimal policy is associated with welfare gains.

1.3 Dynamic Stochastic General Equilibrium Model

In this section I develop a dynamic stochastic general equilibrium (DSGE) version of the baseline model described in Section 1.2. The intuition developed in Section 1.2 carries over to the DSGE model. The objectives of this section are threefold. The first goal is to show that a DSGE version of the above described model can match some empirical patterns well.

FIGURE 1.7: OPTIMAL TAXES RATES AND WELFARE



Notes: Panel (a) depicts the optimal taxation scheme. In period $t = 1$, before the crisis, the policy authority has to tax claims on capital, $\tau^*_{k_2} > 0$. In the crisis period, in $t = 2$, the optimal tax rate on claims on capital is negative, $\tau^*_{k_3}$. This corresponds to a subsidy and it will give rise to an outward shift of the demand schedule of capital claims, as depicted in Figure 1.4. Panel (b) shows that welfare in the constrained efficient equilibrium is higher than in the competitive equilibrium.

Second, the DSGE model will be used to conduct policy experiments and verify that the welfare implications derived above hold in a more complex model. Third, I demonstrate that my DSGE model addresses some of the shortcomings[28] that have led to a debate[29] on the usefulness of DSGE models since the financial crisis of 2008. To this end, I employ non-linear solution techniques to solve for the global dynamics of the model.

[28]Many recent medium-scale macro-financial DSGE models suffer from the following conceptual shortcomings: (i) They rely on large shocks and/or 'financial shocks': Not only is it questionable whether financial crises are triggered by abnormally large shocks, but more importantly, it is all but impossible to study the role of ex ante macroprudential policies if the very event they are supposed to prevent or mitigate is entirely exogenous. Preferably, models of financial crises and macroprudential policy should aim at introducing some degree of *endogeneity of the crisis*. (ii) A role for macroprudential regulation is introduced in an ad-hoc way: Some of the recent medium-scale macro-financial DSGE models have developed very elaborate descriptions of the banking sector in which banks may face a convex cost if they deviate from a certain bank capital ratio. Macroprudential policy in these models essentially has the role of setting the target for this bank capital ratio. The problem with this example of modelling macroprudential policy is not the assumption of some convex bank capital adjustment cost itself but rather the absence of an externality to which policy responds. Ideally, every policy intervention should be motivated by *internalising an externality or an imperfection*. (iii) While financial crises are highly non-linear events, many of the recent medium-scale macro-financial DSGE models cannot account for that. A distinction into 'normal' and 'crisis' states is impossible if only local fluctuations around a deterministic steady state are analysed. Ideally, models of financial crises and macroprudential policy should account for the inherent *non-linearities*. To summarise, many of the existing medium-scale macro-financial DSGE models are ill-suited to study financial crises and ex ante policy interventions because they suffer from conceptual problems associated with (i) endogeneity issues, (ii) policy interventions not being justified and (iii) the lack of accounting for non-linearities.

[29]Romer (2016) and Stiglitz (2017), among others, have expressed their concerns regarding the shortcomings of DSGE models and called the entire approach into question. A constructive discussion and some recommendations on how to go forward with DSGE modelling can be found in Galí (2016), Galí (2017b), Blanchard (2016), Christiano et al. (2017) and Korinek (2017).

1.3.1 The Model

There is a household, who supplies labor l_t, consumes c_t^s and saves by purchasing non-state-contingent nominal securities b_t^s. Moreover, there is an entrepreneur who borrows from this household to finance consumption and purchases of assets. The entrepreneur can purchase claims on capital and therefore decides how much capital there will be. Capital is used by intermediate good producing firms who employ the saver-households. The entrepreneur faces an occasionally binding collateral constraint. If this constraint holds with equality the entrepreneur will be funding constrained. She will reduce her demand for capital claims which further depresses asset prices. The spiralling decline of asset prices makes the constraint even tighter, thereby aggravating the economic contraction.

1.3.1.1 Savers

There is a continuum of households who consume, save and supply labor. These agents will be referred to as savers. The Bellman equation associated with the representative saver's optimisation problem is given by

$$V_s(b_{t,s}, \mathcal{S}_t) = \max_{c_{t,s}, b_{t+1,s}, l_t} \left\{ \log \left[c_{t,s} - \chi \frac{l_t^{1+\varphi}}{1+\varphi} \right] + \beta_s \mathbb{E}_t V_s(b_{t+1,s}, \mathcal{S}_{t+1}) \right\}$$

subject to the sequence of budget constraints for all time periods t and all states of the world $\mathcal{S}_t$

$$\begin{aligned} (\lambda_{t,s}) : \qquad P_t c_{t,s} + b_{t+1,s} &\leq W_t l_t + b_{t,s} R_{t-1}^n \\ \mathcal{S}_{t+1} &= \Gamma(\mathcal{S}_t). \end{aligned}$$

$c_{t,s}$ denotes the consumption basket consumed by the saver

$$c_{t,s} \equiv \left[\int_0^1 (c_{r,t,s})^{1-\frac{1}{\epsilon}} dr \right]^{\frac{\epsilon}{\epsilon-1}},$$

which comprises differentiated consumption goods $c_{r,t,s}$ and where $\epsilon > 1$ is the elasticity of substitution. β_s denotes the saver's discount factor, the inverse Frisch elasticity φ describes the convexity in the disutility from labor and χ denotes the weight of the disutility of labor. The period utility of the saver follows the Greenwood-Hercowitz-Huffman (GHH) form, introduced by Greenwood et al. (1988). This specification eliminates the wealth effect on labor supply and simplifies the solution of the model. $b_{t,s}$ denotes savings which are deposited into a bank deposit account by savers. This can also be interpreted as a non-state-contingent nominal one-period security held by the saver. The saver-household does not have access to an alternative investment or savings technology. The only way for him to transfer resources to the next period is to lend to the entrepreneur.[30] W_t is the nominal wage. $\lambda_{t,s}$ is the Lagrange multiplier associated with the budget constraint. R_{t-1}^n is the nominal gross return on the nominal riskless security $b_{t,s}$. The function Γ denotes the law of motion of the aggregate state variables $\mathcal{S}_t$.

The aggregate price index P_t is defined as a CES function of individual goods prices $P_{r,t}$

$$P_t \equiv \left[\int_0^1 P_{r,t}^{1-\epsilon} dr \right]^{\frac{1}{1-\epsilon}}.$$

[30] Due to the patient/impatient agent setting borrowing and lending will not be zero in equilibrium. The model is calibrated such that the saver will always lend to the entrepreneur.

A No-Ponzi-scheme condition implies that the saver must not be in debt at the end of time

$$\lim_{T\to\infty} b_{T,s} \geq 0.$$

The optimisation delivers the standard intra- and inter-temporal optimality conditions

$$-\frac{U_{l_t}}{U_{c_{t,s}}} = \chi l_t^{\varphi} \quad = \quad \frac{W_t}{P_t} \tag{1.3.1}$$

$$1 \quad = \quad \mathbb{E}_t \left[\Lambda_{t,t+1}^s \frac{R_t^n}{\Pi_{t+1}} \right], \tag{1.3.2}$$

where $\Lambda_{t,t+1}^s$ denotes the stochastic discount factor (SDF) of the saver

$$\Lambda_{t,t+1}^s \quad \equiv \quad \beta_s \frac{U_{c_{t+1,s}}}{U_{c_{t,s}}} = \beta_s \left(\frac{c_{t,s} - \chi \frac{l_t^{1+\varphi}}{1+\varphi}}{c_{t+1,s} - \chi \frac{l_{t+1}^{1+\varphi}}{1+\varphi}} \right). \tag{1.3.3}$$

and Π_t denotes gross inflation and it is defined as the gross growth rate of the price level P_t

$$\Pi_{t+1} \equiv \frac{P_{t+1}}{P_t}.$$

1.3.1.2 Entrepreneurs

The second type of agent in this simple heterogenous agent economy is a representative entrepreneur. The entrepreneur is more impatient than the saver, $\beta_e < \beta_s$, which is why the entrepreneur will always borrow from (and never lend to) the saver. Given the assumption of limited market participation which implies that firms cannot directly obtain funds from savers, the entrepreneur borrows from the saver-household and lends to the firm. There is an agency problem between the saver and the entrepreneur. The entrepreneur might find it optimal to abscond with a fraction $(1-\theta)$ of her stock of assets thereby stealing funds she received from the saver instead of paying him back. This agency problem will give rise to a collateral constraint that limits the amount of deposits the entrepreneur can receive from the saver. The Bellman equation of the representative entrepreneur looks as follows

$$V_e(b_t, k_t, \mathcal{S}_t) = \max_{b_{t+1}, k_{t+1}, c_{t,e}} \{\log(c_{t,e}) + \beta_e \mathbb{E}_t V_e(b_{t+1}, k_{t+1}, \mathcal{S}_{t+1})\}$$

s.t.

$$(\lambda_t): \quad P_t c_{t,e} + Q_t^n k_{t+1} + b_{t+1} \quad \leq \quad \left(\mathcal{R}_t^K + \tilde{Q}_t^n \right) k_t + b_t R_{t-1}^n \tag{1.3.4}$$

$$(\mu_t): \quad -b_{t+1} \quad \leq \quad \theta Q_t^n k_{t+1} \tag{1.3.5}$$

$$\mathcal{S}_{t+1} \quad = \quad \Gamma(\mathcal{S}_t)$$

$c_{t,e}$ refers to entrepreneurial dividends and it constitutes the consumption basket[31] consumed by the entrepreneur. $b_t < 0$ denotes borrowing by the entrepreneur, it represents the amount of non-state-contingent nominal securities issued by the entrepreneur. k_t refers to the amount of a risky asset with a stochastic gross nominal net return $\mathcal{R}_t^K$ and a reselling

[31] It follows the same functional form as in the saver case

$$c_{t,e} \equiv \left[\int_0^1 (c_{r,t,e})^{1-\frac{1}{\epsilon}} \right]^{\frac{\epsilon}{\epsilon-1}}$$

value $\tilde{Q}_t^n$. The asset can be interpreted as a claim to a capital good and is therefore equivalent to the capital stock in the model. Q_t^n refers to the price of this asset. In addition to the budget constraint (1.3.4) there is also a collateral constraint (1.3.5) which may bind occasionally. λ_t and μ_t are the Lagrange multipliers associated with the budget constraint and the collateral constraint respectively. $\mathcal{S}_t$ refers to the vector of state variables.

The entrepreneur's optimality conditions are given by

$$U_{c_{t,e}} = \beta_e \mathbb{E}_t \left[U_{c_{t+1,e}} \frac{P_t}{P_{t+1}} R_t^n \right] + \mu_t \quad (1.3.6)$$

$$U_{c_{t,e}} = \beta_e \mathbb{E}_t \left[U_{c_{t+1,e}} \frac{P_t}{P_{t+1}} R_{t+1}^K \right] + \mu_t \theta. \quad (1.3.7)$$

The entrepreneur owns and controls two types of firms, intermediate good producers and capital good producers. Their optimisation problems will be discussed below.

1.3.1.3 Intermediate Good Producers

There is a continuum of perfectly competitive intermediate good producing firms who operate at zero profit and are owned by the entrepreneur. The representative intermediate good producing firm produces intermediate output Y_t^i according to a standard Cobb-Douglas production function

$$Y_t^i = A_t K_t^{\alpha} L_t^{1-\alpha} \quad (1.3.8)$$

and sells this intermediate good for price P_t^i to the retailers. A_t refers to a TFP shock. There are no frictions between the entrepreneur and the firms. The intermediate good producing firm's problem is given by

$$\max_{K_t, L_t} \left\{ P_t^i Y_t^i - W_t L_t - \mathcal{R}_t^K K_t \right\}$$

The cost of production for the intermediate good producing firm corresponds to the input factor prices. The nominal factor price for labour and the rental rate of capital are given by (1.3.9) and (1.3.10)

$$W_t = P_t^i (1-\alpha) \frac{Y_t^i}{L_t} \quad (1.3.9)$$

and w.r.t. to capital

$$\mathcal{R}_t^K = P_t^i \alpha \frac{Y_t^i}{K_t}.$$

The gross rate of return on capital is given by

$$R_t^K = \frac{P_t^i \alpha \frac{Y_t^i}{K_t} + \tilde{Q}_t^n}{Q_{t-1}^n} \quad (1.3.10)$$

which is in accordance with the standard definition of the gross rate of return on capital[32]. Note that the rate of return R_t^K is subject to a shock in t, because it is a function of Y_t^i which is hit by a TFP shock.

[32]Note that capital depreciation is assumed to take place after the capital has been sold to the capital good producing firm. It shows up in the investment equation of the capital good producer which implies that she loses some of the capital when the time period moves from t to $t+1$.

1.3.1.4 Capital Good Producers

Capital good producers purchase the old capital stock at the end of the period and produce capital for the next period thus undertaking investment. They are owned and controlled by the entrepreneur and operate at zero profits. Given the price of the capital good Q_t^n, they maximise profits by choosing the level of capital K_{t+1}

$$\max_{K_{t+1},K_t} \left\{ Q_t^n K_{t+1} - \tilde{Q}_t^n K_t - P_t I_t \right\}$$

and where investment I_t is subject to a quadratic adjustment cost so that

$$I_t = K_{t+1} - (1-\delta)K_t + \frac{a}{2}\left(\frac{K_{t+1} - K_t}{K_t}\right)^2 K_t.$$

The solution of the capital good producers maximisation problem implies the following relationship between the real asset price and the marginal adjustment cost of investment

$$\frac{Q_t^n}{P_t} = 1 + a\left(\frac{K_{t+1} - K_t}{K_t}\right). \tag{1.3.11}$$

1.3.1.5 Monopolistically Competitive Retailers

The DSGE model outlined here also features price stickiness. In a real model with a standard collateral constraint and GHH utility, key variables such as output would be determined independently of the state of debt. In order for the binding constraint to have a relevant impact on output and employment an additional friction is required to generate crisis patterns consistent with the data.[33]

There is a continuum of r monopolistically competitive retail firms where $r \in [0,1]$. They buy intermediate goods Y_t^i from the intermediate goods producing firm and use them as the sole input when transforming one unit of it into one unit of retail output

$$Y_t^r = Y_t^i$$

where Y_t^r denotes the output produced by retailer r. The retailers sell their retail output for P_t^r facing the following demand schedule

$$Y_t^r = \left(\frac{P_t^r}{P_t}\right)^{-\epsilon} Y_t \tag{1.3.12}$$

where Y_t is final output which is produced by final output producers who purchase the retailers output and assemble it to final output according to a CES aggregator

$$Y_t = \left[\int_0^1 (Y_t^r)^{\frac{\epsilon-1}{\epsilon}} dr\right]^{\frac{\epsilon}{\epsilon-1}}.$$

Let Ψ_t be the real marginal cost associated with producing retail output and note that it is simply given by the relative intermediate goods price

$$\Psi_t \equiv MC^r(Y_t^r) = P_t^m = \frac{P_t^i}{P_t}.$$

Given the assumption of perfect competition among the intermediate good producing firms,

[33] Refer to Appendix 1.5.2 for a detailed discussion of the role of nominal rigidities.

the price P_t^m corresponds to the real marginal cost of producing one unit of intermediate output. The monopolistically competitive retailers can charge a markup on top of their price. Following Rotemberg (1982), it is assumed that retail firms face a quadratic cost of adjusting their price given by

$$\frac{\vartheta}{2}\left(\frac{P_t^r}{P_{t-1}^r}-1\right)^2 Y_t$$

where $\vartheta > 0$ determines the magnitude of the adjustment cost. It is assumed that the retail firm has the same discount factor as the saver. Moreover, as each firm faces the same type of price adjustment cost, each firm faces the same maximisation problem and therefore, in a symmetric equilibrium, prices are equal across firms. The retailer maximises the expected discounted stream of profits through setting her price P_t^r

$$\max_{P_t^r}\left\{\mathbb{E}_t \sum_{k=0}^{\infty}\left(\Lambda_{t,t+k}^s\left[\left(\frac{P_{t+k}^r}{P_{t+k}}\right)^{1-\epsilon}-\Psi_{t+k}\left(\frac{P_{t+k}^r}{P_{t+k}}\right)^{-\epsilon}-\frac{\vartheta}{2}\left(\frac{P_{t+k}^r}{P_{t+k-1}^r}-1\right)^2\right]Y_{t+k}\right)\right\}.$$

The resulting optimality condition is then given by

$$\vartheta\left(\Pi_t-1\right)\Pi_t=(1-\epsilon)+\epsilon\Psi_t+\vartheta\mathbb{E}_t\left[\Lambda_{t,t+1}^s\left(\frac{Y_{t+1}}{Y_t}\right)\left(\Pi_{t+1}-1\right)\Pi_{t+1}\right]. \tag{1.3.13}$$

If there was no adjustment cost, $\vartheta = 0$, then the real marginal cost Ψ_t would simply be equal to

$$\Psi=\frac{\Psi^n}{P}=\frac{\epsilon-1}{\epsilon}\equiv\frac{1}{\mathcal{M}}$$

so that, in a symmetric equilibrium under flexible prices, the price set by the retailer is equal to the desired markup $\mathcal{M}$ charged on top of the nominal marginal cost

$$P_t=\mathcal{M}\Psi_t^n.$$

The presence of price adjustment costs distorts this relationship so that the markup, which is inversely related to the real marginal cost

$$\mathcal{M}_t=\frac{1}{\Psi_t} \tag{1.3.14}$$

will fluctuate over time in response to shocks.

1.3.1.6 Monetary Policy

It is assumed that the central bank sets the gross nominal interest rate R_t^n according to the following simple rule

$$R_t^n=\frac{1}{\beta_s}\left(\Pi_t\right)^{\kappa_\Pi}, \tag{1.3.15}$$

where κ_Π determines the responsiveness of the gross nominal interest rate to inflation.

1.3.1.7 Market Clearing and TFP Shock

Aggregate goods market clearing requires that total output is equal to investment and consumption.

$$Y_t \left[1 - \frac{\vartheta}{2} (\Pi_t - 1)^2\right] \quad = \quad C_t + I_t. \tag{1.3.16}$$

where I defined total consumption C_t as the sum of saver consumption and entrepreneurial consumption[34] $C_t \equiv C_{t,s} + C_{t,e}$. Moreover, bond market clearing requires

$$B_t \quad = \quad -B_{t,s}. \tag{1.3.17}$$

The TFP shock is assumed to follow a standard AR(1) process with mean $\bar{A} = 1$

$$A_t \quad = \quad (1 - \rho_A)\bar{A} + \rho_A A_{t-1} + \epsilon_t^A. \tag{1.3.18}$$

1.3.1.8 Recursive Equilibrium Definition and Numerical Solution

Definition 2 *For a given initial state $\mathcal{S}_0$ the recursive equilibrium consists of a collection of prices $\{Q^n(\mathcal{S}_t)$, $\tilde{Q}^n(\mathcal{S}_t)$, $R^n(\mathcal{S}_t)$, $R^K(\mathcal{S}_t,\mathcal{S}_{t+1})$, $W(\mathcal{S}_t)$, $P^m(\mathcal{S}_t)$, $\Psi(\mathcal{S}_t)$, $\Pi(\mathcal{S}_t)$, $\Lambda^s(\mathcal{S}_t,\mathcal{S}_{t+1})$, $\Lambda^I(\mathcal{S}_t,\mathcal{S}_{t+1})\}$, and allocations $\{L(\mathcal{S}_t)$, $C_s(\mathcal{S}_t)$, $C_e(\mathcal{S}_t)$, $B(\mathcal{S}_t)$, $B_s(\mathcal{S}_t)$, $K(\mathcal{S}_t)$, $\phi(\mathcal{S}_t)$, $I(\mathcal{S}_t)$, $Y^i(\mathcal{S}_t)$, $Y(\mathcal{S}_t)$, $\mathcal{M}(\mathcal{S}_t)\}$ and the value functions $\{V_s(\mathcal{S}_t), V_e(\mathcal{S}_t)\}$ such that*

1. *Given the pricing functions, the policy functions solve the saver's, the entrepreneur's, the capital good producer's, the intermediate good producer's problem and $\{V_s(\mathcal{S}_t), V_e(\mathcal{S}_t)\}$ are the associated value functions,*

2. *Goods, Labor and Asset markets clear.*

1.3.1.8.1 Global Solution Method

I use a standard policy function iteration approach[35] to solve the model globally. There are three state variables, $\mathcal{S}_t = (K_t, B_t R^n_{t-1}, A_t)$. I guess a vector of policy functions $\Gamma^0(\mathcal{S}_t)$ and use this guess to solve for the unconstrained equilibrium solution in order to obtain $\Gamma^{uc}(\mathcal{S}_t)$. If the collateral constraint is violated I impose that the constraint binds and obtain the constrained equilibrium solution, I update the policy function $\Gamma^1(\mathcal{S}_t) = \Gamma^c(\mathcal{S}_t)$. If the collateral constraint is not violated I update $\Gamma^1(\mathcal{S}_t) = \Gamma^{uc}(\mathcal{S}_t)$. Iterate until Convergence.

1.3.1.9 Calibration

There are 13 parameters which need to be calibrated. The saver discount factor is calibrated to the standard value $\beta_s = 0.99$. The entrepreneur is more impatient, so her discount factor is lower, $\beta_e = 0.985$. The parameter that limits leverage is θ. I calibrated it to be $\theta = 0.5$ which will mean that the maximum level leverage[36] can reach is 2. The discount factor gap and the level of θ will determine how often a crisis event occurs on average. With the calibration at hand, a crisis event occurs in 1 out of 100 quarters in the simulation of the model, so that the model displays a 'crisis probability' of around 1%.

[34] Entrepreneurial consumption can be interpreted as dividend emission.

[35] Refer to Appendix 1.5.4 for more details on the procedure.

[36] There are several real world counterparts to leverage and most of them will typically be above 2. However, since this model only covers short-term debt, whereas the real world also features medium and long-term debt, it is natural that leverage in my model will be lower. Moreover, increasing θ above 0.5 causes numerical problems.

TABLE 1.1: CALIBRATION OF PARAMETER VALUES

Parameter	Value	Description
Savers		
β_s	0.990	Discount Factor of Savers
χ	2.4720	Relative utility weight of labor
φ	0.5	Inverse Frisch Elasticity
Entrepreneurs		
β_e	0.985	Discount Factor of Entrepreneurs
θ	0.5	Collateral Coefficient
Intermediate Good Firm		
α	0.33	Effective capital share
Capital Producing Firm		
a	1	Capital Adjustment Cost
δ	0.025	Depreciation Rate
Retail Firm		
ϵ	5	Elasticity of Substitution
ϑ	10	Price Adjustment Cost
Monetary Policy		
κ_Π	1.5	Inflation Reaction Coefficient
Shocks		
σ_A	0.01	St. Dev of TFP Shock
ρ_A	0.9	Persistence of TFP Shock

Notes: Calibration of the non-linear New Keynesian DSGE Model.

The remaining parameters are standard. χ is chosen such that employment in the stochastic steady state is 1/3. The parameters that govern the behaviour of the TFP shock are chosen such that the annualised standard deviation of output is 2.5%.

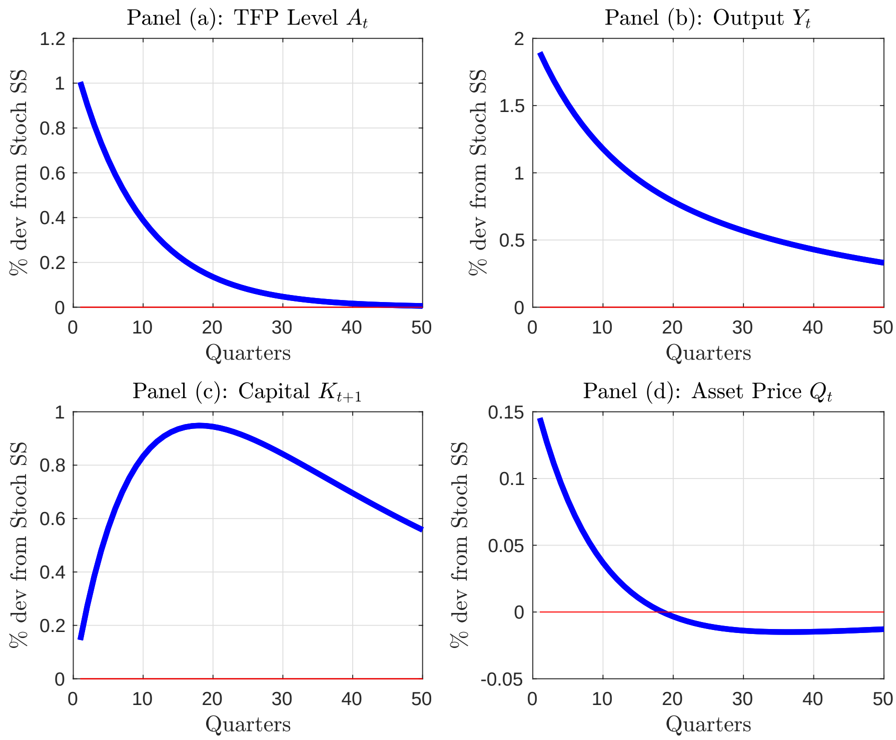
1.3.2 Properties of the Model

In this subsection I discuss some key properties of the non-linear DSGE model. I will first look at impulse response functions (IRFs) in response to a TFP shock. Then I will present an analysis of the average financial crisis event. Finally, I will show that the properties of the model are well in line with the empirical evidence.

1.3.2.1 Impulse Response Functions

I analyse the dynamic behaviour of some key variables in response to a 1 standard deviation TFP shock. Note that the variables start at their stochastic steady state level which is too far away from the constraint so that the associated non-linearities will not play a role in this generalised impulse response analysis. The effects of a positive TFP shock are as follows. Output, consumption and investment increase. Due to consumption smoothing the saver's savings increase as well, and as a consequence debt $-B_{t+1}$ accumulates. The increase in productivity will be associated with an increase in investment and capital accumulation. K_{t+1} and Q_t increase. In the short run, the total stock of capital Q_tK_{t+1} accumulates faster than debt $-B_{t+1}$, leverage therefore goes down initially. However, as can be seen in Panel (d) of Figure 1.8, the asset price response fades out quickly after the initial increase, it is not very persistent. After around 8 quarters the increase in borrowing outweighs the increase in total assets. Thus, in response to a positive TFP shock, leverage will initially decline for a short period of time and then increase with a lag of a few quarters. This in turn implies that leverage can reach very high levels if a sequence of positive TFP shocks (which will increase leverage after a while) is followed by a sequence of adverse TFP shocks (which increase leverage in the short run). As a consequence, the average financial crisis in the model will be triggered by a sequence of initially positive and then negative TFP shocks.

FIGURE 1.8: IMPULSE RESPONSES OF KEY VARIABLES TO A POSITIVE TFP SHOCK OF 1 ST.DEV.



Notes: In response to a positive TFP Shock of 1 st.dev., as depicted in Panel (a), Output expands, as depicted in Panel (b). This will be associated with an increase in capital accumulation, as depicted in Panel (c), investment, and asset prices, as depicted in Panel (d).

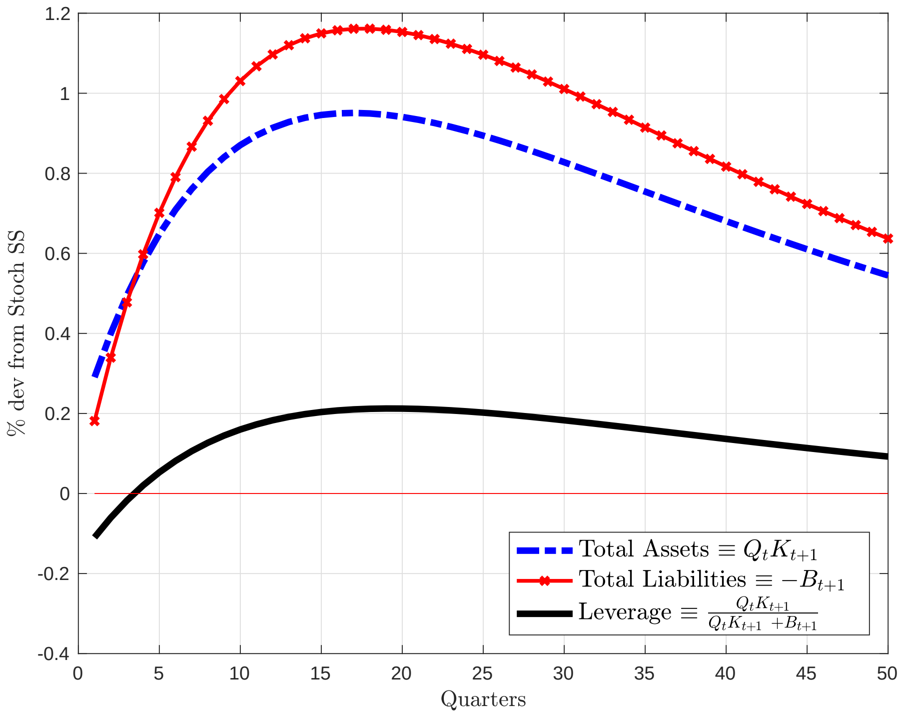
1.3.2.2 Financial Crisis Analysis

In order to generate the 'average financial crisis path' I simulate the model for 500000 periods and plot the median path of the respective variable 20 quarters before and after a crisis event. A 'crisis' is defined as the period $t = 0$ in which the collateral constraint holds with equality. I plot the crisis path together with a counterfactual path in which the same TFP process that caused the crisis was fed into a model in which there is no collateral constraint[37]. Thus, I can disentangle the 'financial crisis effects' (due to the collateral constraint) from the generally adverse effects of negative TFP shocks. Figure 1.10 shows the 'average crisis path' (the blue-straight line) and the counterfactual 'unconstrained' path (the red-dashed line).

The average financial crisis is triggered by a relatively long sequence of small positive TFP shocks followed by a few adverse TFP shocks. To some extent, the model is therefore able to replicate the empirical observation that financial crises occur out of prolonged boom periods.

[37]Borrowing in the 'always' unconstrained model is stabilised through the introduction of a tiny bond adjustment cost.

FIGURE 1.9: IMPULSE RESPONSES OF LEVERAGE AND ITS COMPONENTS TO A POSITIVE TFP SHOCK OF 1 ST.DEV.



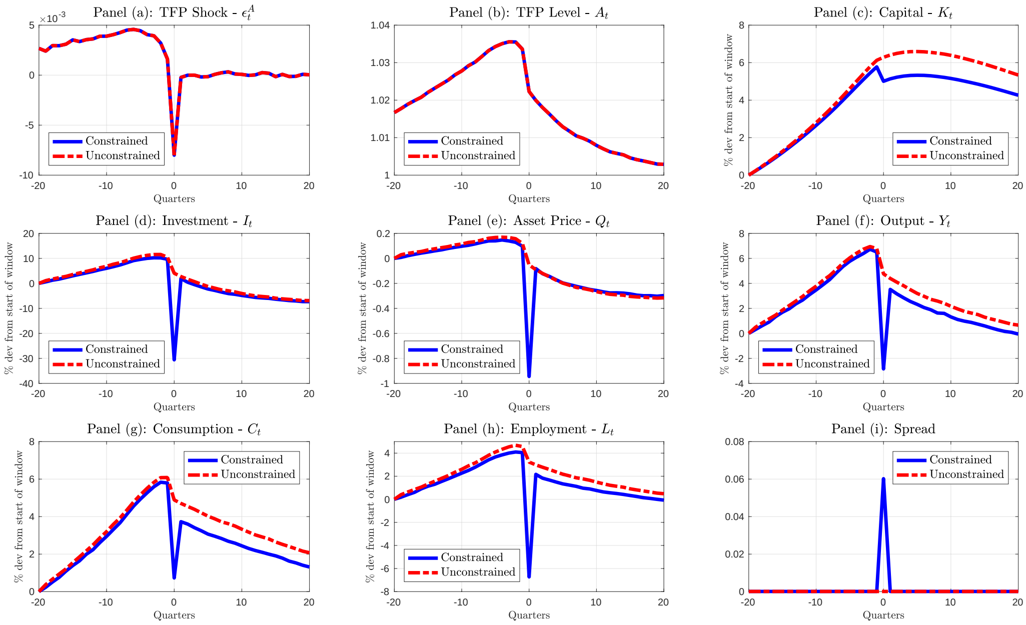
Notes: The magnitude of the expansion of asset prices and capital determines the expansion of collateral, and together with the response of borrowing, it pins down leverage. Initially, the collateral, $Q_t K_{t+1}$ expands more than borrowing, so that leverage declines. Since the asset price response fades out quickly, and since the accumulation of borrowing outweighs capital accumulation, the leverage response is persistently positive after a few quarters.

When the constraint binds there is a sharp decline in investment of around 30% with respect to the start of the window. This decline will lead to a drop in the capital stock K_{t+1} which causes a persistent post-crisis gap between the 'crisis path' and the 'unconstrained path'. Compared to the start of the window, output, consumption and employment decrease significantly. As illustrated above, there will be a spread of around 6% between the rate of return on capital and the interest rate when the constraint binds.

1.3.2.3 Empirical Performance of the Model

In Figure 1.11 I plot the US utilisation-adjusted TFP series in order to point out that the crisis patterns generated by the model are in line with the empirical evidence. In the DSGE model the crisis is triggered by a series of TFP shocks which are initially slightly positive and then negative (the negative TFP shock in the crisis period $\epsilon^A_{t=0}$ is roughly -0.75% which is not huge). This is not completely out of range when comparing it with the utilisation-adjusted TFP series (based on measures according to Fernald (2014)). Note that I do not want to make the point that TFP shocks caused the financial crisis of 2008 (or that it is the primary driver of macroeconomic fluctuations in general). Rather, the point I want to emphasise is that in

FIGURE 1.10: TYPICAL FINANCIAL CRISIS



Notes: In order to obtain the 'typical financial crisis' path I simulate the model for 500000 periods and plot the median of the 20 quarters before and after a crisis event (when the collateral constraint binds). I then collect the associated TFP shock series and feed it into a version of the model in which the borrowing constraint is completely absent (instead there is a tiny bond adjustment cost that helps determining debt levels). This 'unconstrained path' is plotted as the red/dashed line and it is a useful benchmark for assessing the effects of the binding collateral constraint.

my quantitative model a sequence of relatively mild shocks can trigger severe (and highly non-linear) crisis events under certain (leverage) conditions. In principle, other shocks, or combinations of shocks, could drive the model into regions of the state-space where crisis events occur. Moreover, it is noteworthy that a combination of positive and negative shocks is required, thus generating the typical boom-bust pattern observed around financial crises.

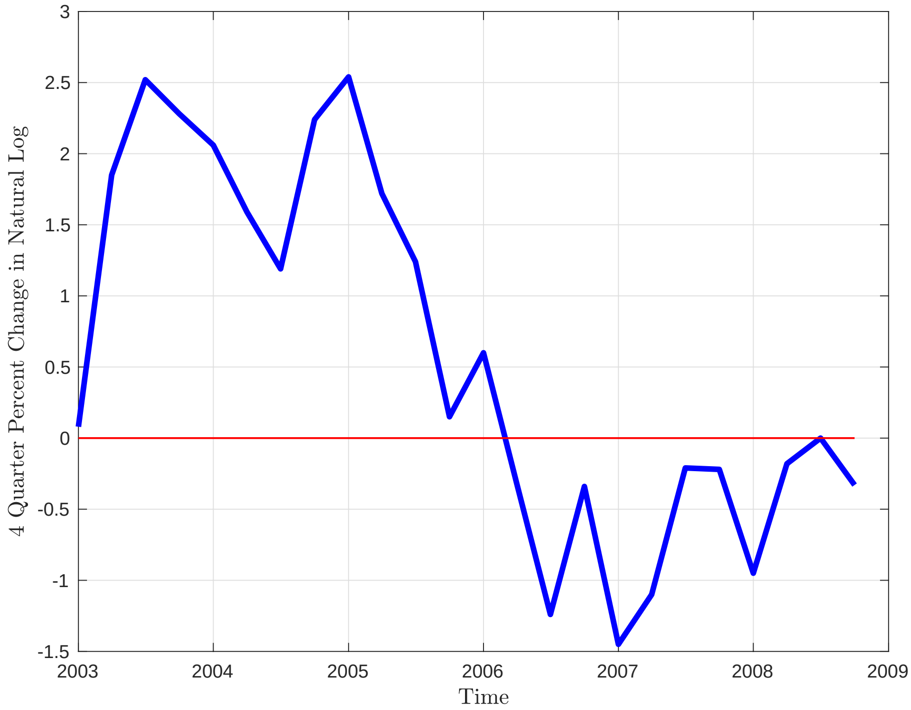
The investment boom-bust pattern generated by the quantitative model, depicted in Figure 1.10 is in line with the behaviour of investment in the US in the run-up to the crisis, depicted as the deviation from the cubic trend in the lower panel in Figure 1.1. Based on the start of the event window investment expands by around 10% and then declines sharply by around 30% so that the overall decline in investment is roughly 40%. However, compared to what has happened in the aftermath of the 2008/2009 recession my model predicts a more rapid recovery of investment.

1.3.3 Policy Interventions

Based on the intuition for policy interventions derived above in subsection 1.2.7.2, I now consider an 'optimised simple rule'[38] and report the corresponding welfare gains. Consider a tax $\tau_t^{K,SR}$ being charged on the purchases of claims on capital in the entrepreneur's budget

[38] A derivation and analysis of the 'joint optimal policy', taking into account the price stickiness friction when solving the planner problem, is left to future research efforts.

FIGURE 1.11: UTILISATION-ADJUSTED TFP-SERIES



Notes: The depicted utilisation-adjusted TFP-series (based on Fernald (2014)) expanded during the early and mid 2000s and started to decline in 2005. The slow-down in the growth rates of the utilisation-adjusted TFP series persisted throughout the crisis years.

constraint

$$P_t c_{t,e} + \left(1 + \tau_t^{K,SR}\right) Q_t^n k_{t+1} + b_{t+1} \quad \leq \quad Q_{t-1}^n k_t R_t^K + b_t R_{t-1}^n - T_t^\tau . \tag{1.3.19}$$

The design of the simple rule is motivated by the real optimal taxation scheme derived above. The rule I consider takes the following form

$$\tau_t^{K,SR} = \gamma \left(\mathbb{E}_t \mu_{t+1} - \mu_t\right). \tag{1.3.20}$$

Combining (1.3.6) and (1.3.7) one can express the Lagrange multiplier μ_t in terms of the spread between the gross return on capital and the gross interest rate. One can therefore think of μ_t as being observable

$$\mu_t \quad = \quad \frac{\beta_e}{(1-\theta)} \mathbb{E}_t \left[U_{C_{t+1,e}} \frac{P_t}{P_{t+1}} \left(R_{t+1}^K - R_t^n \right) \right]. \tag{1.3.21}$$

In analogy to the real constrained-efficient case, this simple rule would imply a tax on purchases of claims on capital if the collateral constraint is not binding in period t, and a subsidy if it is binding in t. In order to quantify the welfare effects of this policy intervention I calculate the consumption equivalent welfare gains of switching from regime n ('no policy') to regime p ('policy'). The consumption equivalent $\eta(\mathcal{S}_t)$ measures by how much the regime n consumption would have to be increased to make the saver and the entrepreneur indifferent with being in regime p

$$\mathbb{E}_0\left[\sum_{t=0}^{\infty}\beta_s^t U(C_{t,s}^n(1+\eta_s(\mathcal{S}_t)),L_t^n)\right] = \mathbb{E}_0\left[\sum_{t=0}^{\infty}\beta_s^t U(C_{t,s}^p,L_t^p)\right],$$
$$\mathbb{E}_0\left[\sum_{t=0}^{\infty}\beta_e^t U(C_{t,e}^n(1+\eta_e(\mathcal{S}_t)))\right] = \mathbb{E}_0\left[\sum_{t=0}^{\infty}\beta_e^t U(C_{t,e}^p)\right].$$

Regime p can be regarded as welfare-superior if $\eta(\mathcal{S}_t)) > 0$, because if $\eta(\mathcal{S}_t)) > 0$ it means that the 'no-policy-regime' consumption has to be increased to make the agent indifferent with being in the 'policy-regime'.

TABLE 1.2: EFFECTS OF POLICY

	Baseline	Simple Rule
Crisis Probability	1.008%	0.797%
Mean Dividend Welfare Equivalent $\eta_{t,e}$		0.059%
Mean Consumption Welfare Equivalent $\eta_{t,s}$		0.037%

Notes: Effects of Policy conducted via the optimised simple rule. I compare the baseline model ($\tau_t^K = 0$) with the one where the optimised simple rule ($\tau_t^K = \tau_t^{K,SR}$) is in place. All results are obtained through simulating the models (with and without policy) for 500000 periods.

I solve and simulate the model with the simple rule for various values of γ and calculate the sum of the values $V^s(B_t^s,\mathcal{S}_t)$ and $V_e(B_t^s,\mathcal{S}_t)$ to look for the value that maximises this sum. I find that a value of $\gamma = 0.001$ maximises this sum. Since both, the saver-households and the entrepreneurs are representative agents in continua with unit-mass, the sum of the values is essentially equivalent to a weighted-average of agents welfare in which both agents receive equal weight. In Table 1.2 I summarise the welfare effects of the policy intervention. With the optimised simple rule in place, the crisis occurs less frequent when simulating the model. The policy under consideration implements a tax on asset purchases in non-crisis times, $\tau^{K,SR} = \gamma\mathbb{E}_t\mu_{t+1} > 0$ which puts a wedge between the return on assets and the interest rate at which the entrepreneur funds himself. Capital and debt accumulation are slightly reduced under this macroprudential tax.

The effect of the debt reduction dominates so that leverage under the simple rule is lower on average. The trade-off for the policy maker is as follows. While a macroprudential policy intervention will reduce leverage and therefore the crisis frequency, it will also reduce investment and therefore output and consumption. Thus, it is not optimal to fully eliminate the occurrence of the crisis through macroprudential policy since the cost in terms of depressing investment outweighs the benefits of reducing the crisis frequency.

In addition to the frequency of the crisis, the severity of the crisis is also reduced since the policy maker subsidises asset purchases in the crisis period, $\tau_t^{K,SR} < 0$ so that asset prices are stabilised. Moreover, the reduction of investment and capital supply ex ante has also stabilised asset prices in the crisis period (as illustrated in Figure 1.4). Reductions in the severity and the frequency of the crisis are associated with mild consumption equivalent welfare gains for the saver and for the entrepreneur.[39]

[39]The saver-household's consumption equivalent welfare gain is smaller than the entrepreneur's because due to the reduced severity of the crisis, the drop in employment is less pronounced, the saver-household will 'enjoy less leisure' and this has slightly adverse effects for the consumption equivalent welfare metric.

1.4 Conclusion

In this paper I study the relationship between investment and collateral. I derive normative regulatory implications for the time before and during financial crisis events. The key insight of the paper is that there is a close relation between investment and collateral since investment affects the stock of capital goods and their price. The pecuniary externality that arises in my model provides a motivation for the regulation of investment and asset purchases ex ante and ex post.

I study a setting in which conventional macro-modelling assumptions on capital adjustment costs give rise to an asset price that is negatively correlated with previous-period capital. Since this asset price is a component of leverage, and since atomistic agents who are subject to collateral constraints ignore the effects their individual investment decisions have on this asset price, a situation may arise in which the privately optimal level of investment ex ante exceeds the social optimum. Once collateral constraints become binding, entrepreneurs are constrained in their ability to obtain funds and they reduce their demand for purchases of claims on capital, and hence investment, below the social optimum. Thus, a key feature of the model is that there can be overinvestment in periods of loose credit before the crisis breaks out, and a shortfall of investment in periods of tight credit conditions. There is room for a policy intervention because atomistic agents do not internalise the effects of their individual investment decisions on asset prices and hence on the collateral constraint. A policy maker can tax and subsidise investment decisions such that the private and social benefits of investment coincide.

In the paper, I first develop the key mechanism in the context of a simple 3-period model. I then embed this into a non-linear New Keynesian DSGE model and show that the model can match the data well. Importantly, the model can generate crisis patterns that are in line with the empirical evidence. A sequence of initially positive and then modestly adverse shocks can trigger highly non-linear boom-bust patterns. I then use the New Keynesian DSGE model for policy analysis and show that a simple rule for macroprudential policy and crisis interventions motivated by the findings of the 3-period model is associated with small positive welfare gains. The paper therefore makes an important contribution to the debate on macro-financial modelling of macroprudential policy and the incorporation of financial stability considerations into monetary policy frameworks. In contrast to many recent macro-financial DSGE models, my models addresses the important issues of endogeneities and non-linearities associated with financial crises.

In future extensions of the present paper I intend to (i) include more shocks, (ii) conduct more policy experiments and (iii) explicitly study the joint optimal policy for ex ante macroprudential policy and conventional monetary policy. While many agree that conventional monetary policy should not be used to address financial stability considerations[40] others have argued that a separation between the objectives and instruments of monetary policy and macroprudential policy is hardly possible and that both spheres interact with each other[41]. More research in this direction is needed.

While my non-linear DSGE model developed in the present paper does a solid job in replicating the patterns of key economic variables such as investment before and during the financial crisis of 2007/08, the model does not explain satisfactorily why the recovery since the Great Recession has been so slow. Future research efforts are needed to provide a better explanation for the slow recoveries often associated with financial recessions since the potential benefit of macroprudential policies may be underestimated otherwise. In this

[40] Among others, Lars Svensson has a series of papers in which he argues against using the nominal interest rate as a tool to address financial stability concerns (Svensson (2016), Svensson (2017b), Svensson (2017a)).

[41] Proponents of the this integrated perspective, such as Markus Brunnermeier among others, argue that the objectives of price stability and financial stability and the instruments and transmission mechanism of monetary policy and macroprudential policy are so closely interwoven that monetary policy cannot solely focus on the narrow objective of price stability. Indeed, macroprudential measures affect lending and thus they also affect money creation and potentially price stability.

respect, models with endogenous growth components[42], models with multiple equilibria[43] and quantitative OLG models with collapsing rational bubbles[44] are promising fields of ongoing research.

[42] A persistent shortfall of aggregate demand could lead to a slowdown of innovation and TFP growth. Refer to Queralto (2016) for a recent contribution along those lines.

[43] Boissay et al. (2016) develop a model with asymmetric information in the interbank market. A sequence of small shocks may drive the economy into a region of the state-space with multiple equilibria. Some of these equilibria are characterised by interbank market freezes, credit crunches and a resulting prolonged recession. Papers such as Arifovic et al. (2018), Aruoba et al. (2018) and Jarocinski and Mackowiak (2017) interpret the crisis and subsequent persistent slump with an equilibrium path converging to a steady state in a liquidity trap. Other recent contributions that involve models with multiple equilibria were made by Benigno and Fornaro (2018) and Gertler et al. (2017b).

[44] Recent contributions in this field have been made by Galí (2014), Galí (2017a), Martin and Ventura (2016) and Larin (2016).

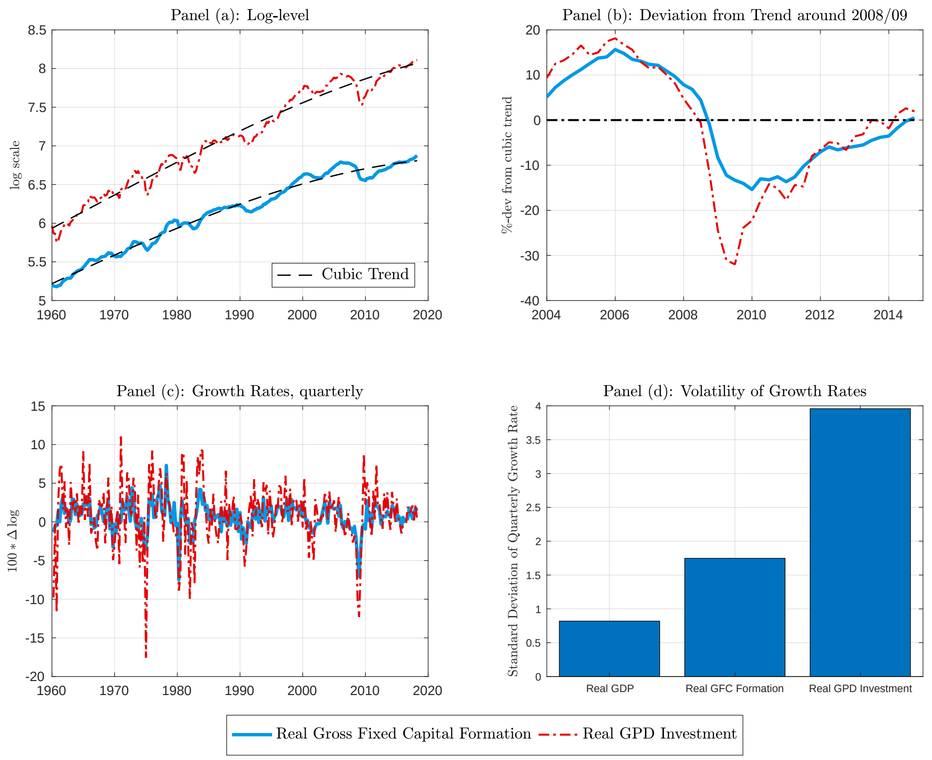
1.5 Appendix of Chapter 1

1.5.1 GPD Investment versus Gross Fixed Capital Formation

In the Introduction in Section 1.1 I visualised and discussed the deviation of real GPD investment from its trend. Moreover, I highlighted the comparatively high degree of volatility of investment relative to output.

An alternative measure of investment is the 'Real Gross Private Capital Formation'. This series is often used as an empirical counterpart of investment I_t in the estimation of DSGE models. In this appendix section, I highlight that the key insights from Figure 1.1 and Figure 1.2, and therefore the motivation of this project, are still valid when using this alternative measure of investment.

FIGURE 1.5.1: US REAL GROSS PRIVATE DOMESTIC INVESTMENT



Source: FRED

Note: Panel (a) depicts the US real Gross Private Domestic (GPD) Investment series (GPDIC1) in billions of chained dollars, quarterly and seasonally adjusted and the real gross fixed capital formation (USAGFCFQDSMEI). Panel (b) depicts the deviation of the measures of investment from their cubic trend 20 quarters before and after the trough of the Great Recession in 2009Q2. Panel (c) and (d) depict the volatilities of the measures of investment and output.

Figure 1.5.1 Panel (a) illustrates that GPD investment is a broader measure[45] of investment activity than gross fixed capital formation. Both measures of investment were elevated in the run to the crisis and then sharply contracted. Moreover, both measures of investment

[45] GPD investment entails non-residential investment and residential investment in addition to the change in firm inventories in a given period.

are much more volatile than output. The investment measure associated with gross fixed capital formation is twice as volatile, GPD investment is five times as volatile as output.

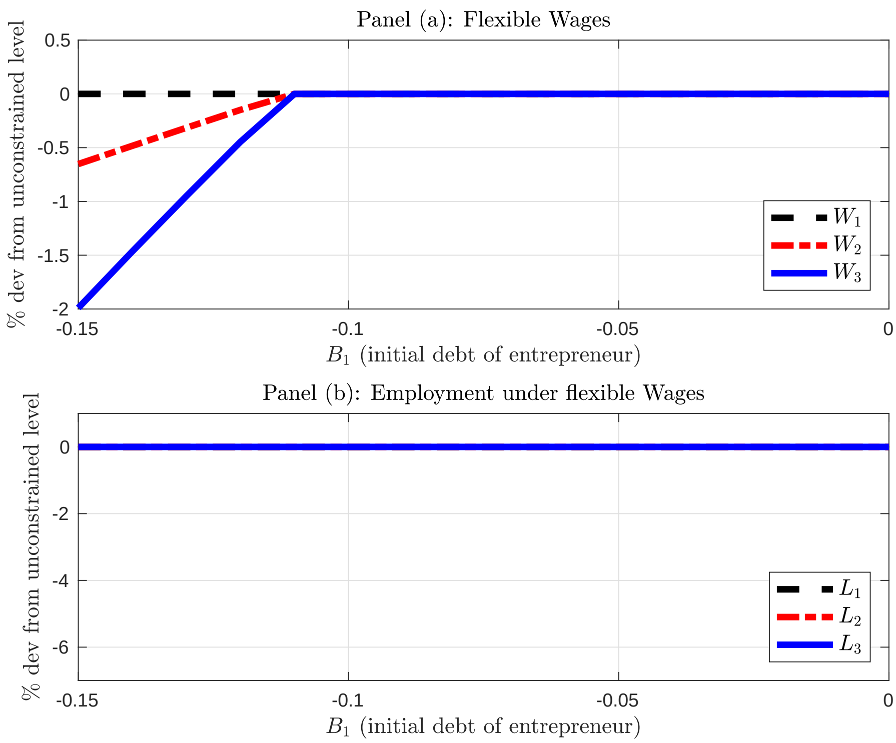
1.5.2 The Role of Nominal Rigidities

In the numerical illustration of the baseline model, in Section 1.2.8, I showed the policy functions of several important variables. In the region of the state-space in which the borrowing constraint in time period 2 would be binding, the variables in period 1 are also affected. However, there was no significant drop in investment, capital and output in the crisis period 2. One way to show that a binding constraint can translate into a more severe drop would be to assume nominal rigidities, as I did in the quantitative section of the paper. In order to highlight this point, I will outline an extension of the baseline model in which I introduce wage stickiness[46].

1.5.2.1 Nominal Rigidities in the Baseline Model

In the baseline model described above, prices and wages are fully flexible. In the region of the state-space in which the collateral constraint binds, wages decline. Employment is fixed, since I assumed a fixed labor supply for simplicity. In order to highlight the role

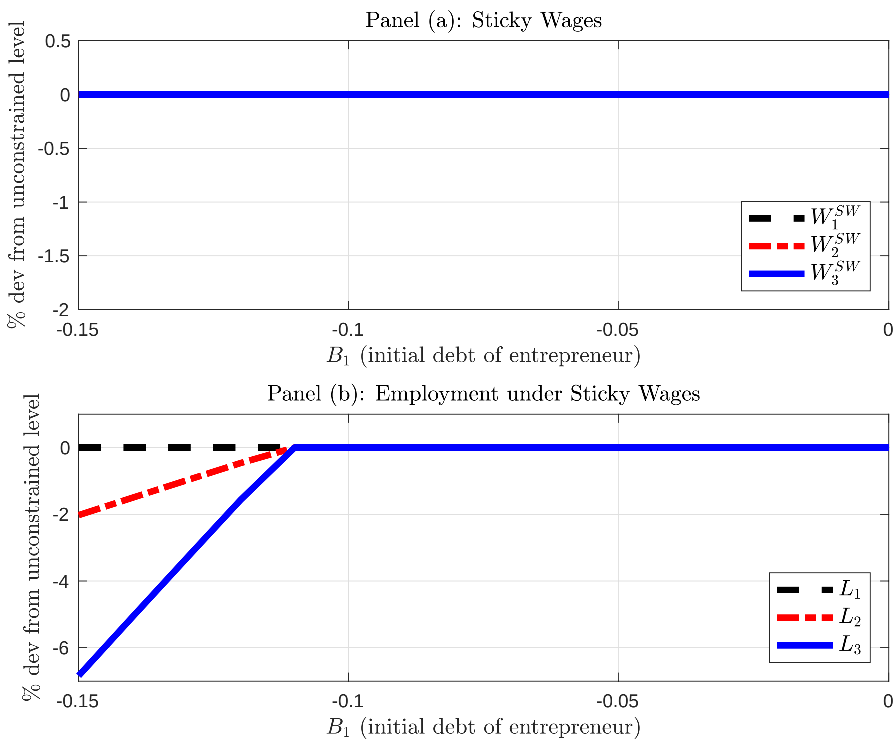
FIGURE 1.5.2: WAGES AND EMPLOYMENT UNDER FLEXIBLE WAGES



Notes: Panel (a): In the above described real baseline model wages are flat in the unconstrained region and decline in the constrained region of the state-space. Panel (b): Labor is in fixed supply in the real baseline model.

[46]It is easier to model wage stickiness in the context of the simple 3-period model. The intuition is equivalent to a model with price stickiness.

FIGURE 1.5.3: WAGES AND EMPLOYMENT UNDER STICKY WAGES



Notes: Panel (a): Under the assumption of wage stickiness and full wage inflation stabilisation, wages will now be completely flat. (b): In the extended model with full wage stickiness employment declines in regions of the state space in which the constraint binds.

of nominal rigidities for the severity of the crisis I will now extend the baseline model and assume that wages are sticky and subject to a downward rigidity constraint[47]

$$W_t = \gamma_t W_{t-1}. \tag{1.5.1}$$

This assumption captures a friction on wage adjustments and may possibly prevent the labor market from clearing. The equilibrium labor market condition will be given by

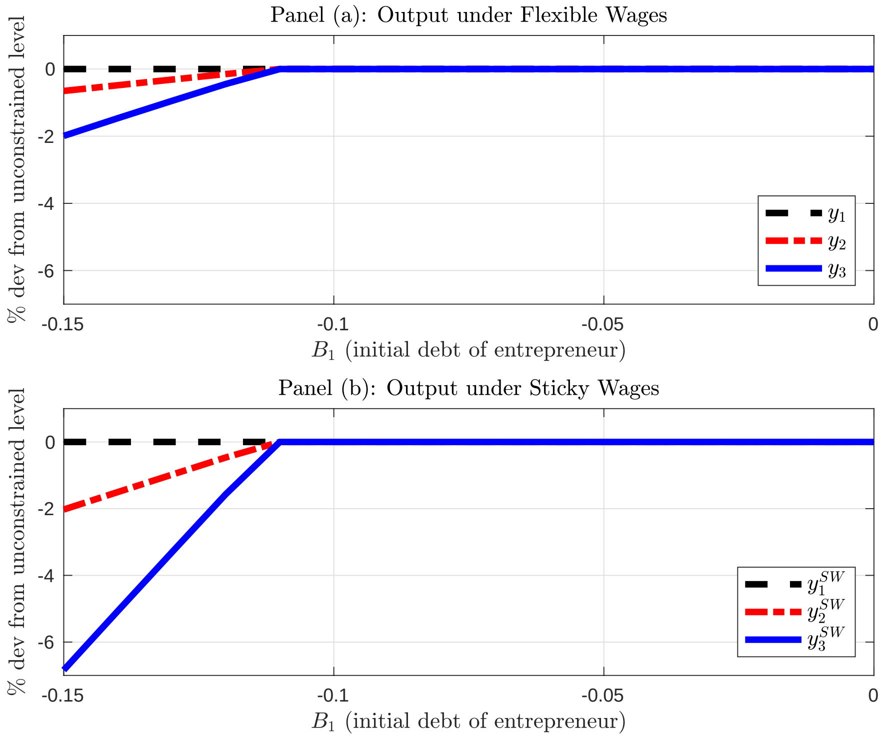
$$l_t \leq 1, \quad W_t \geq \gamma_t W_{t-1} \quad \text{with complementary slackness.} \tag{1.5.2}$$

If the constraint on wage adjustment binds, unemployment may arise. Monetary policy is characterised by the following simple rule

$$R_t = \bar{R}_t \left(\frac{\Pi_t}{\bar{\Pi}_t} \right)^{\phi_\Pi} \tag{1.5.3}$$

[47]In the numerical solution of the baseline model I will have to allow for two different values of γ in period $t = 2$ and period $t = 3$. This is due to the fact that variables such as capital and output and therefore also wages are not stable over time in this simple 3-period model. They are flat in the unconstrained state-space region, but over time they have different levels. It might be possible to find calibrations and initial endowments such that they are stable, however, since the baseline model is not meant to generate realistic quantitive insights but merely intuition it should not matter that the inflation targets γ_1 and γ_2 for period $t = 2$ and $t = 3$ are different.

FIGURE 1.5.4: OUTPUT UNDER FLEXIBLE AND STICKY WAGES



Notes: Panel (a): Output declines moderately under flexible wages. Panel (b): The decline is stronger in the presence of wage stickiness.

where inflation is defined as wage inflation

$$\Pi_t \equiv \frac{W_t}{W_{t-1}}.$$

The target interest rate $\bar{R}_t$ is the gross nominal rate consistent with implementing the inflation target $\Pi_t = \bar{\Pi}_t$ and since I assume for simplicity that $\phi_{\Pi} \to \infty$ inflation is always at the target. The consequence of the imperfect wage adjustment will be that employment declines in regions of the state-space in which the constraint binds. A comparison of Figure 1.5.2 with Figure 1.5.3 illustrates that if wages cannot adjust in the crisis region, employment will decline. The decline in employment will amplify the adverse effects of the binding leverage constraint since it further reduces output. In Figure 1.5.4 I compare the policy functions for output in the real baseline model and in the extended baseline model with wage rigidities. The latter generates a more severe drop in output.

1.5.2.2 A Note on Real Models with Occasionally Binding Constraints and GHH Utility

In order to highlight the relevance of the financial friction in the context of the DSGE model, I have plotted the crisis path in Figure 1.10 together with a benchmark model in which the same shock sequence that generated the crisis path has been fed into a model in which there is no borrowing constraint. This is an important exercise since it allows disentangling the effect of the shock from the effect of the binding borrowing constraint.

Many authors have introduced working capital components into their leverage constraints in order to allow for a contemporaneous response of output to the binding constraint. In the context of a real model, such an augmented leverage constraint could look as follows

$$-B_{t+1} + \phi R_t(W_t L_t) \quad \leq \quad \theta Q_t K_{t+1} \tag{1.5.4}$$

so that a fraction ϕ of the wage bill has to be borrowed and paid at the beginning of the period. If the borrowing constraint becomes binding, then the limited availability of credit will also constrain this working capital component and lead to an immediate response of employment and therefore output in the crisis period.

In the absence of such a working capital component it can easily be shown that output and employment levels are entirely determined by the capital and the TFP state-variable. Consider that output is defined as

$$Y_t \quad = \quad A_t K_t^{\alpha} L_t^{1-\alpha} \tag{1.5.5}$$

where A_t and K_t are exogenous and endogenous state-variables. Under the preferences put forward by Greenwood et al. (1988) (GHH), the following relationship holds

$$\chi L_t^{\varphi} \quad = \quad (1-\alpha)\frac{Y_t}{L_t} \tag{1.5.6}$$

which implies that employment and output are determined by the TFP and the capital state variables A_t, K_t.

$$L_t \quad = \quad \left[\frac{(1-\alpha)}{\chi} A_t K_t^{\alpha}\right]^{\frac{1}{\varphi+\alpha}} \tag{1.5.7}$$

$$Y_t \quad = \quad A_t K_t^{\alpha} \left[\frac{(1-\alpha)}{\chi} A_t K_t^{\alpha}\right]^{\frac{1-\alpha}{\varphi+\alpha}} \tag{1.5.8}$$

In the New Keynesian DSGE model above, this is not true anymore since the intermediate good price P_t^m enters the marginal product of labor

$$\chi L_t^{\varphi} \quad = \quad P_t^m (1-\alpha)\frac{Y_t}{L_t}. \tag{1.5.9}$$

The crisis pattern in a real model with GHH utility would thus primarily[48] be driven by the exogenous shock process. The suitability of the GHH utility specification is also discussed in a recent study by Auclert and Rognlie (2017) in the context of New Keynesian models.

1.5.3 Non-linear Policy Functions and the Lack of Persistence

The policy functions in the DSGE model are highly non-linear. The amount of borrowing $B_{t+1,s}$ is increasing in the state variable $B_{t,s}$, previous period borrowing. However, when capital K_t is very low, leverage will be high, until a point where the constraint binds and the policy function folds down. In other words, the policy function for borrowing $B_{t+1,s}$ is increasing in regions of the state-space in which leverage is low. Once the leverage limit is reached, borrowing is constrained and the policy function for borrowing $B_{t+1,s}$ is decreas-

[48] There would be a tiny difference between the occasionally-constrained and the always-unconstrained path due to the potentially contractionary effects of increased precautionary savings when approaching regions of the state-space in which the leverage constraint binds.

ing.[49] The policy function for the real asset price Q_t is flat in regions of the state-space in which the constraint is not binding and sharply decreasing once the leverage limit is reached. The declining asset price and the decreasing availability of funds are connected. The more the asset price declines, the tighter the borrowing constraint gets. A tighter leverage constraint will translate into even less borrowing and less capital demand which in turn further depresses asset prices. This asset price deflation spiral gives rise to the non-linearities associated with the crisis.

However, when simulating the model, the state-space in which the policy functions fold down significantly is hardly reached.[50] Moreover, once the constraints binds for one period, the model will have moved away from the non-linear region back into the normal 'flat' region of the state-space. Thus, the model is hardly able to generate a persistent crisis effect from the binding constraint. The observed persistence is entirely due to the drop in investment and the associated adverse effect on the capital stock. Given the empirical evidence of slow recoveries after financial recessions and the debate on hysteresis effects, the lack of persistent effects of crises constitutes a major shortcoming in the context of occasionally binding constraint models.

1.5.4 Policy Function Algorithm for Solving the DSGE Model globally

I apply a standard policy function iteration procedure to solve the DSGE model globally. I use the toolkit provided by Richter et al. (2014) and mostly follow their approach. In the associated paper they also provide detailed discussions of their material for solving models via policy function iteration.

The first step of the solution procedure is to obtain a first guess of policy functions. It turns out that starting with a good initial guess is quite important, since otherwise the policy functions would not converge or it might take very long. I use the software package *dynare* to obtain an initial guess. I set up a version of the model in which the borrowing constraint is not present. Following Schmitt-Grohe and Uribe (2003), borrowing is pinned down in this model through the introduction of a tiny bond adjustment cost. It would also be possible to start with an initial guess derived from the always binding case, but it turns out that starting from the unconstrained case is more accurate and faster.

The initial guess of the policy function vector is defined as $\Gamma^0 = \{\Pi^0, K^0, B^0, L^0\}$. There are four policies over which one has to iterate since there are four relevant first-order optimality equations containing expectations of next period variables: (i) the saver consumption Euler equation, (ii) the entrepreneurial consumption Euler equation, (iii) the entrepreneurial capital-investment Euler equation and (iv) the inflation equation. At every point in the state-space one seeks to find the arguments that minimise the Euler residuals associated with the aforementioned Euler equations. In order to obtain these residuals one has to calculate the expectational components in these Euler equations which requires interpolation and the application of numerical integration methods such as the Trapezoid rule. The arguments that minimise the Euler residuals are then stored and used in the next iteration round $\Gamma^1 = \{\Pi^1, K^1, B^1, L^1\}$. I iterate until the absolute distance between the policy functions of two iteration steps is below a tolerance level of 1e-8.

[49]When solving the model it is convenient to work with positive values which is why I choose $B_{t,s}$ instead of B_t.

[50]Note for example that the asset price Q_t only declines by roughly 1% point in the crisis as depicted in Figure 1.10. The policy function for Q folds down by more than 20%, but this extreme region is never reached in the simulation.

1.5.5 Simple Rule Optimization

Recall the period budget constraint of the entrepreneur, including that tax/capital on purchases of claims on capital

$$P_t c_{t,e} + (1 + \tau_t^{K,SR}) Q_t^n k_{t+1} + b_{t+1} \quad \leq \quad Q_{t-1}^n k_t R_t^K + b_t R_{t-1}^n - T_t^\tau.$$

And the simple rule for the tax rate $\tau_t^{K,SR}$. The design of the simple rule is motivated by the real optimal taxation scheme derived in the baseline model.

$$\tau_t^{K,SR} = \gamma\left(\mathbb{E}_t \mu_{t+1} - \mu_t\right).$$

The Lagrange multiplier μ_t and its expectation are observable to the extent that they correspond to the current or expected interest rate spread

$$\mu_t \quad = \quad \frac{\beta_e}{(1-\theta)} \mathbb{E}_t \left[U_{c_{t+1,e}} \frac{P_t}{P_{t+1}} \left(R_{t+1}^K - R_t^n \right) \right] \tag{1.5.10}$$

I solve and simulate the model with the simple rule for various values of γ and calculate the sum of the values $V^s(B_t^s, \mathcal{S}_t)$ and $V_e(B_t^s, \mathcal{S}_t)$ to look for the value that maximises this sum. I find that a value of $\gamma = 0.001$ maximises this sum. Since both, the saver-households and the entrepreneurs are representative agents in continua with unit-mass, the sum of the values is essentially equivalent to a weighted-average of agents welfare. Even though the level of saver consumption is more than ten times higher than entrepreneurial dividend consumption in the stochastic steady state, both values should be weighted equally when optimising over γ since both types of agents are of unit-mass.

A simple rule that is associated with too strong an intervention will not be welfare improving any longer. The cost from reducing investment ex ante too much and from increasing the crisis probability too much through an excessive crisis intervention outweigh the benefits of reducing leverage ex ante and stabilising asset prices.

1.5.5.1 Effects of Policy on Investment

If the optimal simple rule is implemented, the crisis will occur less frequently, as outlined and argued above. When solving and simulating the model with the optimised simple rule, I find that investment is slightly reduced ex ante and declines less during the crisis. Since the crisis occurs less frequent in the simulation with policy a more severe shock sequence will be required to drive the model into the crisis. This has to be taken into account when comparing the two investment crisis paths.

Chapter 2

The Interaction of Macroprudential and Monetary Policy

2.1 Introduction

In the aftermath of the financial crisis of 2007/08 there has been a significant increase in macroprudential regulation. The objective of macroprudential policy is to stabilise 'the financial system as a whole'. Its purpose is to prevent the build-up and materialisation of systemic risk, to reduce the probability of a financial crisis and mitigate its costs if it occurs.

The appropriate role of macroprudential policy and financial stability considerations in the context of monetary policy frameworks is still a matter of debate. The post-crisis consensus view seems to be that monetary policy should be kept in charge of inflation stabilisation and that targeted macroprudential instruments should respond to financial stability considerations. According to this view, the two policy fields should have their own explicit objectives, they should be conducted in a separate albeit coordinated fashion.[1]

Some authors have argued that the separation between the objectives is impossible and that the instruments of one policy field will inevitably interfere with the objective of the other. Some even call into question the normative dimension of the 'separation principle', arguing that conventional monetary policy should respond to financial stability considerations.[2]

The interaction between macroprudential regulation and monetary policy motivates the need to develop models that speak to the positive and normative questions of how macroprudential policy interacts with monetary policy. To address these question, I develop a model that allows me to assess how macroprudential policy affects the role of monetary policy, and vice versa. I extend a real model by Gertler et al. (2012) into a New Keynesian

[1] A prominent proponent of the 'separation view', among others, is Lars Svensson (Svensson (2017e), Svensson (2017c), Svensson (2017d)).

[2] The proponents of this view argue that loose monetary policy and low interest rates lead to excessive credit growth, leverage and the build-up of systemic risk. A remedy to prevent these developments would then be tighter monetary policy and higher interest rates.

version in which banks can fund their risky investment activities either with non-state-contingent debt or with state-contingent outside equity. Equity provides the bank with insurance value since the cost of equity moves in conjunction with the risky return on its assets. Bankers are subject to an incentive compatibility constraint which requires that the value of running the bank has to be at least as high as the value of diverting a fraction of their assets. The presence of an asset price in the constraint gives rise to a pecuniary externality. Bankers do not internalise that the adverse effects of binding constraints could be mitigated if the degree of equity funding was higher. In the context of this model, macroprudential policy can improve welfare through incentivising banks to increase their equity-to-assets ratio. I show that a conventional monetary policy reaction function with standard coefficients is generally welfare-maximising. In this paper, I assume that the monetary authority has the mandate to stabilise inflation. Thus, the reaction function under consideration in the model does not contain financial variables.[3]. Only in the case of low risk, insufficient self-insurance by banks and in the absence of macroprudential policy should monetary policy target inflation more aggressively.

The remainder of the paper is organised as follows. In section 2.2 I introduce the model and I describe in detail how the endogenous bank balance sheet determination with two types of liabilities affects the economy. In section 2.3 I analyse how monetary policy and macroprudential policy interact.[4] In section 2.4 I conclude.

2.1.1 Related Literature

My paper is closely related to Gertler et al. (2012), de Groot (2014) and Liu (2016). The difference between my paper and Gertler et al. (2012) and Liu (2016) is that I develop a New Keynesian model to study monetary policy. While de Groot (2014) also extended the model by Gertler et al. (2012) into a New Keynesian framework, he omitted macroprudential policy. In contrast to de Groot (2014), I introduce macroprudential policy and study its effects. I am thus able to analyse the interaction of these two policies in the context of a model in which there is a 'role for macroprudential policy'.[5]

Gertler et al. (2012) put forward a real DSGE model in which banks can fund themselves with non-state-contingent debt and state-contingent equity. On the asset side banks hold a representative asset which yields a risky return. In their model, outside equity issuance tightens the bank's incentive compatibility constraint and restricts its ability to raise funds. Gertler et al. (2012) introduce an agency problem in which bankers have an incentive to abscond with bank assets. At the margin, the authors assume, it is easier for a banker to expropriate funds if outside equity accounts for a larger share of the bank's balance sheet. However, since the returns on outside equity are state-contingent it provides a hedging value against fluctuations in the returns of the risky asset.[6] The trade-off between debt and outside equity issuance makes bank risk exposure an endogenous choice. Since risk-perceptions matter for the endogenous determination of the bank's liability composition, the model is solved around a risk-adjusted steady state[7]. Macroprudential policy in Gertler et al. (2012) incentivises banks to increase their outside equity issuance. This intervention improves the resilience of the banking system and dampens fluctuations in asset prices and economic activity.

[3] In future extensions I intend to consider a variety of interest rate reaction functions featuring financial variables.

[4] There is an extensive Appendix associated with this section that shows the responses and steady state levels of various variables in the model.

[5] Many medium-scale DSGE models that *feature* macroprudential policy have no role for it in the sense that it is introduced in an ad-hoc fashion. Moreover, there is a large literature that describes macroprudential policy as exchange rate interventions in the context of open economy models. In Europe and the US macroprudential policy typically takes the form of bank capital based minimum requirements which are implemented so that banks raise their capital/equity levels.

[6] If the liability side of the balance sheet was largely composed of non-state contingent debt, fluctuations in the return on assets would have to be absorbed by the banks net worth.

[7] See Coeurdacier et al. (2011) and de Groot (2013) for details on the methodology.

de Groot (2014) builds on Gertler et al. (2012) and develops a monetary extension of their framework. He examines how monetary policy affects the riskiness of the banking system's aggregate balance sheet. He finds that banks reduce their reliance on debt finance and decrease leverage when monetary policy shocks are prevalent. If monetary policy responds to movements in bank leverage or to movements in credit spreads it will incentivise banks to increase their use of debt finance and increase leverage. In contrast to Gertler et al. (2012), de Groot (2014) does not incorporate the direct regulation of the financial sector into his monetary framework. I address this gap in the literature.

My paper is related to the emerging strand of literature that analyses the interaction between monetary policy and financial stability considerations in the context of macro-financial DSGE models. Recent examples of this literature are Dellas et al. (2015), Levine and Lima (2015), Schlaepfer (2016), Cecchetti (2016), Rubio and Carrasco-Gallego (2016), Curdia and Woodford (2016), Gertler et al. (2016), Gertler et al. (2017a), Nikolov et al. (2017), Cesa-Bianchi and Rebucci (2017), Laseen et al. (2017), Kiley and Sim (2017), Collard et al. (2017), Agur and Demertzis (2018) and Laureys and Meeks (2018). The key difference of my paper with respect to those mentioned is the endogenous bank balance sheet determination that hinges on the availability of two liability types and the presence of risk. A pivotal role for risk is also found in the studies by Adrian and Boyarchenko (2012), Adrian and Liang (2018), Duarte and Adrian (2017) and Abbate and Thaler (2018). Some studies in the literature on the interaction between macroprudential policy and monetary policy focus on particular aspects such as the role of the housing sector (Gelain et al. (2013), Rubio (2016), Alpanda and Zubairy (2017)), the role of the shortage in safe assets (Begenau (2015)), liquidity traps (Korinek and Simsek (2016)) and bailouts (Bianchi (2016)).

My paper is also related to a previous literature on monetary policy and bank capital. In the context of a simple partial equilibrium model den Heuvel (2002) and den Heuvel (2006) address how bank capital and its regulation affect the role of bank lending in the transmission of monetary policy.

Moreover, my paper is related in a wider sense to the literature on macroprudential policies in which the focus is on open economies, exchange rate interventions and capital controls. Examples of this literature would be Fornaro (2015), Ottonello (2015), Mendoza (2016).

2.2 The Model

I develop a New Keynesian extension of Gertler et al. (2012) along the lines of de Groot (2014). In contrast to de Groot (2014) my model also features macroprudential policy.

2.2.1 Households

The model is populated by a representative household with a continuum of members of measure unity. Following Gertler and Karadi (2011) and Gertler et al. (2012), it is assumed that within the household there are $1 - f$ 'workers' and f 'bankers'. Workers supply labor and return their wages to the household. Bankers manage a financial intermediary ('bank') and transfer the associated nonnegative dividends back to the household. Within the household family there is perfect consumption insurance. The only way for households to save is to supply funds to banks (they cannot acquire capital or directly fund non-financial firms). Apart from non-contingent risk-less short term debt ('deposits') banks also offer state contingent debt ('equity'). Gertler et al. (2012) refer to the latter as 'outside equity' in order to distinguish it from internally accumulated retained earnings (net worth or 'inside equity'). The availability of two types of bank liabilities and the distinction between 'outside' and 'inside' equity is a key feature of this model and will play an important role for macroprudential policy.

The lifetime utility of the household is given by the expected, discounted sum of period utilities following the specification by Greenwood et al. (1988)

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \frac{1}{1-\gamma} \left(C_t - hC_{t-1} - \chi \frac{L_t^{1+\varphi}}{1+\varphi} \right)^{1-\gamma}. \tag{2.2.1}$$

C_t denotes the consumption basket consumed by each household

$$C_t \equiv \left(\int_0^1 C_t(i)^{1-\frac{1}{\varepsilon}} di \right)^{\frac{\varepsilon}{\varepsilon-1}},$$

which comprises differentiated consumption goods $C_t(i)$ and where $\varepsilon > 1$ is the elasticity of substitution. L_t is the household's labor supply. β denotes the household discount factor, γ denotes the degree of risk-aversion, φ denotes the inverse Frisch elasticity, χ is the weight parameter associated with the disutility of labor supply and h is the habit parameter.

Households choose their consumption C_t, labor supply L_t, deposits D_t and outside equity E_t in order to maximise their life-time utility subject to the sequence of budget constraints for all time periods t and all states of the world. The budget constraint in real terms is given by

$$C_t + D_t + Q_t^E E_t \quad = \quad W_t L_t + T_t + R_t D_{t-1} + \left[Z_t + (1-\delta) Q_t^E \right] \Psi_t E_{t-1}, \tag{2.2.2}$$

where T_t is a transfer of net profits from banks and capital goods producers to the household[8] Z_t denotes the flow returns at time t from one unit of the bank's (capital) asset. Q_t^E is the associated price of outside equity. Since each unit of outside equity E_t is a claim to the future return of one unit of the security that the bank holds, there is a close relationship between the price and the rate of return on outside equity and the capital asset. As will be explained in detail below, Ψ_t denotes a capital quality shock. The resulting intra- and inter-temporal optimality conditions of the household are as follows

$$\mathbb{E}_t u_{C,t} W_t \quad = \quad \chi L_t^{\varphi} \left(C_t - hC_{t-1} - \chi \frac{L_t^{1+\varphi}}{1+\varphi} \right)^{-\gamma} \tag{2.2.3}$$

$$1 \quad = \quad \mathbb{E}_t \Lambda_{t,t+1} R_{t+1} \tag{2.2.4}$$

$$1 \quad = \quad \mathbb{E}_t \Lambda_{t,t+1} R_{t+1}^E, \tag{2.2.5}$$

where

$$u_{C,t} \quad \equiv \quad \left(C_t - hC_{t-1} - \chi \frac{L_t^{1+\varphi}}{1+\varphi} \right)^{-\gamma} - \beta h \left(C_{t+1} - hC_t - \chi \frac{L_{t+1}^{1+\varphi}}{1+\varphi} \right)^{-\gamma} \tag{2.2.6}$$

$$\Lambda_{t,t+1} \quad = \quad \beta \frac{u_{C,t+1}}{u_{C,t}}. \tag{2.2.7}$$

$$R_{t+1}^E \quad = \quad \frac{\left[Z_{t+1} + (1-\delta) Q_{t+1}^E \right] \Psi_{t+1}}{Q_t^E} \tag{2.2.8}$$

[8] These transfers matter since banker enter and exit in this economy. Exiting bankers transfer a dividend payment to the household, while newly entering bankers receive a 'start-up' endowment.

2.2.2 Non-financial Firms

There are two types of non-financial firms: intermediate goods producers and capital goods producers.

2.2.2.1 Intermediate Goods Producers

Intermediate goods producers produce intermediate output Y_t^i using aggregate capital K_t and aggregate hours L_t

$$Y_t^i \quad = \quad (K_t)^{\alpha} L_t^{1-\alpha}, \quad 0 < \alpha < 1, \tag{2.2.9}$$

The optimality condition of the intermediate goods firm with respect to labor delivers the labor demand schedule (2.2.10). The optimality condition with respect to capital delivers the gross profit per unit of capital[9] held by the firm (2.2.11)

$$W_t \quad = \quad P_t^m (1-\alpha) \frac{Y_t^i}{L_t} \tag{2.2.10}$$

$$Z_t \quad = \quad \frac{P_t^m Y_t^i - W_t L_t}{K_t} = P_t^m \alpha \left(\frac{L_t}{K_t} \right)^{1-\alpha} \tag{2.2.11}$$

where

$$P_t^m \equiv \frac{P_t^i}{P_t}.$$

The aggregate price index P_t is defined as a CES function of individual prices P_t^i

$$P_t \equiv \left[\int_0^1 P_t(i)^{1-\varepsilon} di \right]^{\frac{1}{1-\varepsilon}},$$

The change in the aggregate price index P_t relative to the previous period will be defined as gross inflation Π_t

$$\Pi_t \quad \equiv \quad \frac{P_t}{P_{t-1}}. \tag{2.2.12}$$

2.2.2.2 Capital Producers

Capital good producers produce new units of capital using final good output. They are subject to a convex investment adjustment cost f$(\cdot)$. The capital good producing firm then sells the new capital to the intermediate good producing firm at price Q_t^K. The inter-temporal optimisation problem[10] is given by

$$\max \mathbb{E}_0 \sum_{t=0}^{\infty} \Lambda_{t,t+1} \left(Q_t^K I_t - \left[1 + f\left(\frac{I_t}{I_{t-1}} \right) \right] \right).$$

The resulting optimality condition can be interpreted as a capital supply schedule. Equation (2.2.13) indicates that the price of a new unit of capital is equal to the marginal cost of producing capital

$$Q_t^K \quad = \quad 1 + f\left(\frac{I_t}{I_{t-1}} \right) + \frac{I_t}{I_{t-1}} f'\left(\frac{I_t}{I_{t-1}} \right) - \mathbb{E}_t \Lambda_{t,t+1} \left(\frac{I_{t+1}}{I_t} \right)^2 f'\left(\frac{I_{t+1}}{I_t} \right). \tag{2.2.13}$$

[9] The gross profit per unit of capital are equivalent to the net return on capital.

[10] Note that both firms are owned by the household so that the relevant stochastic discount factor is the same as for the household.

To complete the description of the role of capital, I now describe how the capital quality shock affects the economy in this model. Following Gertler et al. (2012) I define S_t as the aggregate capital stock at the end of period t that is in preparation for being used in period $t+1$, so that

$$S_t \quad = \quad (1-\delta)K_t + I_t. \tag{2.2.14}$$

The actual amount of capital that can be used in period $t+1$ is the product of a multiplicative 'capital quality shock' and the capital stock in preparation

$$K_{t+1} \quad = \quad \Psi_{t+1}S_t. \tag{2.2.15}$$

Since the market price of capital is endogenous in this framework, the capital quality shock will serve as an exogenous trigger of asset price dynamics. Rather than actual physical depreciation, the capital quality shock causes a decline in the valuation of the bank's security.[11] It is assumed that the capital quality shock Ψ_t follows an i.i.d. process, with an unconditional mean of unity. Following Gertler et al. (2012), I allow for occasional disasters in the form of sharp contractions in capital quality. These contractions constitute the key source of aggregate risk in the economy against which financial intermediaries want to insure themselves via equity issuance as will become clear below.

2.2.2.3 Monopolistically Competitive Retailers

In contrast to Gertler et al. (2012), the model outlined here also features price stickiness. There is a continuum of r monopolistically competitive retail firms where $r \in [0,1]$. They buy intermediate goods Y_t^i from the intermediate goods producing firm and use them as the sole input when transforming one unit of it into one unit of retail output, $Y_t^r = Y_t^i$, where Y_t^r denotes the output produced by retailer r. The retailers sell their retail output for P_t^r facing the following demand schedule

$$Y_t^r = \left(\frac{P_t^r}{P_t}\right)^{-\epsilon} Y_t,$$

where Y_t is final output

$$Y_t = \left[\int_0^1 (Y_t^r)^{\frac{\epsilon-1}{\epsilon}} dr\right]^{\frac{\epsilon}{\epsilon-1}}$$

which is produced by final output producers who purchase the retailers output and assemble it to final output according to a CES aggregator. Note that the real marginal cost associated with producing retail output $MC^r(Y_t^r)$ is given by the relative intermediate goods price ratio

$$MC^r(Y_t^r) = P_t^m = \frac{P_t^i}{P_t}.$$

The monopolistically competitive retailers can charge a markup on top of their price. Following Rotemberg (1982), it is assumed that retail firms face a quadratic cost of adjusting their price given by

$$\frac{\vartheta_P}{2}\left(\frac{P_t^r}{P_{t-1}^r} - 1\right)^2 Y_t$$

[11] This security or asset can be interpreted as a claim on the unit of capital.

where $\vartheta_P > 0$ determines the magnitude of the adjustment cost. It is assumed that the retail firm has the same discount factor as the saver. Moreover, as each firm faces the same type of price adjustment cost, each firm faces the same maximisation problem and therefore, in a symmetric equilibrium, prices are equal across firms. The retailer maximises the expected discounted stream of profits through setting her price P_t^r. The corresponding optimisation problem is given by

$$\max \mathbb{E}_t \sum_{i=0}^{\infty} \Lambda_{t,t+i} \left(\frac{P_{r,t+i}}{P_{t+i}} Y_{r,t+i} - (1-\tau^{MC}) P_{t+i}^m Y_{r,t+i} - \frac{\vartheta_P}{2} \left(\frac{P_{r,t+i}}{P_{r,t+i-1} \Pi_{rss}} - 1 \right)^2 Y_{t+i} \right).$$

The resulting optimality condition gives rise to the inflation equation[12]

$$\vartheta_P \left(\frac{\Pi_t}{\Pi_{rss}} - 1 \right) \Pi_t = (1-\varepsilon) + \varepsilon P_t^m \left(1 - \tau^{MC} \right) + \vartheta_P \left(\Lambda_{t,t+1} \left(\frac{\Pi_{t+1}}{\Pi_{rss}} - 1 \right) (\Pi_{t+1}) \frac{Y_{t+1}}{Y_t} \right) \tag{2.2.16}$$

2.2.3 Banks

So far, the model described above is a standard model with sticky prices and capital adjustment costs. In the absence of frictions in the financial intermediation process, the rate of return that the household receives when she invests in bank equity R_{t+1}^E and the rate of return the banker receives when she invests in capital R_{t+1}^K would be equivalent. However, as I will describe below, the presence of an agency problem drives a wedge between these two.

The balance sheet of an individual[13] bank (in the absence of macroprudential policy) is given by the flow of funds relation

$$Q_t^K s_t = n_t + Q_t^E e_t + d_t. \tag{2.2.17}$$

Equation (2.2.17) states that the amount of securities the bank holds, $Q_t^K s_t$[14], is either funded by net worth ('inside equity') n_t, by state-contingent outside equity $Q_t^E e_t$, or by non-state-contingent debt d_t. As mentioned above, a key feature of this model is the bank's endogenous balance sheet determination, the choice between d_t and e_t. Whereas the two liability forms e_t and d_t, are external sources of funding provided by households, net worth n_t is linked to the bank-internal accumulation of retained earnings

$$n_t = R_t^K Q_{t-1}^K s_{t-1} - R_t^E Q_{t-1}^E e_{t-1} - R_t d_{t-1}. \tag{2.2.18}$$

R_t^K, the gross rate of return on investing in securities, is associated with the gross rate of return on capital. The bank provides friction-less funding to the perfectly competitive intermediate goods producing firm. At the end of period t the intermediate goods producing firm purchases capital S_t at price Q_t^K. The intermediate good producing firm will then use the capital in production and sell the non-depreciated capital stock. The gross rate of return

[12] The subsidy τ^{MC} eliminates the steady state inefficiency associated with the presence of monopolistic competition. In the deterministic steady state the subsidy takes the standard form $\tau_{ssd}^{MC} = \frac{1}{\varepsilon}$. However, in the risk-adjusted steady state, as risk-adjustment term enters the subsidy so that $\tau^{MC} = \frac{1+\frac{1}{2}\Pi\Lambda\vartheta_P\left(3\left(g_{CQ}^{\Pi}\right)^2 + 2g_{CQ}^{\Lambda}g_{CQ}^{\Pi} + 2g_{CQ}^{\Pi}g_{CQ}^{Y}\right)\eta_{CQ}^2}{\varepsilon}$. The derivation of the risk-adjustment terms is described in the appendix section 2.5.1.

[13] Before aggregating, i now illustrate the problem of an individual bank. I therefore use lowercase notation for quantities such as s_t, e_t, d_t. Since all banks are symmetric, all relevant banking equations will be unchanged after aggregating.

[14] $Q_t^K s_t$ can be thought of as loans a bank provides to a firm so that the firm can purchase capital. Therefore the security s_t corresponds to an individual bank's claim on a unit of capital. The aggregate behaviour of s_t was described above in (2.2.14) and (2.2.15).

on capital is therefore given by[15]

$$R_t^K = \frac{\left[Z_t + (1-\delta)Q_t^K\right]\Psi_t}{Q_{t-1}^K} \tag{2.2.19}$$

The resemblance between the two rates of return (2.2.8) and (2.2.19) reflects that one unit of outside equity is normalised to correspond to a claim on one unit of capital. The simple but important intuition behind this is that if the rate of return on capital investment changes the bank can pass this on to the household. In contrast to non-state-contingent debt, outside equity financing thus provides the bank with the opportunity to hedge the risky returns on its asset side.

In order to prevent bankers from accumulating net worth to the point where the financial constraint (which will be described in detail below) becomes irrelevant, bankers face a probability of becoming a worker. It is therefore assumed that with i.i.d. probability a banker may exit next period. If a banker exits, she transfers her accumulated net worth as a dividend payment to the worker. In order to have a constant household composition, a number of workers turn into bankers each period. Since a banker cannot operate with a net worth of zero, she receives a 'start-up' payment from the household family. The net funds transferred to the household are then given by T_t.

It is convenient to combine the flow of funds relation (2.2.17) with the bank's net worth accumulation equation (2.2.18) and rewrite it in terms of the bank's equity-to-assets ratio x_t

$$n_t = \left[R_t^K - x_{t-1}R_t^E - (1-x_{t-1})R_t\right] Q_{t-1}^K s_{t-1} + R_t n_{t-1} \tag{2.2.20}$$

where

$$x_t = \frac{Q_t^E e_t}{Q_t^K s_t}. \tag{2.2.21}$$

In addition to the equity-to-assets ratio x_t it is also useful to introduce the bank's leverage ratio

$$\phi_t = \frac{Q_t^K s_t}{n_t} \tag{2.2.22}$$

as the ratio between a bank's total assets and its net worth. The banker's objective is to maximise her expected discounted value of the terminal dividend payment at the point of exit. This value V_t is given by

$$V_t = \mathbb{E}_t\left[\sum_{\tau=t+1}^{\infty}(1-\sigma)\sigma^{\tau-t-1}\Lambda_{t,\tau}n_\tau\right] \tag{2.2.23}$$

where the parameter σ denotes the survival rate of the bank. Following Gertler et al. (2012) I introduce a moral hazard problem in order to limit the ability of banks to expand their balance sheet and maximise their terminal dividend value. It is assumed that banks are able to abscond with a fraction Θ of their assets[16]. Households understand this and thus limit their funding of banks such that the current franchise value V_t is at least as large as the

[15] Consider that the value of the output of the perfectly competitive intermediate goods producing firm has to equal the cost of the inputs in production

$$P_t^m Y_t^i = W_t L_t + R_t^K Q_{t-1}^K S_{t-1} - (1-\delta)Q_t^K K_t.$$

Recall the relationship between capital before and after the capital quality shock, $K_t = \Psi_t S_{t-1}$ and solve for R_t^K to arrive at 2.2.19.

[16] This decision would have to be made at the end of the period t.

asset stock that can be diverted

$$V_t \quad \geq \quad \Theta(x_t) Q_t^K s_t. \tag{2.2.24}$$

It is furthermore assumed that the fraction of assets that can be stolen depends on the liability composition of the banker. Following studies such as Calomiris and Kahn (1991), Gertler et al. (2012) argue that the more (outside) equity a bank uses to finance itself, the more opaque and the more difficult to monitor its balance sheet becomes. In terms of repayments and returns, debt on the other hand is assumed to be more transparent and can therefore serve as a 'disciplining device'. As a consequence, Gertler et al. (2012) postulate a functional form for the diversion rate Θ according to which the fraction of assets that can be stolen is increasing in equity and decreasing in debt

$$\Theta(x_t) \quad = \quad \theta\left(1 + \epsilon_1 x_t + \frac{\epsilon_2}{2} x_t^2\right) \tag{2.2.25}$$

where $\theta > 0$, $\epsilon_1 < 0$ and $\epsilon_2 > 0$. The calibration[17] of the parameters $\theta, \epsilon_1, \epsilon_2$ will be such that the marginal diversion rate is positive $\Theta'(x_t) = \theta(\epsilon_1 + \epsilon_2 x_t) > 0$.

The two roles of outside equity e_t in this model are now clear. On the one hand, outside equity provides a hedging value for the banker since it is state-contingent and is therefore tied to the return on assets. On the other hand, issuing outside equity is assumed to increase the fraction Θ and will therefore tighten the overall borrowing capacity of the banker.[18]

Assuming that the incentive compatibility constraint (2.2.24) always binds, it can be shown that[19] the franchise value of the bank can be rewritten as a function of s_t, x_t and n_t so that

$$V_t(s_t, x_t, n_t) \quad = \quad (\mu_{s,t} + x_t \mu_{e,t}) Q_t^K s_t + \nu_t n_t \tag{2.2.26}$$

where $\mu_{s,t}$ denotes the bank's excess return from investing in assets over the cost of issuing deposits. $\mu_{e,t}$ denotes the excess funding cost from issuing deposits over issuing equity. ν_t denotes the cost of issuing deposits (which is equivalent to the benefit of having one more unit of net worth). These three objects are defined as follows

$$\mu_{s,t} \quad = \quad \mathbb{E}_t \left[\Lambda_{t,t+1} \Omega_{t+1} \left(R_{t+1}^K - R_{t+1}\right)\right] \tag{2.2.27}$$

$$\mu_{e,t} \quad = \quad \mathbb{E}_t \left[\Lambda_{t,t+1} \Omega_{t+1} \left(R_{t+1} - R_{t+1}^E\right)\right] \tag{2.2.28}$$

$$\nu_t \quad = \quad \mathbb{E}_t \left[\Lambda_{t,t+1} \Omega_{t+1}\right] R_{t+1} \tag{2.2.29}$$

where Ω_{t+1} is the shadow price of net worth tomorrow

$$\Omega_{t+1} \quad = \quad (1-\sigma) + \sigma \left[\nu_{t+1} + \phi_{t+1} \left(\mu_{s,t+1} + x_{t+1} \mu_{e,t+1}\right)\right]. \tag{2.2.30}$$

The expression $\mu_{s,t} + x_t \mu_{e,t}$ in Equation (2.2.26) can be interpreted as the net profit a bank makes when investing in assets given a liability composition x_t. Since the incentive compatibility constraint (2.2.24) is assumed to be always binding one can derive an expression of the leverage ratio in terms of the auxiliary objects $\mu_{s,t}, \mu_{e,t}$ and ν_t by combining (2.2.22) and (2.2.26)

$$\phi_t \quad = \quad \frac{\nu_t}{\Theta(x_t) - (\mu_{s,t} + x_t \mu_{e,t})}. \tag{2.2.31}$$

[17] The reason for allowing for a negative ϵ_1 is that Gertler et al. (2012) want to calibrate a sufficiently high level of equity financing to match the respective data counterpart. Crucially, at the margin, $\Theta'(x_t) > 0$.

[18] Note that if one assumes that Θ is a constant, unresponsive to equity e_t, then banks would prefer to exclusively fund themselves with state-contingent outside equity e_t and their net worth would not at all respond to asset returns.

[19] Refer to Appendix Section 2.5.2

The leverage ratio ϕ_t is increasing in those elements that raise the franchise value of the bank. First, it is increasing in the discounted excess value of a bank's assets $(\mu_{s,t} + x_t\mu_{e,t})$. Second, the leverage ratio is also increasing in the saving in deposit costs from having one more unit of net worth. The intuition is that these two components raise the franchise value of the bank so that the incentive to divert funds decreases, the borrowing capacity therefore increases and leverage may be higher as a consequence. By the same logic, an increase in the fraction of assets that can be stolen, Θ, would reduce the borrowing capacity and restrict the leverage ratio.

If one combines the first-order conditions obtained from maximising the bank's objective function (2.2.23) subject to (2.2.24) over the choice variables s_t and x_t one obtains

$$\frac{\mu_{e,t}}{\mu_{s,t} + x_t\mu_{e,t}} = \frac{\Theta'(x_t)}{\Theta(x_t)} \tag{2.2.32}$$

which can be rewritten as

$$x_t = -\frac{\mu_{s,t}}{\mu_{e,t}} + \left[\left(\frac{\mu_{s,t}}{\mu_{e,t}}\right)^2 + \frac{2}{\epsilon_2}\left(1 - \epsilon\frac{\mu_{s,t}}{\mu_{e,t}}\right)\right]. \tag{2.2.33}$$

Based on equation (2.2.33), it can be shown that x_t, the fraction of assets that is financed by outside equity, is increasing in $\mu_{e,t}/\mu_{s,t}$, the ratio of the value of the excess return of deposits over equity ($\mu_{e,t}$) relative to the excess return on assets over the costs of deposits ($\mu_{s,t}$) so that

$$x'\left(\frac{\mu_{e,t}}{\mu_{s,t}}\right) > 0. \tag{2.2.34}$$

The intuition behind statement 2.2.34 is as follows. The bank prefers to finance herself with a lot of equity (which translates into a high x_t) if $\mu_{e,t}$ is high and/or $\mu_{s,t}$ is low. The latter part is straightforward. If $\mu_{s,t}$ is low, it means that the excess return on assets is relatively low and/or the cost of financing herself with debt is relatively high. Under these circumstances, the insurance and flexibility provided by outside equity finance is attractive.

If $\mu_{e,t}$ is high then the cost of equity finance is relatively low compared to the cost of debt finance. Naturally, a high $\mu_{e,t}$ would then incentivise the bank to finance herself with equity. This raises the question of why equity finance generates an 'excess value'[20] for the bank in the first place. The intuition for this is that the presence of the incentive compatibility constraint and the associated funding restriction makes the banker more risk-averse than the household. In contrast to the household who discounts her returns with the standard stochastic discount factor $\Lambda_{t,t+1}$, the banker discounts with the augmented discount factor $\Lambda_{t,t+1}\Omega_{t+1}$. The latter is more volatile and more countercyclical. Therefore, equity provides a hedging value for the banker which gives rise to a positive 'excess value' of equity over debt finance.[21] To summarise: the bank has to decide (i) how much to invest in assets s_t and (ii) to what extent these assets are funded with equity e_t. The choices of s_t and e_t are influenced by several determinants such as the relative profitability of investing in assets, the relative attractiveness of equity finance over debt finance and risk. The leverage ratio ϕ_t and the liability composition x_t are direct consequences of these choices.

Since bankers in this economy all face the same problem, one can aggregate Equation

[20]It is important to note that equity finance is not actually 'cheaper' than debt finance, but that it generates an 'excess value' for the bank due to the associated hedging value of equity.

[21]Note that in the deterministic steady state the cost of debt and equity are equal, $\mu_{e,dss} = 0$, the Modigliani-Miller theorem holds. Only in the risk-adjusted steady state (which will be described in detail below) will the 'excess value' be positive

$$\mu_{e,rss} = \text{Cov}(\Omega_{t+1}, \Lambda_{t,t+1}R_{t+1}) - \text{Cov}(\Omega_{t+1}, \Lambda_{t+1}R_{E,t+1}) > 0.$$

However, the reason for this steady state variable to be positive is risk rather than the return on equity being below the return on debt.

(2.2.22) to derive a relationship between the aggregate demand for securities by banks S_t and aggregate net worth in the banking sector N_t

$$Q_t^K S_t = \phi_t N_t. \tag{2.2.35}$$

Aggregate net worth is the sum of the net worth of 'old' bankers (who have not exited) and of 'new' bankers (who have entered to replace those who exited)

$$N_t = N_{o,t} + N_{y,t} \tag{2.2.36}$$

The net worth of old bankers $N_{o,t}$ is the difference of earnings on assets net of the cost of funding.

$$N_{o,t} = \sigma\left\{\left[Z_t + (1-\delta)Q_t^K\right]\Psi_t S_{t-1} - \left[Z_t + (1-\delta)Q_t^E\right]\Psi_t E_{t-1} - R_t D_{t-1}\right\} \tag{2.2.37}$$

Since a fraction of $\xi/(1-\sigma)$ has been transferred to the young, their net worth is a fraction ξ of the total earnings on assets

$$N_{y,t} = \xi\left[Z_t + (1-\delta)Q_t^K\right]\Psi_t S_{t-1}. \tag{2.2.38}$$

Combining these equations one can derive an equation that pins down aggregate net worth as follows

$$N_t = (\sigma+\xi)\left[Z_t + (1-\delta)Q_t^K\right]\Psi_t S_{t-1} - \sigma\left[Z_t + (1-\delta)Q_t^E\right]\Psi_t E_{t-1} - \sigma R_t D_t (4) \tag{2.2.39}$$

Based on Equation (2.2.39) one can see that adverse capital quality shocks reduce net worth.

2.2.4 Monetary Policy and the Risk Channel

It is assumed that the central bank sets the short-term nominal interest rate R_t^n and that it follows a simple rule[22] in which it responds to deviations of inflation and the real marginal cost[23] from their respective risky steady state levels

$$\frac{R_t^n}{R_{rss}^n} = \left[\left(\frac{\Pi_t}{\Pi_{rss}}\right)^{\kappa_\Pi}\left(\frac{P_t^m}{P_{rss}^m}\right)^{\kappa_{P^m}}\right]^{1-\rho_{Rn}}\left(\frac{R_{t-1}^n}{R_{rss}^n}\right)^{\rho_{Rn}}. \tag{2.2.40}$$

The gross nominal interest rate R_t^n is assumed to be adjusted in response to gross inflation Π_t and in response to a measure of the output gap such as P_t^m. κ_Π and κ_{P^m} are the respective reaction coefficients. Apart from the policy reaction component, the nominal interest rate is also assumed to be a function of the previous period nominal rate. The relationship between the gross real interest rate R_t, the gross nominal rate R_t^n and the gross inflation rate Π_{t+1} is pinned down[24] by a Fisher-type equation

$$R_t \mathbb{E}_t\left[\Lambda_{t,t+1}\right] = R_t^n \mathbb{E}_t\left[\Lambda_{t,t+1}\Pi_{t+1}^{-1}\right]. \tag{2.2.41}$$

de Groot (2014) describes how monetary policy affects bank variables via the risk channel (in a model without macroprudential policy). As explained above, the bank's decisions on

[22]In future extensions I will analyse different monetary policy reaction functions in which the central bank also responds to financial variables, such as leverage, spreads and asset and equity prices. de Groot (2014) did this in a model without macroprudential policy.

[23]The real marginal cost serves as a proxy for the output gap in this specification.

[24]It could be derived as a no-arbitrage relation by setting up the household problem with both real and nominal risk-less bonds available.

outside equity issuance depends on risk perceptions. In order to account for risk, the model will be solved around a risk adjusted steady state in which the co-movements of variables in the economy will play an important role. Monetary policy affects the co-movements of variables and since these co-movements in turn affect the risk-adjusted steady state, de Groot (2014) refers to this as the 'risk channel' of monetary policy. In section 2.3 I will assess the role of monetary policy and the risk channel, in the presence of macroprudential policy.

2.2.5 Macroprudential Policy

The key motive for macroprudential policy in this model is to encourage banks to use outside equity and discourage the use of short term debt. Since asset prices affect the incentive compatibility constraint, a pecuniary externality arises. An individual bank fails to internalise that if the banking system were to collectively issue outside equity they would make the banking sector better hedged against risk, thus dampening fluctuations in asset prices and economic activity. In other words, there is a potential reduction in volatility which atomistic banks fail to achieve collectively because each bank considers herself infinitesimally small. The failure to recognise the external benefits of outside equity issuance leads to a reduction in welfare.

Following Gertler et al. (2012), the implementation of macroprudential policy works as follows. The government subsidises every unit of outside equity issued with τ_t^{MPP} and finances this subsidy with a tax on total assets τ_t. This measure will raise the relative attractiveness of issuing outside equity. Replacing (2.2.17), the bank's flow of funds constraint with macroprudential policy is given by

$$(1+\tau_t)Q_t^K s_t \quad = \quad n_t + (1+\tau_t^{MPP})Q_t^E e_t + d_t \tag{2.2.42}$$

where the bank takes τ_t^{MPP} and τ_t as given. The net effect on bank revenues is zero. The macroprudential policy instrument τ_t^{MPP} is assumed to respond to the inverse of the shadow cost of deposits[25] ν_t such that

$$\tau_t^{MPP} \quad = \quad \frac{\tau^s}{\nu_t}. \tag{2.2.43}$$

The macroprudential policy instrument is τ_t^{MPP}. The key policy parameter that governs the sensitivity and the aggressiveness of macroprudential policy is the constant τ_s, the numerator of τ_t^{MPP}. τ_s can be interpreted as a sensitivity parameter. It tunes the sensitivity with which the macroprudential authority responds to the inverse of the shadow costs of deposits. If this shadow cost of deposits is low, the inverse will be high, the macroprudential subsidy τ_t^{MPP} would be high. If the parameter τ_s is larger, the macroprudential regulator would respond stronger to this low level of the shadow cost of deposits. By increasing the macroprudential subsidy τ_t^{MPP}, the regulator would provide an incentive for banks to have more equity even though the cost of deposits is low. The responsiveness of the macroprudential instrument τ_t^{MPP} to the shadow cost conditions is pinned down by τ_s.

Consider that the marginal benefit to the bank from issuing outside equity is now the sum of the excess value from issuing outside equity and the constant component of the macroprudential subsidy $\mu_{e,t} + \tau^s$. If the policy parameter τ_s takes a large value, macroprudential policy can be interpreted as 'aggressive' because it will then substantially increase the marginal benefit to the bank from issuing outside equity compared to the case in which macroprudential policy is absent ($\tau_s = 0$).

As described above, the benefit from macroprudential policy is the reduction in aggregate volatility[26]. The cost of macroprudential policy in this model is that the increase in

[25] Alternative macroprudential rules are discussed in Liu (2016).

[26] In Gertler et al. (2012) another important benefit of macroprudential policy is to offset the moral hazard problems that arise

outside equity tightens the incentive compatibility constraint. This is the reason why it is not optimal for the macroprudential regulator to incentivise banks to completely fund themselves with outside equity.

2.2.6 Market Clearing

Market clearing in the market for securities, outside equity, deposits and labor implies the following equations

$$Q_t^K S_t = \frac{\nu_t}{\theta\left(1+\epsilon_1 x_t + \frac{\epsilon_2}{2}x_t^2\right) - (\mu_{s,t} + x_t \mu_{e,t})} N_t \tag{2.2.44}$$

$$Q_t^E E_t = x_t Q_t^K S_t \tag{2.2.45}$$

$$D_t = (1-x_t) Q_t^K S_t - N_t \tag{2.2.46}$$

$$\chi L_t^{\varphi} = P_t^m (1-\alpha) \frac{Y_t}{L_t} \mathbb{E}_t \left[\frac{u_{C,t}}{\left(C_t - hC_{t-1} - \chi \frac{L_t^{1+\varphi}}{1+\varphi}\right)^{-\gamma}} \right]. \tag{2.2.47}$$

Aggregate output is divided between household consumption C_t and investment expenditures I_t.

$$Y_t \left(1 - \frac{\vartheta_P}{2}\left(\frac{\Pi_t}{\Pi} - 1\right)^2\right) = C_t + \left(1 + \frac{\vartheta_I}{2}\left(\frac{I_t}{I_{t-1}} - 1\right)^2\right) I_t \tag{2.2.48}$$

2.2.7 Welfare

In order to analyse the normative role of monetary and macroprudential policy in the model under consideration, I compute the household's risk-adjusted steady state welfare as

$$\mathcal{W} = \frac{U\left(C^N, L^N\right) + M_{\mathcal{W}}}{1-\beta} \tag{2.2.49}$$

where $M_{\mathcal{W}}$ is the risk-adjustment term associated with welfare.[27] Moreover, I calculate the steady state consumption welfare equivalent η via

$$\mathcal{W}^P = \frac{U\left((1+\eta)C^N, L^N\right) + M_{\mathcal{W}}^N}{1-\beta}. \tag{2.2.50}$$

The idea behind the consumption welfare equivalent is to calculate by how much the regime N ('no policy') consumption would have to be increased to make the household indifferent with being in regime P ('policy')

$$\mathbb{E}_0 \left[\sum_{t=0}^{\infty} \beta^t U(C_t^N(1+\eta), C_{t-1}^N, L_t^N) \right] = \mathbb{E}_0 \left[\sum_{t=0}^{\infty} \beta^t U(C_t^P, C_{t-1}^P, L_t^P) \right].$$

Regime P can be regarded as welfare-superior if $\eta > 0$, because in that case the 'no-policy-regime' consumption has to be increased to make the agent indifferent with being in the 'policy-regime'.

from the anticipation of credit policy.

[27] Refer to section 2.5.5 in the appendix for details on the risk-adjustment terms.

2.2.8 Exogenous Shock Processes

The model features only one exogenous shock.[28]

As mentioned above, the capital quality shock serves as the main source of aggregate risk in the economy. Following Gertler et al. (2012) it is assumed that the capital quality shock follows an i.i.d. process that allows for random and infrequent disasters. Ψ_t is the product of a component for 'normal' times and one for 'disaster'

$$\Psi_t = \tilde{\Psi}_t \tilde{\Psi}_t^D \tag{2.2.51}$$

where

$$\log \tilde{\Psi}_t = \varsigma \epsilon_{\Psi,t}, \qquad \log \tilde{\Psi}_t^D = \zeta_t,$$

where $\epsilon_{\Psi,t}$ is distributed $N(0,1)$, and ζ_t is binomial

$$\zeta_t = \begin{cases} -(1-\pi)\Delta & \text{with probability } \pi \\ \pi\Delta & \text{with probability } 1-\pi \end{cases}$$

where Δ is a positive number, in which case the disaster innovation $-(1-\pi)\Delta$ is negative. The variance of ζ_t is then $\pi(1-\pi)\Delta^2$.

2.2.9 Calibration and Solution Method

In this section I will describe the calibration of the model parameters and the solution technique.

2.2.9.1 Calibration

There are 24 parameters that have to be calibrated to match the empirical patterns of key variables at quarterly frequency. The six household parameters $\{\gamma, \beta, \chi, \varphi, \epsilon, h\}$ all take standard values consistent with the literature. The same is true for the three parameters $\{\alpha, \vartheta_I, \delta\}$ of the non-financial firms and the retailers ϑ_P.

The five parameters associated with the bank $\{\sigma, \xi, \theta, \epsilon_1, \epsilon_2\}$ are calibrated as follows. $\sigma = 0.9685$ implies that the average survival rate of the bank is 8 years. In calibrating the remaining four bank parameters I follow Gertler et al. (2012) who aim at hitting four targets: (i) an average credit spread of around 100 basis points (annualised, in the low-risk case), (ii) an aggregate leverage ratio of 4 (total assets over both inside and outside equity), (iii) a ratio of outside equity relative to inside equity of two thirds and (iv) a reduction of leverage of one third when moving from the low risk to the high risk economy. Recall that in Gertler et al. (2012) the authors use a real model to match these targets. For the asset diversion parameters $\{\theta, \epsilon_1, \epsilon_2\}$ I therefore follow de Groot (2014) who aims at matching the above described targets in the context of a New Keynesian model (without macroprudential policy).[29]

The parameters associated with the reaction function of monetary policy are $\kappa_\Pi = 1.5$ and $\kappa_{Pm} = 0.5/4$. I will later assess the welfare implications of varying the inflation sensitivity coefficient. The macroprudential policy parameter τ_s is chosen such that welfare is optimised. I will discuss the details below.

[28] I refrained from augmenting the model with more shocks in order to simplify and clarify the effects of the capital quality shock and the associated impact of risk. In future research, the model can be augmented with various supply and demand shocks.

[29] Moreover, de Groot (2014) uses a different solution technique which gives rise to a smaller risk-adjustment. I follow de Groot (2014) here as well. I deviate from him in that I allow for macroprudential policy.

TABLE 2.1: PARAMETER VALUES

Parameter	Definition	Value
Households		
γ	Risk Aversion	2
β	Discount Factor	0.99
χ	Utility Weight of Labor	0.25
φ	Inverse Frisch Elasticity	1/3
ε	Substitution Elasticity	4.17
h	Habit Formation Parameter	0.75
Firms		
α	Capital Share	0.33
ϑ_I	Investment Adjustment Coefficient	1
δ	Depreciation Rate	0.025
Retailers		
ϑ_P	Price Adjustment Cost Coefficient	48
Banks		
σ	Survival Rate of Bankers	0.9685
ξ	Transfer to entering Bankers	0.0289
θ	Moral hazard parameter	0.264
ϵ_1	Asset diversion parameter 1	-1.21
ϵ_2	Asset diversion parameter 2	13.41
Monetary Policy		
κ_Π	Interest Rate Sensitivity to Inflation	1.5
κ_{pm}	Interest Rate Sensitivity to Output gap	0.5/4
ρ_{R^n}	Interest Rate Persistence	0.85
Macroprudential Policy		
τ_s	MPP parameter	0.002
Shock Processes		
ρ_Ψ	Persistence of Capital Quality Shock	0
$\sigma_\Psi^{\text{high}}$	Standard Deviation of Capital Quality Shock (high risk)	0.02
σ_Ψ^{low}	Standard Deviation of Capital Quality Shock (low risk)	0.0069

The model dynamics are driven by the capital quality shock which is calibrated such that two cases can be distinguished: (i) a 'high risk' case in which the standard deviation of the capital quality shock is high $\sigma_\Psi^{\text{high}} = 0.02$ and (ii) a 'low-risk' case in which $\sigma_\Psi^{\text{low}} = 0.0069$.

The motivation for the case distinction into two risk states is that the risk environment affects the endogenous bank balance sheet determination, and thus the risk-adjusted steady state and the dynamic responses of the economy to shocks. The properties of the risk-adjusted steady state and the dynamics associated with the 'high risk' and the 'low risk' cases will be analysed below.

2.2.9.2 Solution Method

Since the bank balance sheet structure in this model depends on risk perceptions, one cannot simply solve the model around a non-stochastic steady state. Moreover, as the risk environment changes, households will adjust their precautionary savings. In order to capture these effects, one has to construct a 'risk-adjusted' steady state. The risk-adjusted steady state is defined as the 'point where agents choose to stay at a given date if they expect future risk and if the realisation of shocks is 0 at this date' (Coeurdacier et al. (2011)). Given agents perceptions of second moments, variables remain unchanged if the realisation of the (mean-zero) exogenous disturbance is zero. The risk-adjusted steady state differs from the non-stochastic steady state only by terms that are second-order. To analyse the dynamics of the model, one then looks at a first-order approximation around the risk-adjusted steady state. I follow de Groot (2014) and employ a solution algorithm that works as follows

1. Log-linearise the model around the deterministic steady state

2. Use the second moments calculated from the deterministic model and compute the risk-adjusted steady state
3. Calculate the second moments from the risk-adjusted steady state
4. Iterate until the moments generated by the first order dynamics around the risk-adjusted steady state are consistent with the moments used to construct it

Note that monetary policy and macroprudential policy affect the risk-adjusted steady state levels of the variables in this model.[30]

2.3 The Interaction of Macroprudential and Monetary Policy

In this section I analyse the interaction between monetary policy (MP) and macroprudential policy (MPP). First, I describe how these two policy interventions affect the steady state levels of several relevant variables. Second, I look at the effects of monetary policy and macroprudential policy on the dynamic responses of variables. Third, I study the welfare implications of both policies.

2.3.1 Steady State Analysis

A key feature of the model outlined above is that the degree of risk in the economy affects banks balance sheets. In order to capture these effects it is necessary to solve the model around a risk-adjusted steady state. I highlight the difference between the deterministic and the risk-adjusted steady state in the next section. Note that I also consider a benchmark real version of the model in which the financial sector is absent.

2.3.1.1 The Deterministic Steady State

In Table 2.2 I illustrate the deterministic steady state of 4 different versions of the model. The two columns on the left correspond to a New Keynesian and an RBC version of the model with a financial sector, as outlined above. The columns on the right depict a benchmark model in which the financial sector was removed.[31]

The deterministic steady state levels of the RBC version and the New Keynesian version coincide since the distortion associated with monopolistic competition was offset in the New Keynesian model via a subsidy.

A comparison of the models with and without the financial sector reveals that the presence of a funding constraint (2.2.24) gives rise to a spread between the gross return on capital and the gross real rate of interest. Since the gross return on capital is higher than the gross real interest rate, the level of capital in the deterministic steady state will be lower compared to the model without a financial sector. As a result, output, consumption and welfare are lower in the model with a financial sector.

2.3.1.2 The Risk-adjusted Steady State

The difference between the deterministic and the risk-adjusted steady state is driven by 'risk-adjustment terms'.[32] For the risk-adjusted steady state values risk matters. Risk in the context of this paper refers to the standard deviation of the capital quality shock. 'High

[30] A more detailed description of the solution algorithm is to be found in the appendix, in section 2.5.5.

[31] Note that one cannot simply remove the 'financial friction' without modifying the model in another way. The presence of an always binding incentive compatibility constraint is necessary to solve the model. If one were to remove it entirely, one would need to introduce some other kind of friction e.g. a bond adjustment cost in order to pin down the steady state level of bonds and net worth. Thus, in order to establish a benchmark, it is useful to remove the entire financial sector.

[32] I derive and plot these risk-adjustment terms in section 2.5.5.1 and 2.5.7 in the appendix.

TABLE 2.2: DETERMINISTIC STEADY STATES WITH AND WITHOUT THE FINANCIAL SECTOR

Steady State	With Financial Sector NK	With Financial Sector RBC	Without Financial Sector NK	Without Financial Sector RBC
Y	24.3289	24.3289	27.1690	27.1690
C	18.9224	18.9224	20.7833	20.7833
L	8.2942	8.2942	9.0103	9.0103
K	216.2607	216.2607	255.4280	255.4280
I	5.4065	5.4065	6.3857	6.3857
N	28.5791	28.5791		
R	1.0101	1.0101	1.0101	1.0101
Spread (%)	0.0081	0.0081		
R^E	1.0100	1.0101		
x	0.0898	0.0898		
ν	1.8728	1.8728		
μ_e	0	0		
μ_s	0.0038	0.0038		
ϕ	7.5671	7.5671		
$Q^K K/(N + xQ^K K)$	4.5051	4.5051		
$N/(xQ^K K)$	0.1321	0.1321		
Π	1.0000		1.0000	
R^n	1.0101		1.0100	
$\mathcal{W}$	-63.1877	-63.1877	-59.5121	-59.5121

Note: Deterministic steady state values for versions of the model with and without the financial sector and with and without the price stickiness friction. For the New Keynesian model the distortion associated with monopolistic competition has been offset so that the deterministic steady state values for real variables such as output and consumption coincide.

risk' means that the standard deviation of the capital quality shock is high and the economy could potentially be hit by large capital quality shocks. Since second-order terms enter the risk-adjustment terms a change in the standard deviation of the shock will directly affect the risk-adjusted steady state.

In addition to the standard deviation of the capital quality shock, the risk-adjustment terms are also affected by the model's policy functions $g(x_t, z_t)$ and $h(x_t, z_t)$[33]. This has two important implications. First, a correction of the distortions associated with monopolistic competition will no longer let the steady state of the New Keynesian model and the RBC model coincide. Since the presence of price stickiness affects the policy functions of the model, and since these in turn affect the risk-adjusted steady state, a model with price stickiness cannot have a 'flexible-price risk-adjusted steady state'. Disentangling the dynamics from the steady state is not possible.[34]

Second, monetary policy and macroprudential policy will affect the risk-adjusted steady state levels via the same link between dynamics and risk-adjustment terms. This implies that different degrees of inflation sensitivity and macroprudential incentivisation of outside equity issuance will affect the risk-adjusted steady state levels.

In Table 2.3 I look at the risk-adjusted steady state values in the presence and in the absence of macroprudential policy. In addition to distinguishing between the cases of low and high risk, I also analyse different values for the degree of inflation sensitivity κ_Π and their impact on the risk-adjusted steady state levels. In this section I consider a macroprudential policy with a coefficient of $\tau_s = 0.002$ irrespective of the risk environment or the inflation sensitivity κ_Π.[35]

Based on Table 2.3 there are three key messages. First, one can see that the risk-adjusted

[33]Refer to section 2.5.5 in the appendix for more details.

[34]Nevertheless, all results reported below are associated with the above described New Keynesian model in which there is a subsidy in place which eliminates the distortions associated with monopolistic competition, so that $P^m_{rss} = 1$.

[35]In the subsection in which I conduct the welfare analysis I will compute the optimal degree of macroprudential intervention τ_s^* depending on the risk state and the inflation sensitivity.

TABLE 2.3: RISK-ADJUSTED STEADY STATES UNDER LOW AND HIGH RISK WITHOUT AND WITH MPP $\tau_s = \{0, 0.002\}$

	Without MPP ($\tau_s = 0$)				**With MPP ($\tau_s = 0.002$)**			
	$\kappa_\Pi = 1.5$		$\kappa_\Pi = 2.5$		$\kappa_\Pi = 1.5$		$\kappa_\Pi = 2.5$	
Risk Level	Low Risk	High Risk	Low Risk	High Risk	Low Risk	High Risk	Low Risk	High Risk
Column	1	2	3	4	5	6	7	8
Steady State								
Y	23.9631	23.6042	23.9813	23.5937	24.1143	23.7035	24.1106	23.6732
C	18.6777	18.4238	18.6898	18.4169	18.7779	18.4866	18.7755	18.4667
L	8.1998	8.0968	8.2045	8.0942	8.2381	8.1195	8.2371	8.1120
K	211.4141	207.2140	211.6561	207.0738	213.4551	208.6792	213.4062	208.2621
I	5.2854	5.1804	5.2914	5.1768	5.3364	5.2170	5.3352	5.2066
N	30.8608	34.3151	30.7469	34.4540	30.0078	33.7961	30.0338	34.1101
R	1.0101	1.0097	1.0101	1.0097	1.0101	1.0096	1.0101	1.0096
Spread	0.0024	0.0032	0.0024	0.0032	0.0023	0.0031	0.0023	0.0031
R^E	1.0101	1.0100	1.0101	1.0100	1.0101	1.0100	1.0101	1.0100
x	0.1091	0.1708	0.1075	0.1732	0.1681	0.2245	0.1685	0.2293
ν	1.7045	1.5473	1.7121	1.5426	1.8095	1.6551	1.8080	1.6453
μ_e	0.0005	0.0014	0.0004	0.0015	0.0003	0.0011	0.0003	0.0012
μ_s	0.0027	0.0019	0.0028	0.0018	0.0034	0.0027	0.0034	0.0026
ϕ	6.8491	6.0379	6.8826	6.0094	7.1131	6.1749	7.1053	6.1056
$Q^K K/(N + xQ^K K)$	3.9199	2.9724	3.9559	2.9442	3.2399	2.5875	3.2341	2.5440
$N/(xQ^K K)$	1.3382	0.9696	1.3516	0.9605	0.8365	0.7213	0.8354	0.7143
Π	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
R^N	1.0101	1.0097	1.0101	1.0097	1.0101	1.0096	1.0101	1.0096
$\mathcal{W}$	-63.7543	-64.4102	-63.7266	-64.4274	-63.5220	-64.2321	-63.5275	-64.2822

Note: Risk-adjusted steady state values for a given inflation sensitivity coefficient $\kappa_\Pi = \{1.5, 2.5\}$ and a given macroprudential reaction coefficient $\tau_s = \{0, 0.002\}$ under low and high risk.

steady state levels of variables depend substantially on the risk environment. In a riskier environment banks have the desire to ensure themselves against large shocks. As a consequence the outside equity funding ratio x is substantially higher in the case with high risk. The increased degree of precautionary behaviour is associated with a reduction in financial intermediation, a reduction in investment, capital formation, output and consumption and hence a reduction in welfare. A comparison of column 1 with 2, 3 with 4, 5 with 6 and 7 with 8 illustrates that this is true regardless of the policy environment.

Second, macroprudential policy can enhance welfare. It was argued above that for a given risk-level the bank's choice of the outside equity funding ratio x is inefficiently low. If banks fund themselves with equity the effects of binding collateral constraints can be mitigated by the increased absorption capacity that equity provides. Equity provides insurance and thus asset prices will not fall as much as they would otherwise. The atomistic banker considers herself infinitesimally small and does not take into account the effects of her action on asset prices. By doing so, bankers forego a potential reduction in the severity of the asset price deflation associated with binding collateral constraints. In Table 2.3 columns 1 to 4 depict the risk-adjusted steady state levels without macroprudential policy and columns 5 to 8 depict the levels with macroprudential policy. Compared to the case with no MPP ($\tau_s = 0$), a macroprudential policy coefficient of $\tau_s = 0.002$ is shown to improve welfare. Below, I will assess how strong the macroprudential subsidy of outside equity issuance should be.

Third, the effects of monetary policy on the risk-adjusted steady state levels are small in comparison with the effects of risk or macroprudential policy. When comparing columns 1 with 3, 2 with 4, 5 with 7 and 6 with 8, one can see that the welfare levels are relatively similar. Nevertheless, it is noteworthy that in general, a more aggressive response of the monetary authority to inflation will reduce welfare, except in the case in which macroprudential policy is absent and in which risk is low. This can be seen in the welfare improvement from column 1 to 3. I will illustrate this finding in more detail in the next subsections.

2.3.2 Impulse Response Analysis

As argued above, the risk-adjusted steady state depends on the policy functions $g(.)$ and $h(.)$ of the model. The impacts to a capital quality shock enter various risk-adjustment terms and thereby affects the steady state values. I analyse the impulse response dynamics in the case of high and low risk, with and without macroprudential policy, for three different levels of inflation sensitivity. I plot the entire variable space in the appendix in section 2.5.6. Here, I focus on the impact of a capital quality shock on inflation, output, the real and nominal interest rate under the various risk and policy specifications.

In Figure 2.3.1 I plot the dynamic responses of inflation, output, the real and the nominal interest rate to a capital quality shock. The first row depicts the IRFs of inflation, the second row the IRFs of output to a contractionary capital quality shock. The two columns on the left depict the case of low risk, the two columns on the right the case of high risk. The column on the very left is associated with the case in which there is no macroprudential policy, the same holds for the third column. In each panel I plot three lines. The green (dashed) line corresponds to a case in which the inflation sensitivity of the monetary policy reaction function for the nominal interest rate is $\kappa_{\Pi} = 1.5$. The red (straight) line corresponds to a more aggressive regime $\kappa_{\Pi} = 2.5$ and the blue (dotted) line corresponds to a very aggressive regime $\kappa_{\Pi} = 3.5$. The capital quality shock under consideration is a contractionary shock, as can be seen when inspecting the full set of IRFs in the appendix (Figure 2.5.1 to 2.5.4).

Aggressive inflation targeting stabilises inflation and output in general. However, in the case of low risk and in the absence of macroprudential policy a more aggressive targeting of inflation (blue-dotted line) leads to a milder *decline* in inflation. In the other cases (high risk and/or sufficiently strong macroprudential policy) stricter inflation targeting leads to a milder *increase* in inflation.

Under low risk and in the absence of macroprudential policy the differences between the impacts associated with the three sensitivity levels $\kappa_{\Pi} = \{1.5, 2.5, 3.5\}$ are more pronounced than in the high risk case or in the case with MPP. The economy is more sensitive to shocks in the low risk case since it is precisely under low risk when banks do not hold enough equity.

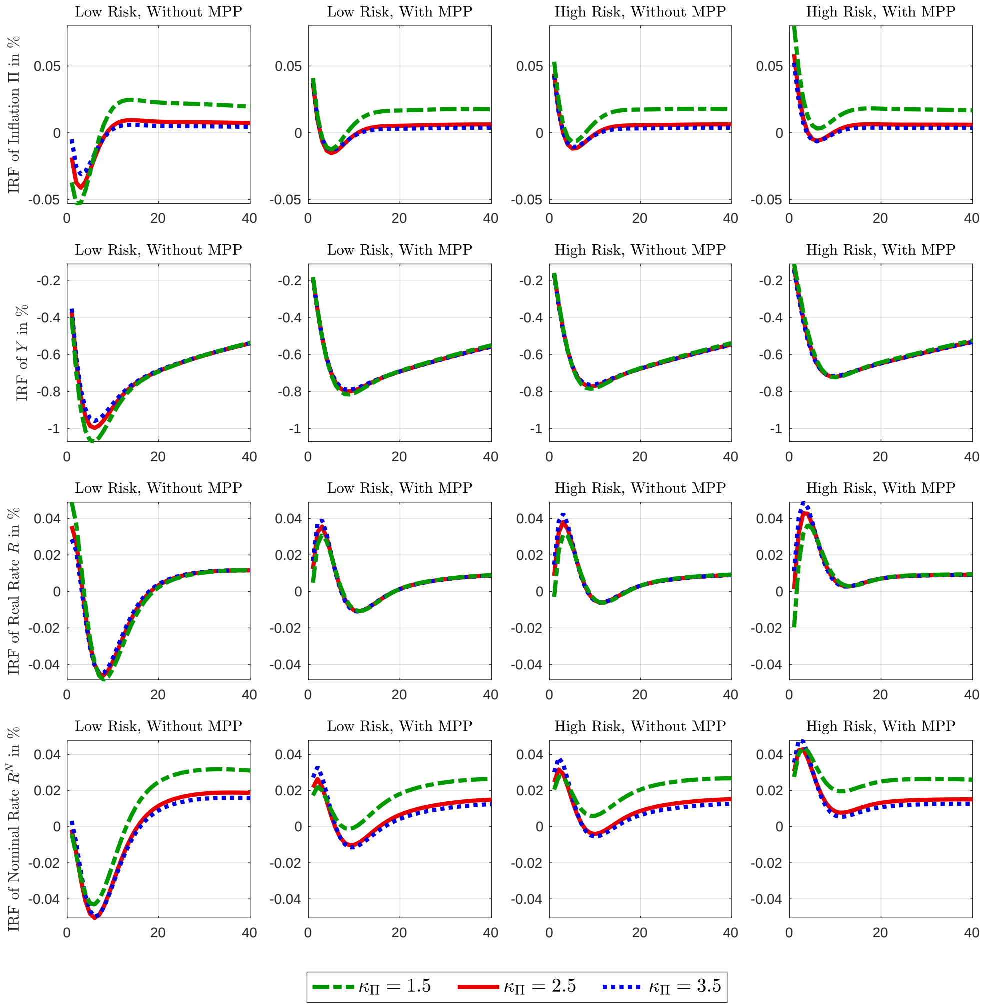
Looking solely at the impulse responses, it appears to be reasonable to target inflation aggressively in order to stabilise inflation and output. However, since the dynamics and the risk-adjusted steady levels cannot be disentangled in this model, it is important to assess the effects of the impacts on the risk-adjustments and on the risk-adjusted steady state levels before drawing policy conclusions.

In the third row of Figure 2.3.1 I depict the responses of the real interest rate. In the case of low risk with MPP and in the case of high risk, an aggressive inflation targeting policy ($\kappa_{\Pi} = 3.5$) will prevent inflation from increasing a lot. This avoided increase in inflation will translate into a stronger increase in the real interest rate. The increased responsiveness of the real interest rate which can be seen in the 2nd, 3rd and 4th column (low risk and MPP, high risk) affects the risk-adjustment terms[36] such that it becomes more attractive for bankers to

[36] As argued above, the difference between the deterministic steady state and the risk-adjusted steady state is determined by 'risk-adjustment terms'. These terms in turn are functions of the standard deviation of the shock and of the policy function ('impact') of a variable to the capital quality shock. The risk-adjustment term for which the inflation sensitivity parameter plays a role is M10.

$$R_{N,rss} = R_{rss} + \underbrace{\frac{1}{2}\Pi_{rss}R_{rss}(g^{\Pi}_{CQ})^2\eta^2_{CQ}}_{\text{Risk adjustment M10}}.$$

Figure 2.3.1: Dynamic Responses of Π, Y, R and R^N under low and high risk with and without MPP and $\kappa_\Pi = \{1.5{,}2.5{,}3.5\}$

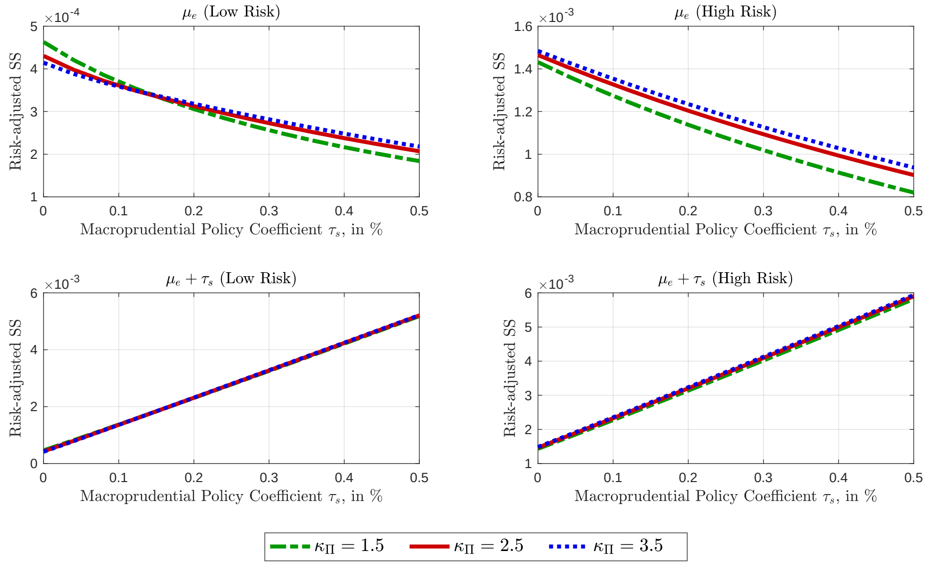


Note: Each column corresponds to a specific risk environment and macroprudential policy regime. The two left columns depict the dynamic responses in the case of low risk. The very left column depicts the case without MPP ($\tau_s = 0$), the second from the left column depicts the case with MPP ($\tau_s = 0.002$). The two columns on the right depict the IRFs under high risk. In each panel the two lines correspond to IRFs under a different calibration of the inflation sensitivity $\kappa_\Pi = \{1.5{,}2.5{,}3.5\}$.

fund themselves with more outside equity, which ceteris paribus hurts intermediation and which will ultimately hurt welfare.

The effects of stricter inflation targeting can be seen in Figure 2.3.2. I show the risk-adjusted steady state levels of key variables as a function of the risk and policy environment. As argued above, under stricter inflation targeting the real interest rate will be more volatile in the case with macroprudential policy and in the cases with high risk. This increases the attractiveness of state-contingent outside equity issuance, which in the presence of macroprudential policy corresponds to $\mu_e + \tau_s$. In Figure 2.3.2 I plot the steady state levels of μ_e and $\mu_e + \tau_s$. The macroprudential subsidy τ_s is on the x-axis, the risk-adjusted steady state levels are on the y-axis. The panels on the left correspond to the case with low

FIGURE 2.3.2: EFFECTS OF VARIATION IN $\{\tau_s, \kappa_\Pi\}$ ON THE RISK-ADJUSTED STEADY STATE OF $\{\mu_e, \mu_e + \tau_s\}$



Note: The left (right) column depicts the risk-adjusted steady state of $\{\mu_e, \mu_e + \tau_s\}$ as a function of τ_s and κ_Π in the case of low (high) risk. In each panel the three lines correspond to a different calibration of the inflation sensitivity $\kappa_\Pi = \{1.5, 2.5, 3.5\}$.

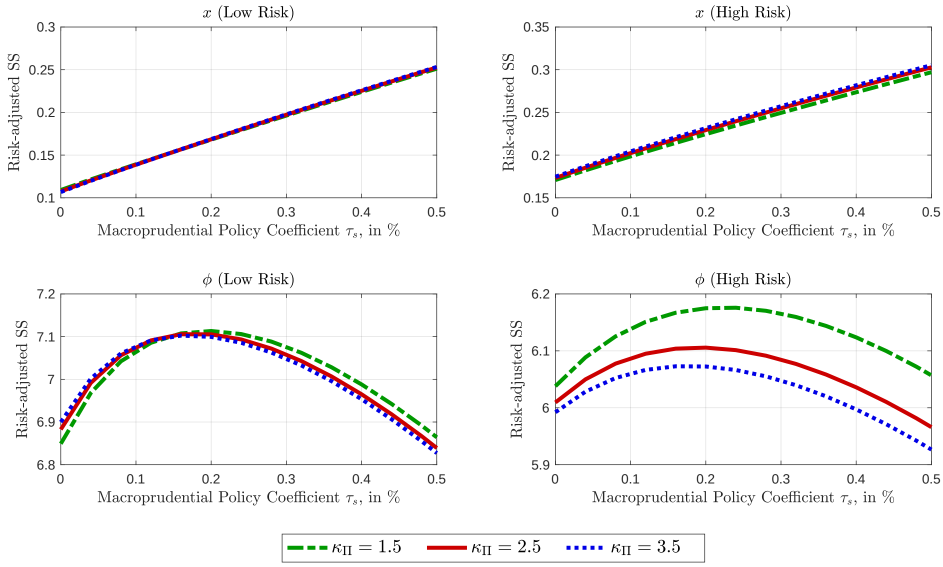
risk and the panels on the right correspond to the case with high risk. The three lines in each panel (green-dashed, red-straight and blue-dotted) correspond to the three inflation targeting regimes $\kappa_\Pi = \{1.5, 2.5, 3.5\}$.

In the lower row of Figure 2.3.2 one can see that macroprudential policy (in the form of a subsidy on outside equity issuance τ_s) always increases the marginal benefit of issuing outside equity. In accordance with the intuition developed above, under high risk and in the presence of macroprudential policy ($\tau_s > 0$) stricter inflation targeting (depicted by the blue-dotted line) exacerbates fluctuations in the real interest rate and thus increases the desire of banks to insure themselves and to issue outside equity. Hence, under high risk and in the presence of macroprudential policy μ_e tends to be higher under stricter inflation targeting (κ_Π).

As a consequence of the increased marginal benefit of outside equity issuance, banks will increase their outside equity issuance, as can be seen in the first row of Figure 2.3.3. Stricter inflation targeting will increase the risk-adjusted steady state level of the outside-equity funding ratio x, except in the low risk case with no (or only weak) macroprudential policy. The intuition is that in the case of low risk and without macroprudential policy, stricter inflation targeting ($\kappa_\Pi = 3.5$) stabilises the economy, mitigates the disinflationary response of inflation and thereby stabilises fluctuations in real interest rates. Once macroprudential stabilisation policies are in place or banks have a stronger self-insurance desire due to high risk, a very aggressive targeting of inflation will lead to stronger fluctuations in interest rates.

The increased fluctuations in real interest rates that arise under stricter inflation targeting will increase the marginal benefits of outside equity so that x goes up. The blue-dotted lines lie above the green-dashed and red-straight lines in the panels that depict the risk-adjusted steady state of the outside-equity funding ratio x, except for the case of low risk and no MPP. As a consequence of pushing up outside equity issuance for given levels of risk and

FIGURE 2.3.3: EFFECTS OF VARIATION IN $\{\tau_s, \kappa_\Pi\}$ ON THE RISK-ADJUSTED STEADY STATE OF $\{x, \phi\}$



Note: The left (right) column depicts the risk-adjusted steady state of $\{x, \phi\}$ as a function of τ_s and κ_Π in the case of low (high) risk. In each panel the three lines correspond to a different calibration of the inflation sensitivity $\kappa_\Pi = \{1.5, 2.5, 3.5\}$.

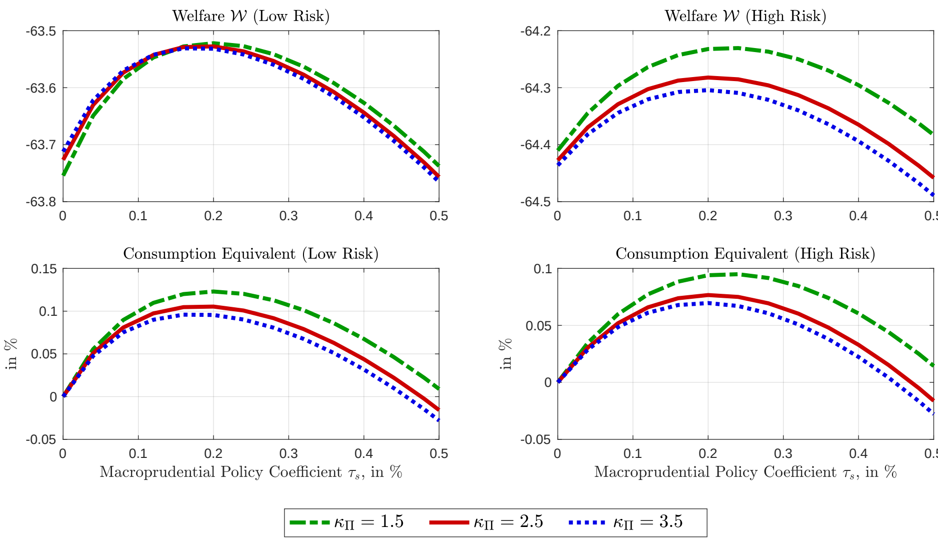
macroprudential policy, the financial intermediation capacity of banks declines. As argued in section 2.2.3 an increase in equity finance tends to tighten the incentive compatibility constraint and reduce leverage, lending, investment and capital accumulation. It can be seen in the lower panels in Figure 2.3.3 that a macroprudential subsidy of around 0.2% maximises the borrowing capacity of the banking system.

2.3.3 Welfare Analysis

In Figure 2.3.4 I show the risk-adjusted steady state levels of welfare in the upper panels. Again, the macroprudential subsidy τ_s is on the x-axis. Up until around $\tau_s = 0.002$, macroprudential policy will increase the risk-adjusted steady state level of welfare. A macroprudential policy that pushes the outside equity funding ratio up too much will start to tighten the incentive compatibility constraint. In accordance with the intuition developed above, aggressive inflation targeting is generally not associated with increases in the risk-adjusted steady state level of welfare. Only under low risk, and in the absence of macroprudential policy will aggressive inflation targeting be welfare-improving due to its dampening effects on real interest rates and the corresponding reduction in μ_e.

The consumption welfare equivalents are plotted in the lower panels in Figure 2.3.4. As stated in section 2.2.7 a particular policy regime ('P') is superior to a regime without policy ('N') if the consumption equivalents are positive. In the lower panels of Figure 2.3.4 I assess whether a macroprudential policy regime ('P') is superior to a regime without macroprudential policy ('N'). Only large values of τ_s (close to 0.5%) will give rise to a negative consumption welfare equivalent. Macroprudential policy delivers the largest consumption equivalent welfare gains for a conventional inflation sensitivity coefficient of $\kappa_\Pi = 1.5$. In Figure 2.3.5 I further illustrate the relationship between macroprudential policy and monetary policy. For given levels of inflation sensitivity, the welfare-maximising macroprudential subsidy tends to be inversely related to the degree of inflation sensitivity. The higher infla-

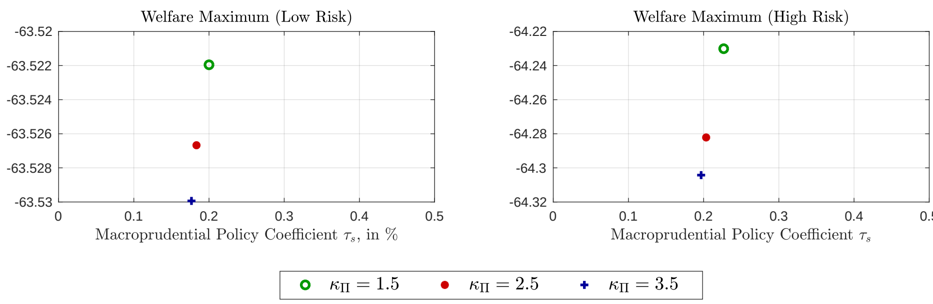
FIGURE 2.3.4: WELFARE EFFECTS OF VARIATION IN $\{\tau_s, \kappa_\Pi\}$



Note: Panel A depicts the welfare metric described above as a function of the macroprudential policy parameter τ_s in the case of low risk, Panel B in the case of high risk. Each of the three lines corresponds to a different calibration of the inflation sensitivity $\kappa_\Pi = \{1.5, 2.5, 3.5\}$. Panel C depicts the corresponding consumption welfare equivalent under low risk. Panel D depicts the same welfare measurement under high risk. The benchmark which is used to construct the consumption welfare equivalent is always the case in which there is no macroprudential policy, $\tau_s = 0$ (meaning that the inflation sensitivity coefficient κ_Π is fixed either at 1.5, 2.5 or at 3.5).

tion sensitivity, the lower the optimising level of the macroprudential subsidy τ_s. However, the level of risk-adjusted steady state welfare is also inversely related to inflation sensitivity. Thus, a simple policy prescription from this exercise is that macroprudential policy, rather than more aggressive monetary policy, should be used to curb banks accumulation of short-term debt and to encourage them to increase equity funding.

FIGURE 2.3.5: WELFARE MAXIMA DEPENDING ON $\{\tau_s, \kappa_\Pi\}$ AND RISK



Note: The left (right) panel depicts the maxima of the welfare functions plotted in Figure 2.3.4 depending on $\{\tau_s, \kappa_\Pi\}$ under low (high) risk.

2.4 Conclusion

In this paper, I develop a New Keynesian DSGE model in which banks can fund their risky investment activities either with non-state contingent debt or with state-contingent outside equity. In the context of this model, the role for macroprudential policy is to incentivise banks to strengthen their equity position. I show that macroprudential policy is welfare-improving, up to a certain point. I analyse to what extent the presence of risk, the financial friction and the presence of macroprudential policy affect the policy prescriptions for an inflation-targeting central bank. The key result is that in general, monetary policy should not respond to inflation more aggressively. Only in the case of low risk and in the absence of macroprudential policy does aggressive inflation targeting lead to improved welfare outcomes.

In future extensions I intend to assess the effects of macroprudential policy and the risk environment on monetary policy rules in which the monetary authority responds to financial variables. Moreover, I intend to work on issues such as (i) deriving the optimal monetary policy, (ii) allowing for regime switching between the low and high risk case and (iii) introducing more shocks.

2.5 Appendix of Chapter 2

2.5.1 Model Derivations

2.5.1.1 The Problem of the Retail Firm under Rotemberg Pricing

The monopolistically competitive retailers can charge a markup on top of their price. However, they face a real quadratic cost of adjusting their price given by

$$\frac{\vartheta_P}{2}\left(\frac{P_t^r}{P_{t-1}^r}-1\right)^2 Y_t \tag{2.5.1}$$

where $\vartheta_P > 0$ determines the magnitude of the adjustment cost.

The retail firm's problem is dynamic, because prices set today may affect costs tomorrow. It is assumed that the retail firm uses the same discount factor as the household. Moreover, as each firm faces the same type of price adjustment cost, each firm faces the same maximization problem and therefore prices are equal across firms. The real profit D_t^r of the retailer firm is given by

$$D_t^r = \underbrace{\left(\frac{P_t^r}{P_t}\right)Y_t^r}_{\text{real revenue}} - \underbrace{\left(1-\tau^{MC}\right)\frac{P_t^i}{P_t}Y_t^r}_{\text{real costs (inputs)}} - \underbrace{\frac{\vartheta_P}{2}\left(\frac{P_t^r}{P_{t-1}^r}-1\right)^2 Y_t}_{\text{real adjustment costs}}$$

and can be rewritten as

$$D_t^r = \left[\left(\frac{P_t^r}{P_t}\right)^{1-\epsilon} - P_t^m(1-\tau^{MC})\left(\frac{P_t^r}{P_t}\right)^{-\epsilon} - \frac{\vartheta_P}{2}\left(\frac{P_t^r}{P_{t-1}^r}-1\right)^2\right] Y_t \tag{2.5.2}$$

where P_t^m is the real marginal cost of producing $Y_t^i = Y_t^r$ units of intermediate/retail output. The retail firm then solves the following optimisation problem

$$\max_{P_t^r}\left\{\mathbb{E}_t\sum_{k=0}^{\infty}\left[\beta^k\Lambda_{t,t+k}^h\left(\left[\left(\frac{P_{t+k}^r}{P_{t+k}}\right)^{1-\epsilon} - P_{t+k}^m(1-\tau^{\mathrm{MC}})\left(\frac{P_{t+k}^r}{P_{t+k}}\right)^{-\epsilon} - \frac{\vartheta_P}{2}\left(\frac{P_{t+k}^r}{P_{t+k-1}^r}-1\right)^2\right]Y_{t+k}\right)\right]\right\}. \tag{2.5.3}$$

The retailer maximizes the expected discounted stream of profits through setting his price P_t^r

$$\begin{aligned}\frac{\partial.}{\partial P_t^r} = Y_t &\left((1-\epsilon)\left(\frac{P_t^r}{P_t}\right)^{-\epsilon}\cdot\frac{1}{P_t} + \epsilon P^m(1-\tau^{MC})\left(\frac{P_t^r}{P_t}\right)^{-\epsilon-1}\cdot\frac{1}{P_t} - \vartheta_P\left(\frac{P_t^r}{P_{t-1}^r}-1\right)\cdot\frac{1}{P_{t-1}^r}\right) \\ &+ \beta\mathbb{E}_t\Lambda_{t,t+1}^h Y_{t+1}\left(\vartheta_P\left(\frac{P_{t+1}^r}{P_t^r}-1\right)\cdot\frac{P_{t+1}^r}{(P_t^r)^2}\right) \overset{!}{=} 0\end{aligned}$$

In a symmetric equilibrium, all retail firms face the same optimization problem and thus they make the same pricing decisions so that

$$P_t^r = P_t$$

and

$$\vartheta_P \left(\frac{P_t}{P_{t-1}} - 1 \right) \cdot \frac{P_t}{P_{t-1}} = (1-\epsilon) + \epsilon P^m (1 - \tau^{MC}) + \beta \mathbb{E}_t \Lambda^h_{t,t+1} \frac{Y_{t+1}}{Y_t} \left(\vartheta_P \left(\frac{P_{t+1}}{P_t} - 1 \right) \cdot \frac{P_{t+1}}{P_t} \right)$$

Defining the gross rate of inflation

$$\Pi_t = \frac{P_t}{P_{t-1}}$$

one can obtain the optimality condition of the retail firm in its final form

$$\vartheta_P \left(\Pi_t - 1 \right) \Pi_t = (1-\epsilon) + \epsilon P^m \cdot (1 - \tau^{MC}) + \vartheta_P \beta \mathbb{E}_t \left[\Lambda^h_{t,t+1} \left(\frac{Y_{t+1}}{Y_t} \right) \left(\Pi_{t+1} - 1 \right) \Pi_{t+1} \right]. \tag{2.5.4}$$

In the determinstic steady state it can be shown that a subsidy of $\tau^{MC} = \frac{1}{\epsilon}$ will correct the distortion associated with monopolistic competition

$$P^m_t = \frac{\epsilon - 1}{\epsilon} \frac{1}{(1 - \tau^{MC})}.$$

However, this subsidy would not correct the distortion associated with monopolistic competition in the risk-adjusted steady state. Below, I will show that in the absence of the subsidy the risk-adjusted steady state of P^m would be given by

$$P^m = \frac{\epsilon - (1 + M_9)}{\epsilon}$$

where

$$M_9 \equiv \frac{1}{2} \Pi \Lambda \vartheta_P \left(3 \left(g^{\Pi}_{CQ} \right)^2 + 2 g^{\Lambda}_{CQ} g^{\Pi}_{CQ} + 2 g^{\Pi}_{CQ} g^{Y}_{CQ} \right) \eta^2_{CQ}$$

so that the subsidy in the risk-adjusted steady state has to be

$$\tau^{MC} = \frac{1 + M_9}{\epsilon}.$$

2.5.2 Deriving an Expression for the Franchise Value of the Bank

In Gertler and Kiyotaki (2010) the authors show how to use the method of 'guess and verify' to derive a simple expression of the bank's franchise value.

The original franchise value from above is

$$V_t = \mathbb{E}_t \left[\sum_{\tau=t+1}^{\infty} (1-\sigma)\sigma^{\tau-t-1} \Lambda_{t,\tau} n_\tau \right] \tag{2.5.5}$$

And it was stated that this franchise value has to be at least as high a certain fraction Θ of the capital stock

$$V_t = \Theta(x_t) Q_t^K s_t. \tag{2.5.6}$$

Since the combination of the flow of funds relation (2.2.17) with the bank's net worth accumulation equation (2.2.18) delivers an expression for n_t according to which it depends on n_t and x_{t-1}

$$n_t = \left[R_t^K - x_{t-1} R_t^E - (1-x_{t-1}) R_t \right] Q_{t-1}^K s_{t-1} + R_t n_{t-1}. \tag{2.5.7}$$

The above stated franchise value at the end of $t-1$ can be written in terms of a Bellman equation so that

$$V_{t-1}(s_{t-1}, x_{t-1}, n_{t-1}) = \mathbb{E}_{t-1} \Lambda_{t,t-1} \left\{ (1-\sigma) n_t + \sigma \max_{s_t, x_t} V_t(s_t, x_t, n_t) \right\}. \tag{2.5.8}$$

Inserting the guess

$$V_t(s_t, x_t, n_t) = (\mu_{s,t} + x_t \mu_{e,t}) Q_t^K s_t + \nu_t n_t.$$

into 2.5.8 and forwarding it, one obtains

$$(\mu_{s,t} + x_t \mu_{e,t})\, Q_t^K s_t + \nu_t n_t = \mathbb{E}_t \Lambda_{t,t+1} \left\{ (1-\sigma) + \sigma \left[(\mu_{s,t+1} + x_{t+1} \mu_{e,t+1})\, \phi_{t+1} + \nu_{t+1} \right] \right\} n_{t+1}$$

where one defines $\Omega_{t+1} \equiv (1-\sigma) + \sigma \left[(\mu_{s,t+1} + x_{t+1} \mu_{e,t+1})\, \phi_{t+1} + \nu_{t+1} \right]$ so that

$$(\mu_{s,t} + x_t \mu_{e,t})\, Q_t^K s_t + \nu_t n_t = \mathbb{E}_t \Lambda_{t,t+1} \Omega_{t+1} n_{t+1}$$

and where the above stated expression of n_t is then used to arrive at

$$(\mu_{s,t} + x_t \mu_{e,t}) Q_t^K s_t + \nu_t n_t = \mathbb{E}_t \Lambda_{t,t+1} \Omega_{t+1} \left(\left[R_{t+1}^K - R_{t+1}(1-x_t) - R_{t+1}^E x_t \right] Q_t^K s_t + R_{t+1} n_t \right).$$

Now recall that above I defined

$$\mu_{s,t} = \mathbb{E}_t \left[\Lambda_{t,t+1} \Omega_{t+1} \left(R_{t+1}^K - R_{t+1} \right) \right],\ \mu_{e,t} = \mathbb{E}_t \left[\Lambda_{t,t+1} \Omega_{t+1} \left(R_{t+1} - R_{t+1}^E \right) \right],\ \nu_t = \mathbb{E}_t \left[\Lambda_{t,t+1} \Omega_{t+1} \right] R_{t+1}.$$

It can thus be shown that the franchise value of the bank can be rewritten as a function of s_t, x_t and n_t so that

$$V_t(s_t, x_t, n_t) = (\mu_{s,t} + x_t \mu_{e,t}) Q_t^K s_t + \nu_t n_t \tag{2.5.9}$$

2.5.3 Model Equations

The model described above consists of 24 variables in 24 equations. The 24 endogenous variables are as follows: $\{Y_t, L_t, C_t, I_t, K_t, N_t, \phi_t, W_t, Q_t^K, Q_t^E, \Pi_t, P_t^m, R_t^n, R_t, R_t^E, R_t^K, u_{C,t}, x_t, \Lambda_{t-1,t}, \mu_{s,t}, \mu_{e,t}, \nu_t, \Omega_t, \tau_t^{MPP}\}$.

2.5.3.1 Households

$$\mathbb{E}_t u_{C,t} W_t = \chi L_t^{\varphi} \left(C_t - hC_{t-1} - \chi \frac{L_t^{1+\varphi}}{1+\varphi} \right)^{-\gamma} \tag{2.5.10}$$

$$u_{C,t} \equiv \left(C_t - hC_{t-1} - \chi \frac{L_t^{1+\varphi}}{1+\varphi} \right)^{-\gamma} - \beta h \left(C_{t+1} - hC_t - \chi \frac{L_{t+1}^{1+\varphi}}{1+\varphi} \right)^{-\gamma} \tag{2.5.11}$$

$$1 = \mathbb{E}_t \Lambda_{t,t+1} R_{t+1} \tag{2.5.12}$$

$$1 = \mathbb{E}_t \Lambda_{t,t+1} R_{t+1}^E \tag{2.5.13}$$

$$\Lambda_{t,t+1} = \beta \frac{u_{C,t+1}}{u_{C,t}} \tag{2.5.14}$$

$$R_{t+1}^E = \frac{\left[P_{t+1}^m \alpha \left(\frac{Y_{t+1}}{K_{t+1}} \right) + (1-\delta) Q_{t+1}^E \right] \Psi_{t+1}}{Q_t^E} \tag{2.5.15}$$

2.5.3.2 Non-financial Firms

$$Y_t^i = K_t^{\alpha} L_t^{1-\alpha} \tag{2.5.16}$$

$$W_t = P_t^m (1-\alpha) \frac{Y_t^i}{L_t} \tag{2.5.17}$$

$$R_{t+1}^K = \frac{\left[P_{t+1}^m \alpha \left(\frac{Y_{t+1}}{K_{t+1}} \right) + (1-\delta) Q_{t+1}^K \right] \Psi_{t+1}}{Q_t^K} \tag{2.5.18}$$

$$Q_t^K = 1 + \frac{\vartheta_I}{2} \left(\frac{I_t}{I_{t-1}} - 1 \right)^2 + \frac{I_t}{I_{t-1}} \vartheta_I \left(\frac{I_t}{I_{t-1}} - 1 \right) - \mathbb{E}_t \Lambda_{t,t+1} \left(\frac{I_{t+1}}{I_t} \right)^2 \vartheta_I \left(\frac{I_{t+1}}{I_t} - 1 \right) \tag{2.5.19}$$

$$K_t = \Psi_t \left[(1-\delta) K_{t-1} + I_{t-1} \right] \tag{2.5.20}$$

$$\vartheta_P \left(\frac{\Pi_t}{\Pi_{rss}} - 1 \right) \Pi_t = (1-\varepsilon) + \varepsilon P_t^m \left(1 - \tau^{MC} \right) \tag{2.5.21}$$

$$+ \vartheta_P \left(\Lambda_{t,t+1} \left(\frac{\Pi_{t+1}}{\Pi_{rss}} - 1 \right) (\Pi_{t+1}) \frac{Y_{t+1}}{Y_t} \right). \tag{2.5.22}$$

2.5.3.3 Banks

$$\phi_t = \frac{Q_t^K K_t}{N_t} \quad (2.5.23)$$
$$\Omega_{t+1} = (1-\sigma) + \sigma\left[\nu_{t+1} + \phi_{t+1}\left(\mu_{s,t+1} + x_{t+1}\mu_{e,t+1}\right)\right] \quad (2.5.24)$$
$$\mu_{s,t} = \mathbb{E}_t\left[\Lambda_{t,t+1}\Omega_{t+1}\left(R_{t+1}^K - R_{t+1}\right)\right] \quad (2.5.25)$$
$$\mu_{e,t} = \mathbb{E}_t\left[\Lambda_{t,t+1}\Omega_{t+1}\left(R_{t+1} - R_{t+1}^E\right)\right] \quad (2.5.26)$$
$$\nu_t = \mathbb{E}_t\left[\Lambda_{t,t+1}\Omega_{t+1}\right]R_{t+1} \quad (2.5.27)$$

$$\phi_t = \frac{\nu_t}{\Theta(x_t) - (\mu_{s,t} + x_t\mu_{e,t})} \quad (2.5.28)$$
$$\frac{\Theta'(x_t)}{\Theta(x_t)} = \frac{\mu_{e,t}}{\mu_{s,t} + x_t\mu_{e,t}} \quad (2.5.29)$$
$$(2.5.30)$$

$$N_t = \sigma\left[\left(R_t^K - x_{t-1}R_t^E - (1-x_{t-1})R_t\right)\phi_{t-1} - R_t\right]N_{t-1} \quad (2.5.31)$$
$$+ \xi R_t^K N_{t-1}\phi_{t-1} \quad (2.5.32)$$

2.5.3.4 Monetary Policy

$$\frac{R_t^n}{R_{rss}^n} = \left[\left(\frac{\Pi_t}{\Pi_{rss}}\right)^{\kappa_\Pi}\left(\frac{P_t^m}{P_{rss}^m}\right)^{\kappa_{Pm}}\right]^{1-\rho_{Rn}}\left(\frac{R_{t-1}^n}{R_{rss}^n}\right)^{\rho_{Rn}}\exp(v_t) \quad (2.5.33)$$
$$R_t^n \mathbb{E}_t\Lambda_{t,t+1}\Pi_{t+1}^{-1} = R_t\mathbb{E}_t\Lambda_{t,t+1} \quad (2.5.34)$$

2.5.3.5 Macroprudential Policy

$$\tau_t^{MPP} = \frac{\tau^s}{\nu_t} \quad (2.5.35)$$

2.5.3.6 Market Clearing

$$Y_t\left(1 - \frac{\vartheta_P}{2}\left(\frac{\Pi_t}{\Pi} - 1\right)^2\right) = C_t + \left(1 + \frac{\vartheta_I}{2}\left(\frac{I_t}{I_{t-1}} - 1\right)^2\right)I_t \quad (2.5.36)$$

2.5.4 Deterministic Steady State

2.5.4.1 Households

$$u_{C,dss} W_{dss} = \chi L_{dss}^{\varphi} \left(C_{dss} - hC_{dss} - \chi \frac{L_{dss}^{1+\varphi}}{1+\varphi} \right)^{-\gamma} \tag{2.5.37}$$

$$u_{C,dss} \equiv \left(C_{dss} - hC_{dss} - \chi \frac{L_{dss}^{1+\varphi}}{1+\varphi} \right)^{-\gamma} - \beta h \left(C_{dss} - hC_{dss} - \chi \frac{L_{dss}^{1+\varphi}}{1+\varphi} \right)^{-\gamma} \tag{2.5.38}$$

$$1 = \Lambda_{dss} R_{dss} \tag{2.5.39}$$

$$1 = \Lambda_{dss} R^E_{dss} \tag{2.5.40}$$

$$\Lambda_{dss} = \beta \tag{2.5.41}$$

$$R^E_{dss} = \frac{\left[P^m_{dss} \alpha \left(\frac{Y_{dss}}{K_{dss}} \right) + (1-\delta) Q^E_{dss} \right] \Psi_{dss}}{Q^E_{dss}} \tag{2.5.42}$$

2.5.4.2 Non-financial Firms

$$Y^i_{dss} = K^{\alpha}_{dss} L^{1-\alpha}_{dss} \tag{2.5.43}$$

$$W_{dss} = P^m_{dss} (1-\alpha) \frac{Y^i_{dss}}{L_{dss}} \tag{2.5.44}$$

$$R^K_{dss} = \frac{\left[P^m_{dss} \alpha \left(\frac{Y_{dss}}{K_{dss}} \right) + (1-\delta) Q^K_{dss} \right] \Psi_{dss}}{Q^K_{dss}} \tag{2.5.45}$$

$$Q^K_{dss} = 1 \tag{2.5.46}$$

$$K_{dss} = [(1-\delta) K_{dss} + I_{dss}] \tag{2.5.47}$$

$$1 = P^m_{dss} \tag{2.5.48}$$

2.5.4.3 Banks

$$\phi_{dss} = \frac{Q^K_{dss} K_{dss}}{N_{dss}} \tag{2.5.49}$$

$$\Omega_{dss} = (1-\sigma) + \sigma \left[\nu_{dss} + \phi_{dss} \left(\mu_{s,dss} + x_{dss} \mu_{e,dss} \right) \right] \tag{2.5.50}$$

$$\mu_{s,dss} = \left[\Lambda_{dss} \Omega_{dss} \left(R^K_{dss} - R_{dss} \right) \right] \tag{2.5.51}$$

$$\mu_{e,dss} = \left[\Lambda_{dss} \Omega_{dss} \left(R_{dss} - R^E_{dss} \right) \right] \tag{2.5.52}$$

$$\nu_{dss} = \left[\Lambda_{dss} \Omega_{dss} \right] R_{dss} \tag{2.5.53}$$

$$\phi_{dss} = \frac{\nu_{dss}}{\Theta(x_{dss}) - (\mu_{s,dss} + x_{dss} \mu_{e,dss})} \tag{2.5.54}$$

$$\frac{\Theta'(x_{dss})}{\Theta(x_{dss})} = \frac{\mu_{e,dss}}{\mu_{s,dss} + x_{dss} \mu_{e,dss}} \tag{2.5.55}$$

$$\tag{2.5.56}$$

$$N_{dss} = \sigma\left[\left(R^K_{dss} - x_{dss}R^E_{dss} - (1-x_{dss})R_{dss}\right)\phi_{dss} - R_{dss}\right]N_{dss} \tag{2.5.57}$$
$$+\xi R^K_{dss}N_{dss}\phi_{dss} \tag{2.5.58}$$

2.5.4.4 Monetary Policy

$$R^n_{dss} = R^n_{dss} \tag{2.5.59}$$
$$R^n_{dss} = R_{dss} \tag{2.5.60}$$

2.5.4.5 Macroprudential Policy

$$\tau^{MPP}_{dss} = \frac{\tau^s}{\nu_{dss}} \tag{2.5.61}$$

2.5.4.6 Market Clearing

$$Y_{dss} = C_{dss} + I_{dss} \tag{2.5.62}$$

2.5.5 Deriving the Risk-adjusted Steady State

The key idea is to solve the model as a first-order approximation around a second-order approximation of the model's risk-adjusted steady state. The models equilibrium conditions can be written as

$$0 = \mathbb{E}_t\left[f(y_{t+1}, y_t, x_{t+1}, x_t, z_{t+1}, z_t)\right] \tag{2.5.63}$$
$$z_{t+1} = \rho z_t + \eta\sigma\epsilon_{t+1} \tag{2.5.64}$$

where y_t is the vector of time t non-predetermined variables (such as employment), x_t is the vector of endogenous predetermined variables (such as capital), z_t is the vector of exogenous predetermined variables and ϵ_t is the vector of exogenous i.i.d innovations with mean zero and unit standard deviations. ρ and η are parameter matrices of dimension $n_z \times n_z$ and σ is a scalar that determines uncertainty in the economy.

The policy functions for the endogenous non-predetermined and predetermined vectors y_t, x_t are defined as $y_t = g(x_t, z_t)$ and $x_{t+1} = h(x_t, z_t)$. The risk-adjusted steady state, x^r, solves

$$x^r = h(x^r, 0) \text{ and } y^r = g(x^r, 0). \tag{2.5.65}$$

When substituting the decision rules into the above stated system of equilibrium conditions, one obtains

$$0 = \mathbb{E}_t\left[f\left(g(x_{t+1}, \rho z_t + \eta\sigma\epsilon_{t+1}), g(x_t, z_t), x_{t+1}, x_t, \rho z_t + \eta\sigma\epsilon_{t+1}, z_t\right)\right]$$
$$f(x^r, \sigma) \equiv \mathbb{E}_t\left[f\left(g(x^r, \eta\sigma\epsilon_{t+1}), g(x^r, 0), x^r, x^r, \eta\sigma\epsilon_{t+1}, 0\right)\right] = 0$$

where the last equation is already evaluated at the risk-adjusted steady state in which shocks today are absent ($z^r = 0$) but possible in the future $z'r = \eta\sigma\epsilon_{t+1}$. The next step then is to take a second-order approximation of f around $\sigma = 0$, while only taking a first-order approximation of g and h around $\sigma = 0$. Following the notation introduced in Schmitt-Grohe and Uribe (2004) one arrives at

$$[f(x^r,\sigma)]^i \approx [f(x^r,0)]^i + \frac{\sigma^2}{2}[f_{\sigma\sigma}(x^r,0)] \quad = \quad 0$$

with

$$f(x^r,0) = f(y^r,y^r,x^r,x^r,0,0)$$

and

$$[f_{\sigma\sigma}(x^r,0)]^i = [f_{y'y'}]^i_{\alpha\gamma}[g_z\eta]^\alpha_\phi[g_z\eta]^\gamma_\xi[I]^\phi_\xi + [f_{y'z'}]^i_{\alpha\delta}[g_z\eta]^\alpha_\phi[\eta]^\delta_\xi[I]^\phi_\xi + [\Theta_{z'z'}]^i_{\beta\delta}[\eta^\beta_\phi][\eta]^\delta_\xi + [I]^\phi_\xi$$

where $i = 1,\ldots,n; \alpha,\gamma = 1,\ldots,n_y$; and $\beta,\delta = 1,\ldots,n_z; \phi,\xi = 1,\ldots,n_\epsilon$.

2.5.5.1 Risk-adjusted Steady State

For the following 10 equations the steady state will contain risk-adjustment terms M_i

$$Q^K_{rss} = 1 + M_1 \tag{2.5.66}$$
$$1 = \Lambda_{rss}R_{rss} + M_2 \tag{2.5.67}$$
$$1 = \Lambda_{rss}(R_{E,rss} - R_{rss}) + M_3 \tag{2.5.68}$$

$$U_{C,rss} = (1-\beta h)\left((1-h)C_{rss} - \frac{\chi}{1+\vartheta}L^{1+\vartheta}_{rss}\right)^{-\gamma} + M_4 \tag{2.5.69}$$
$$Spread_{rss} = R_{K,rss} - R_{rss} + M_5 \tag{2.5.70}$$
$$\mu_{s,rss} = \Lambda_{rss}\Omega_{rss}(R_{K,rss} - R_{rss}) + M_6 \tag{2.5.71}$$
$$\mu_{e,rss} = \Lambda_{rss}\Omega_{rss}(R_{rss} - R_{E,rss}) + M_7 \tag{2.5.72}$$
$$\nu_{rss} = \Lambda_{rss}\Omega_{rss}R_{rss} + M_8 \tag{2.5.73}$$
$$P^m_{rss} = \frac{\epsilon - (1+M_9)}{\epsilon}\frac{1}{(1-\tau^{MC})} \tag{2.5.74}$$
$$R_{N,rss} = R_{rss} + M_{10} \tag{2.5.75}$$

where the risk-adjustment terms M_i, $i = 1, ..., 11$ are given by

$$M_1 \equiv -\frac{1}{2}\Lambda_{rss}\vartheta_I \left(5\left(g^I_{CQ}\right)^2 + 2g^\Lambda_{CQ}g^I_{CQ}\right)\eta^2_{CQ} \tag{2.5.76}$$

$$M_2 \equiv \frac{1}{2}\Lambda_{rss}R_{rss}\left(g^\Lambda_{CQ}\right)^2\eta^2_{CQ} \tag{2.5.77}$$

$$M_3 \equiv \frac{1}{2}\Lambda_{rss}\left(\left(R_{E,rss} - R_{rss}\right)(g^\Lambda_{CQ})^2 + R_{E,rss}\left(2g^\Lambda_{CQ}g^{R_E}_{CQ} + \left(g^{R_E}_{CQ}\right)^2\right)\right)\eta^2_{CQ} \tag{2.5.78}$$

$$\begin{aligned} M_4 \equiv\ & \frac{1}{2}\gamma\beta h\left((1-h)C_{rss} - \frac{\chi}{1+\varphi}L^{1+\varphi}_{rss}\right)^{-\gamma-1} \\ & \times\left(C_{rss}\left(1-(1+\gamma)C_{rss}\left((1-h)C_{rss} - \frac{\chi}{1+\varphi}L^{1+\varphi}_{rss}\right)^{-1}\right)\left(g^C_{CQ}\right)^2\right. \\ & +2(1+\gamma)C_{rss}\chi L^{1+\varphi}_{rss}\left((1-h)C_{rss} - \frac{\chi}{1+\varphi}L^{1+\varphi}_{rss}\right)^{-1} g^C_{CQ}g^L_{CQ} - \chi L^{1+\varphi}_{rss} \\ & \left.\times\left((1+\varphi) + (1+\gamma)\chi L^{1+\varphi}_{rss}\left((1-h)C_{rss} - \frac{\chi}{1+\varphi}L^{1+\varphi}_{rss}\right)^{-1}\right)\left(g^L_{CQ}\right)^2\right)\eta^2_{CQ} \end{aligned} \tag{2.5.79}$$

$$M_5 \equiv -\frac{1}{2}R_{K,rss}\left(g^{R_{K,rss}}_{CQ}\right)^2\eta^2_{CQ} \tag{2.5.80}$$

$$M_6 \equiv \frac{1}{2}\Lambda_{rss}\Omega_{rss}\left(R_{K,rss} - R_{rss}\right)\left(\left(g^\Lambda_{CQ}\right)^2 + 2g^\Lambda_{CQ}g^\Omega_{CQ} + \left(g^\Omega_{CQ}\right)^2\right)\eta^2_{CQ} \tag{2.5.81}$$

$$\begin{aligned} M_7 \equiv\ & -\frac{1}{2}\Lambda_{rss}\Omega_{rss}\left(\left(R_{E,rss} - R_{rss}\right)\left(\left(g^\Lambda_{CQ}\right)^2 + 2g^\Lambda_{CQ}g^\Omega_{CQ} + \left(g^\Omega_{CQ}\right)^2\right)\left(R_{E,rss} - R_{rss}\right)\right. \\ & \left. +R_{E,rss}\left(2g^\Lambda_{CQ}g^{R_E}_{CQ} + 2g^\Omega_{CQ}g^{R_E}_{CQ} + \left(g^{R_E}_{CQ}\right)^2\right)\right)\eta^2_{CQ} \end{aligned} \tag{2.5.82}$$

$$M_8 \equiv \frac{1}{2}\Lambda_{rss}\Omega_{rss}R_{rss}\left((g^\Lambda_{CQ})^2 + 2g^\Lambda_{CQ}g^\Omega_{CQ} + (g^\Omega_{CQ})^2\right)\eta^2_{CQ} \tag{2.5.83}$$

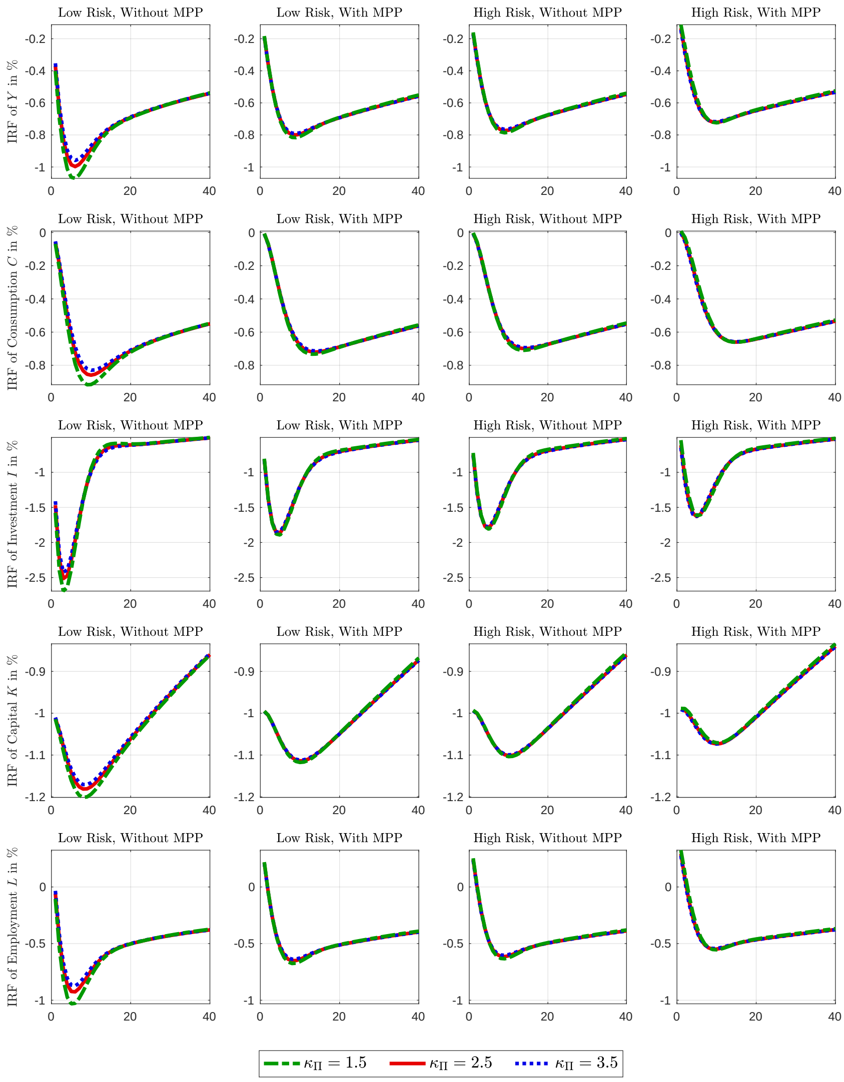
$$M_9 \equiv \frac{1}{2}\Pi_{rss}\Lambda_{rss}\vartheta_P\left(3\left(g^\Pi_{CQ}\right)^2 + 2g^\Lambda_{CQ}g^\Pi_{CQ} + 2g^\Pi_{CQ}g^Y_{CQ}\right)\eta^2_{CQ} \tag{2.5.84}$$

$$M_{10} \equiv \frac{1}{2}\Pi_{rss}R_{rss}(g^\Pi_{CQ})^2\eta^2_{CQ} \tag{2.5.85}$$

$$M_{11} \equiv M_W = \frac{W}{2}(g^W_{CQ})^2\eta^2_{CQ} \tag{2.5.86}$$

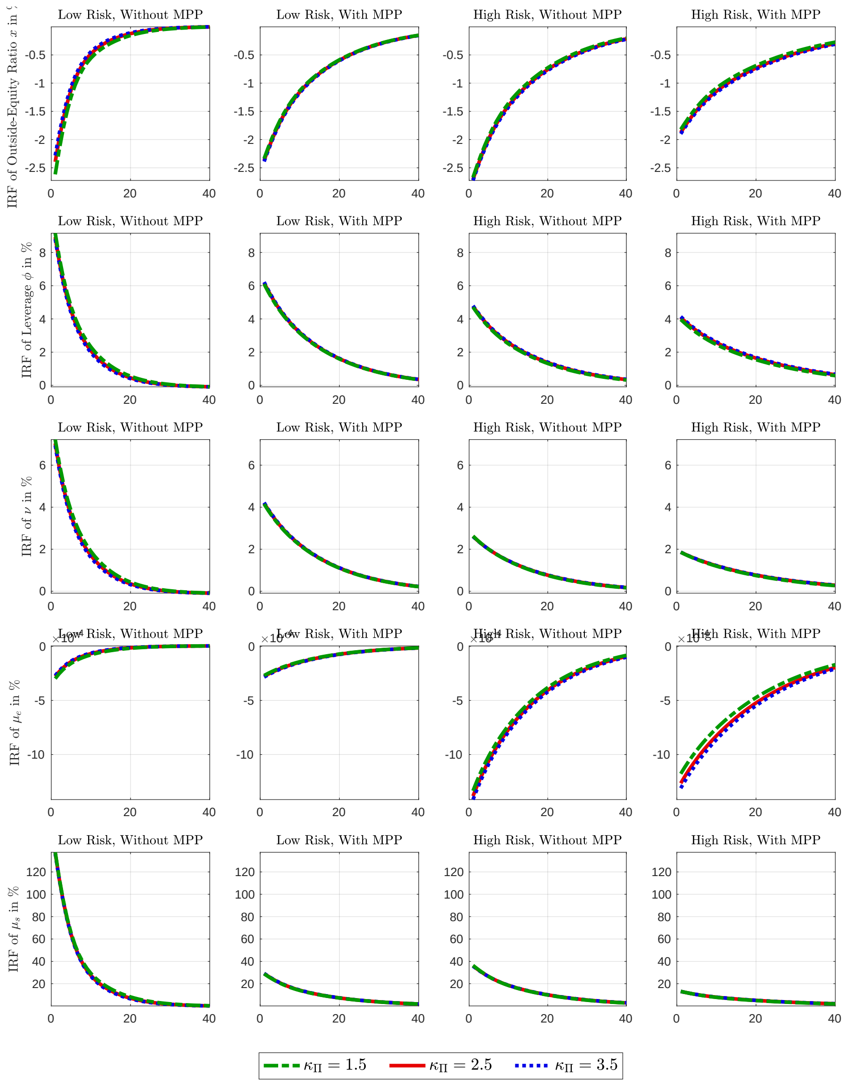
2.5.6 Impulse Response Functions

FIGURE 2.5.1: IRFs OF $\{Y, C, I, K, L\}$ UNDER LOW AND HIGH RISK WITH AND WITHOUT MPP AND $\kappa_{\Pi} = \{1.5, 2.5, 3.5\}$



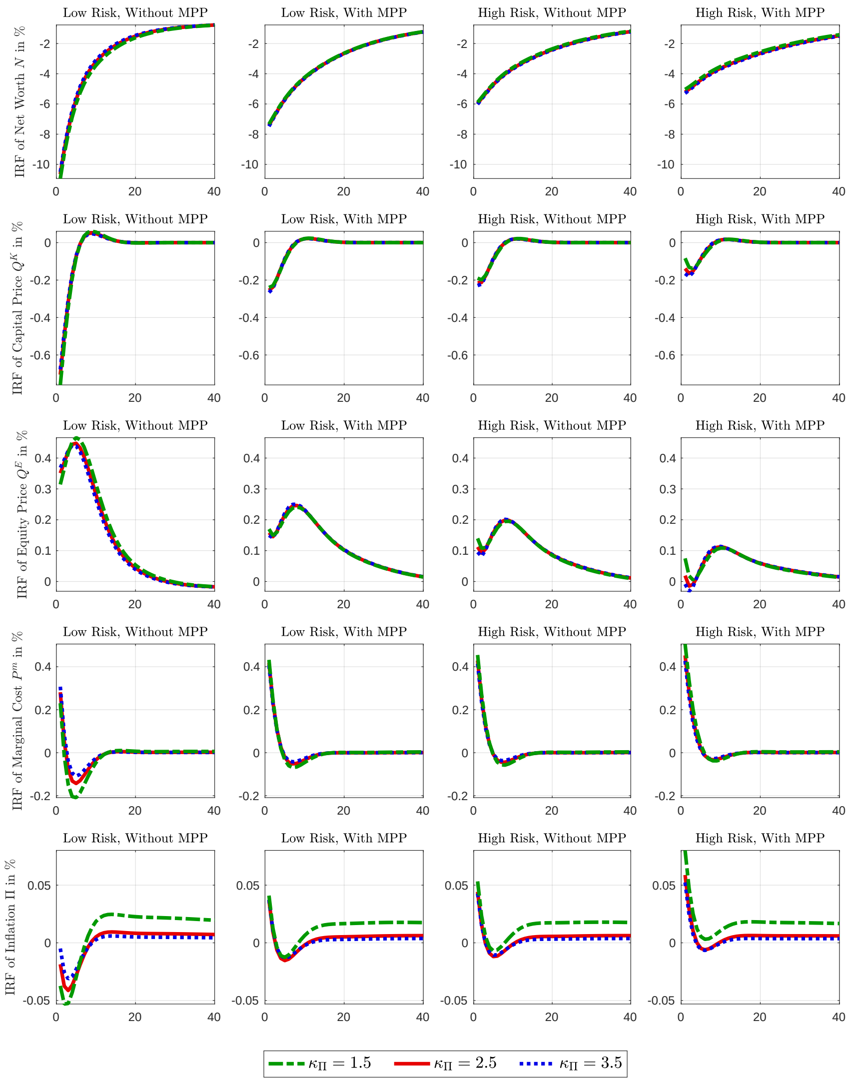
Note: Each row corresponds to one variable of $\{Y, C, I, K, L\}$. Each column corresponds to a specific risk environment and macroprudential policy regime. The two left columns depict the IRFs of $\{Y, C, I, K, L\}$ in the case of low risk. The very left column depicts the case without MPP ($\tau_s = 0$), the second from the left column depicts the case with MPP ($\tau_s = 0.002$). The two right columns depict the IRFs under high risk. In each panel the two lines correspond to IRFs under a different calibration of the inflation sensitivity $\kappa_{\Pi} = \{1.5, 2.5, 3.5\}$.

FIGURE 2.5.2: IRFS OF $\{x,\phi,\nu,\mu_e,\mu_s\}$ UNDER LOW AND HIGH RISK WITH AND WITHOUT MPP AND $\kappa_\Pi = \{1.5, 2.5, 3.5\}$



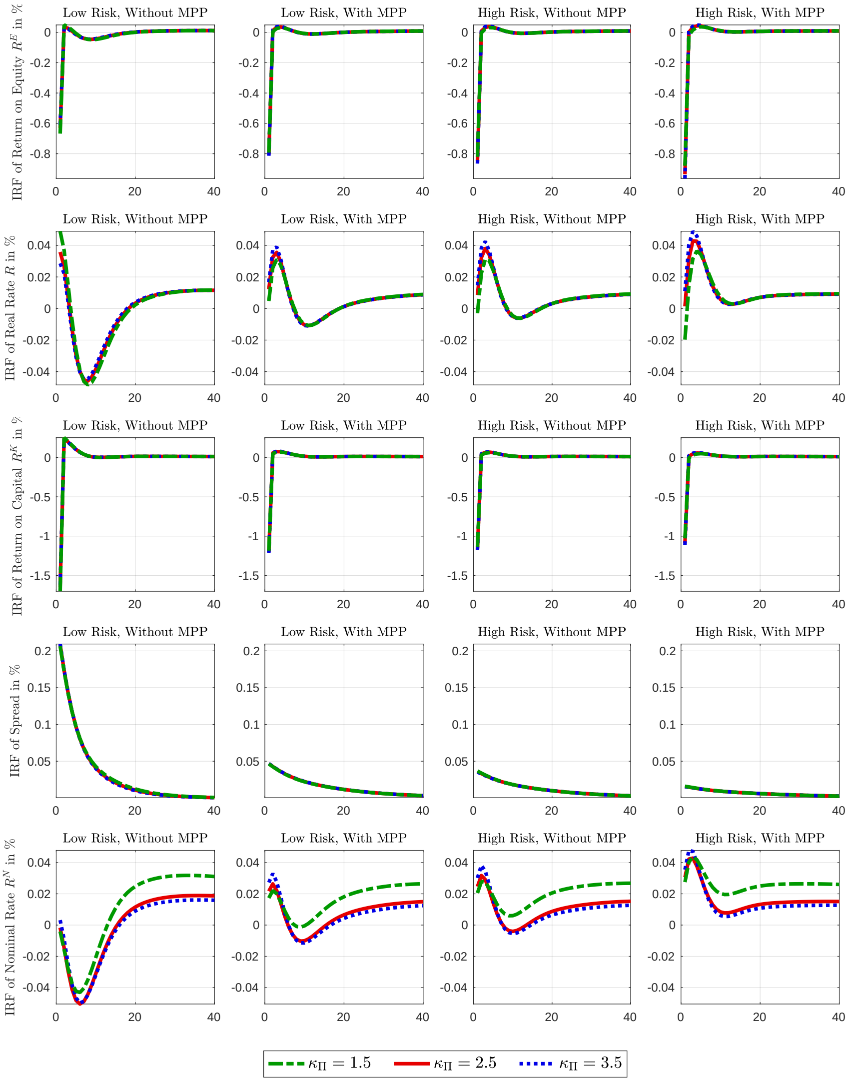
Note: Each row corresponds to one variable of $\{x,\phi,\nu,\mu_e,\mu_s\}$. Each column corresponds to a specific risk environment and macroprudential policy regime. The two left columns depict the IRFs of $\{x,\phi,\nu,\mu_e,\mu_s\}$ in the case of low risk. The very left column depicts the case without MPP ($\tau_s = 0$), the second from the left column depicts the case with MPP ($\tau_s = 0.002$). The two right columns depict the IRFs under high risk. In each panel the two lines correspond to IRFs under a different calibration of the inflation sensitivity $\kappa_\Pi = \{1.5, 2.5, 3.5\}$.

FIGURE 2.5.3: IRFS OF $\{N, Q^K, Q^E, P^m, \Pi\}$ UNDER LOW AND HIGH RISK WITH AND WITHOUT MPP AND $\kappa_\Pi = \{1.5, 2.5, 3.5\}$



Note: Each row corresponds to one variable of $\{N, Q^K, Q^E, P^m, \Pi\}$. Each column corresponds to a specific risk environment and macroprudential policy regime. The two left columns depict the IRFs of $\{N, Q^K, Q^E, P^m, \Pi\}$ in the case of low risk. The very left column depicts the case without MPP ($\tau_s = 0$), the second from the left column depicts the case with MPP ($\tau_s = 0.002$). The two right columns depict the IRFs under high risk. In each panel the two lines correspond to IRFs under a different calibration of the inflation sensitivity $\kappa_\Pi = \{1.5, 2.5, 3.5\}$.

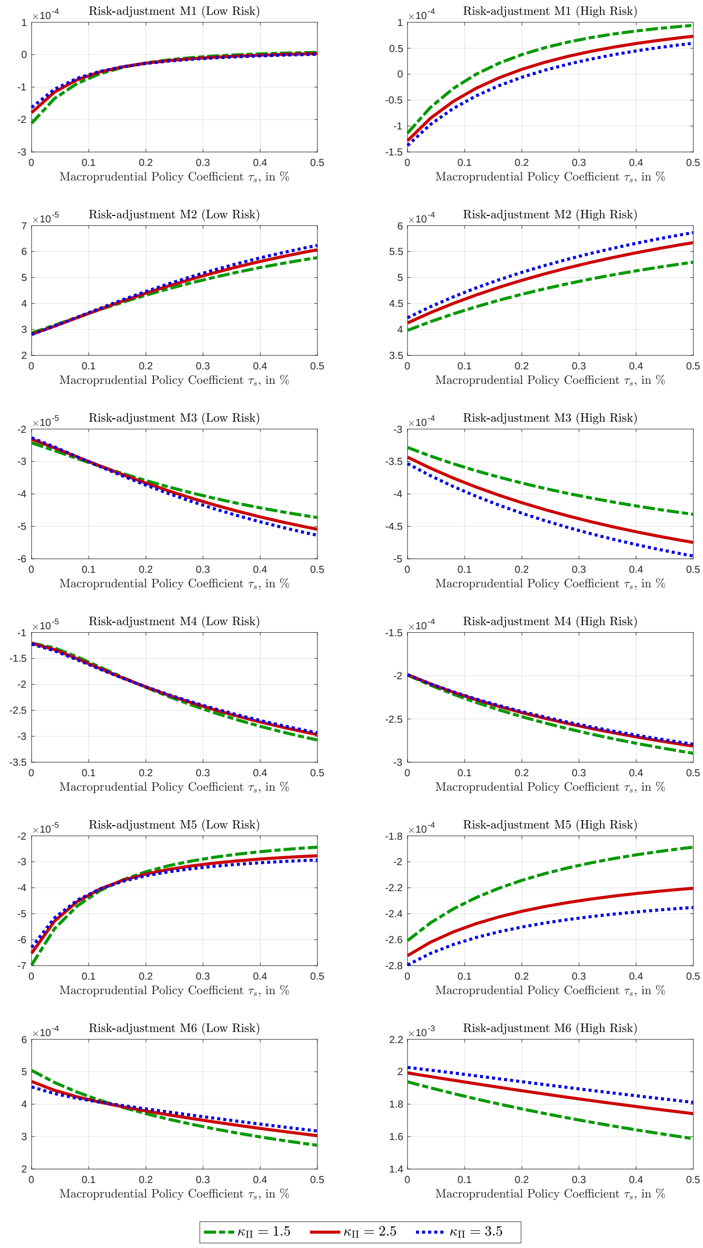
FIGURE 2.5.4: IRFS OF $\{R^E, R, R^K, Spr, R^N\}$ UNDER LOW AND HIGH RISK WITH AND WITHOUT MPP AND $\kappa_\Pi = \{1.5, 2.5, 3.5\}$



Note: Each row corresponds to one variable of $\{R^E, R, R^K, Spr, R^N\}$. Each column corresponds to a specific risk environment and macroprudential policy regime. The two left columns depict the IRFs of $\{R^E, R, R^K, Spr, R^N\}$ in the case of low risk. The very left column depicts the case without MPP ($\tau_s = 0$), the second from the left column depicts the case with MPP ($\tau_s = 0.002$). The two right columns depict the IRFs under high risk. In each panel the two lines correspond to IRFs under a different calibration of the inflation sensitivity $\kappa_\Pi = \{1.5, 2.5, 3.5\}$.

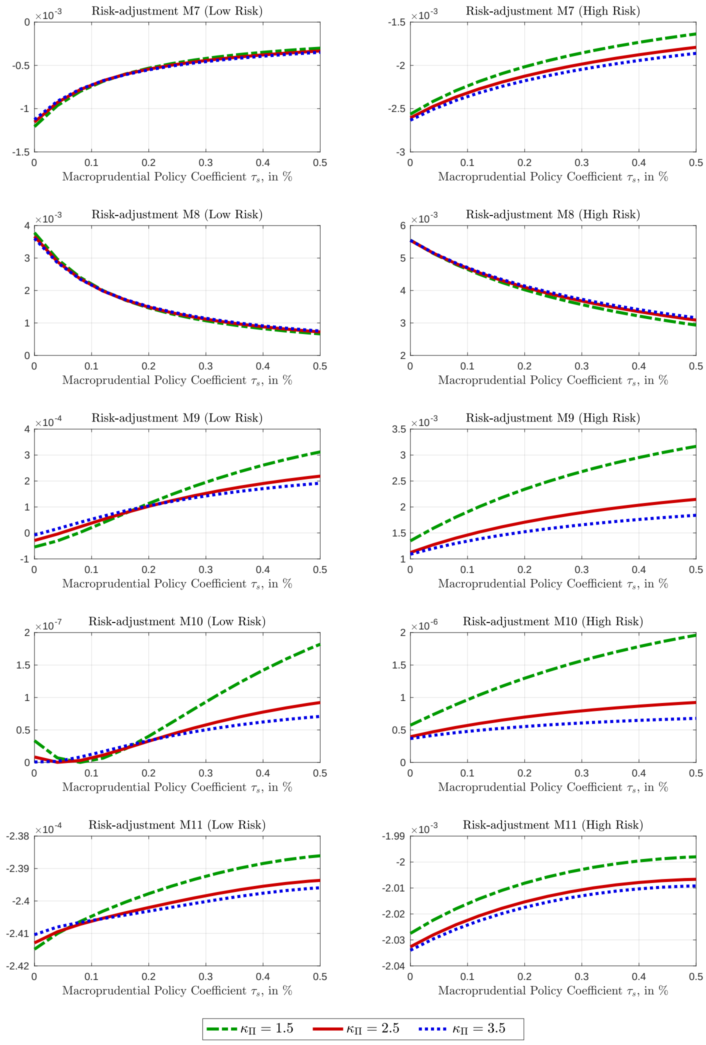
2.5.7 Risk-adjustment terms as functions of $\{\tau_s, \kappa_\Pi\}$

FIGURE 2.5.5: RISK-ADJUSTMENT TERMS $M1 - M6$ AS FUNCTIONS OF $\{\tau_s, \kappa_\Pi\}$



Note: Each row corresponds to one variable of $\{M1, M2, M3, M4, M5, M6\}$. Each column corresponds to a specific risk environment. In each panel the two lines correspond to a risk-adjustment term M under a different calibration of the inflation sensitivity $\kappa_\Pi = \{1.5, 2.5, 3.5\}$.

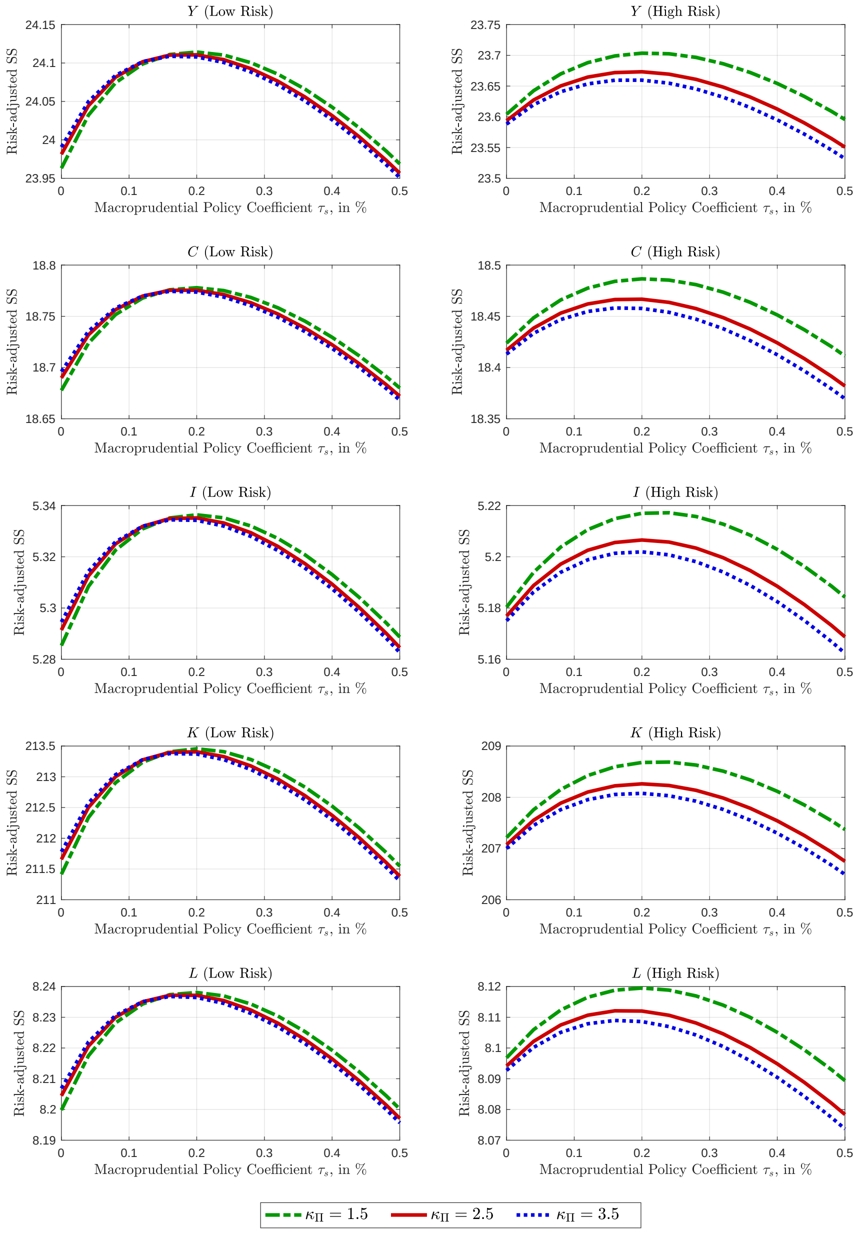
FIGURE 2.5.6: RISK-ADJUSTMENT TERMS $M7 - M11$ AS FUNCTIONS OF $\{\tau_s, \kappa_\Pi\}$



Note: Each row corresponds to one variable of $\{M7, M8, M9, M10, M11\}$. Each column corresponds to a specific risk environment. In each panel the two lines correspond to a risk-adjustment term M under a different calibration of the inflation sensitivity $\kappa_\Pi = \{1.5, 2.5, 3.5\}$.

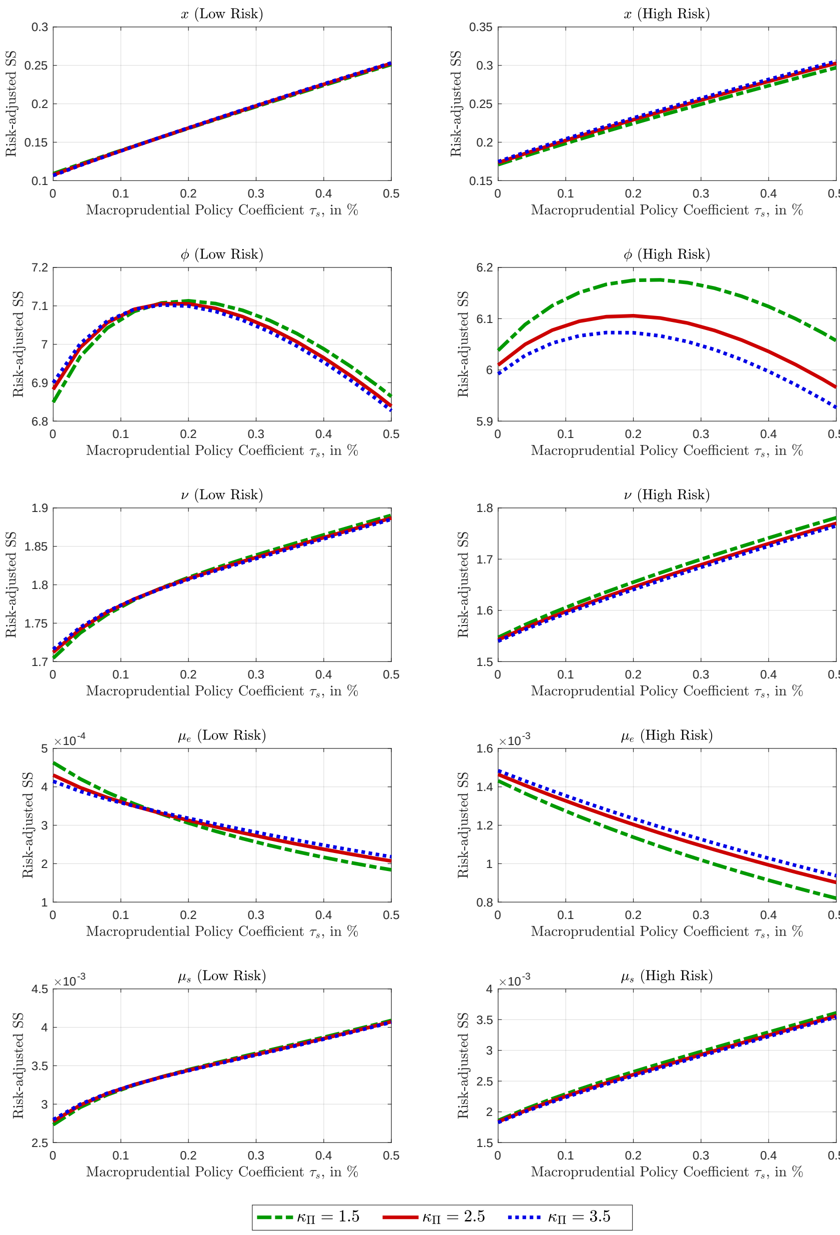
2.5.8 Risk-adjusted Steady States as a Function of τ_s and κ_Π

FIGURE 2.5.7: EFFECTS OF VARIATION IN $\{\tau_s, \kappa_\Pi\}$ ON THE RISK-ADJUSTED STEADY STATE OF $\{Y, C, I, K, L\}$



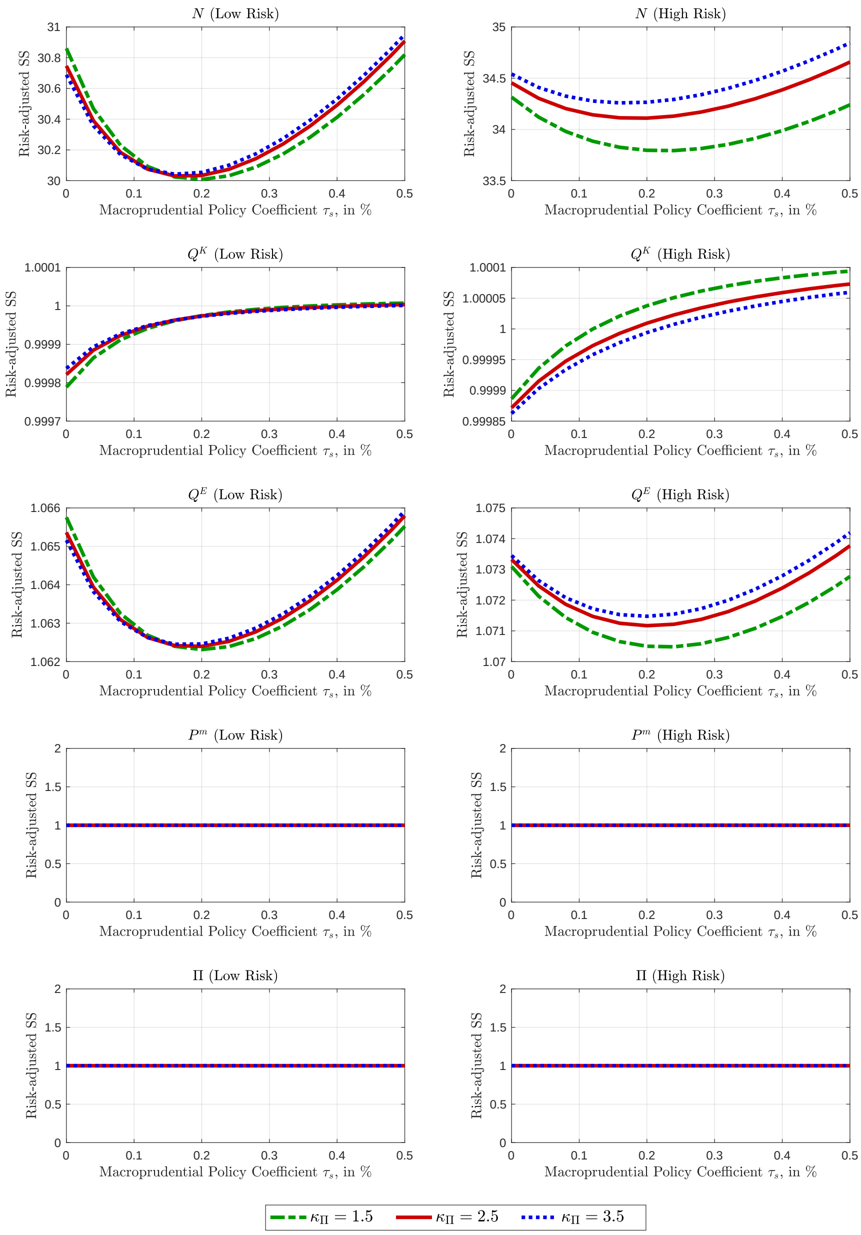
Note: The left (right) column depicts the risk-adjusted steady state of $\{Y, C, I, K, L\}$ as a function of τ_s and κ_Π in the case of low (high) risk. In each panel the three lines correspond to a different calibration of the inflation sensitivity $\kappa_\Pi = \{1.5, 2.5, 3.5\}$.

FIGURE 2.5.8: EFFECTS OF VARIATION IN $\{\tau_s, \kappa_\Pi\}$ ON THE RISK-ADJUSTED STEADY STATE OF $\{x, \phi, \nu, \mu_e, \mu_s\}$



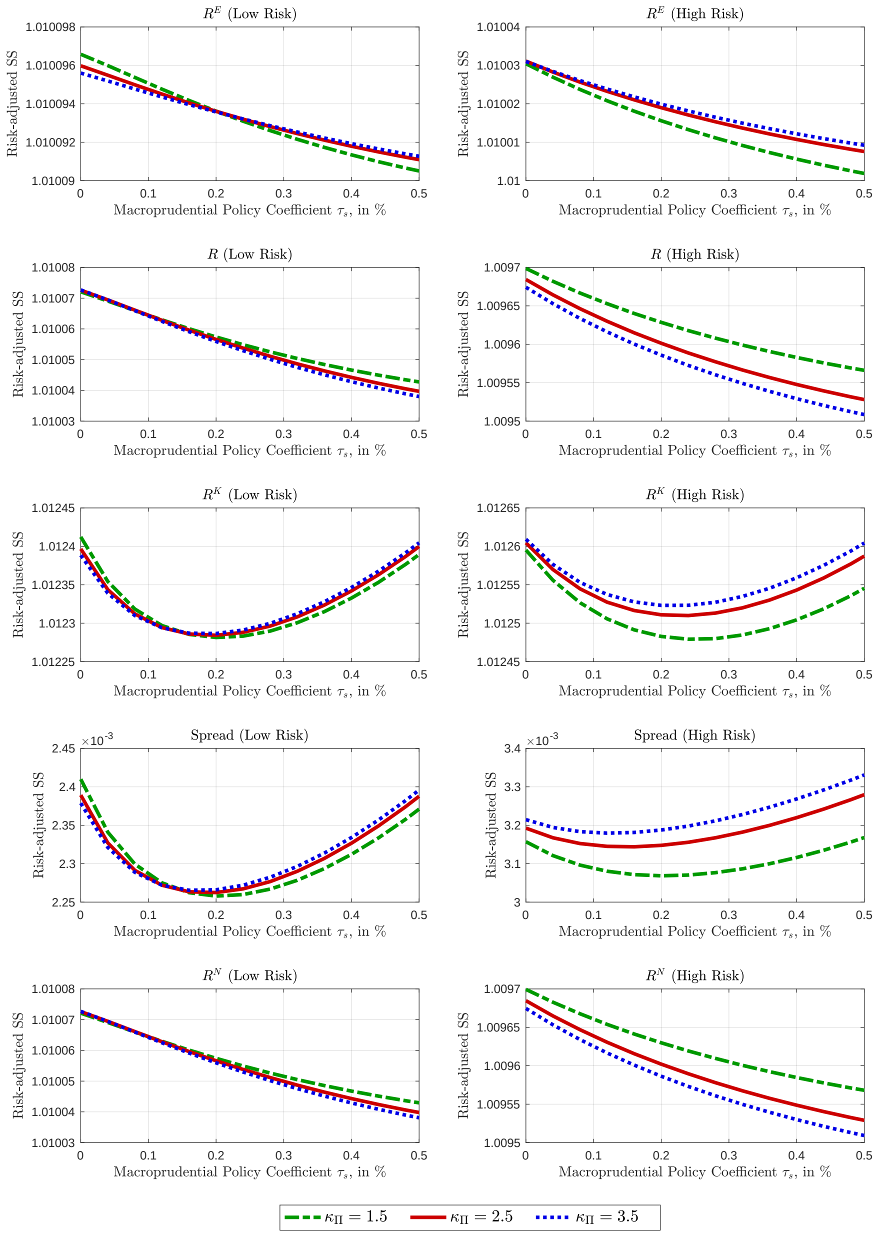
Note: The left (right) column depicts the risk-adjusted steady state of $\{x, \phi, \nu, \mu_e, \mu_s\}$ as a function of τ_s and κ_Π in the case of low (high) risk. In each panel the three lines correspond to a different calibration of the inflation sensitivity $\kappa_\Pi = \{1.5, 2.5, 3.5\}$.

FIGURE 2.5.9: EFFECTS OF VARIATION IN $\{\tau_s, \kappa_\Pi\}$ ON THE RISK-ADJUSTED STEADY STATE OF $\{N, Q^K, Q^E, P^m, \Pi\}$



Note: The left (right) column depicts the risk-adjusted steady state of $\{N, Q^K, Q^E, P^m, \Pi\}$ as a function of τ_s and κ_Π in the case of low (high) risk. In each panel the three lines correspond to a different calibration of the inflation sensitivity $\kappa_\Pi = \{1.5, 2.5, 3.5\}$.

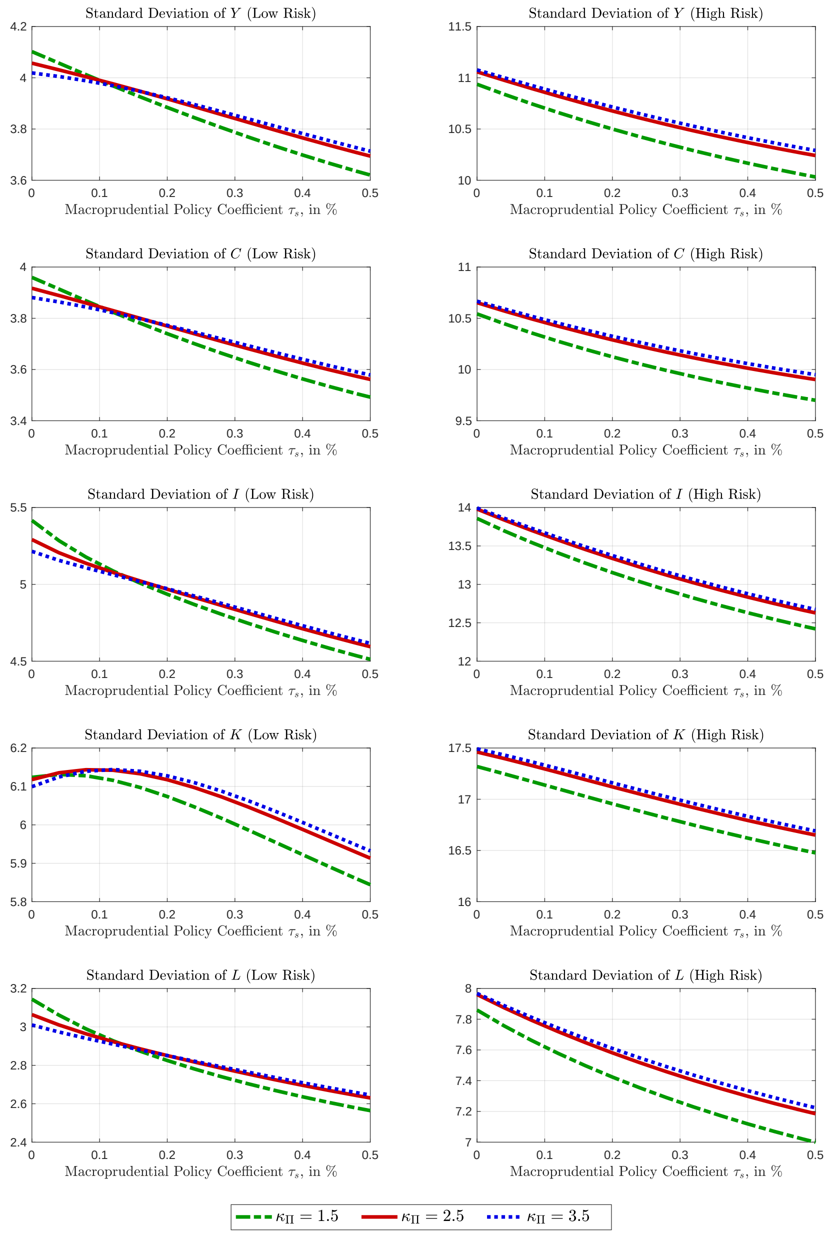
FIGURE 2.5.10: EFFECTS OF VARIATION IN $\{\tau_s, \kappa_\Pi\}$ ON THE RISK-ADJUSTED STEADY STATE OF $\{R^E, R, R^K, Spr, R^N\}$



Note: The left (right) column depicts the risk-adjusted steady state of $\{R^E, R, R^K, Spread, R^N\}$ as a function of τ_s and κ_Π in the case of low (high) risk. In each panel the three lines correspond to a different calibration of the inflation sensitivity $\kappa_\Pi = \{1.5, 2.5, 3.5\}$.

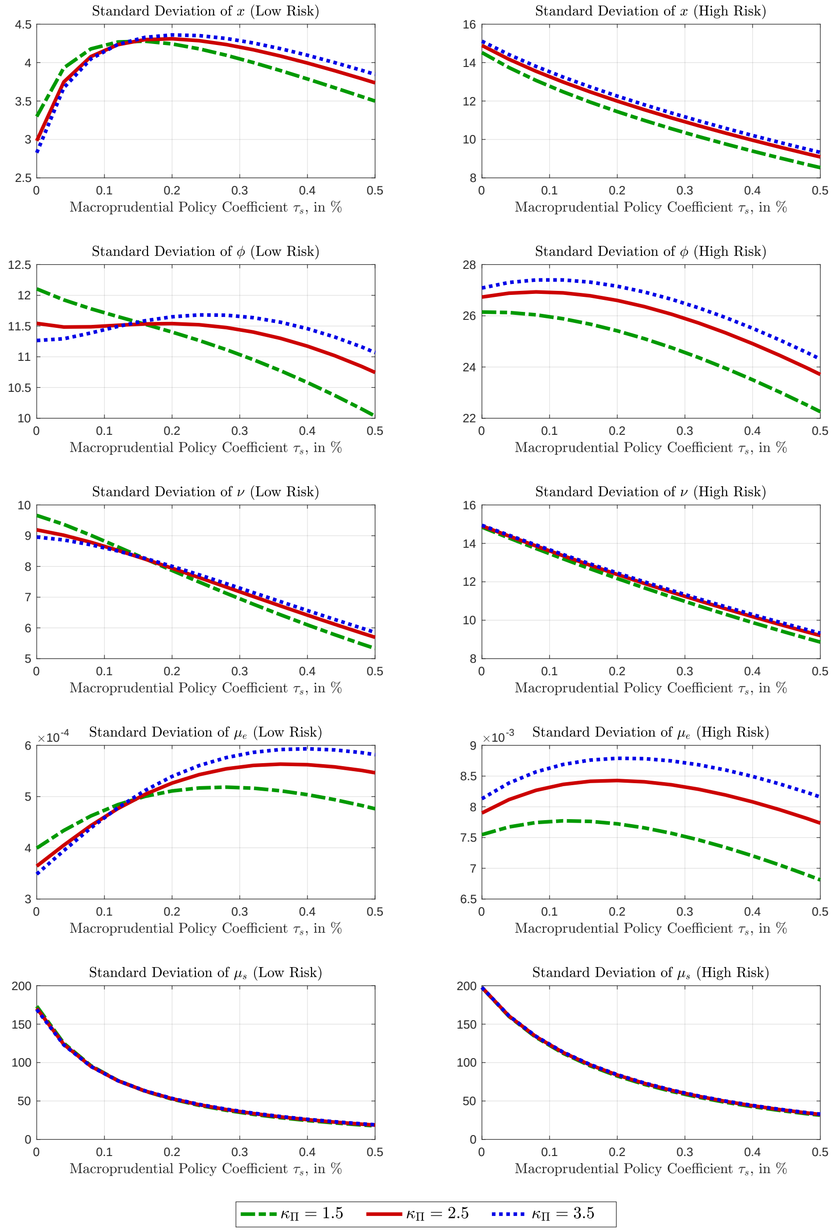
2.5.9 Standard Deviations as a Function of τ_s and κ_Π

FIGURE 2.5.11: EFFECTS OF VARIATION IN $\{\tau_s, \kappa_\Pi\}$ ON THE STDEV OF $\{Y, C, I, K, L\}$



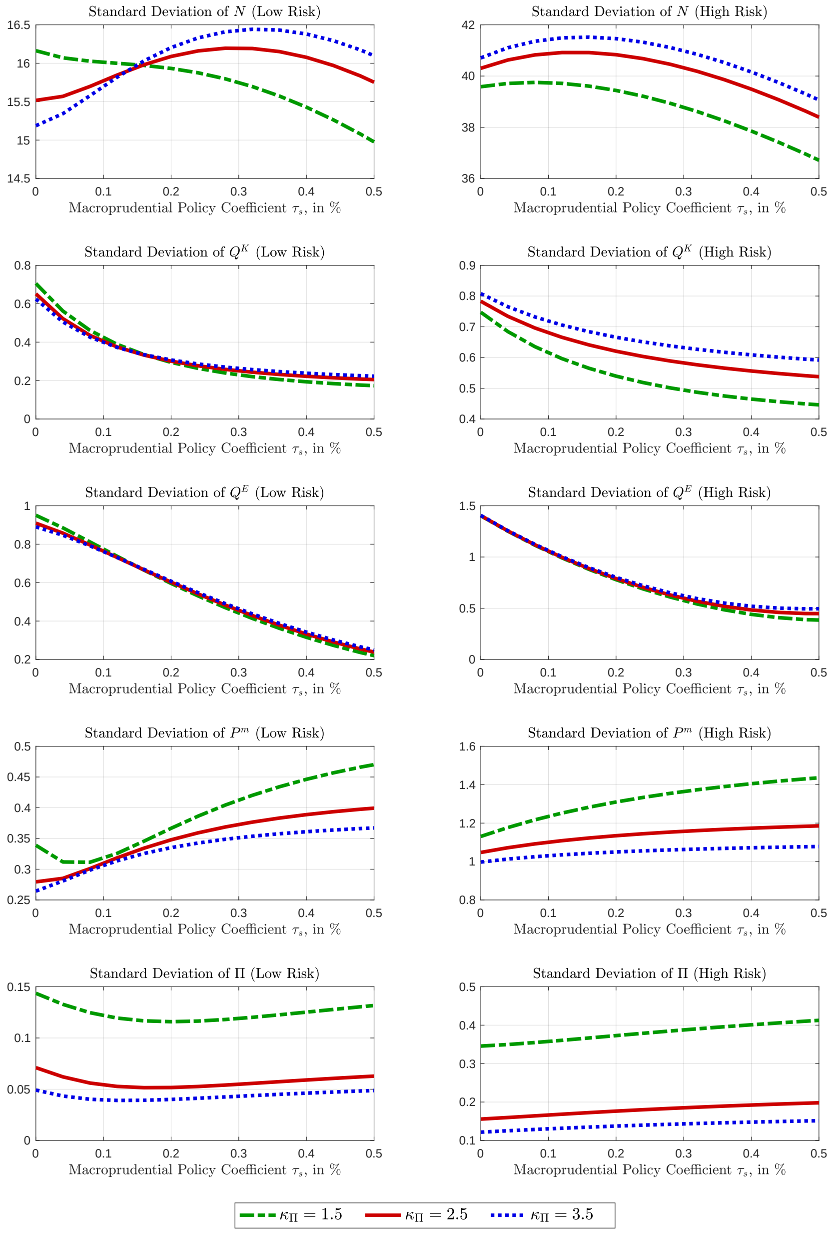
Note: The left (right) column depicts the standard deviations of $\{Y, C, I, K, L\}$ as a function of τ_s and κ_Π in the case of low (high) risk. In each panel the three lines correspond to a different calibration of the inflation sensitivity $\kappa_\Pi = \{1.5, 2.5, 3.5\}$.

FIGURE 2.5.12: EFFECTS OF VARIATION IN $\{\tau_s, \kappa_\Pi\}$ ON THE STDEV OF $\{x, \phi, \nu, \mu_e, \mu_s\}$



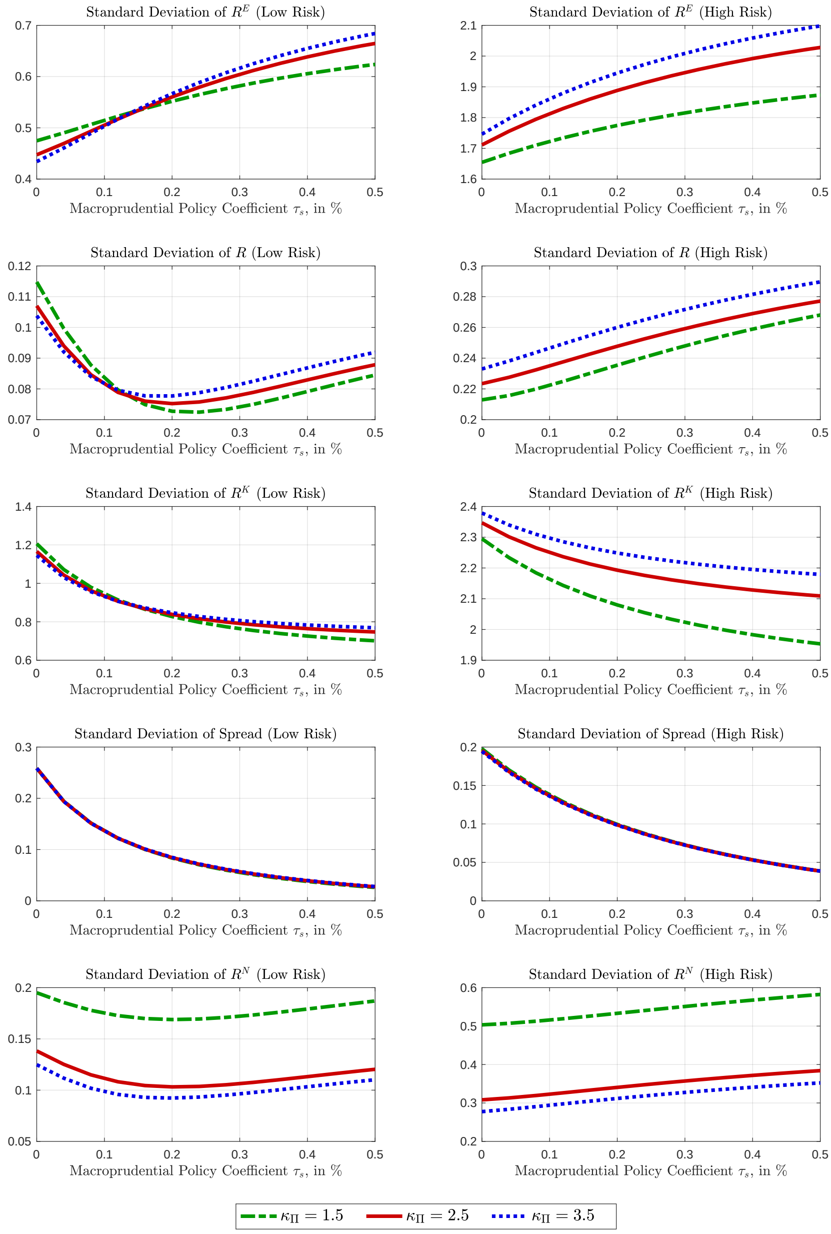
Note: The left (right) column depicts the standard deviations of $\{x, \phi, \nu, \mu_e, \mu_s\}$ as a function of τ_s and κ_Π in the case of low (high) risk. In each panel the three lines correspond to a different calibration of the inflation sensitivity $\kappa_\Pi = \{1.5, 2.5, 3.5\}$.

FIGURE 2.5.13: EFFECTS OF VARIATION IN $\{\tau_s, \kappa_\Pi\}$ ON THE STDEV OF $\{N, Q^K, Q^E, P^m, \Pi\}$



Note: The left (right) column depicts the standard deviations of $\{N, Q^K, Q^E, P^m, \Pi\}$ as a function of τ_s and κ_Π in the case of low (high) risk. In each panel the three lines correspond to a different calibration of the inflation sensitivity $\kappa_\Pi = \{1.5, 2.5, 3.5\}$.

FIGURE 2.5.14: EFFECTS OF VARIATION IN $\{\tau_s, \kappa_\Pi\}$ ON THE STDEV OF $\{R^E, R, R^K, Spr, R^N\}$



Note: The left (right) column depicts the standard deviations of $\{R^E, R, R^K, Spread, R^N\}$ as a function of τ_s and κ_Π in the case of low (high) risk. In each panel the three lines correspond to a different calibration of the inflation sensitivity $\kappa_\Pi = \{1.5, 2.5, 3.5\}$.

Chapter 3

A Note on the Time-Varying Effects of Monetary Policy Shocks

3.1 Introduction

How have the effects of monetary policy shocks changed over time? Has the impact of monetary policy on output and prices declined in the aftermath of the Financial Crisis of 2007/08? I show that based on a recursive ('Cholesky') identification scheme, the effects of monetary policy shocks have declined over time. However, since around 2010 this trend has stopped and the effects of monetary policy shocks have hardly changed.

I follow the seminal studies by Leeper et al. (1996), Bernanke and Mihov (1998), Christiano et al. (1996) and Christiano et al. (1999) as I identify monetary policy shocks via a recursive short-run restriction scheme in which the structural model coefficient matrices are obtained via a Cholesky decomposition. In contrast to most of the (pre-crisis) literature on identifying the effects of monetary policy, I assume that the instrument of the central bank is the 3-Year Treasury Constant Maturity Rate (GS3), rather than the effective Federal Funds Rate (FFR). The latter was constrained by the 'zero lower bound (ZLB)' for roughly 6 years, from 2009 to 2015 and can therefore not be used in an analysis that attempts to identify the effects of external *variation* in the policy instrument. In contrast to Christiano et al. (1999) I exclude data on reserves from my structural vector autoregression (SVAR) model. The main reason is that the reserves series experienced a substantial break after the Financial Crisis of 2008.[1]

A key difference with respect to the abovementioned studies is that I allow for the coefficients in the VAR and the variance covariance matrix of the shocks to be time-varying. My paper is therefore related to the literature on the time-varying effects of shocks developed

[1] I discuss the properties of the raw data and the associated transformations in detail in Appendix 3.6.1. Both, the data on total and on non-borrowed reserves experienced a break which neither a transformation in log-level terms nor one in log-difference terms can account for. Using the latter leads to growth rates of several hundred percent in 2008, as opposed to low one-digit growth figures in the rest of the sample.

by Primiceri (2005), Galí and Gambetti (2009), Galí and Gambetti (2015) and Debortoli et al. (2018).

Primiceri (2005) developed a methodology that allows estimating VAR models with time-varying coefficient and variance-covariance matrices. Allowing for both dimensions of time-variation is crucial since a key objective of the analysis of time-varying coefficient vector autoregression (TVC-VAR) models is to differentiate between changes in the size of the exogenous innovations and changes in the transmission mechanism. Primiceri (2005) focuses on the role of monetary policy in the dynamics of inflation and unemployment for the U.S. economy. Primiceri (2005) argues that the 'non-systematic component' of monetary policy (i.e. monetary policy shocks) has changed considerably over the sample span of 1953:Q1 to 2001:Q3, becoming less important in the last part of the sample. At the same time, he argues that the systematic component of monetary policy has become more aggressive against inflation and unemployment. In my paper, I build on Primiceri (2005). I apply the methodology he developed to an extended dataset and in contrast to him I specify a VAR model in the spirit of Christiano et al. (1999). Moreover, since my extended sample contains the period in which the FFR attained the ZLB I use the 3-Year Treasury Constant Maturity Rate (GS3) as the monetary policy instrument.[2] Based on a dataset that covers the period until 2018 I confirm the finding of Primiceri (2005) that the 'non-systematic component' of monetary policy became less important and thus that monetary policy shocks have tended to affect output and prices less and less. Moreover, I show that the trend seems to reverse around 2010 and that since then the effects of monetary policy shocks seem to have hardly changed.

Galí and Gambetti (2009) and Galí and Gambetti (2015) assess the time-varying effects of productivity and monetary policy shocks[3]. Thus, in particular Galí and Gambetti (2015) is closely related to my paper. Since the focus in Galí and Gambetti (2015) is on the time-varying effects of monetary policy on stock market bubbles their specification contains asset prices and dividends in addition to output, prices and the FFR. Galí and Gambetti (2015) use quarterly data from 1960 to 2011 and find that the responses of GDP and the GDP deflator are relatively stable over time. Using a longer sample until 2018 and using the 3-Year Treasury Constant Maturity Rate instead of the FFR, I find that the responses of GDP and the GDP deflator decline over time.

My paper is closely related to Debortoli et al. (2018) in which the authors estimate the time-varying responses of several macro variables to different identified shocks[4]. The authors employ a combination of long-run, short-run and sign restrictions and find no significant changes in the estimated responses over the period in which the federal funds rate attained the zero lower bound (ZLB). Monetary policy in Debortoli et al. (2018) is identified using sign restrictions whereas I rely on a conventional recursive identification scheme. Another difference is that the authors in Debortoli et al. (2018) assume that the monetary authority used the 10-year rate as the policy instrument, whereas I use the 3-year rate in my paper. The empirical findings in Debortoli et al. (2018) are consistent with my findings to the extent that the presence of the zero lower bound does not seem to have altered the impact of monetary policy shocks on output and prices compared to the 10 years prior to the Financial Crisis of 2008.

In the context of a TVC-VARX approach, Paul (2018) analyses how the effects of monetary policy on asset prices and the real economy have changed over time. In contrast to my paper, Paul (2018) does not rely on any identification scheme but instead obtains dynamic 'shock' responses by conducting a local projection approach based on a monetary policy surprise series[5] which serves as a proxy for the monetary policy shock. In contrast to my

[2] As will be discussed below in detail, I include monetary aggregates in my specification and derive conclusions on the time-varying co-movement between interest rates and money supply.

[3] Galí and Gambetti (2015) identify monetary policy shocks with a conventional recursive identification scheme.

[4] The authors identify shocks to productivity, demand, supply and monetary policy.

[5] This approach was pioneered by Kuttner (2001) and Gürkaynak et al. (2005).

paper, Paul (2018) only looks at the effects of monetary policy since the late 1980s. Moreover, Paul (2018) uses CPI data for prices and the FFR as the policy instrument. As I will discuss in detail below, choosing the CPI series for prices and the FFR for the policy instrument is problematic.

This paper is also related to the literature on the time-varying effectiveness of monetary policy developed by Boivin (2006), Boivin and Giannoni (2006), Boivin and Giannoni (2007) and Boivin et al. (2010). Boivin and Giannoni (2006) analyse whether monetary policy shocks have had a reduced effect on the economy since the beginning of the 1980s. When comparing the results of identified VAR models for the pre- and post 1980 period the authors find a stronger systematic response of monetary policy to the economy in the latter period. The main finding of Boivin and Giannoni (2006) is that changes in the systematic component of monetary policy are consistent with a more stabilising monetary policy in the post-1980 period and largely account for the reduced impact of unexpected exogenous interest rate shocks. Thus, the authors argue, there is little evidence that monetary policy has become less effective.

I build on these papers using TVC-SVAR methodology, extending the sample up until 2018 and assuming that the 3-year rate is the monetary policy instrument. I show that the trend of a dampened effect of the non-systematic component of monetary policy has stopped around 2010 and that there has hardly been any change throughout the period from 2009 to 2015 in which the lower bound on short-term rates became binding.[6]

The remainder of the paper is organised as follows. In Section 2 I introduce the empirical methodology required to estimate the TVC-VAR model and I discuss the identification scheme. In Section 3 I describe and interpret the results. Section 4 contains a discussion of several robustness checks. In Section 5 I conclude.

3.2 Empirical Methodology

In this section I describe the structural vector autoregressive model with time-varying coefficients (TVC-SVAR) which is used to assess whether and how the effects of monetary policy shocks on output, prices and money supply have changed over time. In setting up and implementing the estimation of the reduced form TVC-VAR model I closely follow Primiceri (2005) and Del Negro and Primiceri (2015). Regarding the choice of variables and the identification scheme I follow Christiano et al. (1999), Christiano et al. (2005) and Galí and Gambetti (2015).

Let y_t, p_t, p_t^c i_t, m_t denote, respectively, (log) output y_t, the (log) price level p_t, a (log) commodity price index p_t^c, the nominal interest rate controlled by the central bank i_t and the (log) level of money supply M1 m_t. I define the vector $\mathbf{x}_t = [\Delta y_t, \Delta p_t, \Delta p_t^c, i_t, \Delta m_t]'$ which is assumed to follow an autoregressive process with time-varying coefficients:

$$\mathbf{x}_t \quad = \quad \mathbf{A}_{0,t} + \mathbf{A}_{1,t}\mathbf{x}_{t-1} + \ldots + \mathbf{A}_{p,t}\mathbf{x}_{t-p} + \mathbf{u}_t \tag{3.2.1}$$

where $\mathbf{A}_{0,t}$ is a vector of time-varying intercepts, and $\mathbf{A}_{i,t}$ for $i = 1, \ldots, p$ are matrices of time-varying coefficients, and where the vector of reduced form innovations $\mathbf{u}_t$ follows a white noise Gaussian process with mean zero and covariance matrix Σ_t. It is assumed that the reduced form innovations are linear transformations of the structural shocks ε_t so that

$$\mathbf{u}_t \equiv \mathbf{S}_t \varepsilon_t$$

where $\mathbb{E}[\varepsilon_t \varepsilon_t'] = I$ and $\mathbb{E}[\varepsilon_t \varepsilon_{t-k}'] = 0$ for all t and $k = 1, 2, 3, \ldots$ and $\mathbf{S}_t$ is such that $\mathbf{S}_t \mathbf{S}_t' = \Sigma_t$.

[6] My paper is thus also related to Swanson and Williams (2014) who argue that monetary policy was actually hardly constrained by the lower bound on short-term rates since it could stimulate the economy through implementing reductions of medium- and long-term rates.

I define $\theta_t = vec(\mathbf{A}'_t)$ where $\mathbf{A}_t = \left[\mathbf{A}_{0,t}, \mathbf{A}_{1,t}, \ldots, \mathbf{A}_{p,t}\right]$ and the operator $vec(\cdot)$ implies that the variables are stacked in a column. Moreover, it is assumed that the parameter vector θ_t evolves over time according to the process

$$\theta_t = \theta_{t-1} + \omega_t \tag{3.2.2}$$

where ω_t is a Gaussian white noise process with zero mean and constant covariance Ω. It is assumed to be independent of the reduced-form residuals u_t at all leads and lags. The time variation of Σ_t is modelled as follows. Consider that $\Sigma_t = \mathbf{F}_t \mathbf{D}_t \mathbf{F}'_t$, where $\mathbf{F}_t$ is lower triangular, with ones on the main diagonal, and $\mathbf{D}_t$ a diagonal matrix. Let σ_t be the vector containing the diagonal elements of $\mathbf{D}_t^{1/2}$ and $\phi_{i,t}$ a column vector with the nonzero elements of the $(i+1)$-th row of $\mathbf{F}_t^{-1}$ with $i = 1, \ldots, 5$. We assume that

$$\log \sigma_t = \log \sigma_{t-1} + \zeta_t \tag{3.2.3}$$

$$\phi_{i,t} = \phi_{i,t-1} + \nu_{i,t} \tag{3.2.4}$$

where ζ_t and $\nu_{i,t}$ are white noise Gaussian processes with zero mean and (constant) covariance matrices Ξ and Ψ_i, respectively. We assume that $\nu_{i,t}$ is independent of $\nu_{j,t}$ for $j \neq i$, and that ω_t, ε_t, ζ_t and $\nu_{i,t}$ (for $i = 1, \ldots, 5$) are mutually uncorrelated at all leads and lags. The constant parameter case is a limiting case in which $\Omega = 0$, $\Xi = 0$ and $\Psi_i = 0$.

3.2.1 Identification Strategy

The fourth element in ε_t corresponds to the monetary policy shock ε_t^i. The identification scheme to identify monetary policy shocks, inspired by Christiano et al. (1999), relies on two key assumptions. First, it is assumed that output and prices do not contemporaneously respond to unexpected changes in the short-term nominal interest rate. Second, it is assumed that the central bank does not contemporaneously respond to money supply M1.

The first assumption of the identification scheme implies that the fourth column of $\mathbf{S}_t$ has zeros as its first three elements, while the remaining elements are unrestricted. Second, the last element in the fourth row of $\mathbf{S}_t$ is zero, since the interest rate in this 5-variable setting will be in position 4 and money supply is ordered in position five of the vector $\mathbf{x}_t$. Since the focus is on monetary policy shocks, I do not place any other restrictions on matrix $\mathbf{S}_t$. The transformation $\mathbf{S}_t$ is the Cholesky factor of Σ_t

$$\mathbf{S}_t = chol(\Sigma_t).$$

In order to define the impulse responses I rewrite the model in companion form

$$\tilde{\mathbf{x}}_t = \tilde{\mu}_t + \tilde{\mathbf{A}}_t \tilde{\mathbf{x}}_{t-1} + \tilde{u}_t, \tag{3.2.5}$$

where $\tilde{\mathbf{x}}_t \equiv \left[\mathbf{x}'_t, \mathbf{x}'_{t-1}, \ldots, \mathbf{x}'_{t-p+1}\right]'$, $\tilde{\mu}_t \equiv \left[\mathbf{A}'_{0,t}, 0, \ldots, 0\right]'$ and $\tilde{u}_t \equiv [u'_t, 0, \ldots, 0]'$. The local impulse response at horizon k is then defined as

$$\frac{\partial \mathbf{x}_{t+k}}{\partial \mathbf{u}'_t} = \left[\tilde{\mathbf{A}}_t^k\right]_{5,5} \equiv \mathbf{B}_{t,k} \tag{3.2.6}$$

for $k = 1, 2, \ldots$ where $[\mathbf{M}]_{5,5}$ denotes the first five rows and the first five columns of a matrix $\mathbf{M}$. The dynamic responses associated with a monetary policy shock at horizon k are thus given by

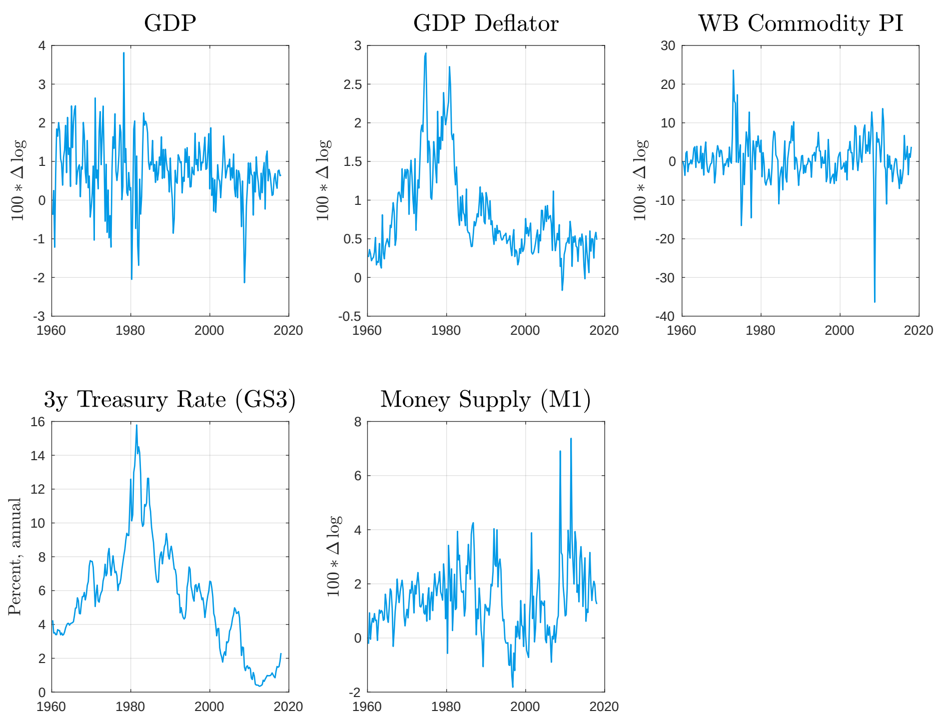
$$\frac{\partial \mathbf{x}_{t+k}}{\partial \varepsilon_t^m} = \frac{\partial \mathbf{x}_{t+k}}{\partial \mathbf{u}'_t} \frac{\partial \mathbf{u}_t}{\partial \varepsilon_t^m} = \mathbf{B}_{t,k} \mathbf{S}_t^{(4)} = \mathbf{C}_{t,k} \tag{3.2.7}$$

for $k = 0, 1, 2, \ldots$ and where $\mathbf{S}_t^{(4)}$ denotes the fourth column of $\mathbf{S}_t$. I estimate the TVC-VAR model with Bayesian methods. I follow Primiceri (2005) and Del Negro and Primiceri (2015) and use a Gibbs sampling algorithm to sample from the joint posterior distribution.

3.2.2 Data

I use quarterly U.S. data obtained from the FRED database, spanning the period from 1960Q1 to 2018Q1. For the five variables (output, prices, commodity prices, nominal interest rates and money supply) in the VAR model specification I use the following data series. For output I use real GDP data (GDPC1, in Billions of Chained 2009 USD), for prices I use the corresponding GDP Deflator (GDPDEF, index where 2009=100), for commodity prices I use the non-energy component of the World Bank commodity price index ('Pink Sheet'), for the nominal interest rate I use the 3-Year Treasury Constant Maturity Rate (GS3, in annual percent terms) and for money supply I use the M1 money supply (M1SL, in Billions of USD). As discussed above, I assume that the instrument of monetary policy over the sample was the 3-year rate rather than the short-term effective federal funds rate (FFR). The data is visualised in Figure 3.6.1[7].

FIGURE 3.2.1: RAW DATA



Source: FRED
Note: Quarterly US data with a sample span from 1960Q01-2018Q1. The variables are: GDP (GDPC1, real Billions of USD), GDP deflator (GDPDEF, index 2009=100), World Bank Commodity Price Index (2010=100), the 3-Year Treasury Constant Maturity Rate (GS3) and M1 Money Supply (M1SL). The variables are in log-difference terms, except for the 3-Year Treasury Constant Maturity Rate (GS3).

[7]Section 3.6.1 in appendix contains a more extensive discussion and visualisation of the data and its transformation.

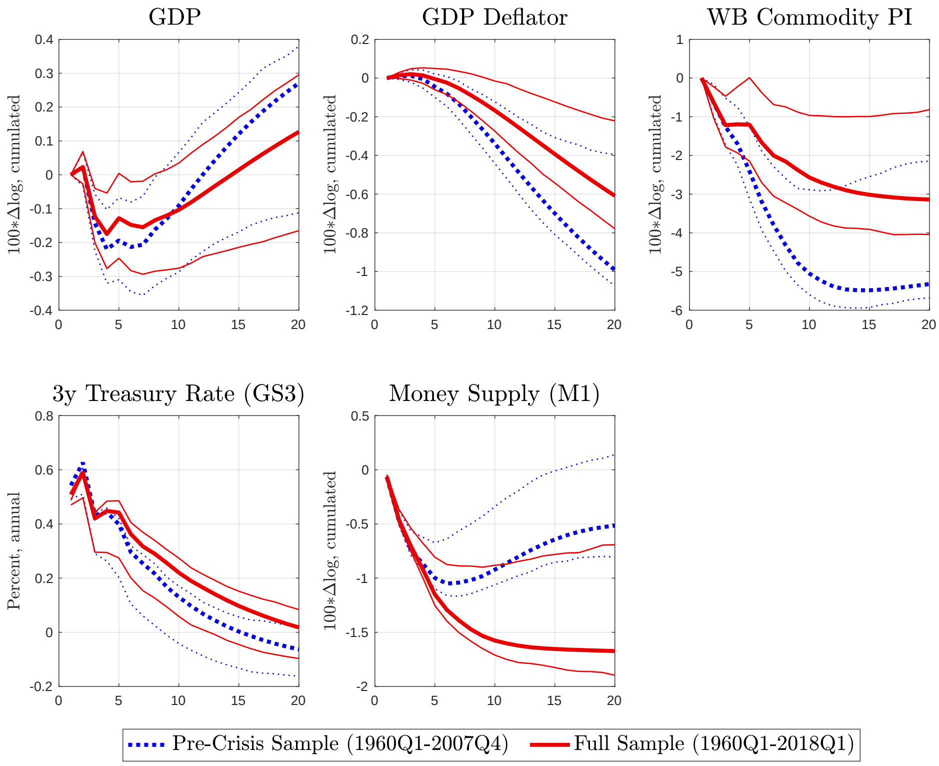
3.3 Empirical Evidence

In this Section I present and discuss the evidence based on a structural VAR model with constant and time-varying coefficients.

3.3.1 Constant Coefficients SVAR

In Figure 3.3.2 I show the estimated impulse response functions for GDP, the GDP Deflator, the WB Commodity Price Index, the 3-Year Rate and M1 Money supply in response to an identified monetary policy shock of 1 standard deviation. I conduct the constant coefficient estimation for two different samples. The first sample is referred to as 'Pre-Crisis Sample' and contains data from 1960Q1 to 2007Q4. The second sample is referred to as the full sample and contains data from 1960Q1 to 2018Q1. In response to a positive monetary policy

FIGURE 3.3.2: ESTIMATED RESPONSES TO A MONETARY POLICY SHOCK: VAR WITH CONSTANT COEFFICIENTS



Note: The thick lines depict the IRFs in response to a monetary policy shock. The thin lines are the corresponding 68% confidence bands. Cumulative IRFs are shown for variables in log-difference terms. The IRFs are based on quarterly data, the sample span is from 1960Q01-2007Q4 (blue, dotted) and 1960Q01-2018Q1 (red, straight). The variables used are: GDP (GDPC1, real Billions of USD), GDP deflator (GDPDEF, index 2009=100), World Bank Commodity Price Index (2010=100), the 3-Year Treasury Constant Maturity Rate (GS3) and M1 Money Supply (M1SL). The lag-order is 4.

shock the medium-term 3-Year rate increases. GDP initially declines before it recovers. The GDP Deflator starts to decline after around 5 quarters. The money supply M1 declines as well, moving in opposition to the nominal interest rate. The latter effect is referred to as 'liquidity effect'. In short, a monetary policy shock identified with a recursive identification scheme delivers theory-consistent patterns for output and prices even when the 3-Year rate is used instead of the Federal Funds Rate.

While the response of GDP to a monetary policy shock has hardly changed when comparing the pre-crisis sample with the full sample, it appears that the price responses are dampened in the full sample. The point estimates of the pre-crisis sample for the GDP Deflator and the Commodity Price Index (the thick dotted blue lines) are not part of the 68% confidence bands corresponding to the full sample (the thin straight red lines). Another significant change seems to have occurred with regard to the response of money supply. Whereas prices seem to respond less to a monetary policy shock in the full sample, money supply seems to respond much stronger. One possibility to interpret this is that accommodative monetary policy shocks in the post-crisis period after 2008 have led to a strong and persistent expansion of M1 money supply.

3.3.2 Time-Varying Coefficients SVAR

In Figure 3.3.3 I show the estimated median impulse responses for the five variables based on the TVC-SVAR model. There is now a different IRF for each quarter since the coefficients are allowed to change. Since the first 8 years of the sample are used as a prior tuning period, Figure 3.3.3 depicts a plain of IRFs that covers the period from 1968Q1 to 2018Q1.

The monetary policy shock to which the variables in Figure 3.3.3 are shown to respond is of 1 standard deviation. Over time, the responses to a one-standard deviation shock have changed. In Panel A of Figure 3.3.3 one can see that GDP used to decline more in response to a monetary policy shock in the 1960s and 1970s. The same is true for prices, as can be seen in Panel B and Panel C. Money Supply M1, on the other hand, was almost non-responsive in the 1960s. Since then the response has increased significantly.

To facilitate the analysis of the time-varying IRFs, I plot the estimated median impulses at different horizons of 4, 8 and 12 quarters after the shock in Figure 3.3.4.

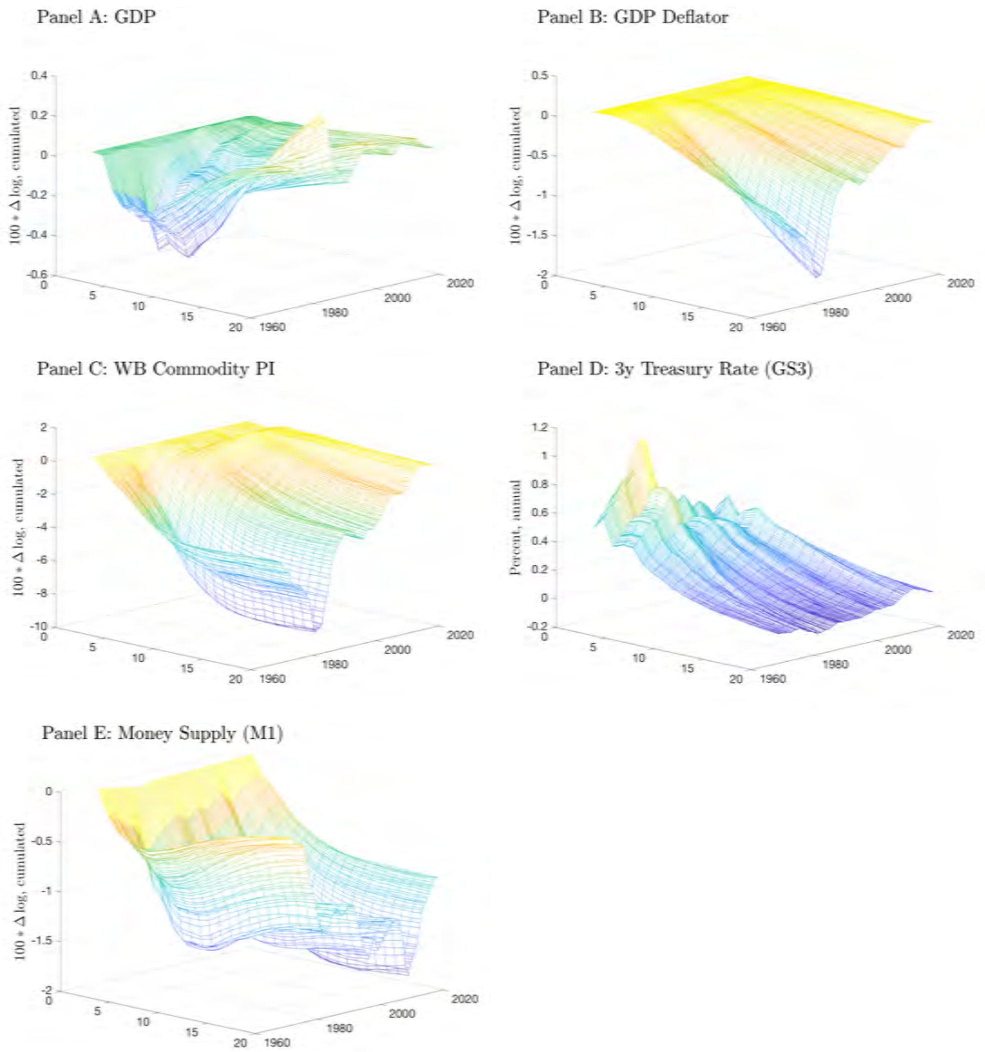
Based on Figure 3.3.4, one can see that the impact on output and prices of a monetary policy shock of one standard deviation has declined since around 1980 until around 2010. Since then, the impact has hardly changed.[8]

In Figure 3.3.5 I show that the median IRFs averaged over the 10 years before and after the Financial Crisis of 2008 are very similar. Only the pre- and post-crisis median IRFs for prices seem to differ somewhat. It is noteworthy that for the post-crisis period, based on a recursive identification scheme, a monetary policy shock does no longer reduce output and prices. For output, even in the pre-crisis years from 1998 to 2007 the impact is hardly contractionary. This pattern is in conflict with the theoretical prediction that an unexpected increase in interest rates will reduce real economic activity in the short run. Thus, one takeaway from this exercise is that in the context of a VAR model with time-varying coefficients, the recursive ('Cholesky') identification scheme works less well, or hardly at all for output, for the period since around the year 2000.

In the Appendix in Section 3.6.1.1.1 in the left column of Figure 3.6.3 I show the original cumulative IRFs from Christiano et al. (1999). One can clearly see the difference between the original IRFs and the average IRFs depicted in Figure 3.3.5. Whereas the cumulative IRFs for output and prices clearly decline in Christiano et al. (1999), the average output and price response between 1998 and 2018 hardly declines in the context of a TVC-VAR model that contains the GS3 rate. In Figure 1 of a recent study on DSGE models, Christiano et al. (2018) use the dynamic responses from a VAR model identified with short-run restrictions to provide empirical evidence that DSGE models supposedly match well. However, I show that if one (i) allows for time-varying coefficients, if one (ii) extends the sample period to 2018 and (iii) if one uses the GS3 interest rate, the recursive short-run ('Cholesky'-decomposition

[8]If anything, it seems as if the effects are becoming stronger again since the lines at all three horizons for output and prices slightly bend down from around 2011.

FIGURE 3.3.3: ESTIMATED RESPONSES TO A MONETARY POLICY SHOCK: VAR WITH TIME-VARYING COEFFICIENTS



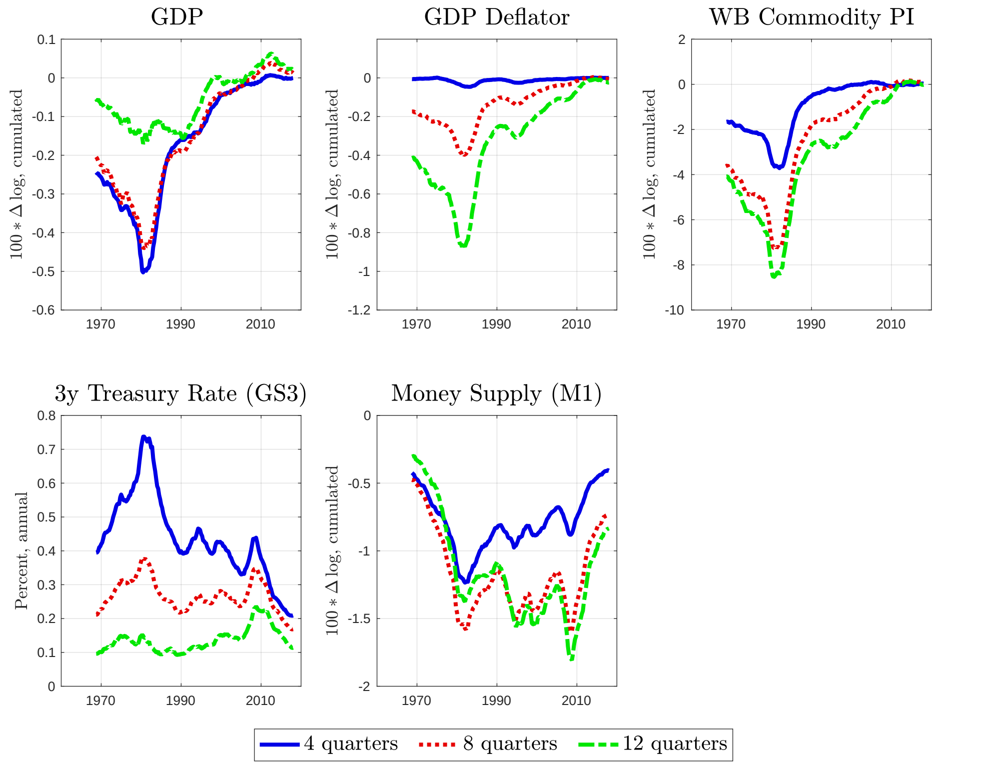
Note: Panels A to E depict the median IRFs for a monetary policy shock of 1 standard deviation from 1968Q1 to 2018Q1. All variables are in log-differences, except for the GS3 series which is in annual percentage terms. Cumulative IRFs are shown for variables in log-difference terms. The results are based on quarterly data, the sample span is from 1960Q1-2018Q1 with 8 years of prior tuning and a lag-order of 4.

based) identification scheme does no longer deliver patterns in line with standard New Keynesian models.

3.4 Robustness Checks

I conduct several robustness checks in order to assess whether the results I described above hinge on certain specificities. First, I compute and visualise the cumulative impulse responses of output relative to the cumulative impulse responses of nominal and real mea-

FIGURE 3.3.4: ESTIMATED RESPONSES TO A MONETARY POLICY SHOCK AT SELECTED HORIZONS



Note: Median IRFs at selected horizons for a monetary policy shock of 1 standard deviation are shown. Cumulative IRFs are shown for variables in log-difference terms. The results are based on quarterly data, the sample span is from 1960Q1-2018Q1 with 8 years of prior tuning and a lag-order of 4.

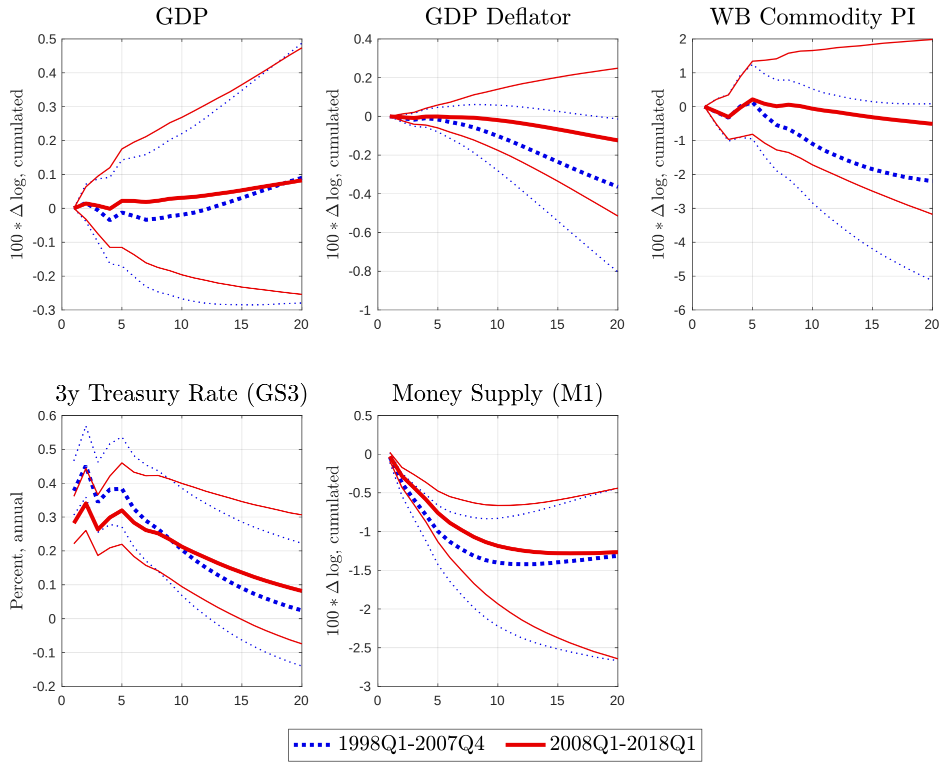
sures of the GS3 interest rate. Second, instead of analysing the impacts of a monetary policy shock of one standard deviation on impact, I repeat the entire TVC-SVAR exercise for a monetary policy shock of 25 basis points on impact. Third, I assess whether using M2 money supply instead of M1 money supply makes a difference. Fourth, I replace the 3-Year Constant Maturity Treasury Yield series with a 'Shadow' Federal Funds Rate based on Wu and Xia (2016). The key results described above are robust to these checks. In the fifth block of cross-checks, I repeat the TVC-SVAR analysis using monthly data. Finally, I repeat the analysis of the standard specifications based on a different sample period. First I conduct the analysis with a sample that begins in 1979Q3, when Paul Volcker became the chairmen of the Federal Reserve. Second, I repeat the TVC-VAR analysis with the above described specification from 1960Q1-2007Q4, thus excluding the crisis and the post-crisis era.

3.4.1 The Cumulative Responses of Output relative to the Cumulative Responses of Interest Rates

In order to properly assess the time-varying impact of a monetary policy shock, I compute the ratio between the cumulative responses of output and the cumulative responses of the nominal and the real interest rate, respectively.

It may be misleading to simply relate the cumulative response of output to some initial

FIGURE 3.3.5: ESTIMATED RESPONSES TO A MONETARY POLICY SHOCK: PRE- AND POST-CRISIS AVERAGE



Note: The thick lines depict the 10-year average of the median IRFs before and after the Financial Crisis of 2008 for a monetary policy shock of 1 standard deviation. The thin lines correspond to the 68% confidence bands. Cumulative IRFs are shown for variables in log-difference terms. The results are based on quarterly data, the sample span is from 1960Q1-2018Q1 with 8 years of prior tuning and a lag-order of 4.

interest rate impact. The subsequent path of the interest rate is relevant and it may have changed over time. It is therefore useful to measure the change of the cumulative output response and compare it to the corresponding cumulative responses of interest rates. This cumulative 'multiplier' can be understood as a ratio of surfaces on the impulse responses.[9]

I relate the cumulative response of output to the cumulative response of the nominal and the real interest rate. The real interest rate response can be backed out using the Fisher equation. The Fisher equation[10] relates the gross rate of inflation to the gross nominal and the gross real rate such that

$$1 + r_t^n = (1 + r_t^r)(1 + \pi_{t+1}). \tag{3.4.1}$$

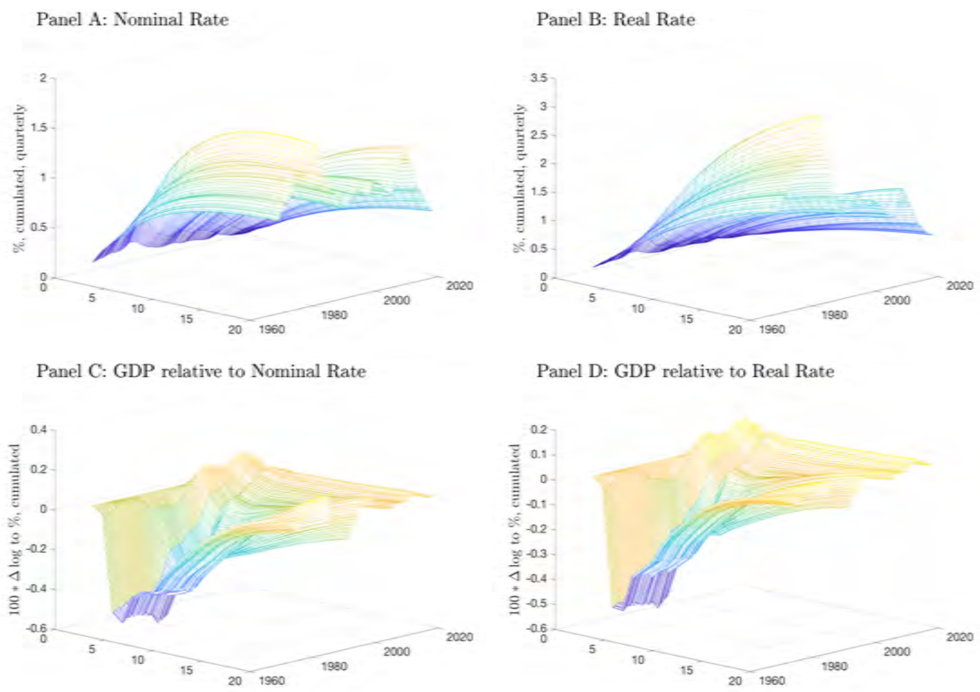
In Figure 3.4.6 I plot the cumulative responses of the nominal (GS3) and the real (GS3) interest rate in the two top panels. In the two panels B and C I show the ratio of the cu-

[9]In a study on fiscal policy, Ramey (2018) makes the case that differences in reported multipliers in the literature are mainly due to the practice of reporting 'quasi-multipliers' which disregard the dynamic path of government spending. In a similar fashion, one can argue that disregarding the dynamic path of interest rates may give rise to misleading conclusions about the time-varying effects of monetary policy shocks on output.

[10]In the context of a New Keynesian DSGE model, the one-period ahead inflation would be conditional on its time-t expectation $1 + r_t^n = (1 + r_t^r)(1 + \mathbb{E}_t \pi_{t+1})$.

mulative response of GDP relative to the cumulative response of the nominal and the real interest rate, respectively.

FIGURE 3.4.6: ESTIMATED RESPONSES TO A MONETARY POLICY SHOCK: VAR WITH TIME-VARYING COEFFICIENTS



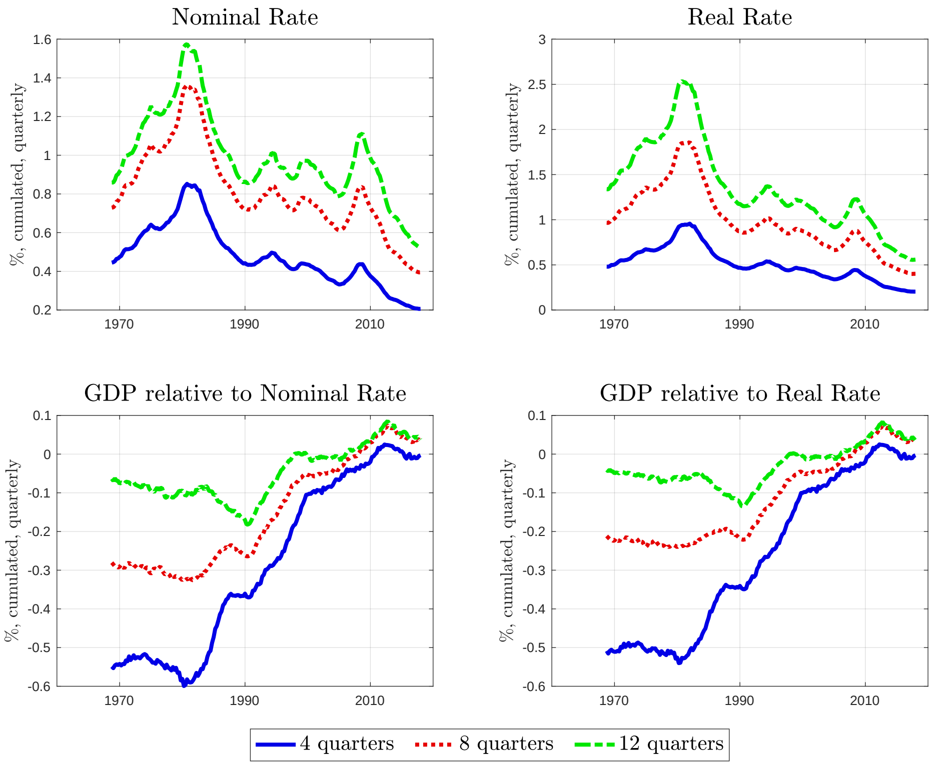
Note: Panels A to D depict the median cumulative IRFs for a monetary policy shock of 1 standard deviation from 1968Q1 to 2018Q1. All variables are cumulated. The Nominal (GS3) Interest Rate and the Real (GS3) Interest Rate were transformed into quarterly percentage terms. The results are based on quarterly data, the sample span is from 1960Q1-2018Q1 with 8 years of prior tuning and a lag-order of 4.

In Figure 3.4.7 I show the cumulative impulses at the horizons of 4, 8 and 12 quarters. The lower panels of Figure 3.4.7 clearly demonstrate that a monetary policy shock identified with a recursive ('Cholesky') identification scheme does no longer reduce output from around 2000 onwards. This is also true if one compares the cumulative responses of output to the cumulative responses of nominal and real versions of the GS3 treasury yield.

3.4.2 Fixed Impact of 25 Basis Points vs 1 Standard Deviation

In the Appendix in Section 3.6.2 I repeat the TVC-SVAR analysis described above. However, instead of fixing the monetary policy shock to one standard deviation, I fix the increase of the GS3 rate to 25 basis points. In Figures 3.6.5 to 3.6.10 one can see that even if the initial impact of the GS3 interest rate is now fixed across time the subsequent dynamics of the IRFs differ substantially. Most importantly, it is still the case that in response to monetary policy shocks output and prices decline less over time. In the last part of the sample output and prices hardly move at all, output even increases.

FIGURE 3.4.7: ESTIMATED RESPONSES TO A MONETARY POLICY SHOCK AT SELECTED HORIZONS



Note: Median IRFs at selected horizons for a monetary policy shock of 1 standard deviation are shown. The results are based on quarterly data, the sample span is from 1960Q1-2018Q1 with 8 years of prior tuning and a lag-order of 4.

3.4.3 M1 vs M2

When replacing the narrower measure of money supply M1 with a wider measure M2 one obtains almost identical results, as can be seen in Figures 3.6.11 3.6.12, 3.6.13, 3.6.14, 3.6.15 and 3.6.16.

3.4.4 GS3 vs Shadow FFR

From around 2009 to 2015 the FFR was constrained by the effective lower bound. For this reason, as argued above, I include a medium-term interest rate in the specification of the VAR model. An alternative could be to use a FFR which has a 'Shadow' component for the period from 2009 to 2015. The 'Shadow FFR' (Wu and Xia (2016)) serves as a metric which captures the monetary policy stance in the period in which the ZLB was binding. In contrast to the actual FFR, the Shadow FFR can take negative values. When regressing with the Shadow FFR instead of the GS3 rate, I find that monetary policy shocks have a stronger overall contractionary impact on GDP compared to the case with the GS3 rate. The associated results are depicted in the Appendix in Figures 3.6.17, 3.6.18, 3.6.19, 3.6.20 and 3.6.21. As in the benchmark case described above, I find that from around 1980 to around 2010, the impact of monetary policy shocks on output and prices weakens and that it strengthens for money supply.

3.4.5 Monthly vs Quarterly Data

I also cross-check the above reported findings by using monthly data instead of quarterly data. The choice of variables is not as simple as in the case of quarterly regressions since GDP and the GDP deflator are not available at a monthly frequency. Moreover, the lag order plays an important role for the dynamics of prices.

3.4.5.1 Using Core PCEPI Data for the Price Level

When using monthly data I replace the GDP series with real Industrial Production (INDPRO, in real Billions of USD) and the GDP Deflator series with the Personal Consumption Expenditures Excluding Food and Energy (PCEPILFE, Chain-Type Price Index, Index 2009=100) which I will refer to as 'Core PCEPI'.[11] The results for the monthly regressions are depicted in Figures 3.6.23, 3.6.24, 3.6.25, 3.6.26, 3.6.27 and 3.6.28 in the Appendix. The lag-order in the case of monthly regressions is 12.[12]

The key result from the quarterly regressions above is unchanged: the impact of monetary policy shocks on output and prices has decreased substantially from around 1980 to around 2010. In the monthly regressions with the Core PCEPI series there is a very pronounced price puzzle since the impulses at several horizons clearly are above zero.[13] It is also noteworthy that the Industrial Production series does not significantly decline in response to a monetary policy shock identified with a recursive 'Cholesky' identification scheme in a monthly regression in which the 3-Year Treasury rate (GS3) is used.

3.4.5.2 Using CPI Data for the Price Level

An alternative measure for prices could the Consumer Price Index (Total All Items for the United States (CPALTT01USM661S), Index 2010=100). Inspection of 3.6.29 to 3.6.34 indicates that there is no big difference between using the CPI or the Core PCEPI measure of prices.

3.4.5.3 The Role of the Lag Order

What matters more in the monthly regressions is the choice of the lag order. In the two cases above I have reported results based on a lag order of 12. If one reduces the lag order to 6 the results, in particular for prices, are very different. Even though based on an Akaike information criterion a lag order choice of 6 might be warranted, as can be seen in the Appendix in Figure 3.6.35, the impulse responses of prices in response to a monetary policy shock are always positive. This counterintuitive result is referred to as the 'price puzzle'. For the severity of the price puzzle the lag order seems to matter considerably. This is also the case in the context of a VAR model with constant coefficients, as can be seen in Figure 3.6.42. The discrepancy between the responses of prices for a model with lag order 6 and a model with lag order 12 widened in comparison with the pre-crisis era. In Figure 3.6.42 I compare the constant coefficient SVAR models with lag 6 and lag order 12 using only data from 1960M01 to 2007M12. Using the pre-crisis sample, the price puzzle was less pronounced.

3.4.6 Sample Period Sensitivity

[11] I also provide a section in the Appendix in which I use CPI data.

[12] A high lag-order is necessary, since the dynamics of a VAR estimated on monthly data would be very different with a small lag order of 6 or less.

[13] This problem becomes even more severe when using a shorter lag order.

Another important cross-check for the exercises conducted above is assessing the sensitivity of the results to changing the sample period. In particular, in Appendix 3.6.8 I show results based on a cross-check in which I start the regression sample in 1979Q3, when Paul Volcker became chairmen of the Federal Reserve. As can be seen in Figures 3.6.44 to 3.6.50, it is still the case that the dynamic responses of output and prices to monetary policy shock decline. However, since the analysis of the time-varying IRFs now only starts in 1987 the decline is less dramatic than in the case in which the start date of the regression was 1960Q1. It is also worth noting that if one starts the sample in 1979Q3 the responses of output and prices do in general decline less than in the case in which the regression started in 1960Q1. Inspection of Figure 3.6.48 in the Appendix reveals that the median responses of the GDP deflator do, on average, not decline if one starts the sample in 1979Q3. In the main specification with a start date of 1960Q1 the cumulative IRFs of the GDP deflator will eventually decline, as can be seen in Figure 3.3.5.

In a second subsample cross-check, I repeat the TVC-VAR exercise based on the sample 1960Q1-2007Q4, thus excluding the crisis and post-crisis era. In order to allow for a meaningful comparison, I still use the 3-year Constant Maturity Treasury Yield rate in this case, even though the ZLB was no concern in this sample period. In Figure 3.6.51 to 3.6.55 I plot the case in which I only use data from 1960Q1 to 2007Q4. In general, it is still the case that the responses of output and prices decline over time. However, this decline is less severe than in the case in which the sample stretches to 2018. In Figure 3.6.55, in which the cumulative responses of output are plotted in relation to the cumulative responses of interest rates, one can see that at the 8 and 12 quarter horizon, the responses are rather flat. This indicates that the detected long-term decline of the output and price responses to a monetary policy shock at least partially hinges on including the post-crisis sample period from 2008 to 2018.

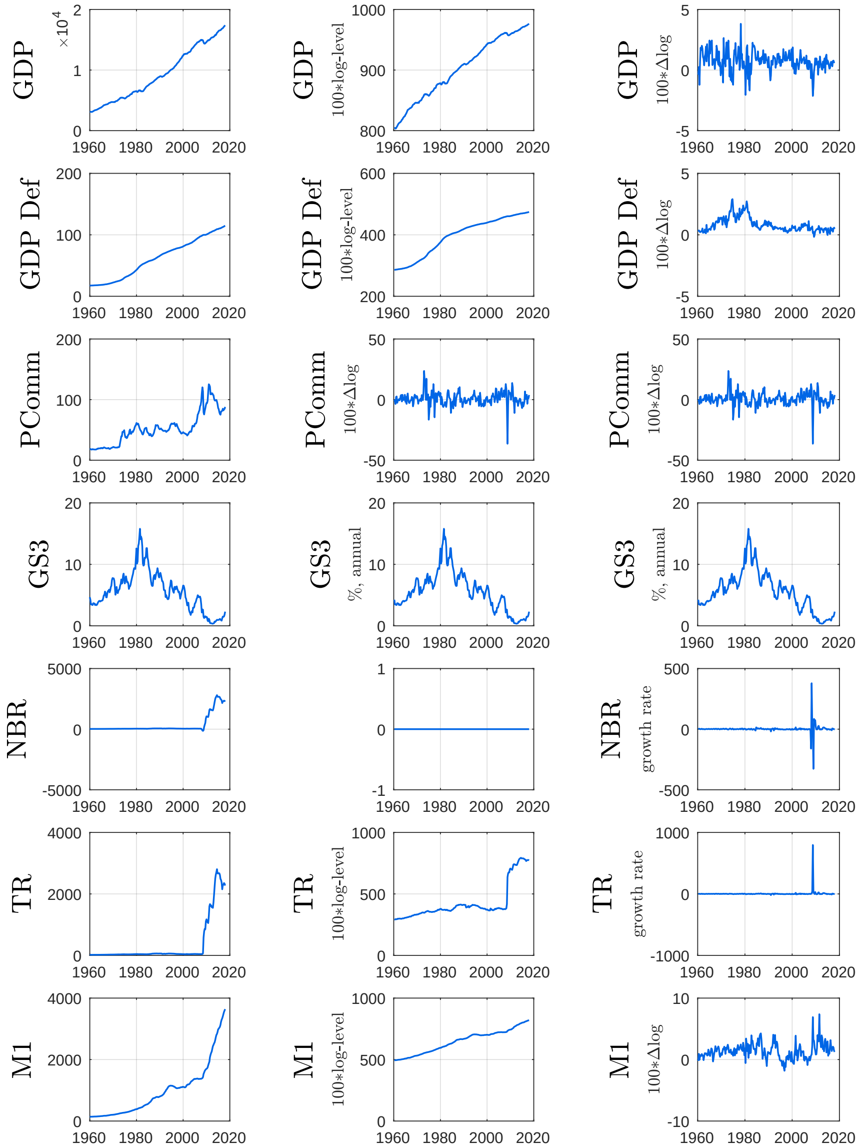
3.5 Concluding Remarks

Using TVC-VAR methodology and a recursive identification scheme I revisit the structural VAR model by Christiano et al. (1999) and confirm the findings by, among others, Primiceri (2005) and Boivin and Giannoni (2006) that since 1980 monetary policy shocks have had a smaller impact on output and prices. I show that this trend ends around 2010 and that since then the impact of monetary policy shocks has hardly changed. This is interesting to the extent that one might have expected that between 2009 and 2015, when the ZLB was binding, the presence of this constraint would have altered the impact of monetary policy shocks. Based on a recursive identification scheme the evidence suggests that it did not. I thus confirm the results found in Debortoli et al. (2018) where, among other shocks, monetary policy shocks are identified with sign restrictions.

3.6 Appendix

3.6.1 Data Transformation

FIGURE 3.6.1: RAW DATA AND TRANSFORMATION IN LOG-LEVELS AND LOG-DIFFERENCES

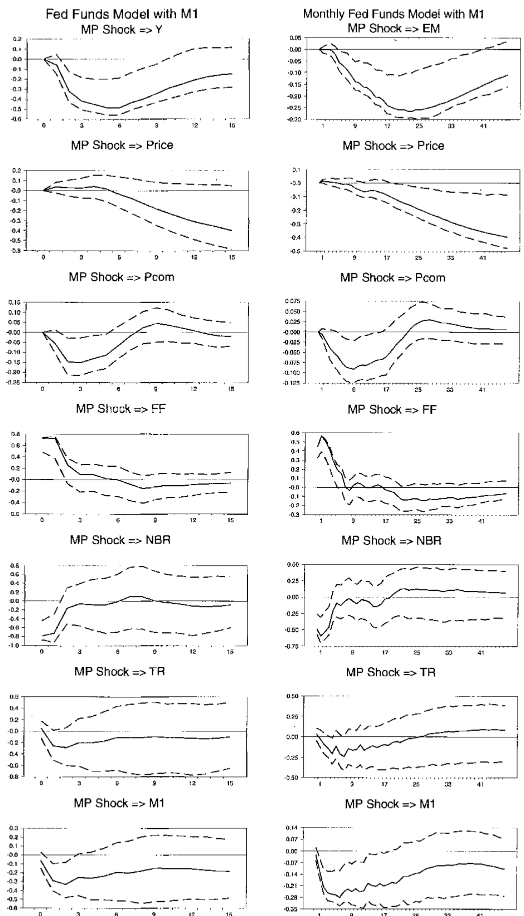


Note: The left column depicts the raw data. GDP is in terms of real Billions of USD; the GDP Def is the implicit price deflator of GDP in terms of an index where 2009=100; the PComm series refers to the World Bank Commodity price index, 2010=100; the GS3 refers to the 3-year Treasury Constant Maturity Rate, NBR refers to non-borrowed reserves in Billions of USD (note that this series turned negative in all four quarters of 2008), TR refers to total reserves in Billions of USD and M1 refers to M1 Money Supply. The center column depicts the data in log-terms (with the exception of the GS3 rate and the NBR series), the right column depicts the data in log-differences terms (except for the GS3 rate).

3.6.1.1 The Role of Commodity Prices

3.6.1.1.1 Revisiting the Results from Christiano et al. (1999) Christiano et al. (1999) used the smoothed change in an index of sensitive commodity prices (a component in the Bureau of Economic Analysis' index of leading indicators) which was discontinued in the late 1990s.

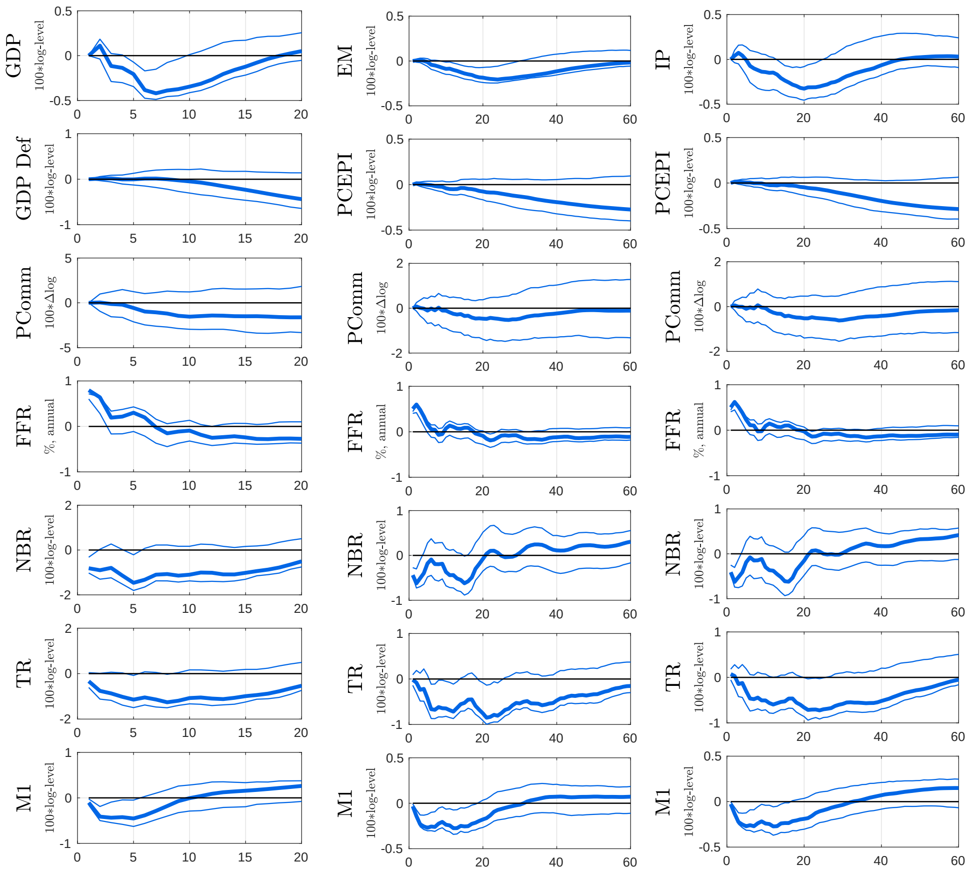
FIGURE 3.6.2: THE ORIGINAL IRFS FROM CHRISTIANO ET AL. (1999) FOR A MP SHOCK (SAMPLE 1965-1995)



Note: The left (right) column depicts the IRFs in response to a MP shock based on a quarterly (monthly) regression. The variables used in the quarterly regression are as follows: 'Y' is real (log) GDP, 'Price' is the (log) implicit GDP Deflator, 'PCom' is the smoothed change in an index of sensitive commodity prices (a component in the Bureau of Economic Analysis' index of leading indicators), 'FFR' is the effective Federal Funds Rate, 'NBR' is (log) non-borrowed reserves, TR is (log) total reserves, M1 is (log) M1 Money Supply. For the monthly regression GDP is replaced by EM, the (log) nonfarm payroll employment series. The aggregate price level is now measured by the (log) implicit deflator for personal consumption expenditures. For the quarterly (monthly) regression the lag-order is 4 (12).

3.6.1.1.2 Replication of Christiano et al. (1999) with WB Commodity Price Data Using the WB commodity price data series does not make a big difference. The price response in the quarterly regression, using the GDP Deflator instead of PCEPI, is more pronounced. Industrial production declines more than employment, with wider bands.

FIGURE 3.6.3: IRFS FOR A MP SHOCK (SAMPLE 1965-1995)



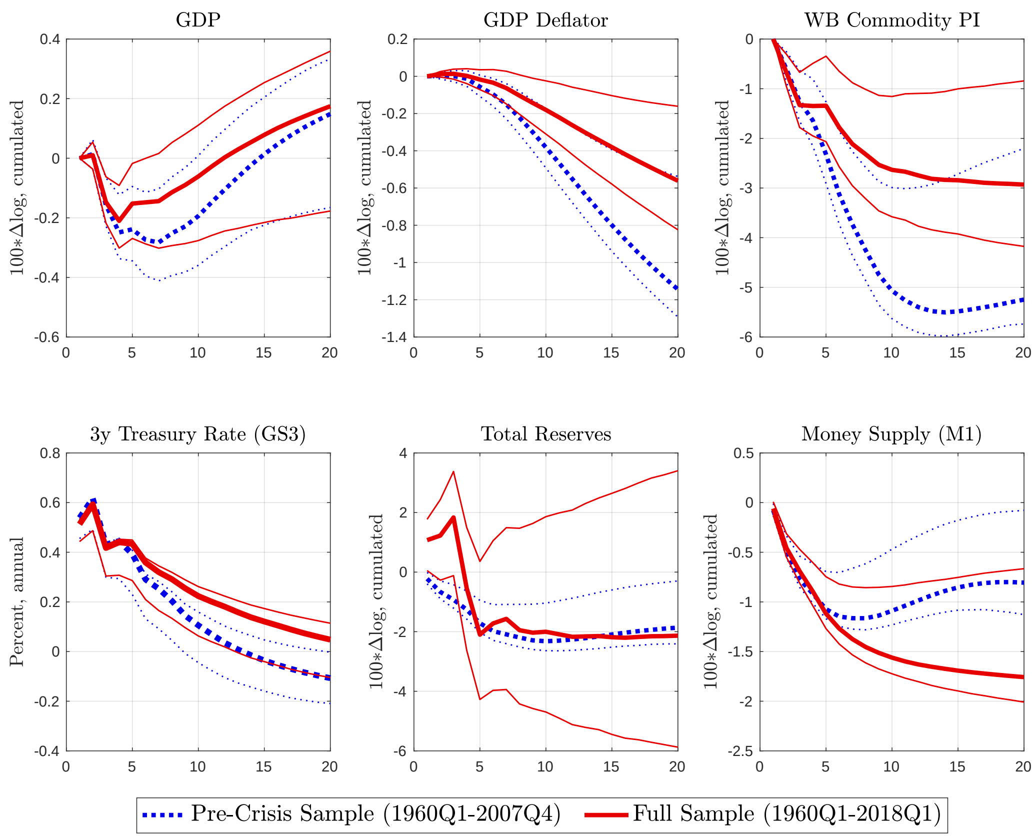
Note: The left column depicts the IRFs in response to a MP shock based on a quarterly regression. The center and right column depict IRFs based on monthly regression, with employment EM (center) and industrial production (right). The variables used in the quarterly regression are as follows: 'GDP' is real (log) GDP, 'GDP Def' is the (log) implicit GDP Deflator, 'PCom' is the Commodity Price Index from the World Bank, 'FFR' is the effective Federal Funds Rate, 'NBR' is (log) non-borrowed reserves, TR is (log) total reserves, M1 is (log) M1 Money Supply. For the monthly regression GDP is replaced by EM and IP, the (log) nonfarm payroll employment series and industrial production (INDPROD). The aggregate price level is now measured by the (log) price index for personal consumption expenditures. For the quarterly (monthly) regression the lag-order is 4 (12).

3.6.1.2 The Role of Reserves

Given how the reserve series has behaved since 2008, it would be difficult to incorporate it into a TVC-VAR setting. Removing the non-borrowed and the total reserve series does not substantially change the effects of a monetary policy shock on the other 5 variables. I therefore remove the reserve series.

3.6.1.2.1 Constant Coefficients SVAR with Total Reserves In the context of a constant coefficient VAR it can be shown that all other 5 variables behave very similar to their counterparts form the setting in which total reserves were omitted.

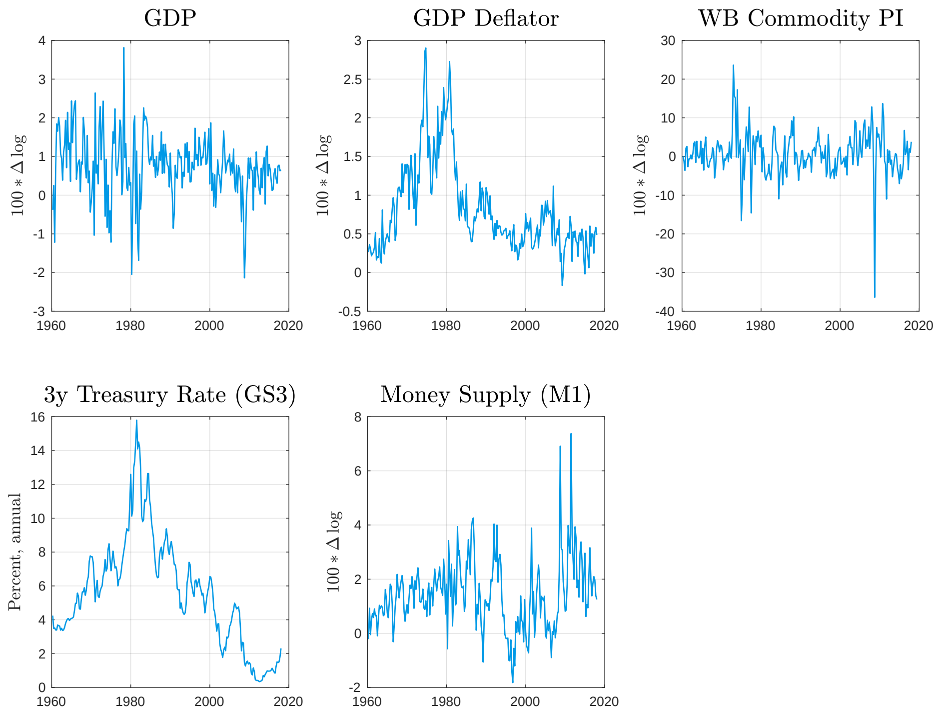
FIGURE 3.6.4: IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK



Note: The thick lines depict the IRFs in response to a MP shock. The thin lines are the corresponding 68% confidence bands. Cumulative IRFs are shown for variables in log-difference terms. The IRFs are based on quarterly data, the sample span is from 1960Q01-2007Q4 (blue, dotted) and 1960Q01-2018Q1 (red, straight). The variables used are: GDP (GDPC1, real Billions of USD), GDP deflator (GDPDEF, index 2009=100), World Bank Commodity Price Index (2010=100), the 3-Year Treasury Constant Maturity Rate (GS3), total reserves (TOTRESNS, Billions of USD) and M1 Money Supply (M1SL).

3.6.2 Time-Varying Coefficients SVAR: 25 Basis Points instead of 1 Stdev on Impact

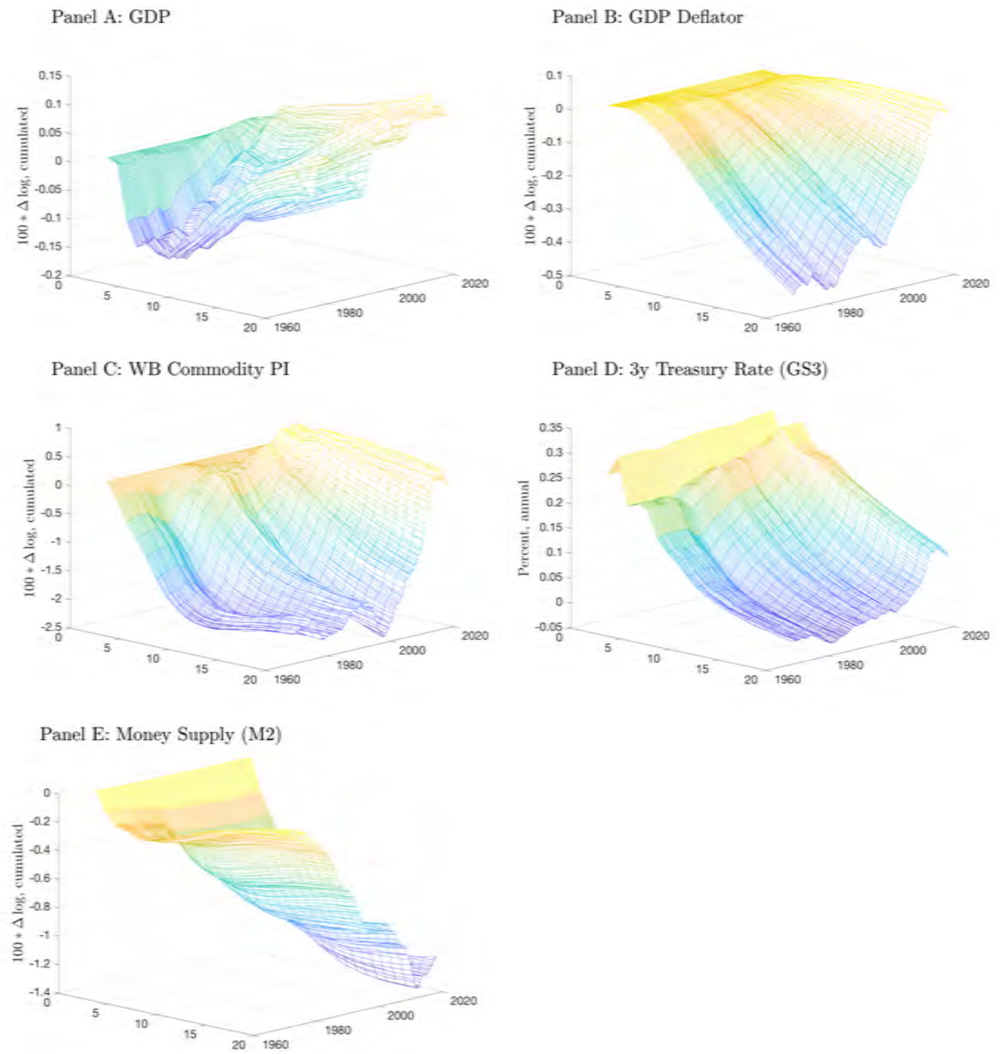
FIGURE 3.6.5: RAW DATA WITH M2



Source: FRED

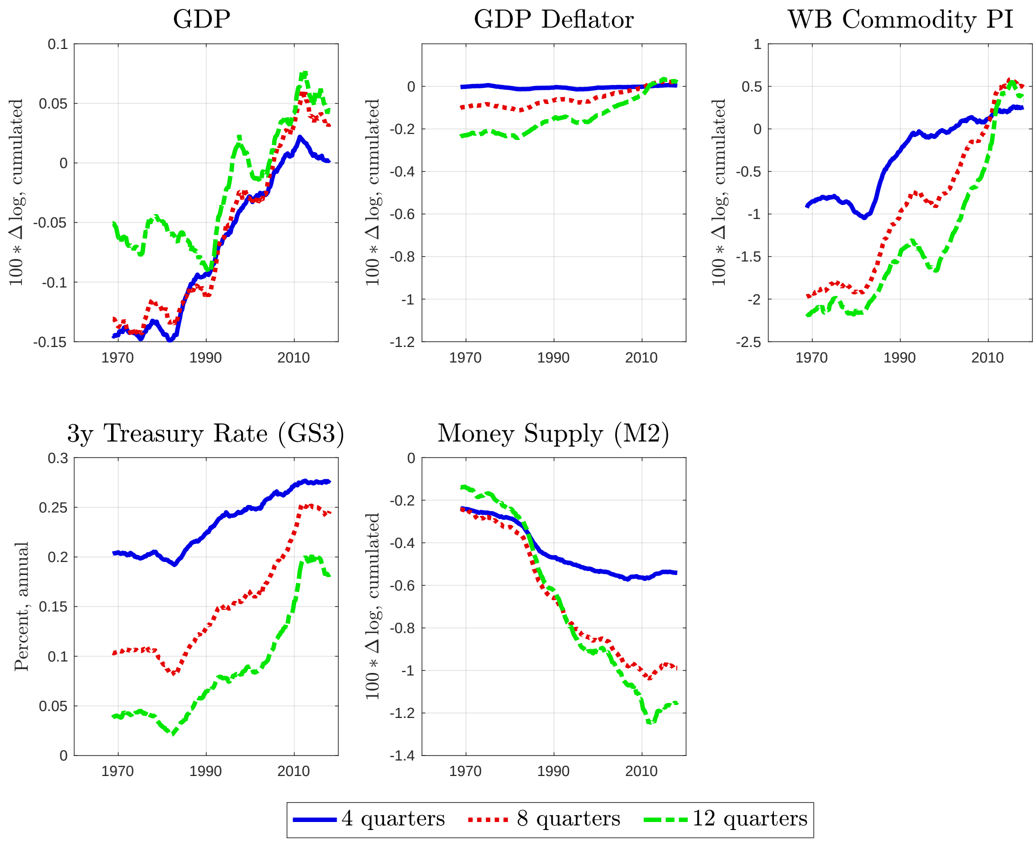
Note: Quarterly US data with a sample span from 1960Q01-2018Q1. The variables are: GDP (GDPC1, real Billions of USD), GDP deflator (GDPDEF, index 2009=100), World Bank Commodity Price Index (2010=100), the 3-Year Treasury Constant Maturity Rate (GS3) and M1 Money Supply (M1SL). The variables are in log-difference terms, except for the 3-Year Treasury Constant Maturity Rate (GS3).

FIGURE 3.6.6: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK FROM 1968Q1 TO 2018Q1



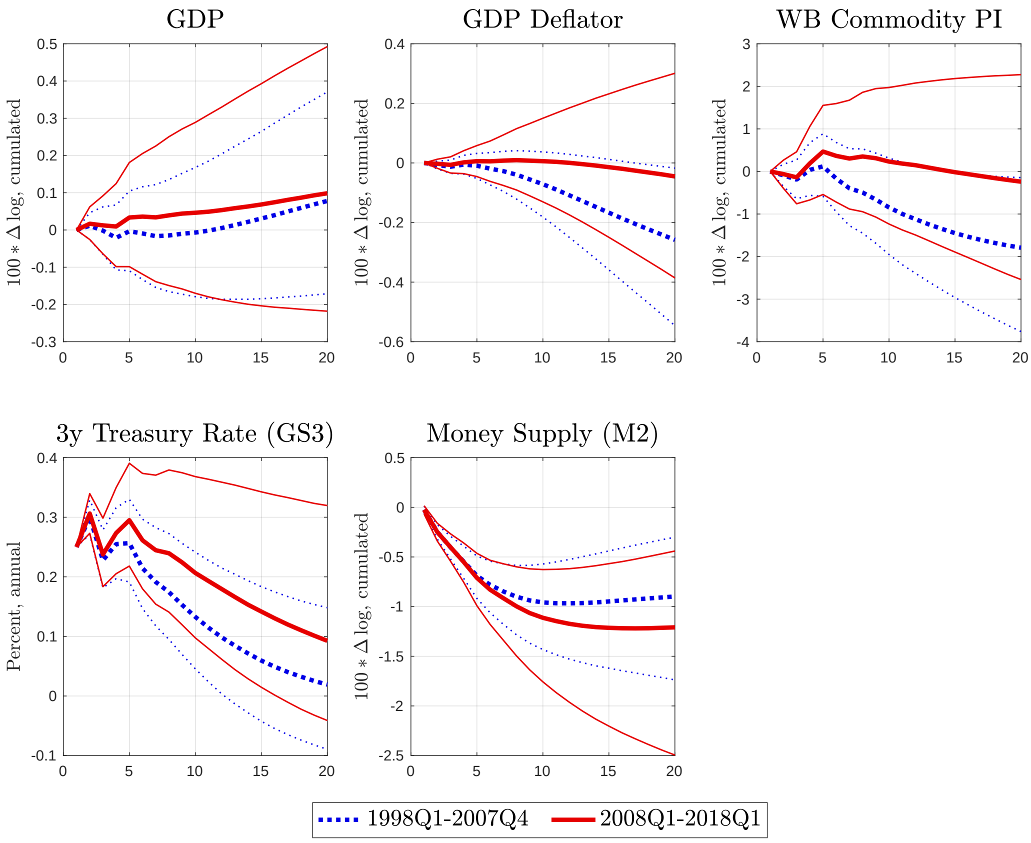
Note: Panels A to E depict the median IRFs for a Monetary Policy Shock in which the initial shock impact was fixed to 25 basis points (instead of one standard deviation). All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on quarterly data, the sample span is from 1960Q1-2018Q1 with 8 years of prior tuning and a lag-order of 4.

FIGURE 3.6.7: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK AT SELECTED HORIZONS



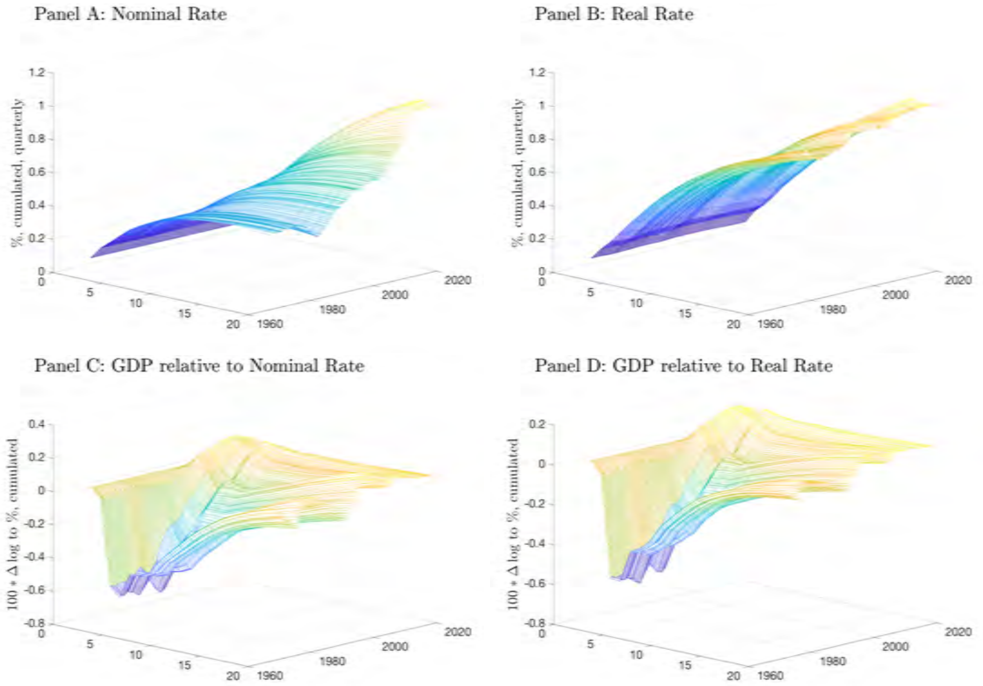
Note: Median IRFs at Selected Horizons (4, 8 and 12 quarters) for a Monetary Policy Shock in which the initial shock impact was fixed to 25 basis points (instead of one standard deviation). All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on quarterly data, the sample span is from 1960Q1-2018Q1 with 8 years of prior tuning and a lag-order of 4.

FIGURE 3.6.8: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK PRE- AND POST-CRISIS



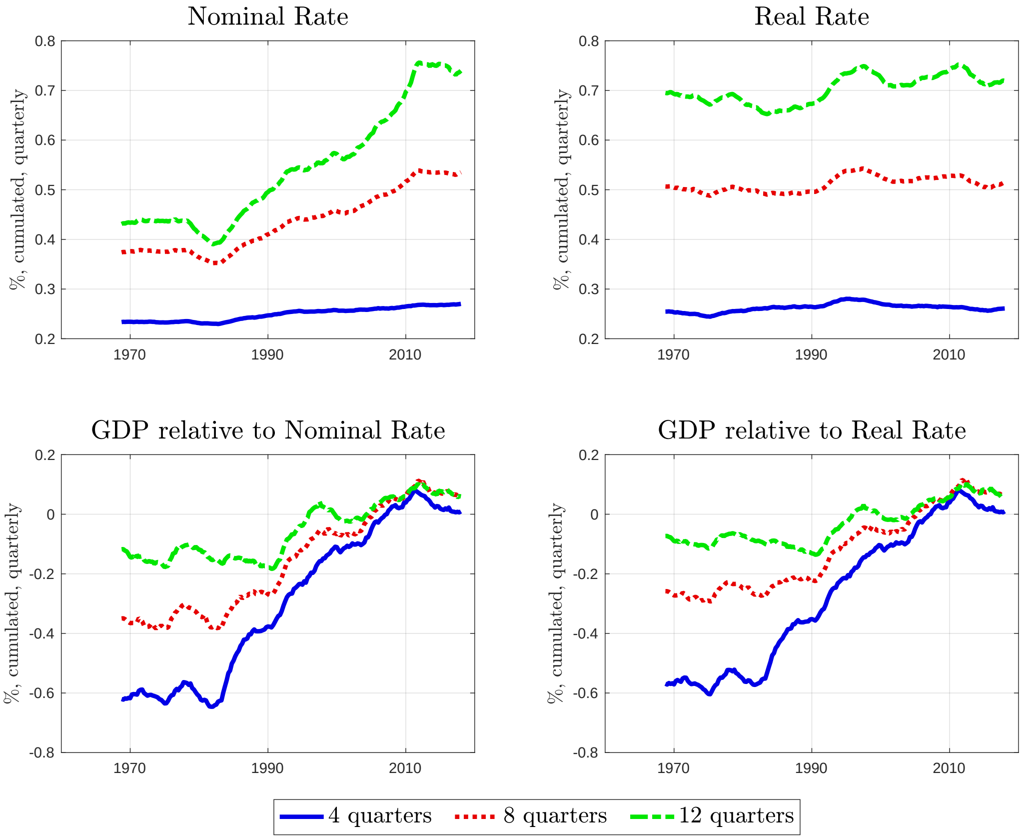
Note: The thick lines depict the 10-year average of the Median IRFs before and after the Financial Crisis of 2008 for a Monetary Policy Shock in which the initial shock impact was fixed to 25 basis points (instead of one standard deviation). The thin lines correspond to the 68% confidence bands. All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on quarterly data, the sample span is from 1960Q1-2018Q1 with 8 years of prior tuning and a lag-order of 4.

FIGURE 3.6.9: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK FROM 1968Q1 TO 2018Q1



Note: Panels A to E depict the median IRFs for a Monetary Policy Shock in which the initial shock impact was fixed to 25 basis points (instead of one standard deviation). All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on quarterly data, the sample span is from 1960Q1-2018Q1 with 8 years of prior tuning and a lag-order of 4.

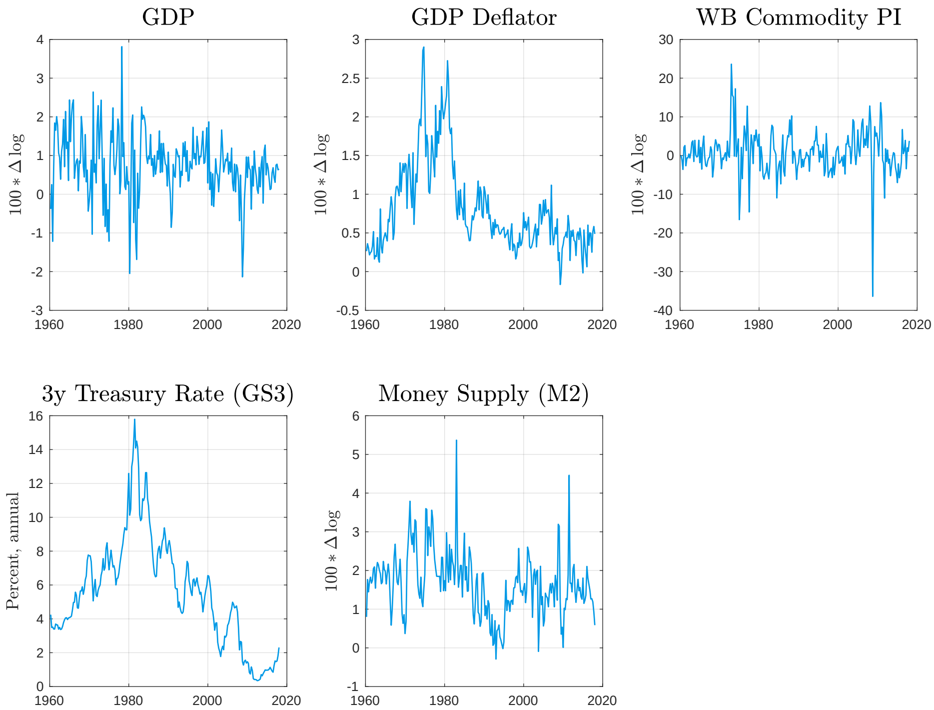
FIGURE 3.6.10: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK AT SELECTED HORIZONS



Note: Median IRFs at Selected Horizons (4, 8 and 12 quarters) for a Monetary Policy Shock in which the initial shock impact was fixed to 25 basis points (instead of one standard deviation). All variables are in log-differences, except for the FFR series which is in annual percentage terms. The results are based on quarterly data, the sample span is from 1960Q1-2018Q1 with 8 years of prior tuning and a lag-order of 4.

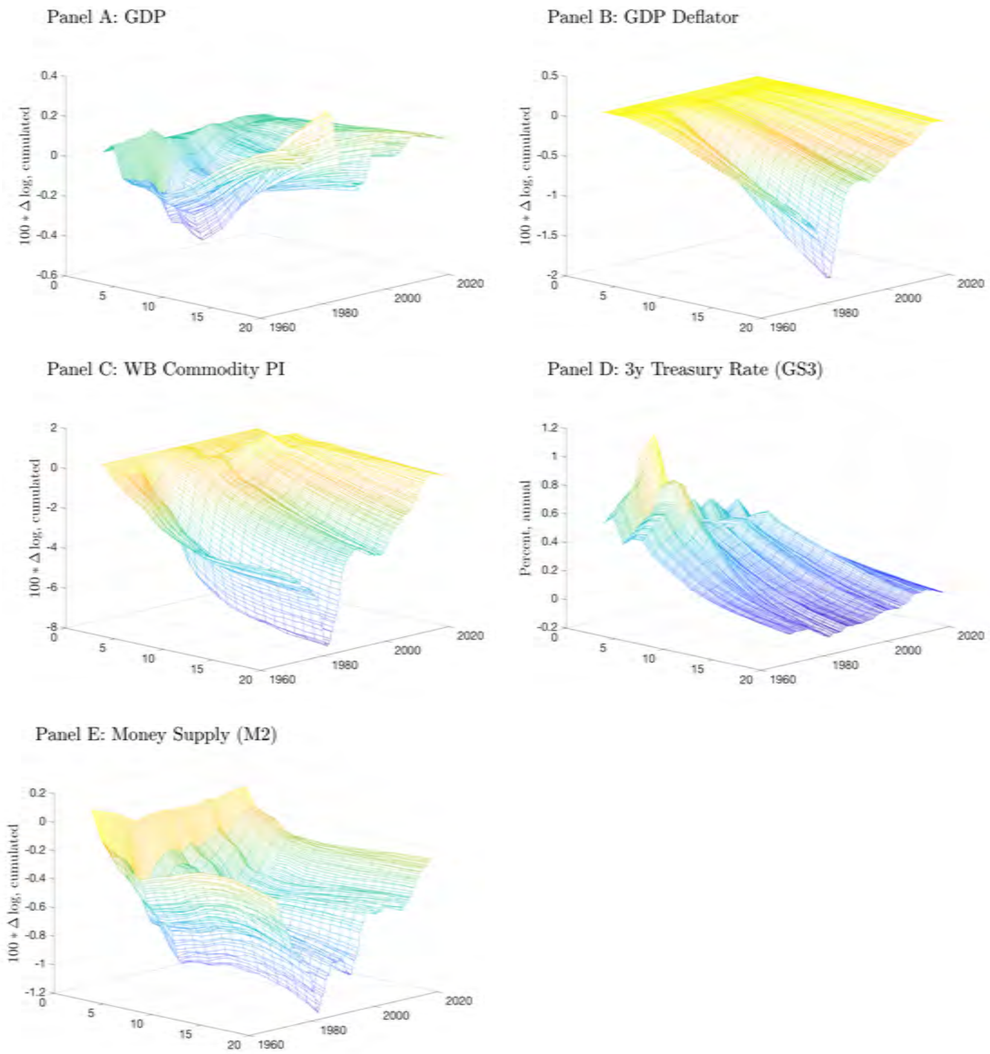
3.6.3 Time-Varying Coefficients SVAR: Using M1 instead of M2

FIGURE 3.6.11: RAW DATA WITH M2



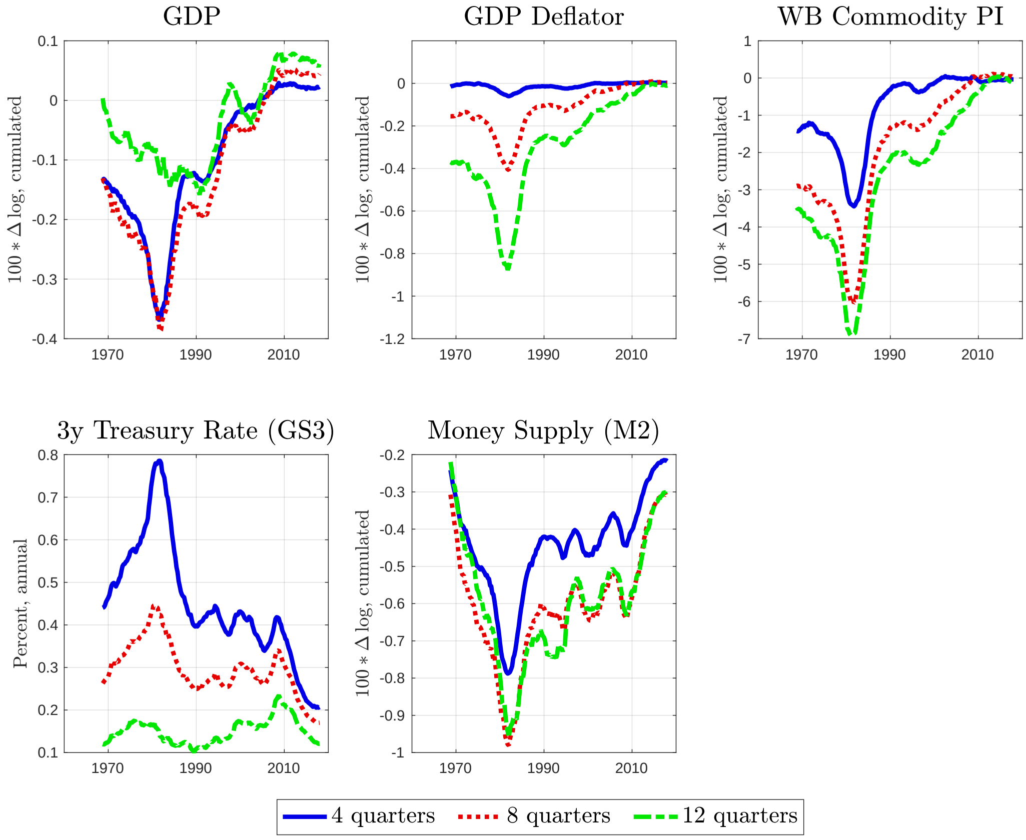
Source: FRED
Note: Quarterly US data with a sample span from 1960Q01-2018Q1. The variables are: GDP (GDPC1, real Billions of USD), GDP deflator (GDPDEF, index 2009=100), World Bank Commodity Price Index (2010=100), the 3-Year Treasury Constant Maturity Rate (GS3) and M2 Money Supply (M2SL). The variables are in log-difference terms, except for the 3-Year Treasury Constant Maturity Rate (GS3).

FIGURE 3.6.12: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK FROM 1968Q1 TO 2018Q1



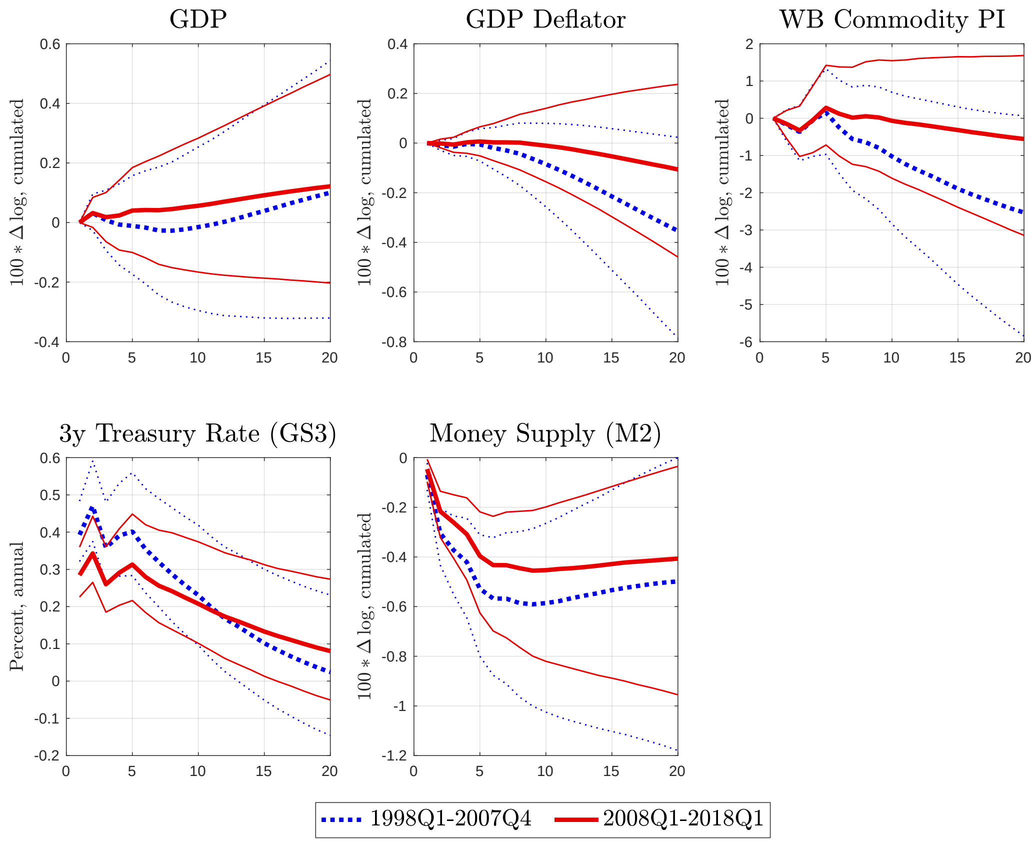
Note: Panels A to E depict the median IRFs for a Monetary Policy Shock of 1 standard deviation. All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on quarterly data, the sample span is from 1960Q1-2018Q1 with 8 years of prior tuning and a lag-order of 4.

FIGURE 3.6.13: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK AT SELECTED HORIZONS



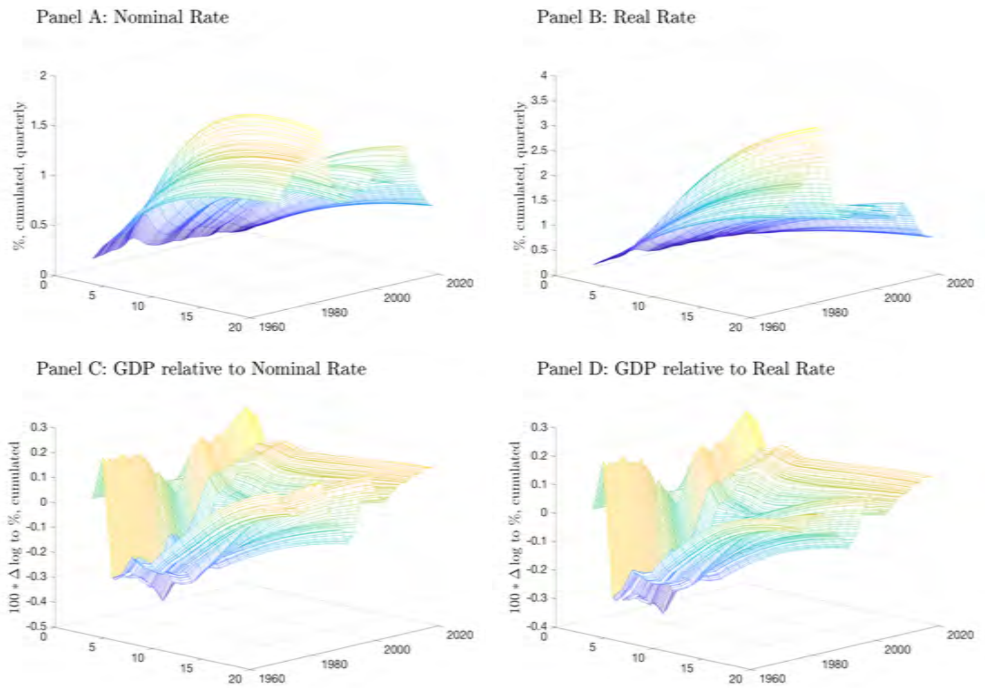
Note: Median IRFs at Selected Horizons (4, 8 and 12 quarters) for a Monetary Policy Shock of 1 standard deviation. All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on quarterly data, the sample span is from 1960Q1-2018Q1 with 8 years of prior tuning and a lag-order of 4.

FIGURE 3.6.14: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK PRE- AND POST-CRISIS



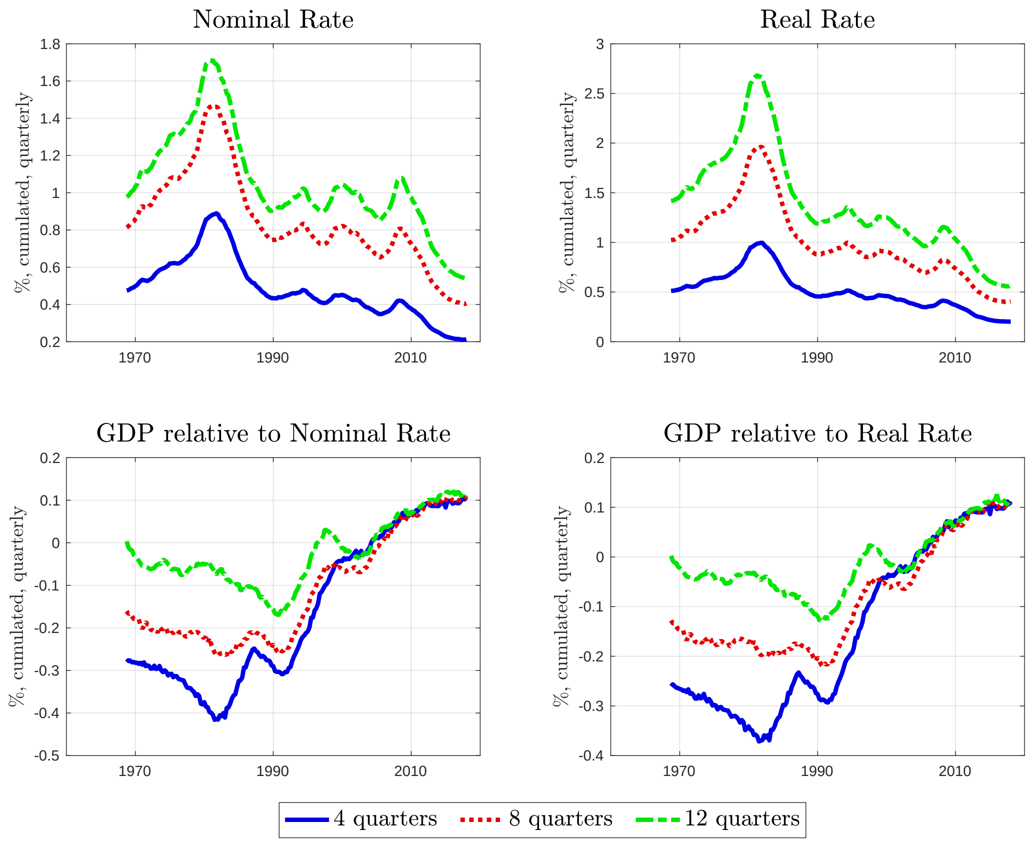
Note: The thick lines depict the 10-year average of the Median IRFs before and after the Financial Crisis of 2008 for a Monetary Policy Shock of 1 standard deviation. The thin lines correspond to the 68% confidence bands. All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on quarterly data, the sample span is from 1960Q1-2018Q1 with 8 years of prior tuning and a lag-order of 4.

FIGURE 3.6.15: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK FROM 1968Q1 TO 2018Q1



Note: Panels A to E depict the median IRFs for a Monetary Policy Shock of 1 standard deviation. All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on quarterly data, the sample span is from 1960Q1-2018Q1 with 8 years of prior tuning and a lag-order of 4.

FIGURE 3.6.16: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK AT SELECTED HORIZONS

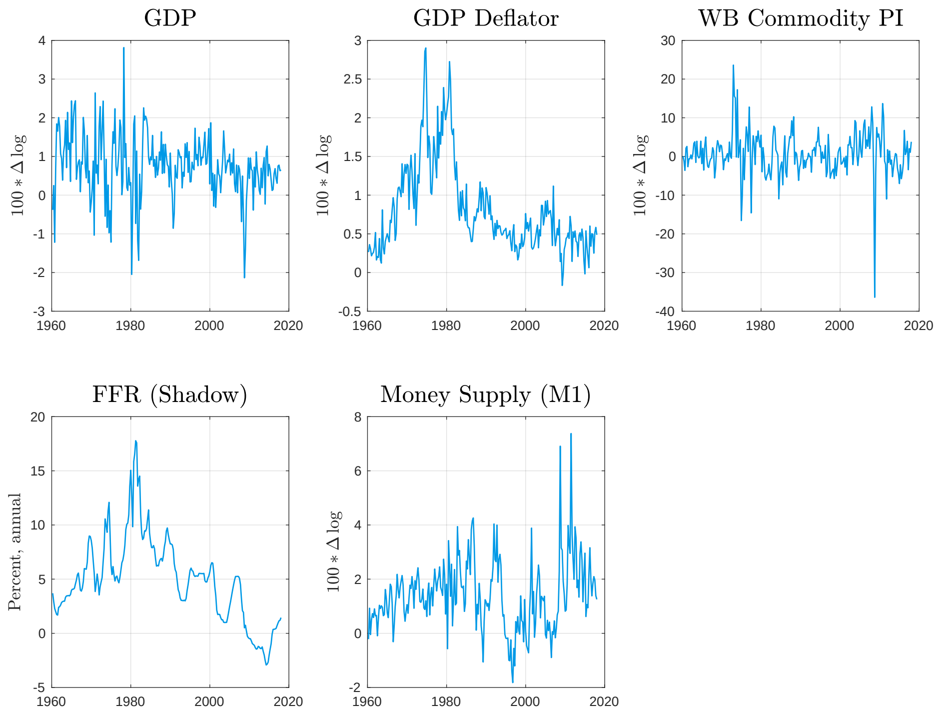


Note: Median IRFs at Selected Horizons (4, 8 and 12 quarters) for a Monetary Policy Shock of 1 standard deviation. All variables are in log-differences, except for the FFR series which is in annual percentage terms. The results are based on quarterly data, the sample span is from 1960Q1-2018Q1 with 8 years of prior tuning and a lag-order of 4.

3.6.4 Time-Varying Coefficients SVAR: Using Shadow FFR (Wu and Xia (2016))

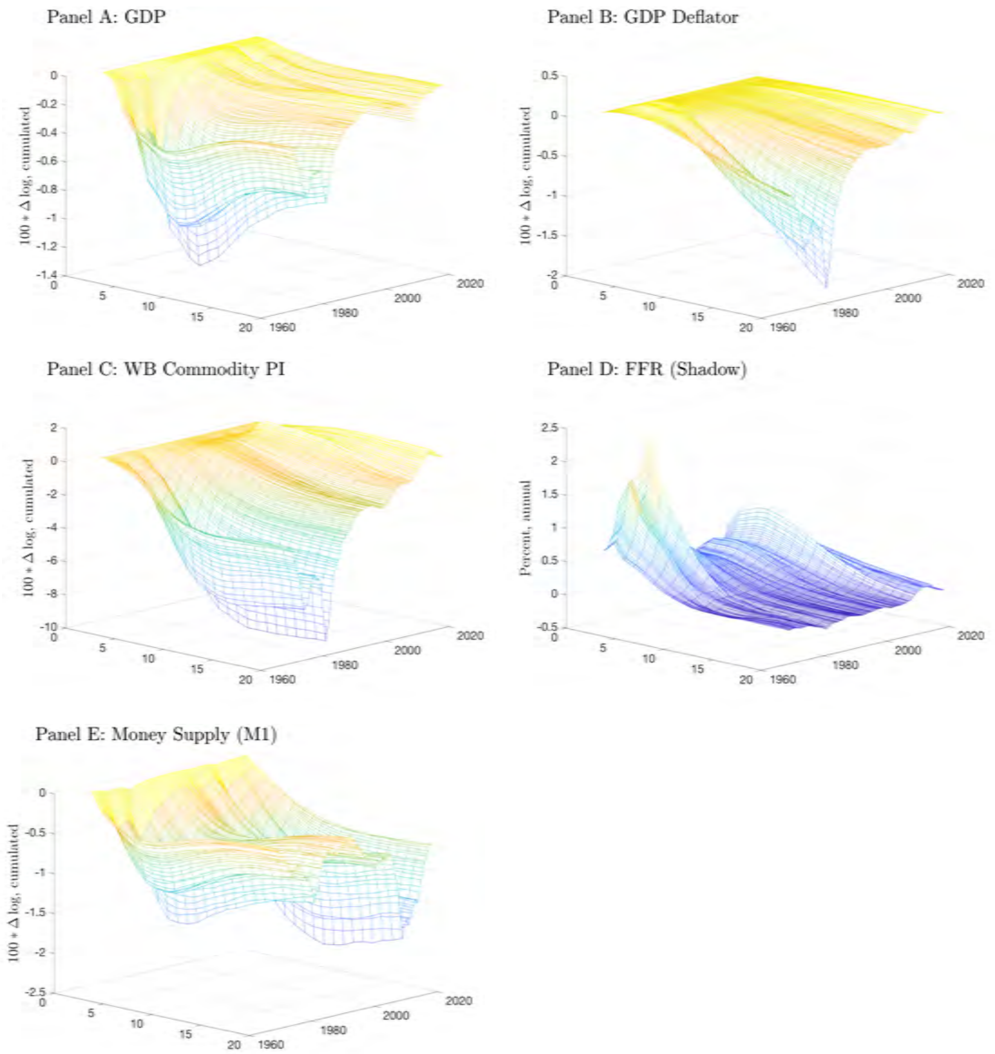
In the main text I used the 3-year Constant Maturity Treasury Yield Rate to account for the fact that the Federal Funds Rate became constrained by the zero lower bound over a significant horizon. During that time, unventional measures were employed to further lower medium- and long-term interest rates. This is the reason why I assumed above that the monetary policy stance is reflected in the 3-year rate. In a similar spirit, Wu and Xia (2016) construct a 'shadow' FFR that can take negative values and that reflects the monetary policy stance in terms of an interest rate.

FIGURE 3.6.17: RAW DATA WITH SHADOW RATE



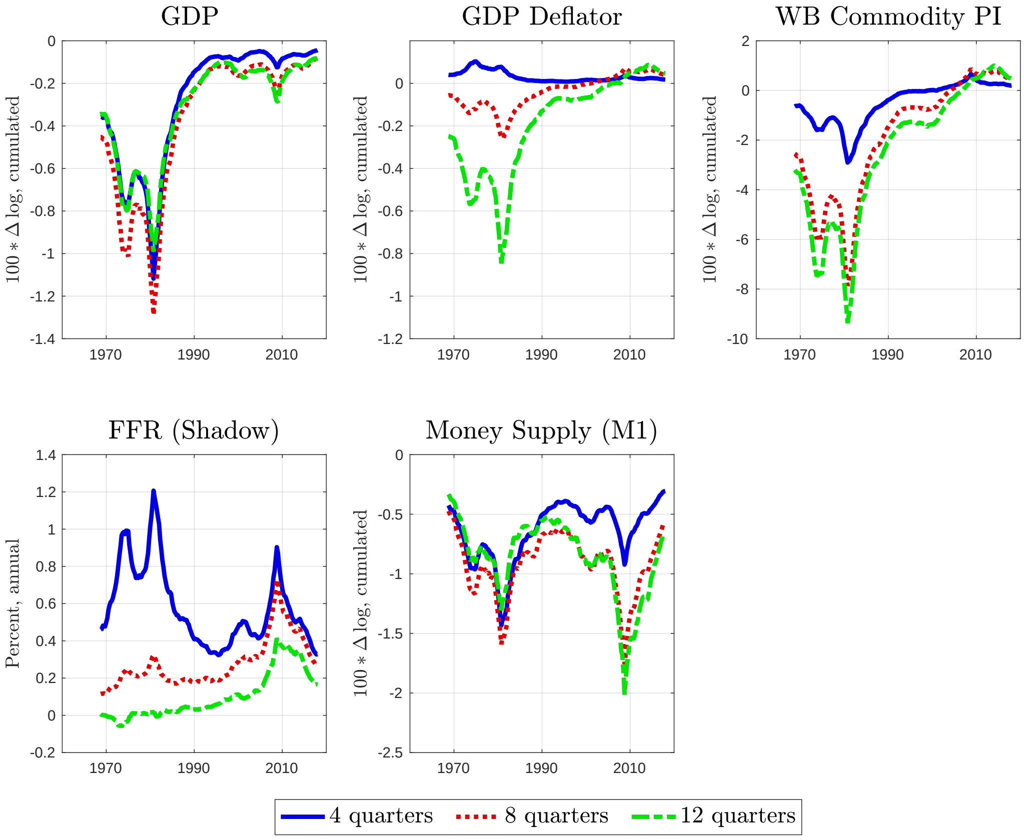
Source: FRED
Note: Quarterly US data with a sample span from 1960Q01-2018Q1. The variables are: GDP (GDPC1, real Billions of USD), GDP deflator (GDPDEF, index 2009=100), World Bank Commodity Price Index (2010=100), the Shadow FFR (Wu and Xia (2016)) and M1 Money Supply (M1SL). The variables are in log-difference terms, except for the 3-Year Treasury Constant Maturity Rate (GS3).

FIGURE 3.6.18: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK FROM 1968Q1 TO 2018Q1



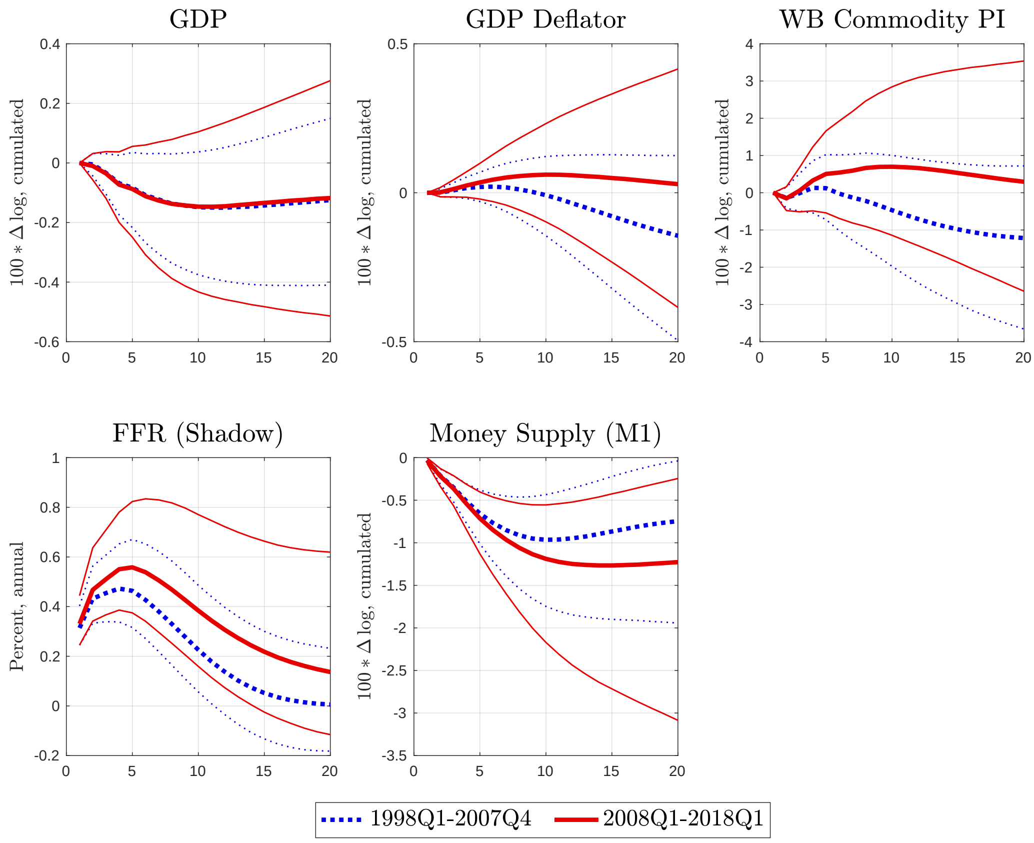
Note: Panels A to E depict the median IRFs for a Monetary Policy Shock of 1 standard deviation. All variables are in log-differences, except for the Shadow FFR series which is in annual percentage terms. The results are based on quarterly data, the sample span is from 1960Q1-2018Q1 with 8 years of prior tuning and a lag-order of 4.

FIGURE 3.6.19: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK AT SELECTED HORIZONS



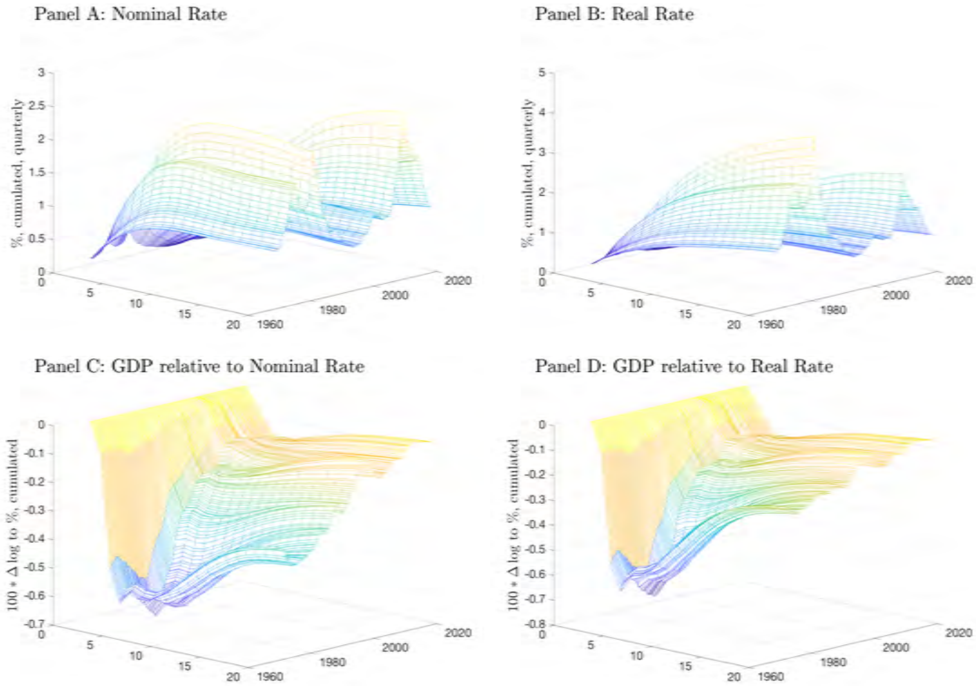
Note: Median IRFs at Selected Horizons (4, 8 and 12 quarters) for a Monetary Policy Shock of 1 standard deviation. All variables are in log-differences, except for the FFR series which is in annual percentage terms. The results are based on quarterly data, the sample span is from 1960Q1-2018Q1 with 8 years of prior tuning and a lag-order of 4.

FIGURE 3.6.20: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK PRE- AND POST-CRISIS



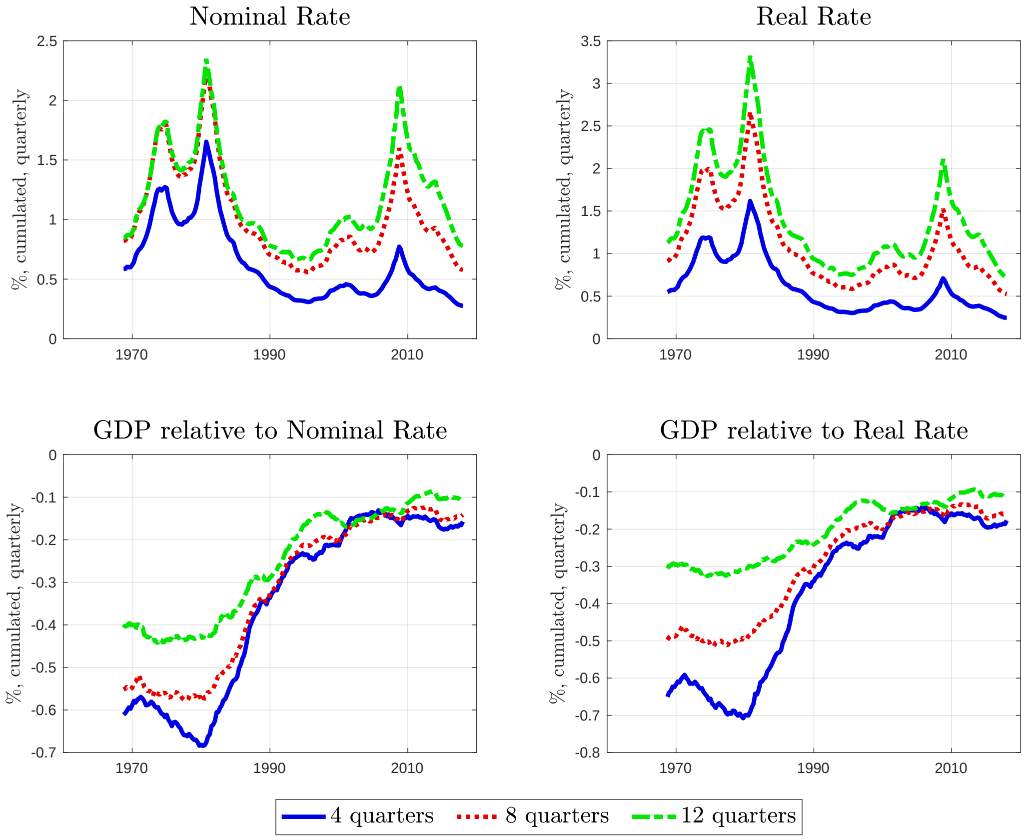
Note: The thick lines depict the 10-year average of the Median IRFs before and after the Financial Crisis of 2008 for a Monetary Policy Shock of 1 standard deviation. The thin lines correspond to the 68% confidence bands. All variables are in log-differences, except for the FFR series which is in annual percentage terms. The results are based on quarterly data, the sample span is from 1960Q1-2018Q1 with 8 years of prior tuning and a lag-order of 4.

FIGURE 3.6.21: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK FROM 1968Q1 TO 2018Q1



Note: Panels A to E depict the median IRFs for a Monetary Policy Shock of 1 standard deviation. All variables are in log-differences, except for the Shadow FFR series which is in annual percentage terms. The results are based on quarterly data, the sample span is from 1960Q1-2018Q1 with 8 years of prior tuning and a lag-order of 4.

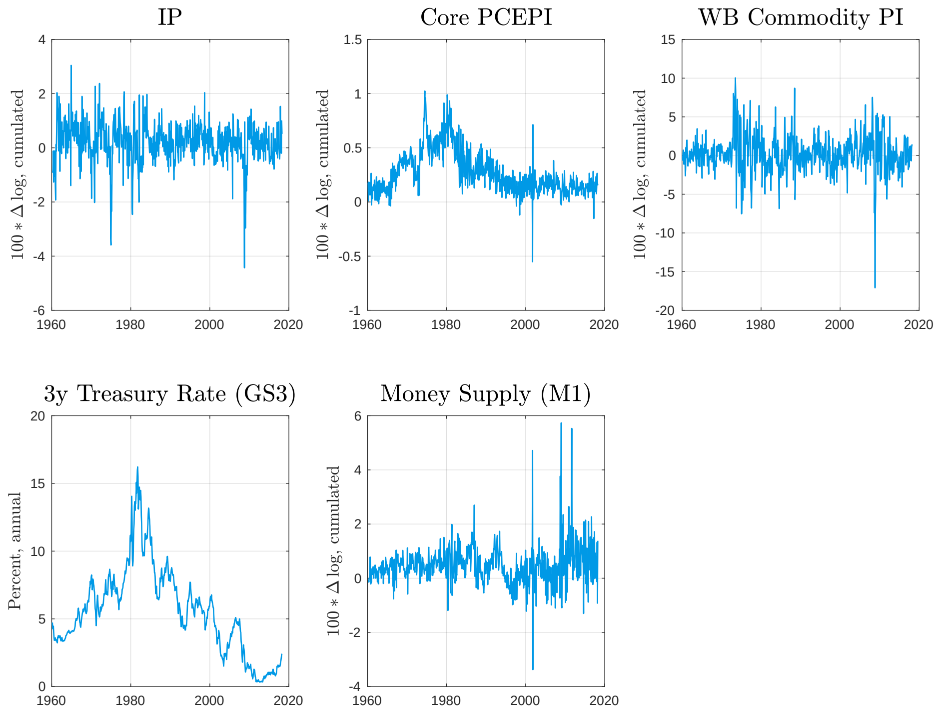
FIGURE 3.6.22: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK AT SELECTED HORIZONS



Note: Median IRFs at Selected Horizons (4, 8 and 12 quarters) for a Monetary Policy Shock of 1 standard deviation. All variables are in log-differences, except for the FFR series which is in annual percentage terms. The results are based on quarterly data, the sample span is from 1960Q1-2018Q1 with 8 years of prior tuning and a lag-order of 4.

3.6.5 Time-Varying Coefficients SVAR: Monthly Data using Core PCEPI

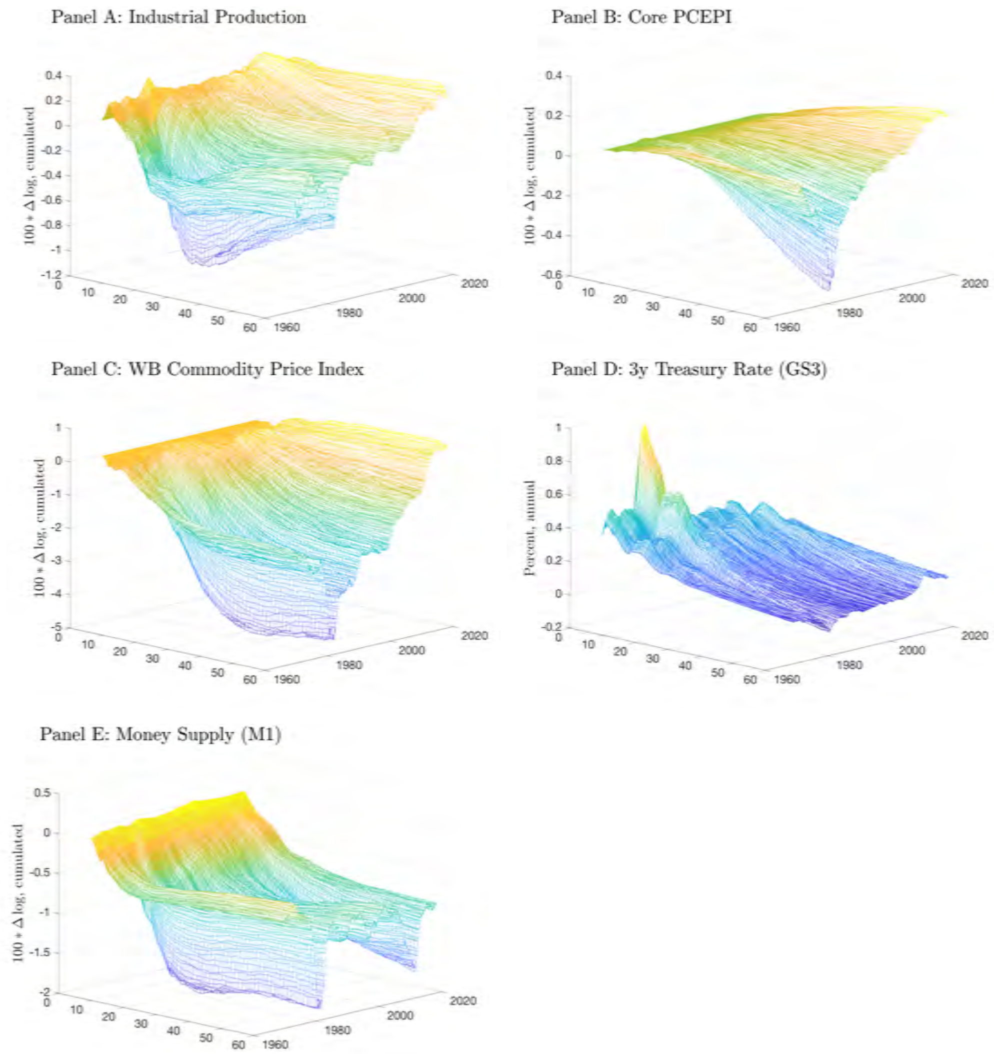
FIGURE 3.6.23: MONTHLY RAW DATA



Source: FRED

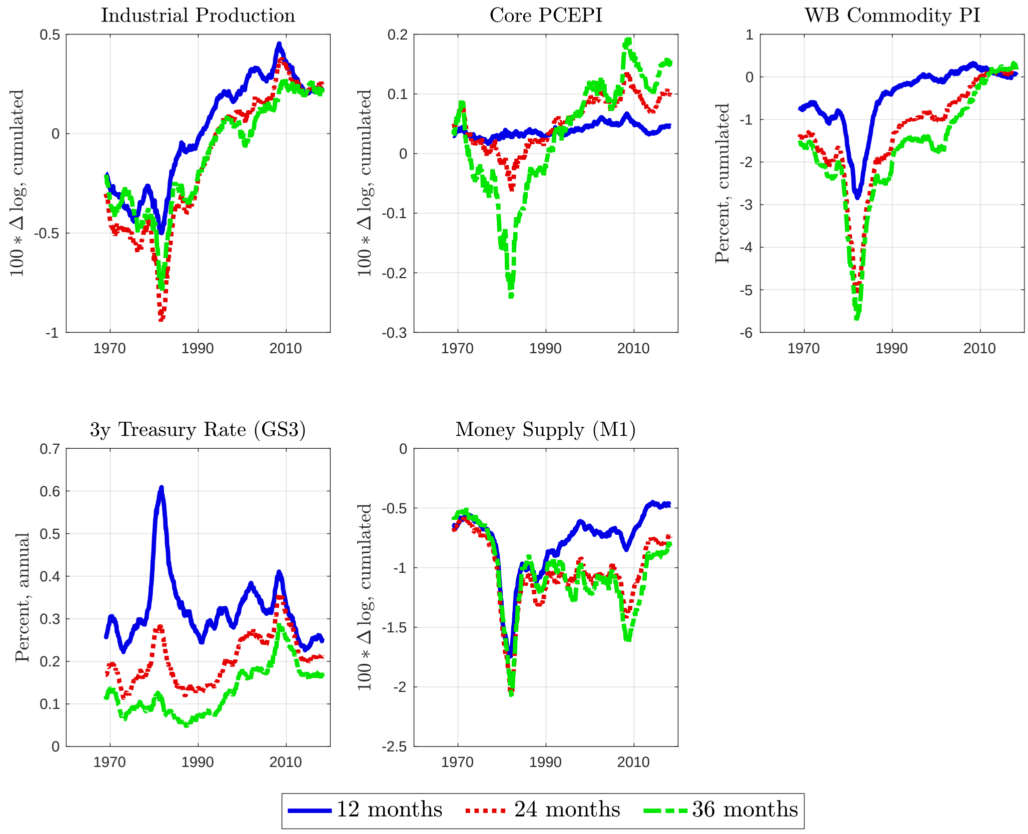
Note: Monthly US data with a sample span from 1960M01-2018M03. The variables are: IP, Core PCEPI (excluding energy and food prices), World Bank Commodity Price Index (2010=100), the GS3 Rate and M1 Money Supply (M1SL). The variables are in log-difference terms, except for the 3-Year Treasury Constant Maturity Rate (GS3).

FIGURE 3.6.24: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK FROM 1968M01 TO 2018M03



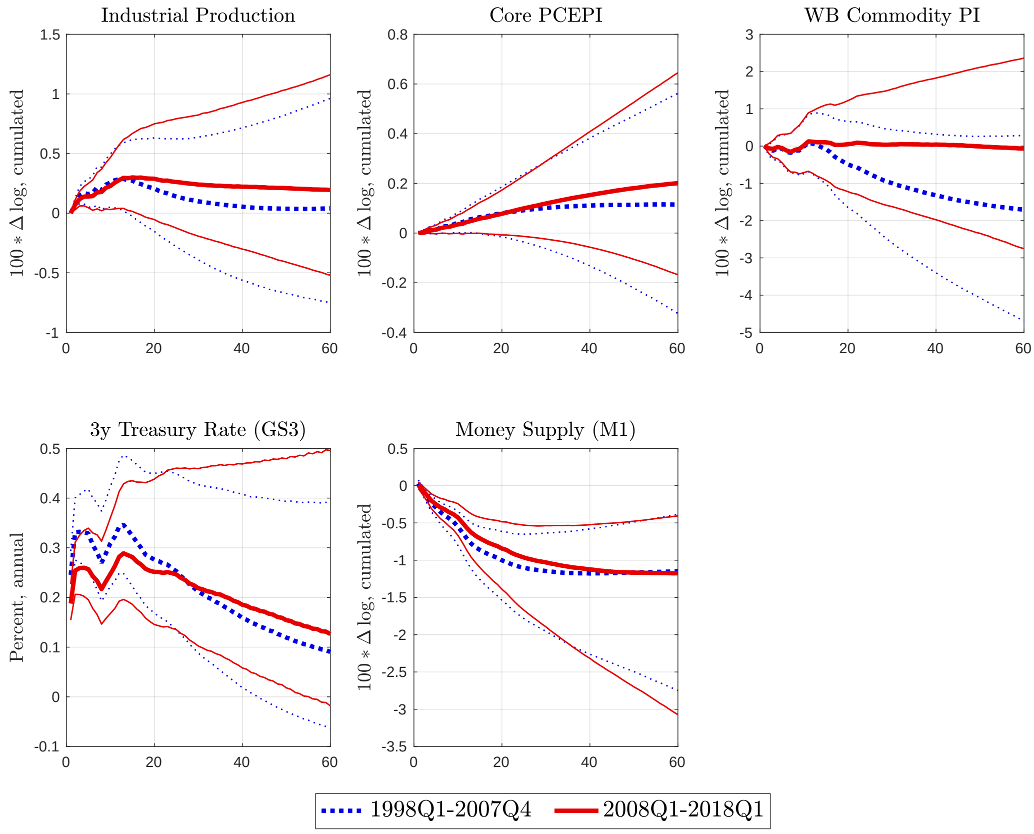
Note: Panels A to E depict the median IRFs for a Monetary Policy Shock of 1 standard deviation. All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on monthly data, the sample span is from 1960M01-2018M03 with 8 years of prior tuning and lag-order 12.

FIGURE 3.6.25: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK AT SELECTED HORIZONS



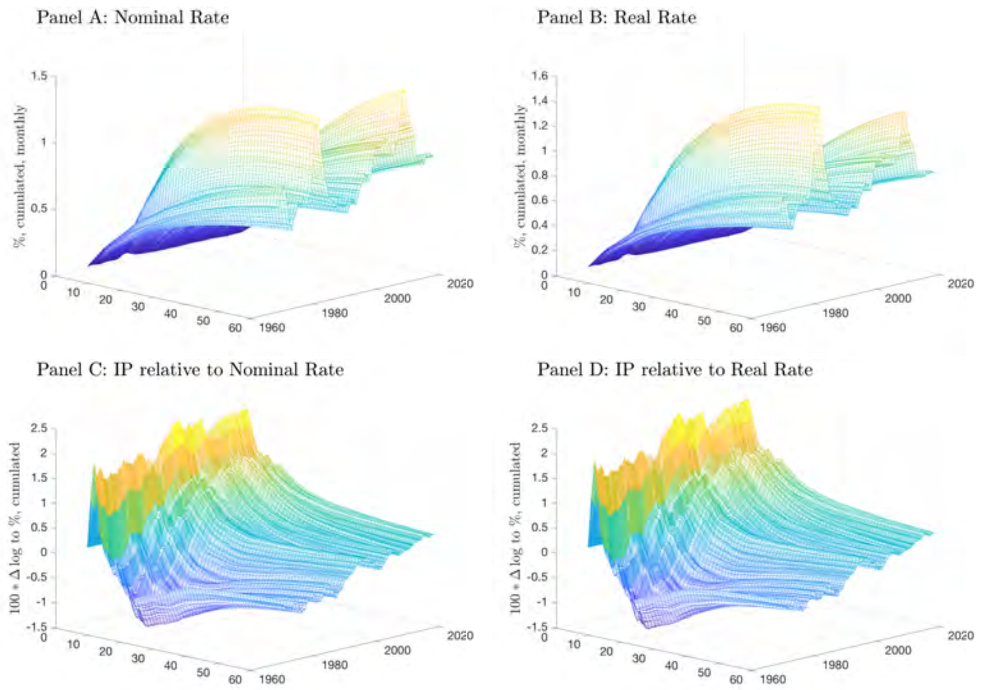
Note: Median IRFs at Selected Horizons (12, 24 and 36 months) for a Monetary Policy Shock of 1 standard deviation. All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on monthly data, the sample span is from 1960M01-2018M03 with 8 years of prior tuning and lag-order 12.

FIGURE 3.6.26: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK PRE- AND POST-CRISIS



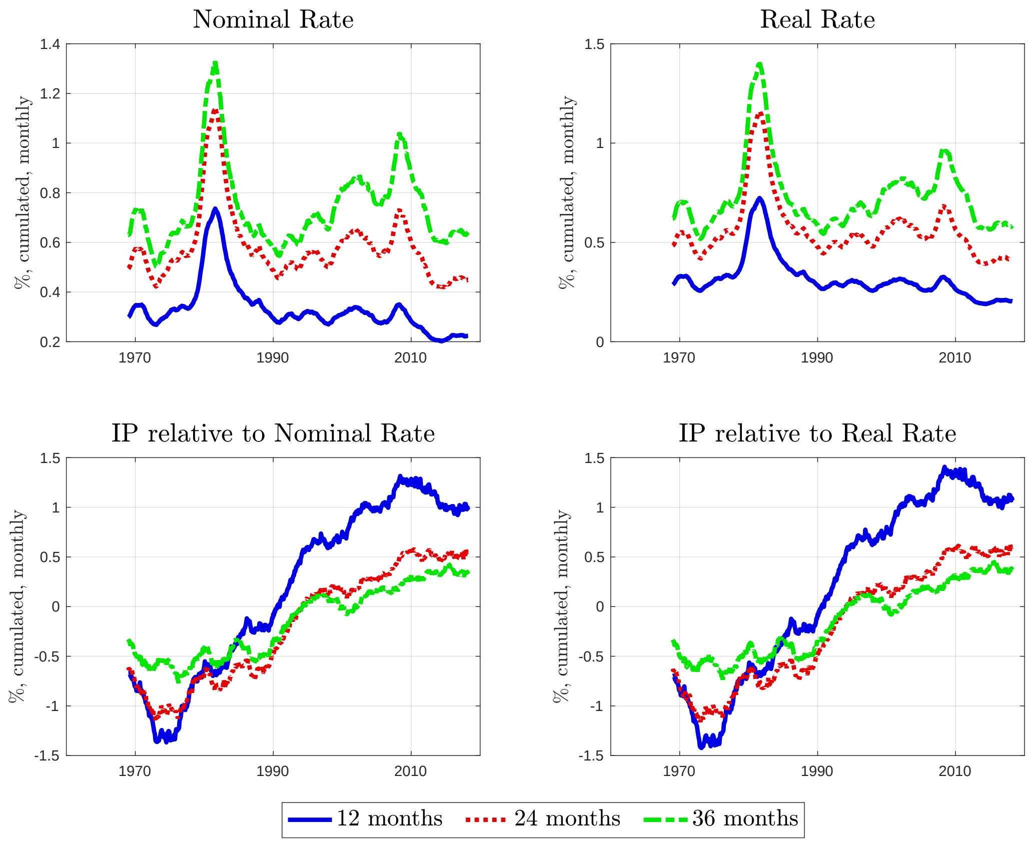
Note: The thick lines depict the 10-year average of the Median IRFs before and after the Financial Crisis of 2008 for a Monetary Policy Shock of 1 standard deviation. The thin lines correspond to the 68% confidence bands. All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on monthly data, the sample span is from 1960M01-2018M03 with 8 years of prior tuning and lag-order 12.

FIGURE 3.6.27: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK FROM 1968M01 TO 2018M03



Note: Panels A to E depict the median IRFs for a Monetary Policy Shock of 1 standard deviation. All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on monthly data, the sample span is from 1960M01-2018M03 with 8 years of prior tuning and lag-order 12.

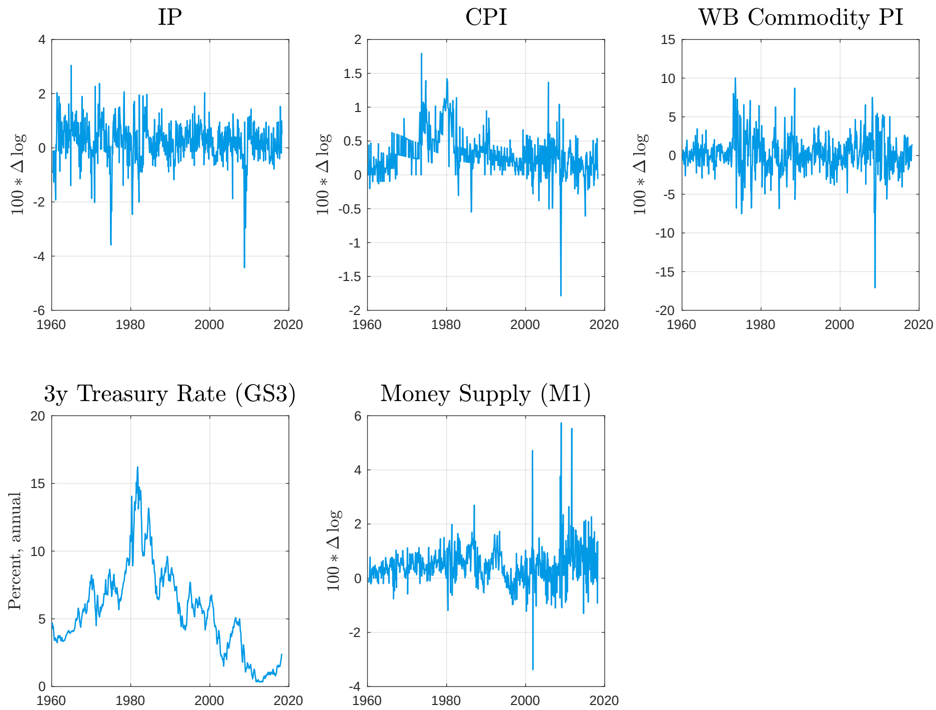
FIGURE 3.6.28: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK AT SELECTED HORIZONS



Note: Median IRFs at Selected Horizons (12, 24 and 36 months) for a Monetary Policy Shock of 1 standard deviation. The results are based on monthly data, the sample span is from 1960M01-2018M03 with 8 years of prior tuning and a lag-order of 12.

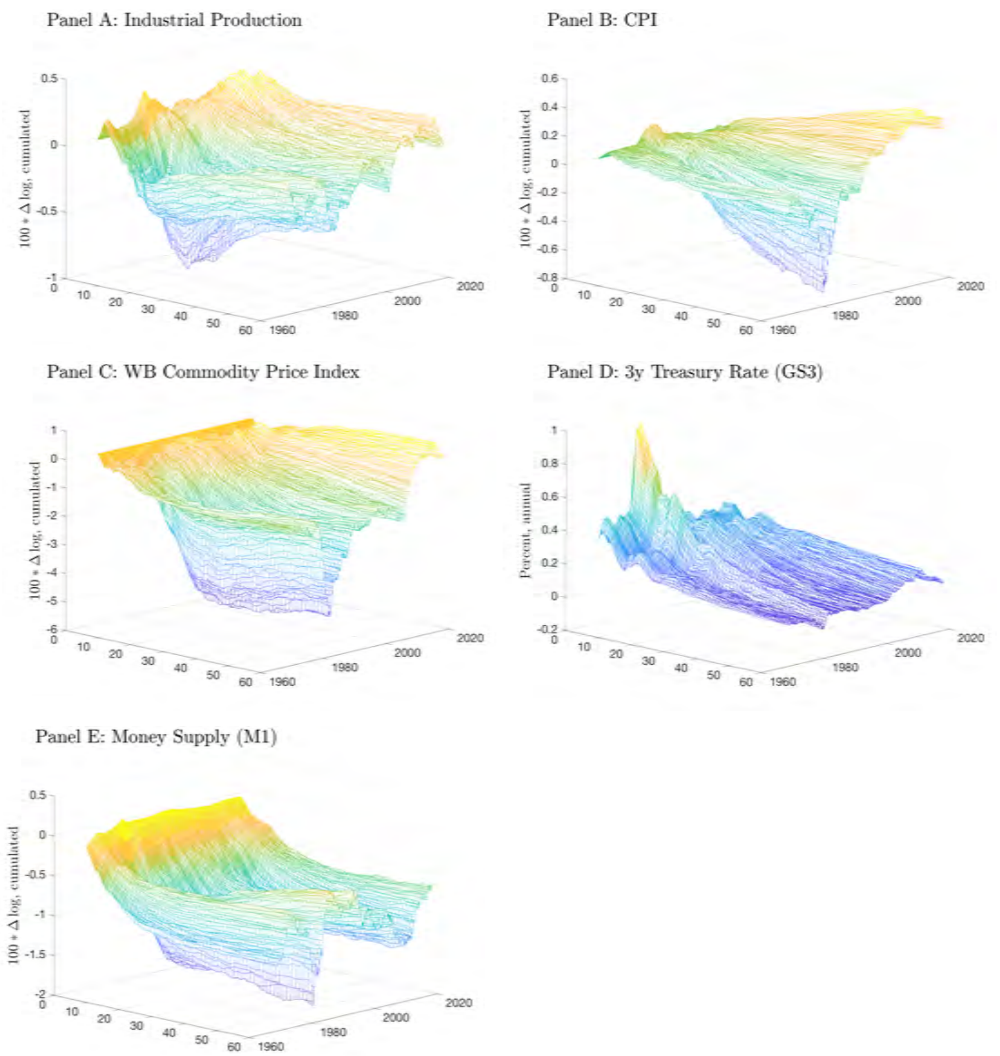
3.6.6 Time-Varying Coefficients SVAR: Monthly Data using CPI

FIGURE 3.6.29: MONTHLY RAW DATA



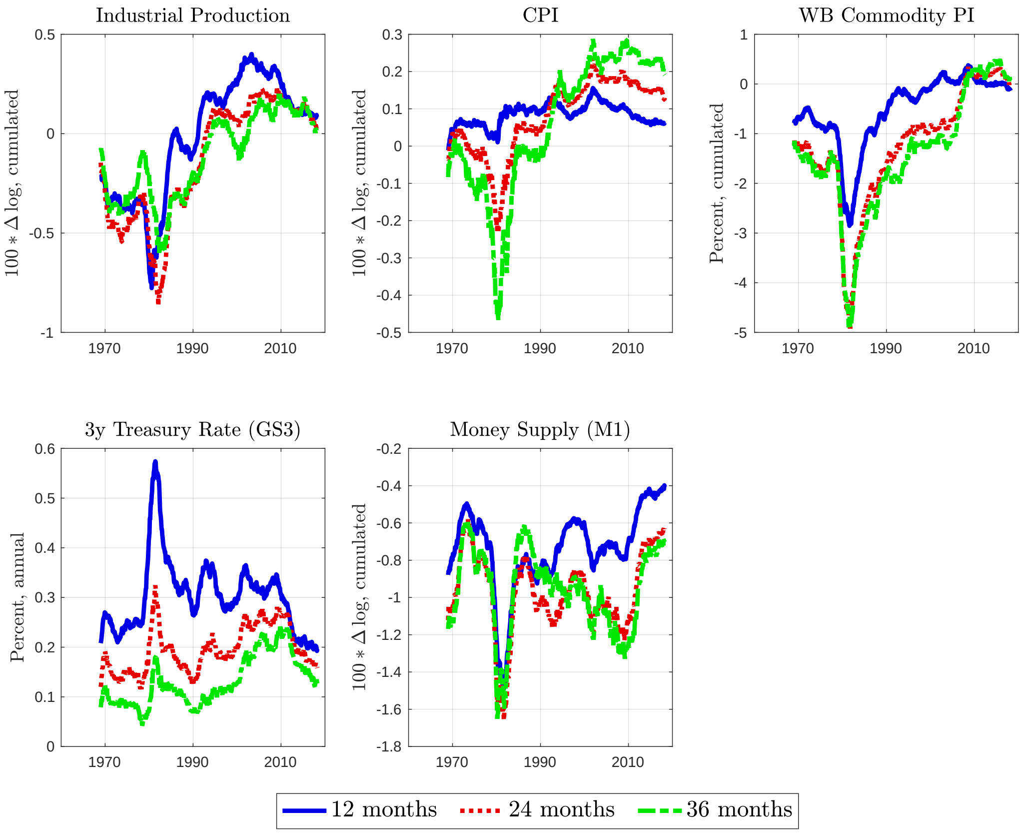
Source: FRED
Note: Monthly US data with a sample span from 1960M01-2018M03. The variables are: IP, CPI (CPALTT01USM661S), World Bank Commodity Price Index (2010=100), the GS3 Rate and M1 Money Supply (M1SL). The variables are in log-difference terms, except for the 3-Year Treasury Constant Maturity Rate (GS3).

FIGURE 3.6.30: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK FROM 1968M01 TO 2018M03



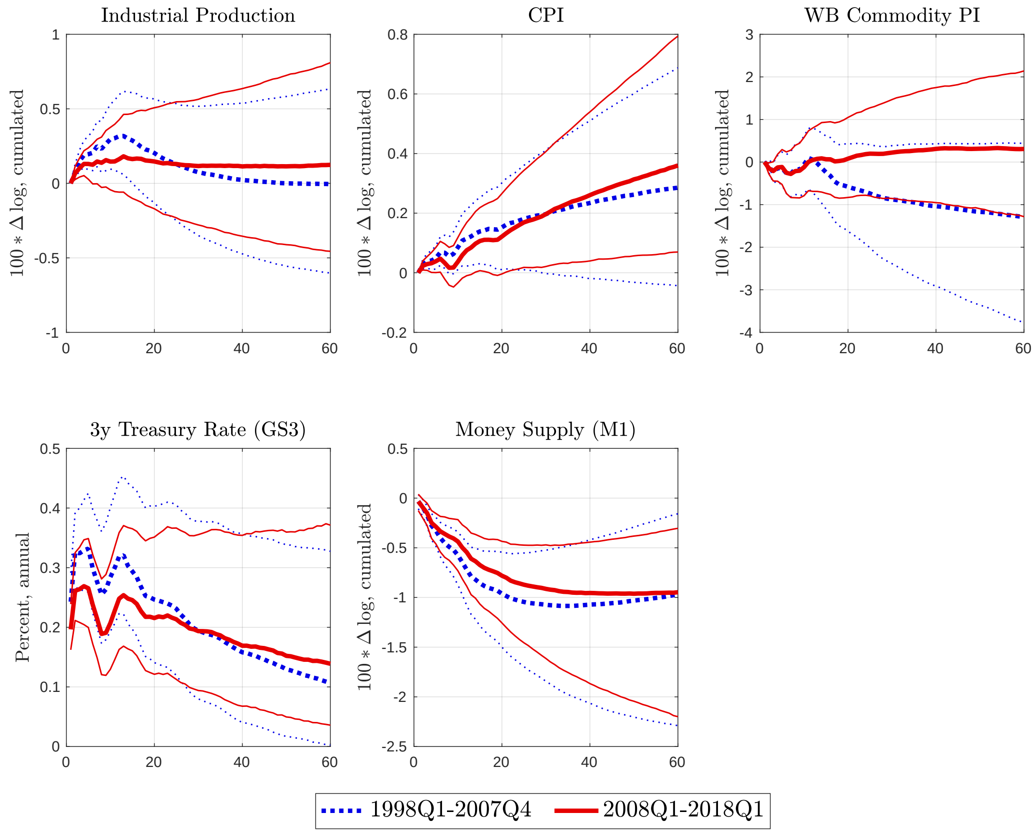
Note: Panels A to E depict the median IRFs for a Monetary Policy Shock of 1 standard deviation. All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on monthly data, the sample span is from 1960M01-2018M03 with 8 years of prior tuning and lag-order 12.

FIGURE 3.6.31: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK AT SELECTED HORIZONS



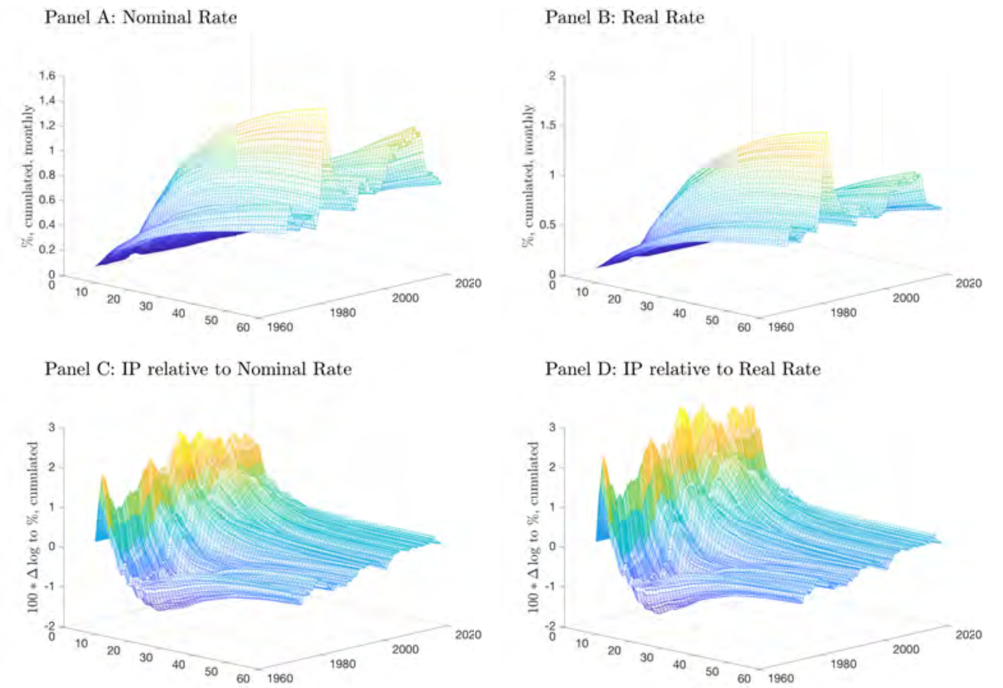
Note: Median IRFs at Selected Horizons (12, 24 and 36 months) for a Monetary Policy Shock of 1 standard deviation. All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on monthly data, the sample span is from 1960M01-2018M03 with 8 years of prior tuning and lag-order 12.

FIGURE 3.6.32: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK PRE- AND POST-CRISIS



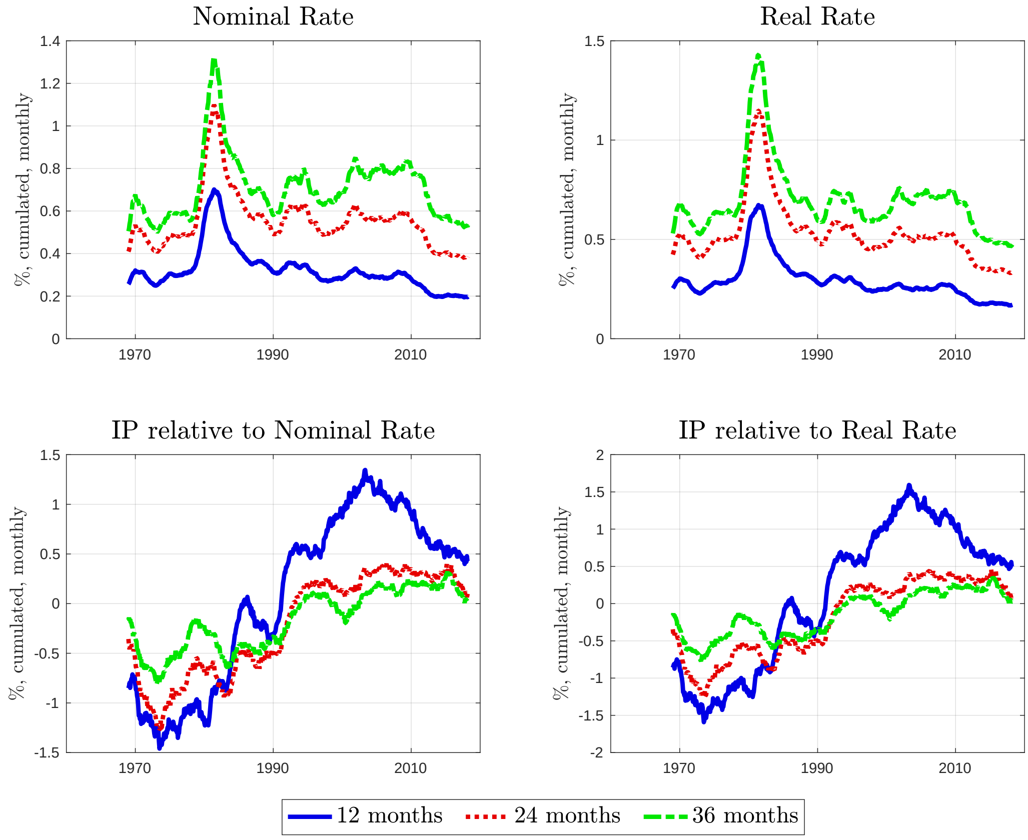
Note: The thick lines depict the 10-year average of the Median IRFs before and after the Financial Crisis of 2008 for a Monetary Policy Shock of 1 standard deviation. The thin lines correspond to the 68% confidence bands. All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on monthly data, the sample span is from 1960M01-2018M03 with 8 years of prior tuning and lag-order 12.

FIGURE 3.6.33: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK FROM 1968M01 TO 2018M03



Note: Panels A to E depict the median IRFs for a Monetary Policy Shock of 1 standard deviation. All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on monthly data, the sample span is from 1960M01-2018M03 with 8 years of prior tuning and lag-order 12.

FIGURE 3.6.34: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK AT SELECTED HORIZONS

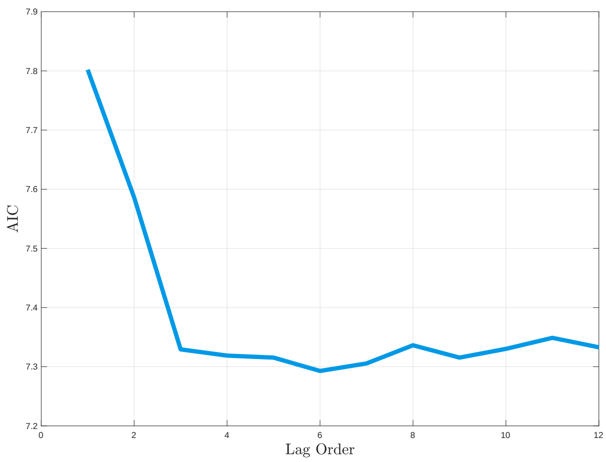


Note: Median IRFs at Selected Horizons (12, 24 and 36 months) for a Monetary Policy Shock of 1 standard deviation. The results are based on monthly data, the sample span is from 1960M01-2018M03 with 8 years of prior tuning and a lag-order of 12.

3.6.7 Time-Varying Coefficients SVAR: Monthly Data using PCEPI and Lag-order 6

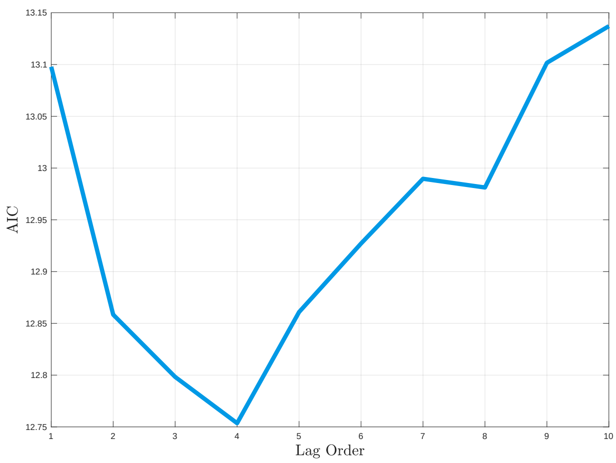
Determining the lag-order for the above described VAR model using monthly data is not as straightforward as it is in the case of quarterly data. The comparison of the AICs for monthly and quarterly data in Figures 3.6.35 and 3.6.36 illustrates this.

FIGURE 3.6.35: AKAIKE INFORMATION CRITERION ON LAG-ORDER CHOICE FOR MONTHLY DATA



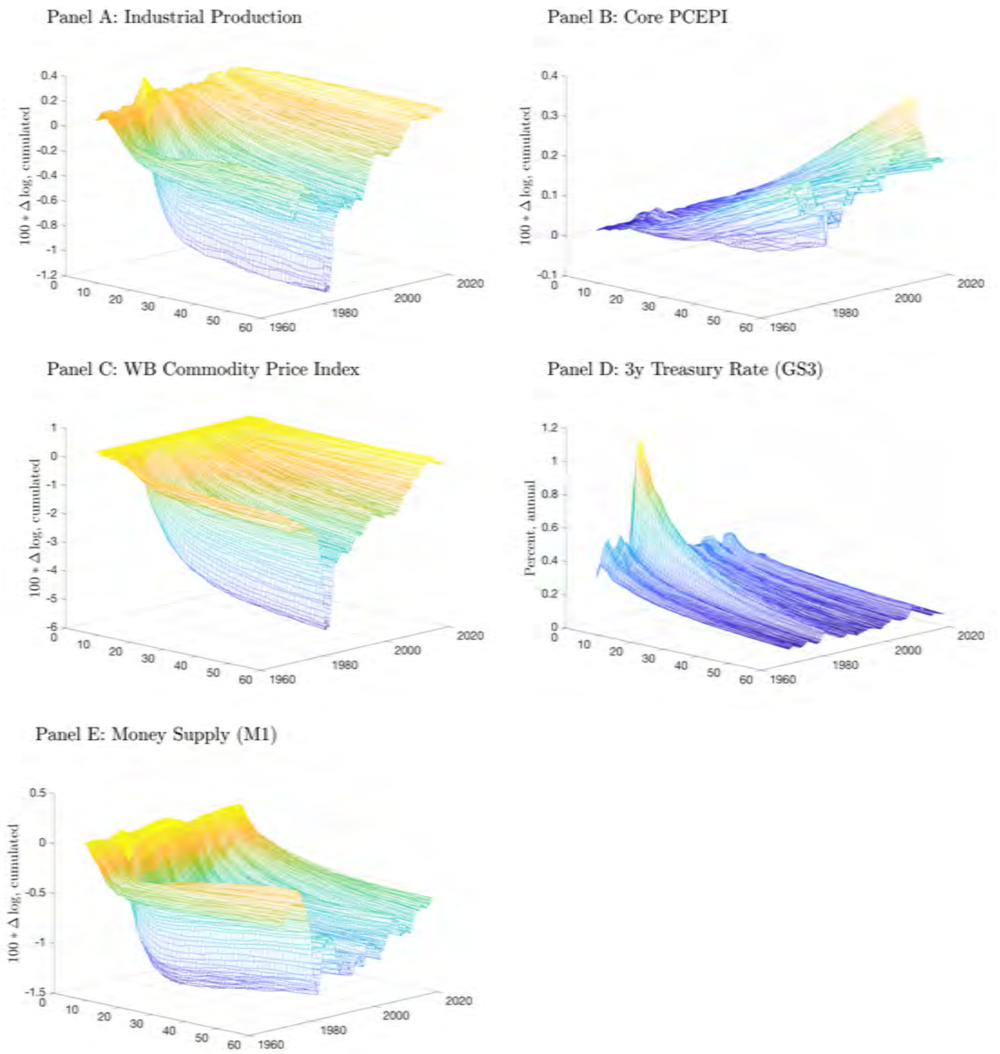
Note: Based on monthly US data with a sample span from 1960M01-2018M03. The variables are: IP, Core PCEPI (excluding energy and food prices), World Bank Commodity Price Index (2010=100), the GS3 Rate and M1 Money Supply (M1SL). The variables are in log-difference terms, except for the 3-Year Treasury Constant Maturity Rate (GS3).

FIGURE 3.6.36: AKAIKE INFORMATION CRITERION ON LAG-ORDER CHOICE FOR QUARTERLY DATA



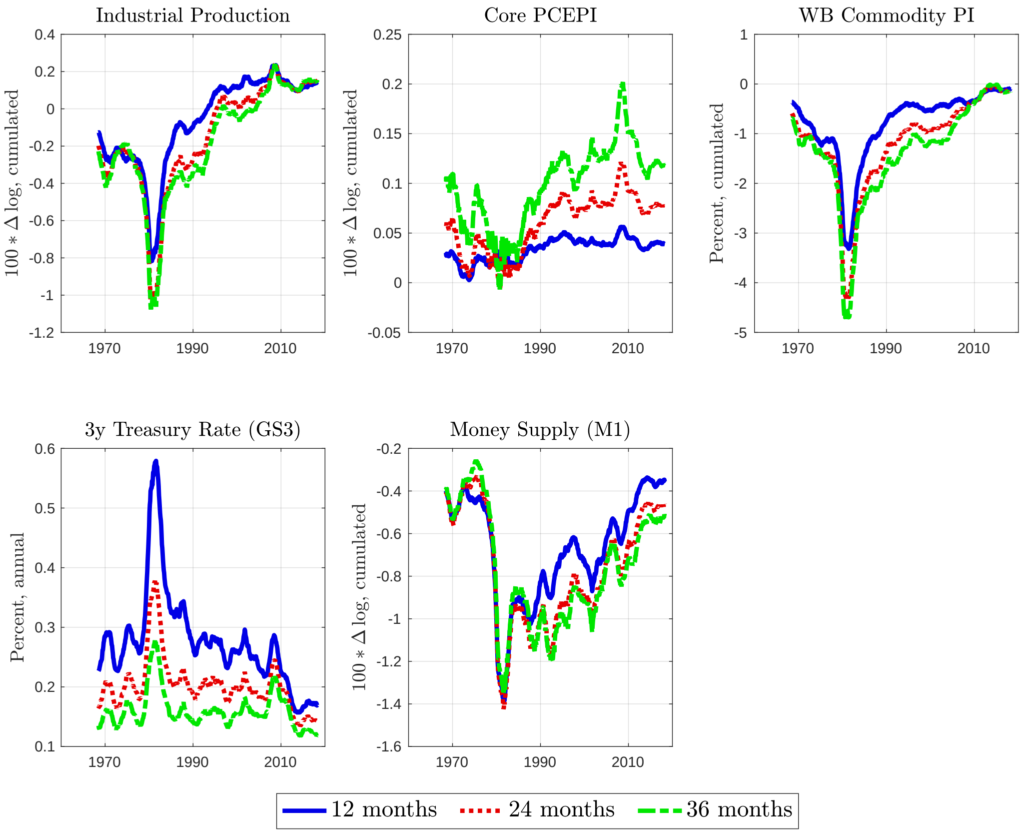
Note: Based on quarterly US data with a sample span from 1960M01-2018M03. The variables are: GDP, GDP Deflator, World Bank Commodity Price Index (2010=100), the GS3 Rate and M1 Money Supply (M1SL). The variables are in log-difference terms, except for the 3-Year Treasury Constant Maturity Rate (GS3).

FIGURE 3.6.37: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK FROM 1968M01 TO 2018M03



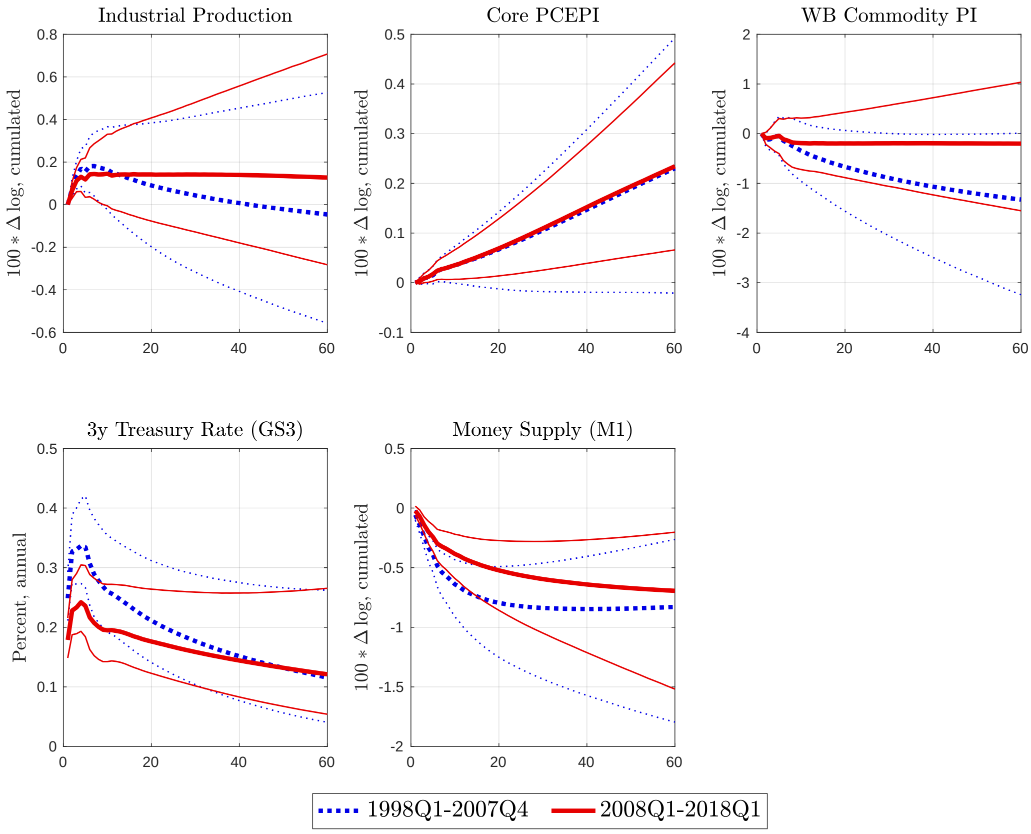
Note: Panels A to E depict the median IRFs for a Monetary Policy Shock of 1 standard deviation. All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on monthly data, the sample span is from 1960M01-2018M03 with 8 years of prior tuning and lag-order 6.

FIGURE 3.6.38: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK AT SELECTED HORIZONS



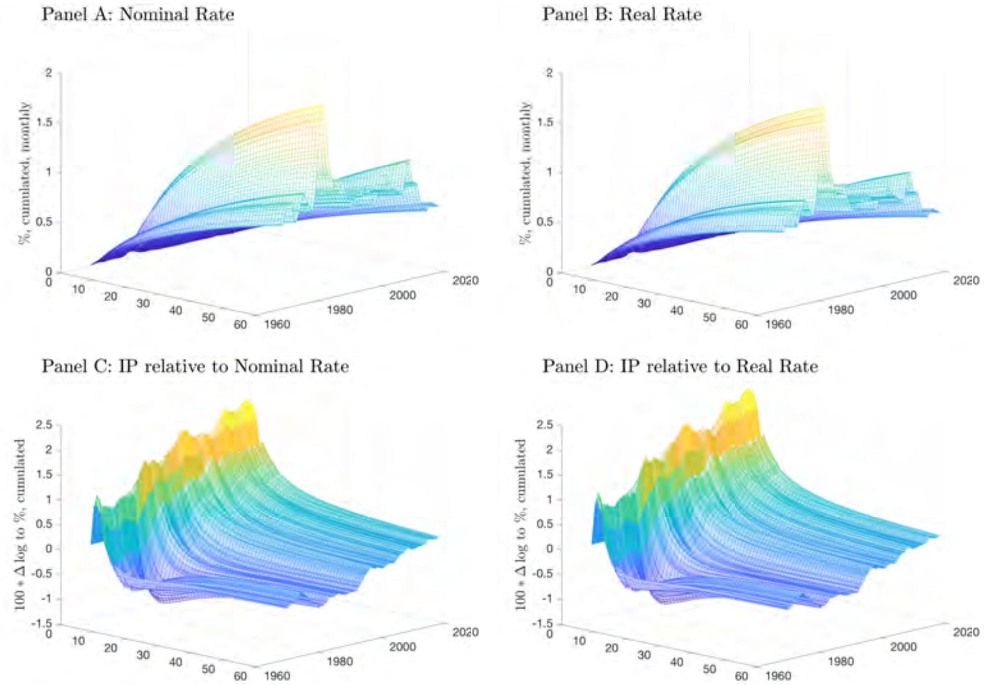
Note: Median IRFs at Selected Horizons (12, 24 and 36 months) for a Monetary Policy Shock of 1 standard deviation. All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on monthly data, the sample span is from 1960M01-2018M03 with 8 years of prior tuning and lag-order 6.

FIGURE 3.6.39: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK PRE- AND POST-CRISIS



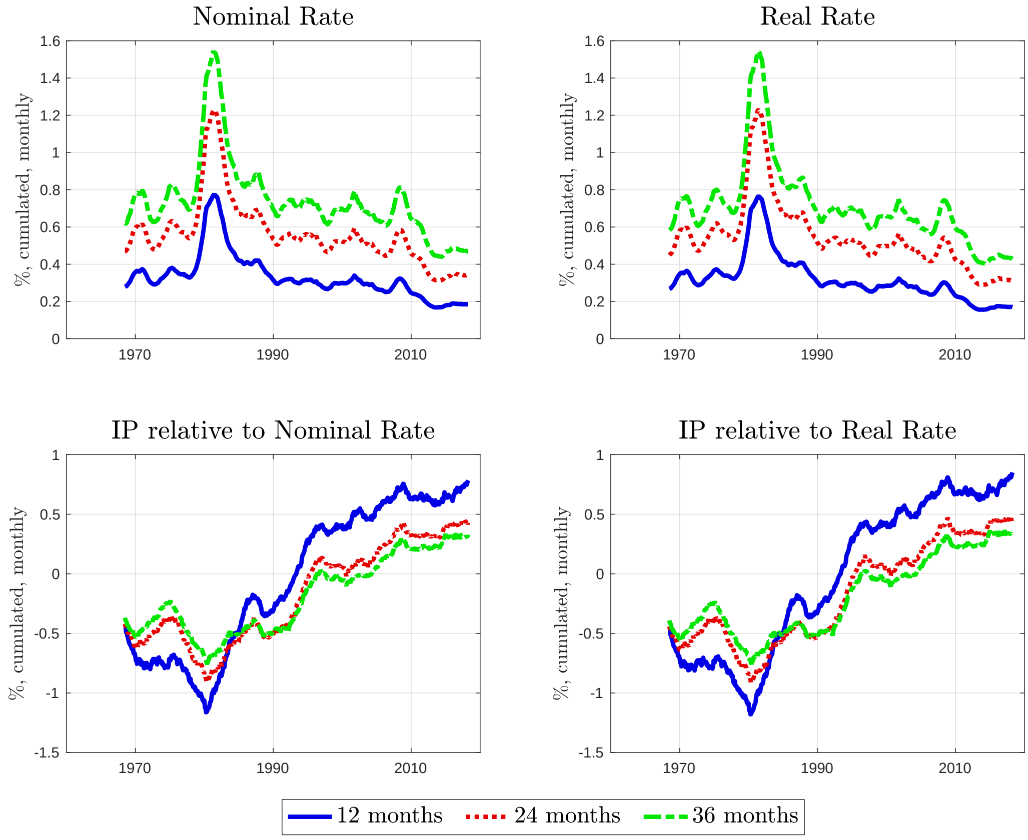
Note: The thick lines depict the 10-year average of the Median IRFs before and after the Financial Crisis of 2008 for a Monetary Policy Shock of 1 standard deviation. The thin lines correspond to the 68% confidence bands. All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on monthly data, the sample span is from 1960M01-2018M03 with 8 years of prior tuning and lag-order 6.

FIGURE 3.6.40: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK FROM 1968M01 TO 2018M03



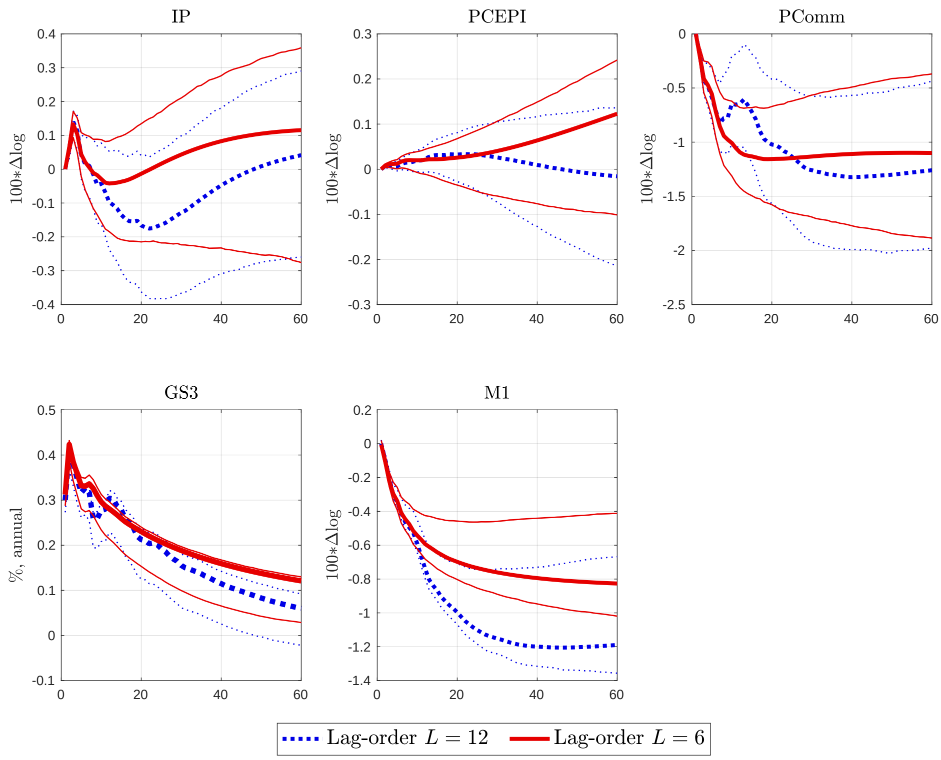
Note: Panels A to E depict the median IRFs for a Monetary Policy Shock of 1 standard deviation. All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on monthly data, the sample span is from 1960M01-2018M03 with 8 years of prior tuning and lag-order 6.

FIGURE 3.6.41: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK AT SELECTED HORIZONS



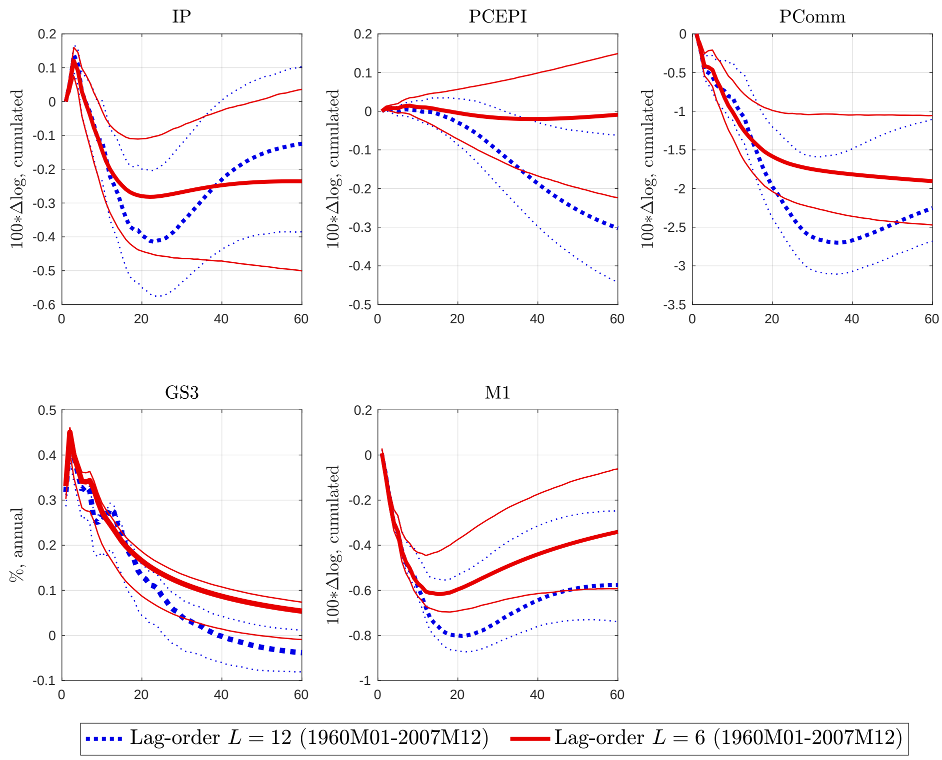
Note: Median IRFs at Selected Horizons (12, 24 and 36 months) for a Monetary Policy Shock of 1 standard deviation. The results are based on monthly data, the sample span is from 1960M01-2018M03 with 8 years of prior tuning and a lag-order of 6.

FIGURE 3.6.42: ESTIMATED RESPONSES TO A MONETARY POLICY SHOCK: VAR WITH CONSTANT COEFFICIENTS AND LAG ORDER OF 6 AND 12



Note: Based on monthly US data with a sample span from 1960M01-2018M03. The variables are: IP, Core PCEPI (excluding energy and food prices), World Bank Commodity Price Index (2010=100), the GS3 Rate and M1 Money Supply (M1SL). The variables are in log-difference terms, except for the 3-Year Treasury Constant Maturity Rate (GS3). The blue-dotted line corresponds to the case with lag-order 12, the red-straight line corresponds to the case with lag-order 6.

FIGURE 3.6.43: ESTIMATED RESPONSES TO A MONETARY POLICY SHOCK: VAR WITH CONSTANT COEFFICIENTS AND LAG ORDER OF 6 AND 12

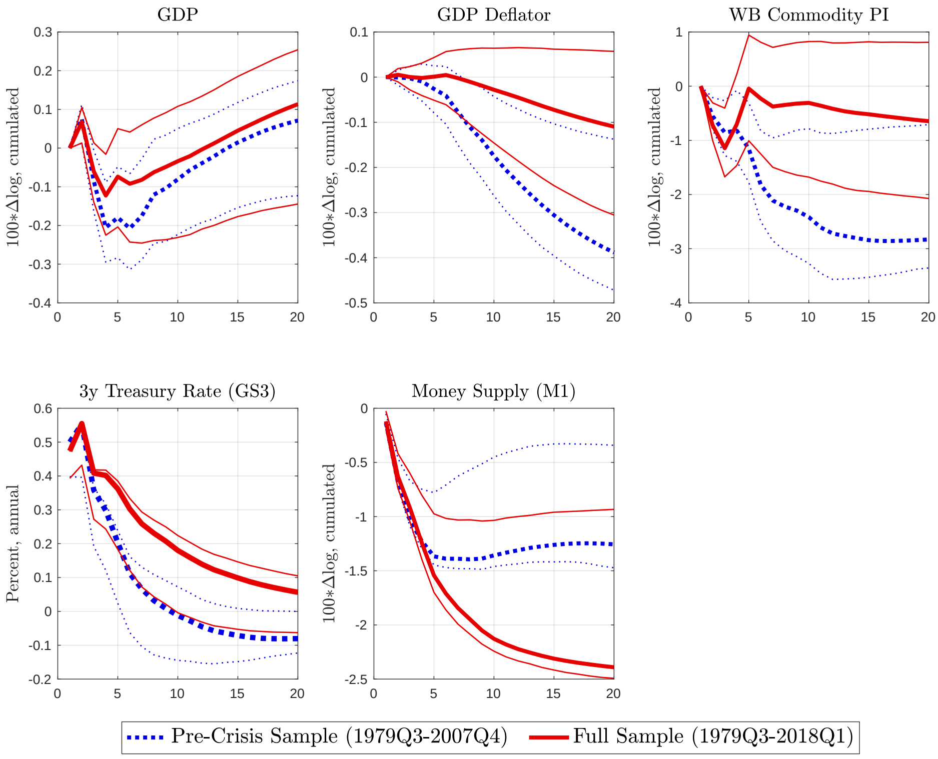


Note: Based on monthly US data with a sample span from 1960M01-2007M12. The variables are: IP, Core PCEPI (excluding energy and food prices), World Bank Commodity Price Index (2010=100), the GS3 Rate and M1 Money Supply (M1SL). The variables are in log-difference terms, except for the 3-Year Treasury Constant Maturity Rate (GS3). The blue-dotted line corresponds to the case with lag-order 12, the red-straight line corresponds to the case with lag-order 6.

3.6.8 Sample Period Sensitivity

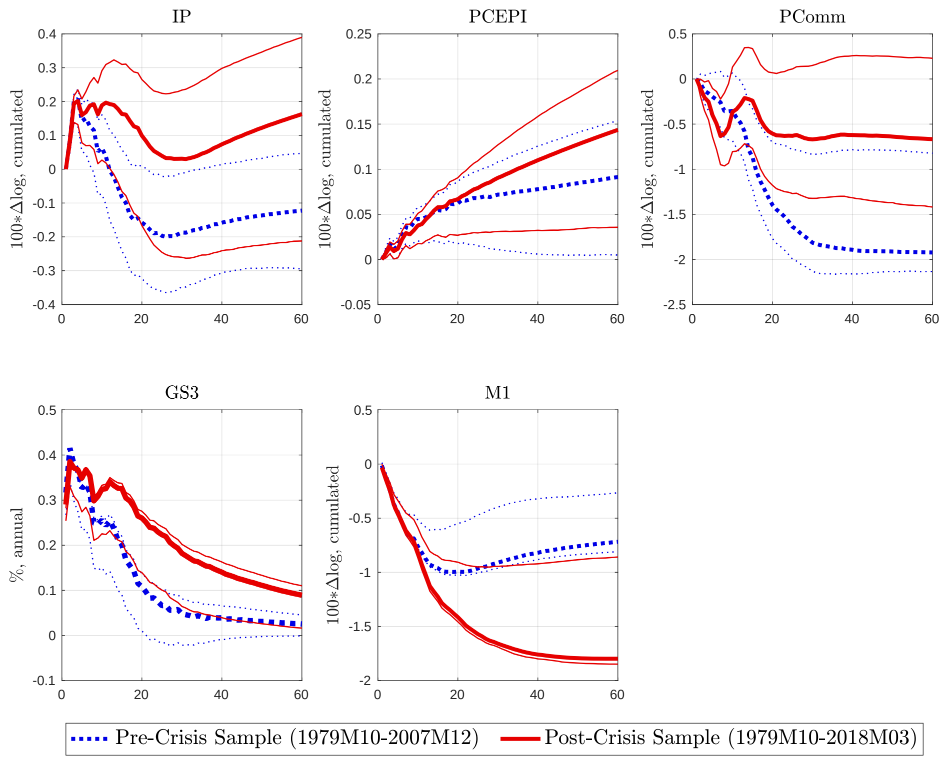
3.6.8.1 Constant Coefficient VAR and TVC-VAR Analysis based on post-Volcker sample (1979Q3-2018Q1)

FIGURE 3.6.44: ESTIMATED RESPONSES TO A MONETARY POLICY SHOCK: VAR WITH CONSTANT COEFFICIENTS AND STARTING DATE IN 1979Q3



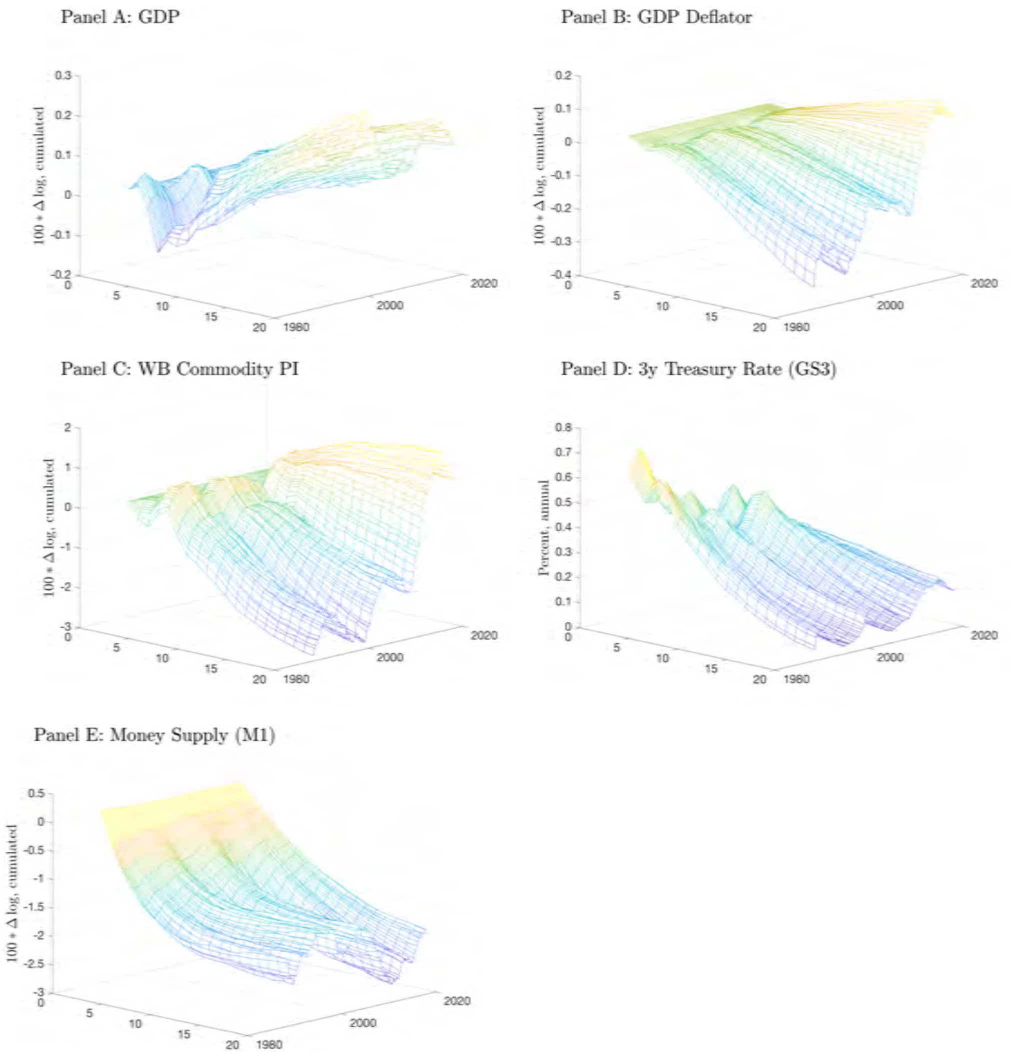
Note: Based on quarterly US data with a sample span from 1979Q3-2018Q1, lag-order 4. The variables are: GDP, GDP Deflator, World Bank Commodity Price Index (2010=100), the GS3 Rate and M1 Money Supply (M1SL). The variables are in log-difference terms, except for the 3-Year Treasury Constant Maturity Rate (GS3).

FIGURE 3.6.45: ESTIMATED RESPONSES TO A MONETARY POLICY SHOCK: VAR WITH CONSTANT COEFFICIENTS AND STARTING DATE IN 1979M10



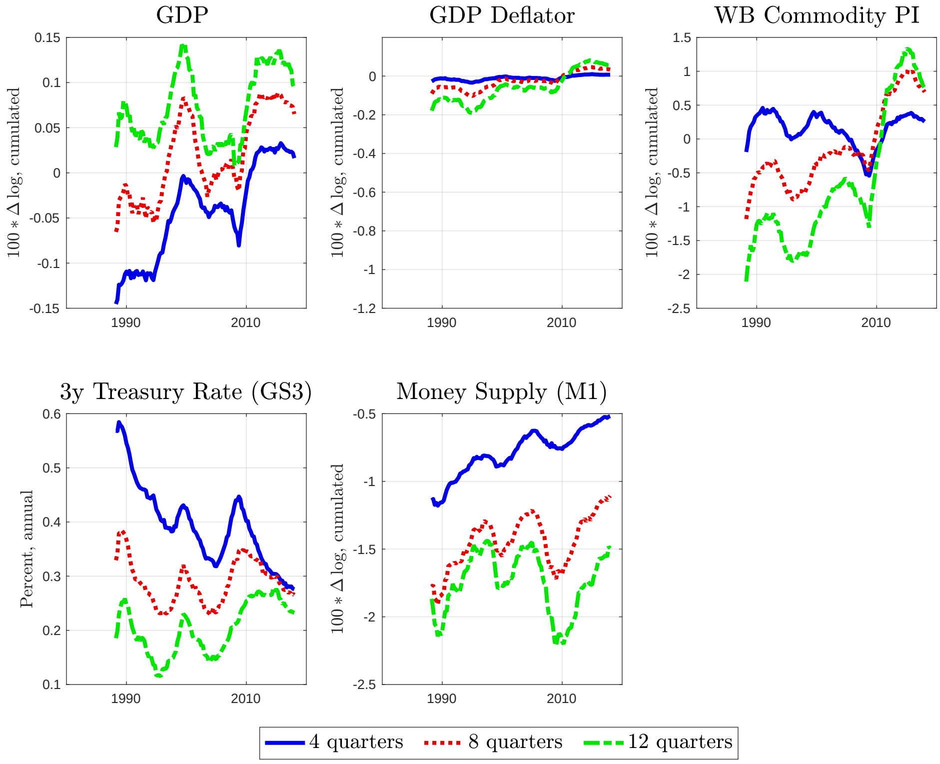
Note: Based on monthly US data with a sample span from 1979M10-2018M03, lag-order 12. The variables are: IP, Core PCEPI, World Bank Commodity Price Index (2010=100), the GS3 Rate and M1 Money Supply (M1SL). The variables are in log-difference terms, except for the 3-Year Treasury Constant Maturity Rate (GS3).

FIGURE 3.6.46: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK FROM 1987Q3 TO 2018Q1



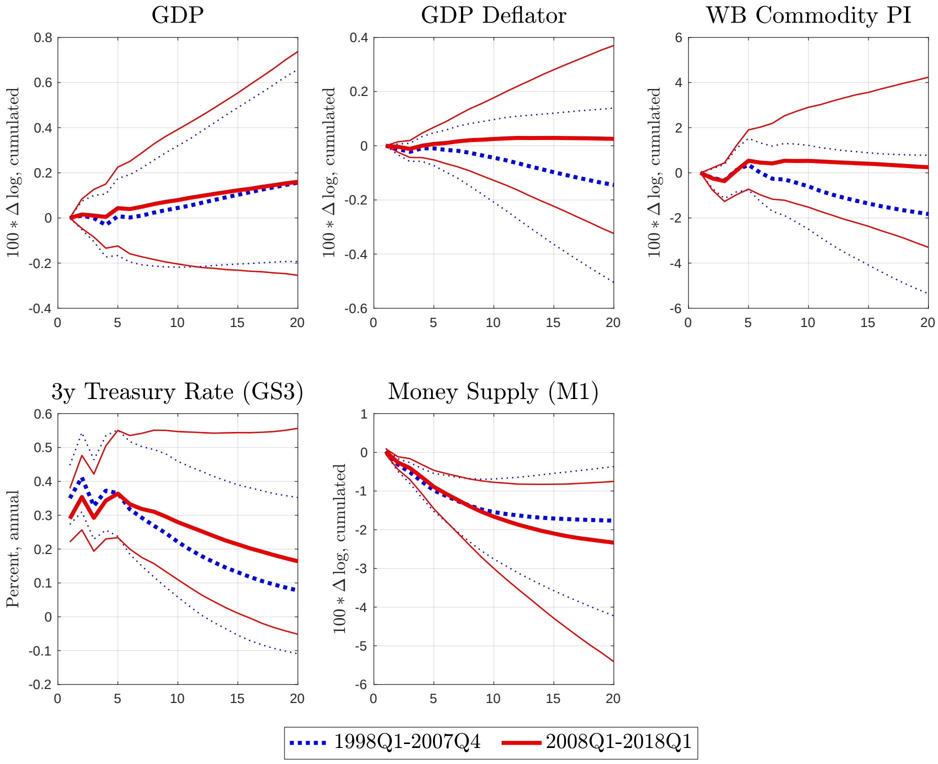
Note: Panels A to E depict the median IRFs for a Monetary Policy Shock of 1 standard deviation. All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on quarterly data, the sample span is from 1979Q3-2018Q1 with 8 years of prior tuning and a lag-order of 4.

FIGURE 3.6.47: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK AT SELECTED HORIZONS



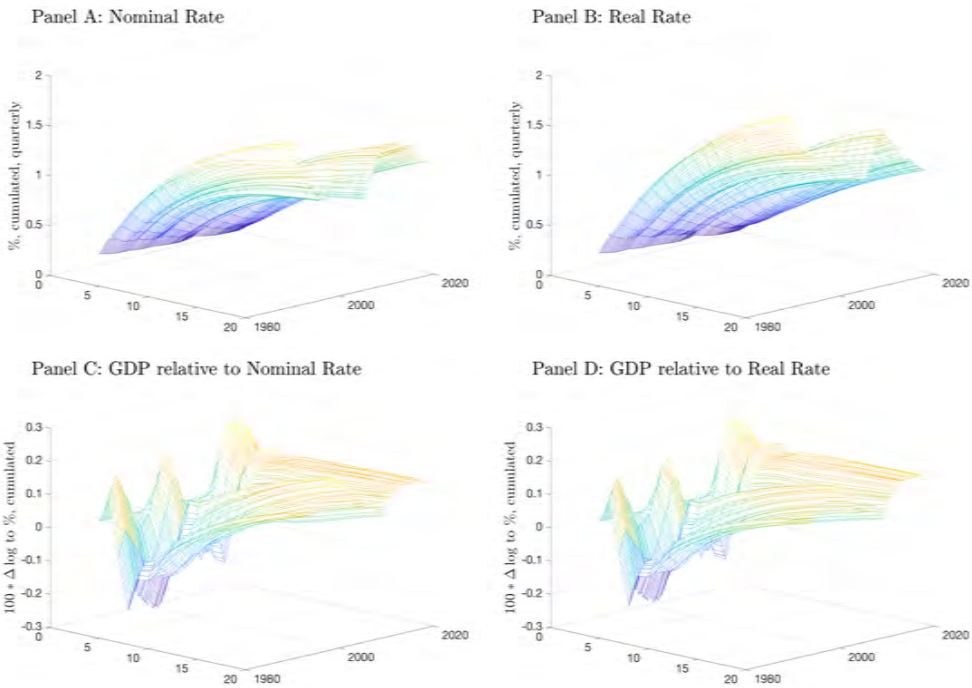
Note: Median IRFs at Selected Horizons (4, 8 and 12 quarters) for a Monetary Policy Shock of 1 standard deviation. All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on quarterly data, the sample span is from 1979Q3-2018Q1 with 8 years of prior tuning and a lag-order of 4.

FIGURE 3.6.48: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK PRE- AND POST-CRISIS



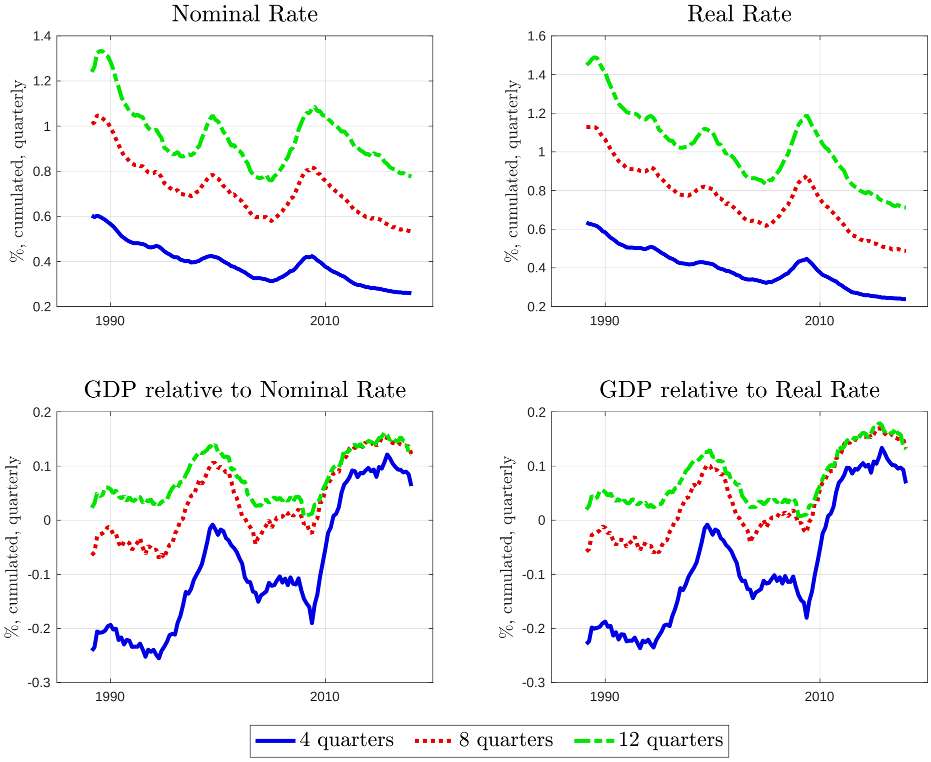
Note: The thick lines depict the 10-year average of the Median IRFs before and after the Financial Crisis of 2008 for a Monetary Policy Shock of 1 standard deviation. The thin lines correspond to the 68% confidence bands. All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on quarterly data, the sample span is from 1979Q3-2018Q1 with 8 years of prior tuning and a lag-order of 4.

FIGURE 3.6.49: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK FROM 1968Q1 TO 2018Q1



Note: Panels A to E depict the median IRFs for a Monetary Policy Shock of 1 standard deviation. All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on quarterly data, the sample span is from 1979Q3-2018Q1 with 8 years of prior tuning and a lag-order of 4.

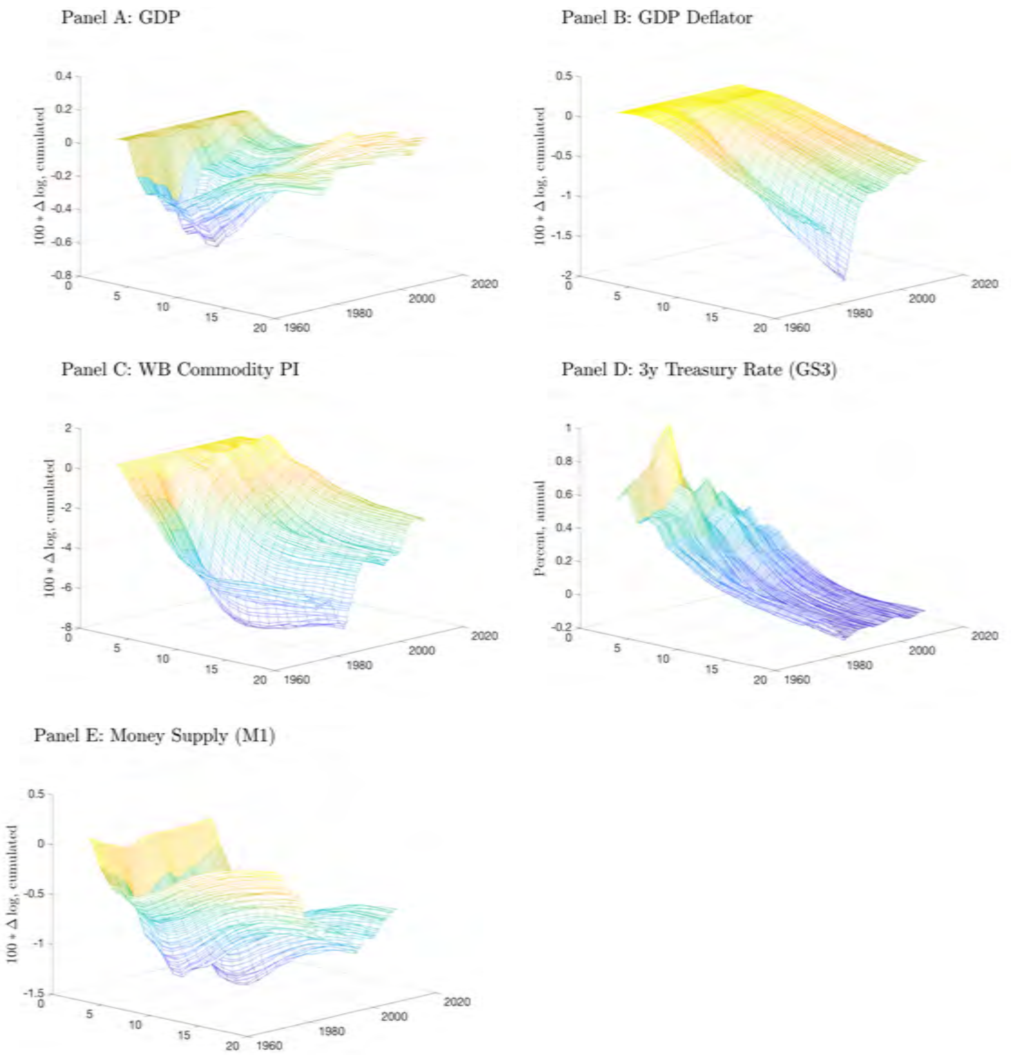
FIGURE 3.6.50: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK AT SELECTED HORIZONS



Note: Median IRFs at Selected Horizons (4, 8 and 12 quarters) for a Monetary Policy Shock of 1 standard deviation. All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on quarterly data, the sample span is from 1979Q3-2018Q1 with 8 years of prior tuning and a lag-order of 4.

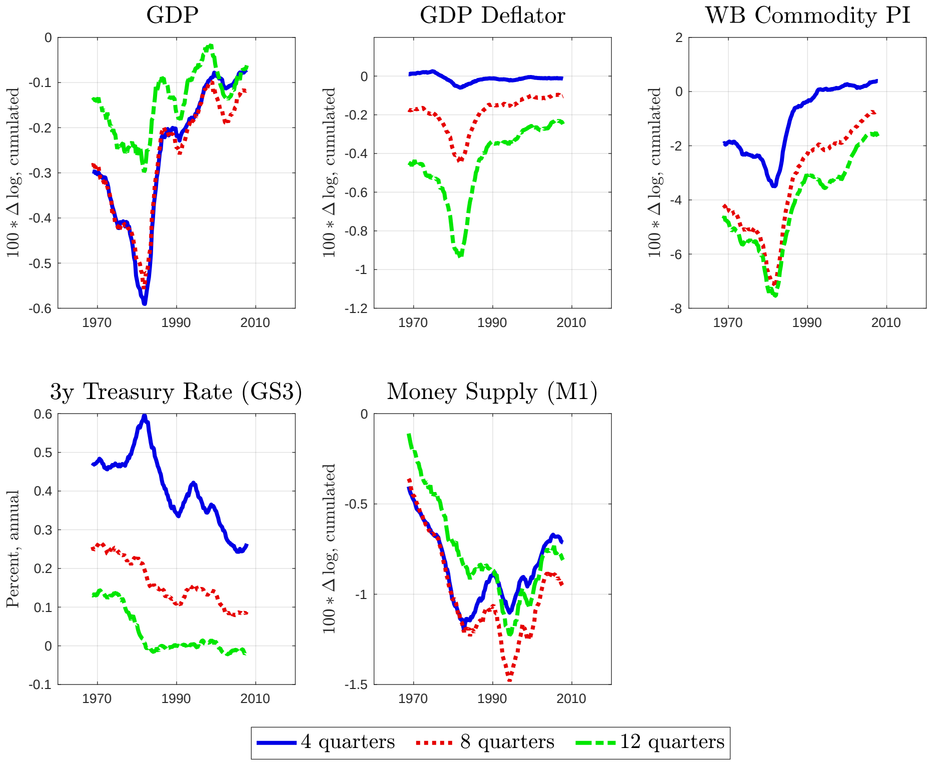
3.6.8.2 TVC-VAR Analysis based on pre-crisis sample (1960Q1-2007Q4)

FIGURE 3.6.51: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK FROM 1960Q1 TO 2007Q4



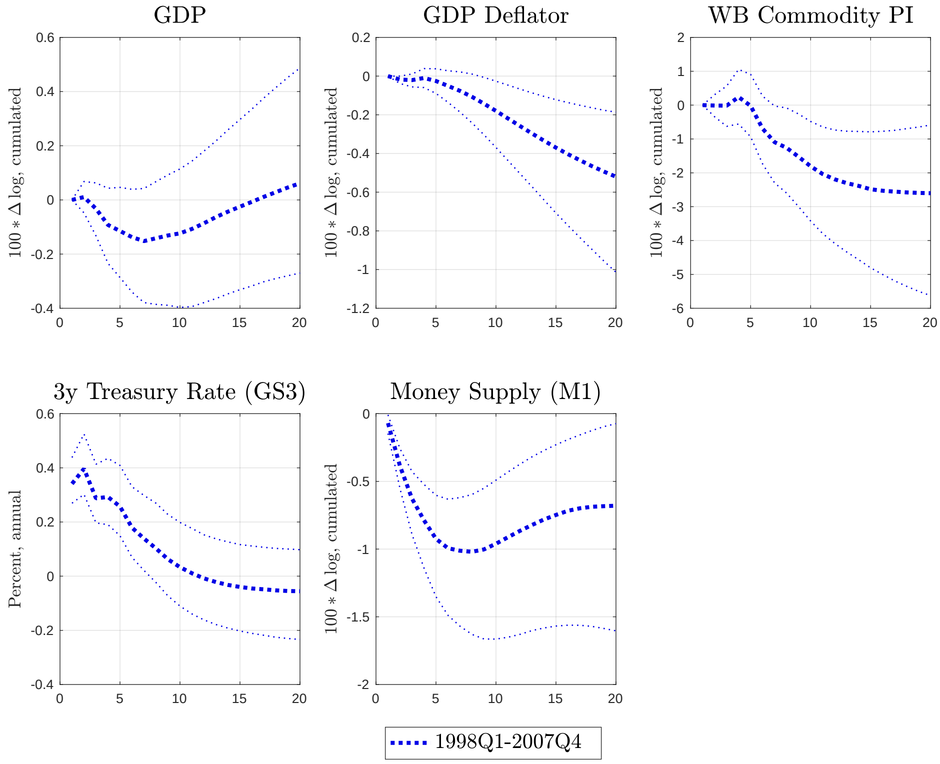
Note: Panels A to E depict the median IRFs for a Monetary Policy Shock of 1 standard deviation. All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on quarterly data, the sample span is from 1960Q1-2007Q4 with 8 years of prior tuning and a lag-order of 4.

FIGURE 3.6.52: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK AT SELECTED HORIZONS



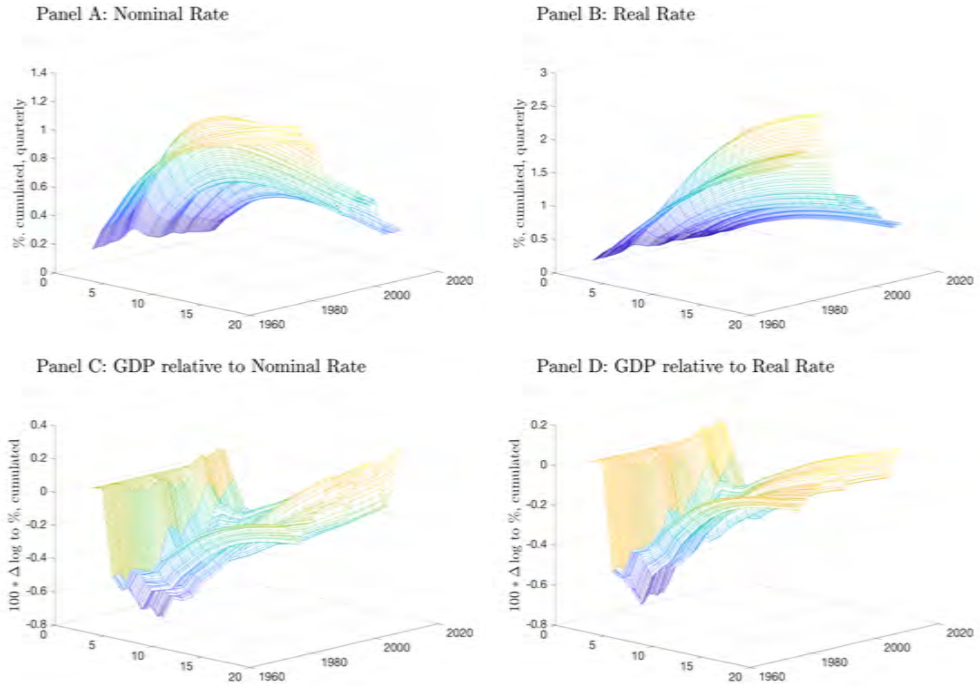
Note: Median IRFs at Selected Horizons (4, 8 and 12 quarters) for a Monetary Policy Shock of 1 standard deviation. All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on quarterly data, the sample span is from 1960Q1-2007Q4 with 8 years of prior tuning and a lag-order of 4.

FIGURE 3.6.53: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK PRE- AND POST-CRISIS



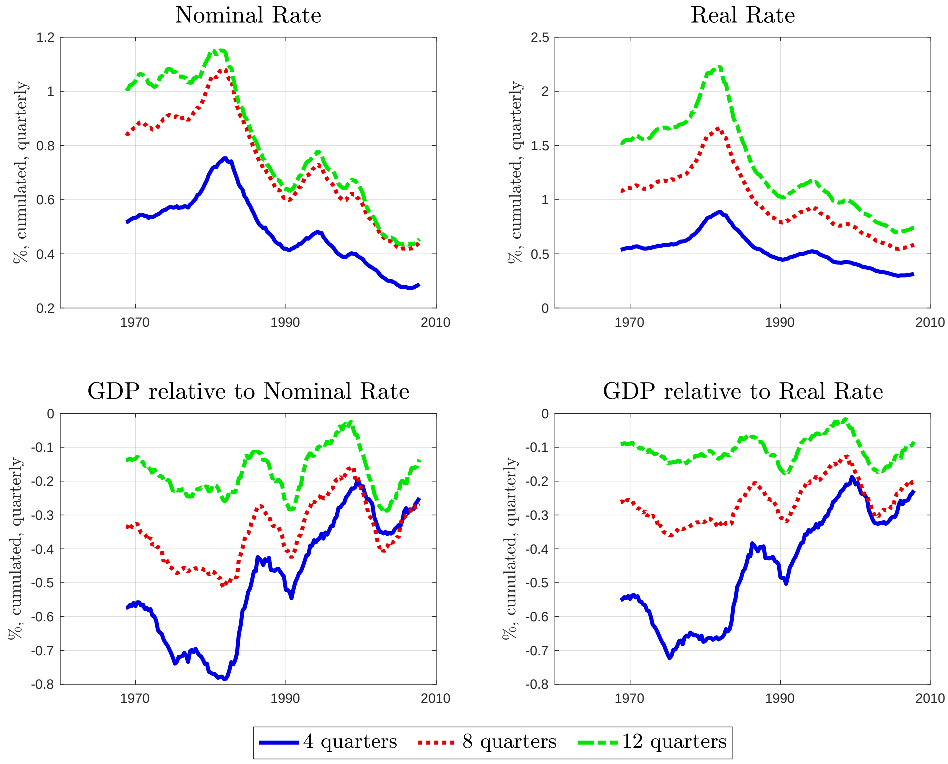
Note: The thick lines depict the 10-year average of the Median IRFs before and after the Financial Crisis of 2008 for a Monetary Policy Shock of 1 standard deviation. The thin lines correspond to the 68% confidence bands. All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on quarterly data, the sample span is from 1960Q1-2007Q4 with 8 years of prior tuning and a lag-order of 4.

FIGURE 3.6.54: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK FROM 1968Q1 TO 2018Q1



Note: Panels A to E depict the median IRFs for a Monetary Policy Shock of 1 standard deviation. All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on quarterly data, the sample span is from 1960Q1-2007Q4 with 8 years of prior tuning and a lag-order of 4.

FIGURE 3.6.55: MEDIAN IMPULSE RESPONSES FOR A MONETARY POLICY SHOCK AT SELECTED HORIZONS



Note: Median IRFs at Selected Horizons (4, 8 and 12 quarters) for a Monetary Policy Shock of 1 standard deviation. All variables are in log-differences, except for the GS3 series which is in annual percentage terms. The results are based on quarterly data, the sample span is from 1960Q1-2007Q4 with 8 years of prior tuning and a lag-order of 4.

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