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Monetary and Macroprudential Policy Rules in a Model with House Price Booms

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Monetary and Macroprudential Policy Rules in a Model with House Price Booms*

Prakash Kannan, Pau Rabanal, and Alasdair M. Scott

Abstract

Using a dynamic stochastic general equilibrium (DSGE) model with housing, this paper shows that strong monetary reactions to accelerator mechanisms that push up credit growth and house prices can help macroeconomic stability. In addition, using a macroprudential instrument specifically designed to dampen credit market cycles would also provide stabilization benefits when an economy faces financial sector or housing demand shocks. However, the optimal macroprudential rule under productivity shocks is to not intervene. Therefore, it is crucial to understand the source of house price booms for the design of monetary and macroprudential policy.

KEYWORDS: monetary policy, regulatory policy, housing prices

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1. Introduction

The Great Recession has caused policymakers to rethink the appropriate policy toolkit to deal with vulnerabilities stemming from financial markets. Before the crisis, consensus was that responding directly to fluctuations in asset prices or other financial variables was potentially harmful due to the inherent difficulty in detecting asset price bubbles in real time (Bernanke and Gertler, 2001). However, a growing body of empirical work has found that large movements in a number of observable variables—credit, residential investment shares, and current account deficits—are reliable indicators of future stock and house price busts, which in turn are typically associated with substantial falls in output.[1] These same variables do reasonably well in explaining the cross-country variation in house price declines during the Great Recession.[2] Such evidence suggests that if central bankers wish to mitigate damaging asset price boom-bust cycles, they should consider reacting to such variables rather than focusing mainly on traditional responses to inflation and the output gap.

Nonetheless, aggressive use of central bank policy rates to address the build-up of financial imbalances, or to deflate an incipient bubble in some asset categories, is viewed by some as too blunt a response, as other sectors of the economy will be adversely affected as a consequence (Kohn, 2010). Hence, macroprudential policies are being proposed as a complement to monetary policy and to address, or at least mitigate, the perverse effects of financial sector imbalances and asset price bubbles.

Several important questions need to be addressed to determine the appropriate policy response:

- What are the potential gains from reacting to signs of emerging financial vulnerability?
- Is monetary policy the appropriate tool for reacting to such indicators, or should other policies be used?
- What are the trade-offs between focusing policy on stabilizing the output gap and CPI inflation and attempting to reduce the risk of asset price crashes?

This paper addresses these questions using a model economy with housing spillover effects, in the spirit of Iacoviello (2005) and Iacoviello and Neri (2010). The model has some of the key features relevant for examining the potential

[1] See Kannan et al. (2011). See also Borio and Lowe (2004) and IMF (2009).
[2] See IMF (2009).

role of monetary policy in mitigating the effects of house price booms. We focus on the effects of house price fluctuations because housing wealth is generally more important for households than financial assets as a store of wealth, and because the housing market has been at the center of the most recent financial crisis.

The results from the simulations suggest that extending monetary policy to include credit aggregates can help counter accelerator mechanisms that push up credit growth and house prices. We find that using a macroprudential instrument designed specifically to dampen credit market cycles is also useful, but that policy mistakes are possible. In particular, when financial or housing demand shocks drive the credit and housing boom, using a macroprudential instrument that reacts to credit growth will improve welfare. On the other hand, restricting credit using macroprudential policies when the source of the housing boom is productivity would decrease welfare. Therefore, expectations should be realistic about what can be achieved by using macroprudential policies: invariant and rigid policy responses raise the risk of policy errors that could lower, not raise, macroeconomic stability.

How do these conclusions compare with those from other studies? There is a vast literature on monetary policy and asset prices. A long-standing debate asks whether central banks should react directly to asset prices; two well-known examples are Bernanke and Gertler (2001), who conclude that there is no role for asset prices in monetary policy rules, and Cecchetti et al. (2000), who argue that central banks should react to asset prices. More recent papers have suggested that there are gains from including additional indicators in monetary policy rules. Christiano et al. (2007, 2008), for example, suggest that the central bank can improve welfare by targeting credit growth in a model with asset price booms. Cúrdia and Woodford (2010) include credit spreads in the monetary policy reaction function, and Gray et al. (2011) find a role for a financial stability indicator in the monetary rule.

This paper belongs to the recent growing literature on macroprudential policies in dynamic stochastic general equilibrium (DSGE) models with financial accelerator effects. In general, this literature stresses that in order to implement optimal monetary and macroprudential policies, it is critical to identify the source of the shock driving the housing or asset price boom. Gruss and Sgherri (2009) study the welfare implications of procyclical loan-to-value ratios in a two-country international real business cycle model with borrowing constraints. However, because their model does not have a nominal side, the reaction of monetary policy cannot be addressed. Angelini, Neri and Panetta (2011) have also studied the role of macroprudential policies in a New Keynesian model with a banking sector and financial accelerator effects on both households and firms. Similar to our paper, they find that macroprudential policies are most helpful to counter financial shocks the lead to a credit and asset price boom. Lambertini et al. (2011) study the role of extending monetary policy and introducing macroprudential tools in a model with expectations-driven business cycles. They find that having monetary policy respond to credit aggregates or introducing a loan-to-value rule for borrowers helps in reducing the volatility of the output gap and credit aggregates when the economy is hit by news shocks.

The paper is structured as follows. Section 2 contains a description of the model and Section 3 a description of the policy regimes evaluated in the simulations. Section 4 summarizes the model's calibration. The results of simulation experiments are presented in Section 5. In Section 6, sensitivity analysis is performed. The final section concludes. An appendix details the linearized conditions for the model.

2. A Model for Analyzing House Price Booms

The model used in this paper has a number of modifications to the standard New Keynesian model (Galí, 2009) with regard to the characterization of households and financial markets, which create a special role for asset prices. Because housing wealth is generally more important for households than equities, and because house purchases typically require debt financing, we concentrate on the role of housing. In addition, the housing market has been at the center of the most recent financial crisis.[3]

Our model is closely related to those in Iacoviello (2005), Iacoviello and Neri (2010), and Monacelli (2009). First, households make choices about how much to invest in housing, as well as how much to consume in nondurable goods. Housing is an asset that provides utility for shelter services and is the main vehicle for accumulating wealth in this economy. Second, we make a distinction between borrowers and lenders, thereby creating conditions for leverage. We assume that savers cannot lend to borrowers directly. Instead, we introduce financial intermediaries that take deposits from savers and lend them to borrowers, charging a spread that depends on the net worth of borrowers. Third, the lending rate is modeled as a spread over the policy rate that depends on loan-to-value ratios, the markup charged over funding (policy) rates, and, in some cases discussed below, a macroprudential instrument. Hence, lending rates can change for a number of reasons: for example, an

[3]For a model that considers the monetary policy implications of stock price fluctuations, see Christiano and others (2007).

increase in house prices will raise market valuations of borrowers' collateral, lowering the average loan-to-value ratio, and will therefore lead to a fall in lending rates even if monetary policy has not eased. Credit market conditions can also change— because of, say, changes in perceptions of risk or competitiveness in lending— which could lead banks to adjust their markups and therefore alter the lending spread. Both of these mechanisms help accelerate a rise in residential investment, nondurable consumption, and consumer prices.[4] In some simulations, policymakers can affect spreads directly, using a macroprudential tool, in addition to influencing lending rates via policy rates.

In other aspects, the model has conventional New Keynesian foundations. The theoretical framework consists of a general equilibrium two-sector model (durables and nondurables) in which each sector operates under monopolistic competition and nominal rigidities. Prices in both sectors are sticky in the short run, as in Calvo (1983). Consumption and residential investment adjust slowly due, respectively, to habit formation and adjustment costs. It is costly for workers to shift from working on the production of consumption goods to building houses, and vice versa. For simplicity, there is no capital used in the production of durable and nondurable goods and the economy is closed.

2.1. Households

Households obtain utility from consuming the stock of durables and the flow of nondurables. There are two types of households in this economy, borrowers and savers. Borrowers are assumed to be more impatient than savers, by having a smaller discount factor. In equilibrium, savers will provide financing to borrowers. A fraction λ of households are considered to be savers, the remaining fraction $1-\lambda$ are borrowers.

2.1.1. Savers

Each saver $j \in [0, \lambda]$ maximizes the following utility function:

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

[4] These features draw on elements of models by Aoki et al. (2004), Cúrdia and Woodford (2010), Iacoviello (2005), and Monacelli (2009). The financial accelerator mechanism goes back to Bernanke et al. (1998). In our model, the accelerator works through housing finance rather than firms' capital.

where C_t^j denotes consumption of nondurable goods, D_t^j denotes consumption of durable goods, and L_t^j denotes total hours worked by household j. β is the discount factor. Households form external habits in consumption, as in Smets and Wouters (2003) and Iacoviello and Neri (2010), with ε denoting the importance of the habit stock, which is last period's aggregate consumption (C_{t-1}). The utility function is hit by a housing preference shock (ξ_t^D), that follows a zero-mean AR(1) process in logs.

Finally, following Iacoviello and Neri (2010), we assume that there is imperfect substitutability of labor supply across sectors, such that the labor disutility index can be written as

$$L_t^j = \left[\alpha^{-\iota_L}\left(L_t^{C,j}\right)^{1+\iota_L} + (1-\alpha)^{-\iota_L}\left(L_t^{D,j}\right)^{1+\iota_L}\right]^{\frac{1}{1+\iota_L}}, \tag{2}$$

where $\iota_L > 0$, α is the economic size of each sector, and $L_t^{x,j}$ denotes hours worked by household j in each sector $x = C, D$. This imperfect substitutability implies that reallocating labor across sectors following a shock is costly. Note that when $\iota_L = 0$ the aggregate is linear in hours worked in each sector, so there are no costs of switching from working in one sector to the other. This switching cost helps the model explain positive comovement of real variables in both sectors in response to shocks, as in the data.

The budget constraint of the savers, in nominal terms, is given by

$$P_t^C C_t^j + P_t^D I_t^j + B_t^j \leq R_{t-1} B_{t-1}^j + W_t^C L_t^{C,j} + W_t^D L_t^{D,j} + \Pi_t^j, \tag{3}$$

where P_t^C and P_t^D are the price indices of durable and nondurable goods, respectively, W_t^x is the nominal wage in each sector $x = C, D$, and B_t^j denotes saving instruments (such as debt instruments or deposits) that borrowers place in financial intermediaries, at a gross interest rate of R_t. Π_t^j denotes nominal profits from intermediate goods producing firms and financial intermediaries, which are ultimately owned by savers. I_t^j denotes residential investment.

We assume that the law of motion of the housing stock evolves as

$$D_t^j = (1-\delta) D_{t-1}^j + \left[1 - S\left(\frac{I_t^j}{I_{t-1}^j}\right)\right] I_t^j, \tag{4}$$

where δ denotes the rate of depreciation of the housing stock and, following Christiano, Eichenbaum, and Evans (2005), we introduce an adjustment cost function, $S(.)$, which is convex (i.e. $S''() > 0$). In the steady state $\bar{S} = \bar{S}' = 0$ and $\bar{S}'' > 0$. The aim of introducing this cost is to allow for the possibility that the model can generate hump-shaped responses of residential investment to shocks.

The first order conditions to the household maximization problem are given by the following expressions, where λ_t is the Lagrange multiplier associated with the budget constraint, and μ_t is the Lagrange multiplier associated with equation (4):[5]

$$U_{C_t} = \lambda_t P_t^C, \tag{5}$$

$$U_{D_t} = \mu_t - \beta(1-\delta)E_t\mu_{t+1}, \tag{6}$$

and

$$\lambda_t P_t^D = \mu_t \left\{1 - S\left(\frac{I_t}{I_{t-1}}\right) - S'\left(\frac{I_t}{I_{t-1}}\right)\frac{I_t}{I_{t-1}}\right\} + \beta E_t\mu_{t+1}\left[S'\left(\frac{I_{t+1}}{I_t}\right)\left(\frac{I_{t+1}}{I_t}\right)^2\right]. \tag{7}$$

Absent adjustment costs to residential investment (i.e. when $S = 0$), these three equations can be reduced to the following condition:

$$\frac{P_t^D}{P_t^C} = \frac{1-\gamma}{\gamma}\frac{\xi_t^D\left(C_t - \varepsilon C_{t-1}\right)}{D_t} + \beta(1-\delta)E_t\left[\left(\frac{C_t - \varepsilon C_{t-1}}{C_{t+1} - \varepsilon C_t}\right)\frac{P_{t+1}^D}{P_{t+1}^C}\right].$$

Note that if the durable good is in fact completely nondurable (i.e. $\delta = 1$), this condition simply equates the marginal utilities of the two consumption goods to their relative prices. Since the durable good has a residual value the following period, an extra term for the value of holding an additional unit of the durable good appears. The Euler equation for the consumption of nondurable goods with habits is standard:

$$1 = \beta R_t E_t\left[\frac{P_t^C}{P_{t+1}^C}\left(\frac{C_t - \varepsilon C_{t-1}}{C_{t+1} - \varepsilon C_t}\right)\right], \tag{8}$$

and the labor supply conditions to both sectors are given by

$$L_t^{\varphi - \iota_L}\alpha^{-\iota_L}\left(L_t^C\right)^{\iota_L} = \left(\frac{\gamma}{C_t - \varepsilon C_{t-1}}\right)\frac{W_t^C}{P_t^C},$$

and

$$L_t^{\varphi - \iota_L}(1-\alpha)^{-\iota_L}\left(L_t^D\right)^{\iota_L} = \left(\frac{\gamma}{C_t - \varepsilon C_{t-1}}\right)\frac{W_t^D}{P_t^C}. \tag{9}$$

[5] Since all savers behave the same way, we drop the j subscripts in what follows.

2.1.2. Borrowers

Each borrower $j \in [\lambda, 1]$ maximizes the following utility function:

$$E_0 \left\{ \sum_{t=0}^{\infty} \beta^{B,t} \left[\gamma \log(C_t^{B,j} - \varepsilon C_{t-1}^{B}) + (1-\gamma)\xi_t^D \log(D_t^{B,j}) - \frac{\left(L_t^{B,j}\right)^{1+\varphi}}{1+\varphi} \right] \right\}, \tag{10}$$

in which all variables with a B superscript are the borrowers' analog to the savers' variables above. $\beta^B < \beta$ is the discount factor of the borrowers; it is assumed that borrowers are more impatient than savers. Their budget constraint in nominal terms is given by

$$P_t^C C_t^{B,j} + P_t^D I_t^{B,j} + R_{t-1}^L B_{t-1}^{B,j} \leq B_t^{B,j} + W_t^C L_t^{C,B,j} + W_t^D L_t^{D,B,j}. \tag{11}$$

Borrowers can obtain loans from financial intermediaries at a lending rate of R_t^L. In the following subsection we discuss how the spread of the lending rate over the deposit rate is determined.

We assume that the functional forms for aggregate labor supply $(L_t^{B,j})$ and for the law of motion of housing stock $(D_t^{B,j})$ are the same as in the case of savers. Hence, the first order conditions for the borrower households are given by similar equations to (5) to (9), but with the relevant interest rate R_t^L in the Euler equation.

2.2. Financial Intermediaries

The single most important element in this model is the presence of financial intermediaries and the determination of the spread between the lending rate and the deposit rate. We assume that savers cannot lend to borrowers directly. Instead, we introduce financial intermediaries that take deposits from savers and lend them to borrowers, charging a spread that depends on the net worth of borrowers. The profits of financial intermediaries are transferred to savers, who own them.

To be clear, our functional form for the determination of the spread is assumed rather than derived from a profit maximization problem. However, the functional form follows the financial accelerator idea of Bernanke et al. (1998) for the spread of the bank lending rate (R_t^L) over the deposit/risk free rate (R_t). It also embeds the idea that the supply of credit is an upward-sloping curve with respect to lending interest rates.[6]

[6] Cúrdia and Woodford (2010) assume that the spread between borrowing and deposit rates depend on the amount of new credit in a given period.

Hence, the spread between the lending and the deposit rates is given by the following functional form:

$$\frac{R_t^L}{R_t} = \upsilon_t F\left(\frac{B_t^B}{P_t^D D_t^B}\right)\tau_t. \tag{12}$$

More precisely, the ingredients of the spread are as follows:

- υ_t is a financial shock that follows an AR(1) process in logs. In the steady state, its mean value υ denotes the markup in the banking sector. Changes in υ_t can be thought of as a reduction in the margin banks charge over funding costs, caused by an increase in competition and a quest for market share, or by a reduction in perceived lending risk.

- F is an increasing function of the leverage of borrowers, denoted by the ratio of debt to the value of the housing stock, $B_t^B/P_t^D D_t^B$. We assume that $F'() > 0$ and that $F(1-\chi) = 1$, with χ being the steady-state downpayment required from borrowers. The parameter $1-\chi$ denotes the loan-to-value ratio. In the model, the steady-state loan-to-value ratio is viewed as a suggested value by regulatory authorities rather than a legally binding one.[7] If borrowers do not meet this requirement, and demand a higher leveraged loan, they are charged a higher lending rate. While the model does not have risk of default, this variable could be seen as a proxy for credit risk.[8]

- τ_t is a macroprudential instrument that allows the central bank to affect market rates by imposing additional capital requirements or loan provisions whenever credit growth is above its steady-state value. BIS (2010) explains how these requirements can affect interest rates in the money market, which in turn affect macroeconomic outcomes. Below, we discuss specific functional forms for this policy tool.

The mechanism embedded in equation (12) introduces a more flexible borrowing constraint than what is usually assumed in the literature. In Iacoviello (2005), the equilibrium real interest rate is smaller than the inverse of the discount factor of borrowers. Hence, borrowers would like to borrow an infinite amount and the borrowing constraint is always binding: that is,

[7] This is the case in most advanced economies, see IMF (2011).

[8] Models with explicit default risk such as Aoki et al. (2004) and Forlati and Lambertini (2011) derive an expression relating credit spreads with the net worth of agents that borrow using housing as collateral.

$B_t^B = (1-\chi) P_t^D D_t^B$. In our model, borrowers can increase their leverage if they wish to do so, but at a higher rate. Also, when house prices increase, borrowers can either take more debt, refinance at a lower rate, or a combination of both. In addition, the following assumptions ensure the return to the steady state: (i) both interest rates equal the inverse of the relevant discount factors: $R^L = (\beta^B)^{-1}$ and $R = \beta^{-1}$; (ii) at the loan-to-value ratio, $F(1-\chi) = 1$; (iii) the macroprudential instrument is $\tau = 1$; and (iv) the mean of the financial shock is exactly the credit spread: $\upsilon = \beta/\beta^B$.

Hence, in the steady-state, the amount of credit is $B^B = (1-\chi) P^D D^B$, but the loan-to-value will fluctuate when shocks hit the economy. Our model can accommodate Iacoviello's mechanism by assuming that $F(\cdot) = \infty$ whenever B_t^B differs from $(1-\chi) P_t^D D_t^B$, in addition to $F(1-\chi) = 1$. In this case, borrowers are always at their steady-state loan-to-value ratio because it is too costly to deviate from it.

There is ample evidence that mortgage credit spreads increase with loan-to-value ratios, which provides empirical support to equation (12). Ambrose et al. (2004) estimate the elasticity of mortgage credit spreads with respect to loan-to-value ratios using a sample of more than 26,000 individual loans originated between 1995 and 1997 in the U.S. After controlling for individual characteristics of borrowers such as FICO scores, ages, income, and conforming loan status, they report elasticities between 0.02 and 0.68. Evidence for the euro area also suggests that mortgage spreads are an increasing function of the loan-to-value ratio, as discussed in Sorensen and Lichtenberger (2007) and ECB (2009). In particular, the ECB (2009) study reports that, on average, an increase of loan-to-value ratios from 75 to 95 percent is associated with an increase of mortgage spreads of about 20 to 40 basis points. An increase of loan-to-value ratios from 50 to 75 percent is associated with an increase of mortgage spreads of between 0 and 20 basis points.

2.3. Producers

There is a continuum of producers that supply imperfectly substitutable intermediate goods and a continuum of final goods producers in each of the two sectors that operate under perfect competition and flexible prices.

2.3.1. Final goods producers

In the durable sector, final goods producers purchase intermediate goods producers and aggregate them according to the following production function:

$$Y_t^D \equiv \left[\int_0^1 Y_t^D(i)^{\frac{\sigma_D - 1}{\sigma_D}} di \right]^{\frac{\sigma_D}{\sigma_D - 1}}. \tag{13}$$

Profit maximization delivers the following demand for individual intermediate nondurable goods:

$$Y_t^D(i) = \left(\frac{P_t^D(i)}{P_t^D} \right)^{-\sigma_D} Y_t^D, \tag{14}$$

where the price level is given by imposing the usual zero-profit condition

$$P_t^D \equiv \left\{ \int_0^1 \left[P_t^D(i) \right]^{1-\sigma_D} di \right\}^{\frac{1}{1-\sigma_D}}.$$

In the nondurable goods sector, expressions are similar.

2.3.2. Intermediate goods producers

Intermediate goods producers face a Calvo-type restriction when setting their prices. In each period, a fraction $1 - \theta_k$ in each sector ($k = C, D$) receive a signal to reset their price optimally. In addition, a fraction φ_k index their price to last period's sectorial inflation rate whenever they are not allowed to reset their price.

Intermediate goods in both sectors are produced with labor only, according to the production functions:

$$\begin{aligned} Y_t^C(i) &= A_t^C L_t^C(i), \text{ for all } i \in [0,1], \text{ and} \qquad (15) \\ Y_t^D(i) &= L_t^D(i), \text{ for all } i \in [0,1]. \qquad (16) \end{aligned}$$

In the nondurable sector, the production function is hit by a total factor productivity (TFP) shock, which follows an AR(1) in logs. In each sector, cost minimization implies that the real marginal cost of production is

$$MC_t^C = \frac{W_t^C / P_t^C}{A_t^C}, \text{ and } MC_t^D = W_t^D / P_t^D.$$

Even though labor is the only production input, labor costs may differ across sectors because of imperfect labor substitutability, which can lead to different real (product) wages. Also, real unit labor costs can differ because of the sector-specific technology shocks in the nondurable sector.

In the remaining part of this subsection, we work out the conditions for the durable sector pricing decisions. Firms in the durable sector face the following maximization problem:

$$\max_{P_t^D(i)} E_t \sum_{k=0}^{\infty} \theta_D^k \Lambda_{t,t+k} \left\{ \left[\frac{P_t^D(i) \left(\frac{P_{t+k-1}^D}{P_{t-1}^D} \right)^{\varphi_D}}{P_{t+k}^D} - MC_{t+k}^D \right] Y_{t+k}^D(i) \right\},$$

subject to future demand

$$Y_{t+k}^D(i) = \left[\frac{P_t^D(i)}{P_{t+k}^D} \left(\frac{P_{t+k-1}^D}{P_{t-1}^D} \right)^{\varphi_D} \right]^{-\sigma_D} Y_{t+k}^D,$$

where $\Lambda_{t,t+k} = \beta^k \frac{\lambda_{t+k}}{\lambda_t}$ is the stochastic discount factor. The optimal choice $(\hat{P}_t^D)$ is given by

$$\frac{\hat{P}_t^D}{P_t^D} = \frac{\sigma_D}{(\sigma_D - 1)} E_t \left\{ \frac{\sum_{k=0}^{\infty} \beta^k \theta_D^k \lambda_{t+k} \left(\prod_{s=1}^{k} \frac{\left(\Pi_{t+s-1}^D\right)^{\varphi_D}}{\Pi_{t+s}^D} \right)^{-\sigma_D} MC_{t+k}^D Y_{t+k}^D}{\sum_{k=0}^{\infty} \beta^k \theta_D^k \lambda_{t+k} \left(\prod_{s=1}^{k} \frac{\left(\Pi_{t+s-1}^D\right)^{\varphi_D}}{\Pi_{t+s}^D} \right)^{1-\sigma_D} Y_{t+k}^D} \right\}. \quad (17)$$

Given the assumptions about Calvo pricing, the evolution of the price level is

$$P_t^D = \left\{ \theta_D \left[P_{t-1}^D \left(\Pi_{t-1}^D\right)^{\varphi_D} \right]^{1-\sigma_D} + (1-\theta_D) \left(\hat{P}_t^D \right)^{1-\sigma_D} \right\}^{\frac{1}{1-\sigma_D}}. \quad (18)$$

Firms in the nondurable sector face a similar maximization problem, and hence the optimal price and the evolution of the price level have similar expressions, with the appropriate change of notation.

2.4. Market Clearing Conditions

For each intermediate good, supply equals demand. We write the market clearing conditions in terms of aggregate quantities. Total production in the nondurable sector is equal to total consumption:

$$Y_t^C = \lambda C_t + (1-\lambda) C_t^B. \quad (19)$$

Total durable production equals aggregate residential investment:

$$Y_t^D = \lambda I_t + (1-\lambda)\, I_t^B. \tag{20}$$

Aggregate real GDP is

$$Y_t = \alpha Y_t^C + (1-\alpha) Y_t^D. \tag{21}$$

Total hours worked equal labor supply in each sector:

$$\int_0^1 L_t^C(i)di = \int_0^\lambda L_t^{C,j} dj + \int_\lambda^1 L_t^{C,B,j} dj, \text{ and} \tag{22}$$

$$\int_0^1 L_t^D(i)di = \int_0^\lambda L_t^{D,j} dj + \int_\lambda^1 L_t^{D,B,j} dj. \tag{23}$$

Market clearing in the deposit/lending market is given by:

$$\lambda B_t + (1-\lambda) B_t^B = 0. \tag{24}$$

In the following section we discuss the role of monetary and financial policies. At this point, it is convenient to define the equilibrium of this economy, that we present in the appendix.

3. Policy Regimes and Welfare

In this model, two types of policy interventions are possible. First, due to the presence of sticky prices, monetary policy has real effects. Second, because of the presence of financial frictions, we assume that policymakers can affect the market lending rate by imposing additional capital requirements or additional provisioning when credit growth is above its steady-state value–the τ_t term in equation (12). We focus on credit growth because in related empirical work (Kannan et al., 2011) we find that significant deviations of this variable from average levels are associated with subsequent house price busts.

We focus on both Taylor rules and macroprudential instruments that react to lagged indicators. This choice is due to two reasons. First of all, when we searched for optimal coefficients on both instruments when they react to current variables, we found implausibly large values for the coefficients in the rules. That is, by promising a large reaction when variables change due to a shock, the policymaker achieves stable outcomes without having to deliver large fluctuations in the instruments. This problem is reduced when backward looking instrument rules are implemented, although optimal coefficients are still large. We also experimented with a version of the model where the macroprudential rule reacts to contemporaneous credit growth. In this case, we found that the optimal value of the reaction coefficient (τ) was arbitrarily large: the second instrument is capable of perfectly offsetting the distortion associated with financial frictions, which is the optimal policy, but unrealistic.[9] Second, from a practical point of view, policymakers receive information with lags (or, they produce "nowcasts" and short-term forecasts based on recent past data), and hence, it makes sense to specify their reaction functions in terms of last period's observables.

Given these two instruments, we model four policy regimes used in the experiments that follow. The baseline policy regime is a Taylor rule, specified with a weight of 1.3 on CPI inflation and 0.5 on the output gap (which means a value for $\gamma_y = 0.125$ in quarterly terms).[10] We allow for interest rate inertia, and as we just discussed, the variables on the right hand side of all rules are lagged. The coefficient on interest rate smoothing is set to $\gamma_R = 0.7$. Let Y_t^* be the level of potential output, which is defined as real GDP when the economy does not include nominal or financial rigidities, and all agents are homogeneous (though costly labor reallocation is in place).

The *Taylor rule regime* is therefore described by the policy rule

$$R_t = \left[\bar{R} \left(\frac{P_{t-1}^C}{P_{t-2}^C} \right)^{\gamma_\pi} \left(\frac{Y_{t-1}}{Y_{t-1}^*} \right)^{\gamma_y} \right]^{1-\gamma_r} (R_{t-1})^{\gamma_r} . \tag{25}$$

where we have normalized steady-state inflation to zero.

With that benchmark, we investigate gains to be achieved by incorporating information from indicators of potential financial vulnerability. Hence, the second regime is implemented as a Taylor-type rule in which monetary policy reacts to the growth rate of nominal credit, $\left(\frac{B_{t-1}^B}{B_{t-2}^B}\right)$, in addition to CPI inflation and the output gap. Hence, the *augmented Taylor rule regime* has the form:

$$R_t = \left[\bar{R} \left(\frac{P_{t-1}^C}{P_{t-2}^C} \right)^{\gamma_\pi} \left(\frac{Y_{t-1}}{Y_{t-1}^*} \right)^{\gamma_y} \left(\frac{B_{t-1}^B}{B_{t-2}^B} \right)^{\gamma_b} \right]^{1-\gamma_r} (R_{t-1})^{\gamma_r} . \tag{26}$$

The macroprudential rule specifies the reaction of a macroprudential instrument to lagged nominal credit changes (the same variable as in the augmented

[9] This result is similar to the one obtained by Gertler and Karadi (2010) in a slightly different context. In their model, the central bank could offset inefficient fluctuations in the spread between lending and deposit rates by providing as much funds as needed by the private sector in a situation of financial stress.

[10] We found that a slightly lower value than the one calibrated by Taylor (1993) of 1.5 works better in order to fit the standard deviation of CPI inflation, deposit rates, and credit growth. See Section 4.

Taylor rule 26):

$$\tau_t = \tau \left(\frac{B^B_{t-1}}{B^B_{t-2}} \right). \tag{27}$$

As the macroprudential instrument affects lending rates, we are assuming that policymakers can directly offset, to some degree, fluctuations in spreads caused by the changes in collateral values and financial shocks described above (see equation 12). This can be thought of as a simple short cut that mimics the effects of, say, regulations that require banks to set aside more capital as asset prices rise, hence raising the margin that banks have to charge over funding costs (the policy rate).[11] Combining the macroprudential rule with the augmented Taylor rule produces the *augmented Taylor plus macroprudential regime*. We study these three regimes in Section 5.1 below.

The final policy regime is a variation on the third, in which the weight on each variable is determined by an optimization procedure that seeks the best response by optimizing over γ_π, γ_y, γ_r, γ_b, and τ. This will be termed the *optimized augmented Taylor plus macroprudential regime*, which we study in Section 5.2.

The welfare criterion that we use to rank all policy options (and that the optimization under the last regime is based on) is the following:

$$W = Var\left(\frac{P^C_t / P^C_{t-1}}{\bar{\Pi}^C} \right) + \varsigma Var\left(Y_t / Y^*_t \right). \tag{28}$$

Hence, we employ a standard welfare criterion whereby the policymaker cares about minimizing the variance of CPI inflation (i.e. nondurables inflation) and the output gap.[12] Microfounded versions of equation (28) that come from taking a second order approximation to the utility function of a representative household (in a one-sector, one-agent economy) tend to give a low value for ς, because the presence of nominal rigidities is the most important friction in the economy, and giving a high relative weight to CPI inflation stabilization is optimal.[13] However, in practice, central banks also care about stabilizing the

[11] See also BIS (2010).

[12] Hence, we abstract from the complicated task of deriving the appropiate welfare criterion based on household's utility function. Note that deriving such a criterion is complicated by the fact that the economy is subject to many nominal, real and financial frictions. In addition, there are two types of agents in the model with different discount factors. A welfare criterion that maximizes the discounted sum of each type of household's lifetime utility function will attach more weight to the current utility of the impatient household. It is not clear that this property of welfare is desirable.

[13] See Schmitt-Grohé and Uribe (2007) and Woodford (2003). In the example provided by Woodford (2003), $\varsigma = 0.048$.

output gap. For instance, the Federal Reserve has a dual mandate for price stability and maximum sustainable employment, which can be interpreted as keeping output at its potential. Therefore, for the U.S. case, setting $\varsigma = 1$ seems appropriate. To incorporate a wide range of policymakers' preferences, we rank the different policy regimes by assuming a range of preferences for the central bank, from a very hawkish one ($\varsigma = 0.01$) to a very dovish one ($\varsigma = 10$). In addition, we assume that the role of the macroprudential instrument is to support the central bank in achieving its objectives.[14]

4. Calibration

The calibration of the model is summarized in Table 1. We aim to match the standard deviation of main macroeconomic time series for the U.S.: consumption growth, residential investment growth, consumer price index (CPI) inflation, nominal house price inflation, short-term deposit rates, spreads between deposit and lending rates, and nominal credit growth (Table 2). All growth rates of nominal and real quantities are quarterly, and all interest rates are also measured on a quarterly basis. We obtain data on personal consumption and residential investment from the Bureau of Economic Analysis, CPI inflation from the Bureau of Labor Statistics, and nominal house prices from the OECD. The short-term (deposit) interest rate is the 3-month T-bill rate, while credit spreads are computed as the difference between the effective rate on all mortgage loans closed and the 3-month T-bill rate (both obtained from the Haver database). Finally, nominal credit growth is measured as the quarterly growth rate of all household credit market debt coming from the Flow of Funds data of the Federal Reserve Board.

We base the calibration of parameters governing real and nominal rigidities on empirical estimates by Iacoviello and Neri (2010), but we adjust the calibration to make sure we can match the relevant second moments in the data. For instance, in order to match the low volatility of personal consumption growth we need a degree of habit formation of 0.8, which is somewhat higher than most estimated DSGE models.

[14] The objective of the macroprudential rule should be financial stability, loosely speaking. There is no consensus in the literature as of how this objective should be introduced in a macroeconomic model. However, episodes of financial instability are associated with large fluctuations in output and inflation such that the goals of monetary and macroprudential policy can safely be assumed to be perfectly aligned.

Table 1: Calibrated Parameters

Parameter	Description	Value
β	Discount factor savers	0.99
β^B	Discount factor borrowers	0.98
δ	Depreciation rate	0.025
λ	Share of savers	0.5
χ	Down payment rate (1 minus LTV)	0.2
$\sigma/(\sigma-1)$	Average markup	1.1
ι_L	Labor disutility of switching sectors	1
φ	Inverse Frisch elasticity of labor supply	1
ε	Habit formation	0.8
η	Adjustment cost residential investment	0.5
κ	Elasticity of spread with respect to net worth	0.05
α	Share of nondurables in GDP	0.9
θ_c	Calvo lottery nondurable	0.75
θ_d	Calvo lottery durable	0.75
ϕ_c	Backward looking behavior nondurable	1
ϕ_d	Backward looking behavior durable	1
γ_π	Taylor rule coefficient on inflation	1.3
γ_y	Taylor rule coefficient on output gap	0.125
γ_r	Taylor rule coefficient on lagged interest rates	0.7
γ_b	Augmented Taylor rule coefficient on credit growth	0.3
τ	Augmented Taylor rule plus macroprudential coefficient on credit growth	0.3
ρ_a	AR(1) coefficient on TFP shocks	0.98
ρ_v	AR(1) coefficient on financial shock	0.95
ρ_d	AR(1) coefficient on housing demand shock	0.95
σ_a	Standard deviation TFP shock (in %)	1.5
σ_v	Standard deviation financial shock (in %)	0.125
σ_d	Standard deviation housing demand shock (in %)	2.5

An important aspect of our calibration is that we introduce sticky prices in the durable sector (housing). In the literature, there is a long standing debate on the degree of nominal rigidities between housing and the other sectors of the economy, and how this might affect the transmission mechanism of monetary policy. In Iacoviello and Neri (2010), housing prices are assumed to be flexible. However, as shown by Monacelli (2009), this assumption is problematic because, in the model, a monetary contraction leads to an expansion of residential investment that is at odds with the data (a fact know as the "comovement problem"). This result arises because the differing degree of nominal rigidity across sectors causes a strong movement of relative prices. Therefore, in our calibration, we assume that house (durable) prices are as sticky than nondurable prices, and this helps us overcome the comovement problem.

Table 2: Second Moments in the Data and in the Model

	Std. Dev.		Variance Decomposition		
	Data	Model	TFP	HD	Financial
Consumption Growth	0.57	0.56	98.0	0.1	1.9
Residential Investment Growth	3.40	3.27	58.4	39.5	2.0
CPI Inflation	0.50	0.50	83.0	0.5	16.5
Nominal House Price Inflation	1.05	1.06	73.8	23.1	3.1
Deposit Rate	0.63	0.59	84.5	0.7	14.8
Spread	0.29	0.32	9.4	9.3	81.3
Credit Growth	1.05	1.07	30.3	12.0	57.7
Output Gap	-	0.38	52.2	30.1	17.7

The κ parameter is key in the model since it measures the size of the financial accelerator effect. We calibrate the elasticity of credit spreads with respect to the loan-to-value ratio to $\kappa = F'(1-\chi) = 0.02$, which is on the lower side of the estimates reported by Ambrose et al. (2004). If κ is calibrated to a higher value, then the model falls short of explaining the volatility of credit aggregates while it implies a volatility of credit spreads that is too large. Overall, the calibrated value for κ strikes the right balance between these trade-offs and the available empirical evidence. We assume that half of the population are borrowers and half are savers. Two other aspects of the model's steady state are particularly important for the results. First, we assume that debt is an important component for financing the purchase of houses—the steady-state loan-to-value ratio is 80 percent. Second, the share of residential investment in GDP is calibrated to 10 percent, which is higher than for most countries, but accurately reflects the typical share of residential investment in the sum of consumption and residential investment (which is the definition of GDP in this model). Together, these shares create a significant role for housing in economic fluctuations.

We set the persistence of all shocks to high values. The AR(1) coefficients of the housing demand and financial shocks are set to 0.95. We also increase the persistence of the TFP shock in the nondurable sector to a higher value of 0.98. We found that higher persistence of TFP shocks in the model helps in explaining the high volatility of residential investment and house prices better, since it leads to larger and more persistent wealth effects. Finally, we calibrate the standard deviation of the shocks to help match the volatility of the second moments of the data. As in Iacoviello and Neri (2010), the housing demand shock is more volatile than the TFP shock, and it is needed in order to explain the higher volatility of house prices and residential investment with respect to CPI inflation and real consumption. The volatility of the financial shock is much lower (50 basis points on an annualized basis). This is in the range of estimated monetary shocks in similar DSGE models (see Christiano, Eichenbaum and Evans, 2005). The sensitivity of the results to some of the parameters relating to non-standard aspects of the model–such as the endogeneity of lending rates–is evaluated later.

In Table 2 we present the second moments from the data and from the model. The second moments from the data are obtained without any filtering method (i.e. the first row of Table 2 is the standard deviation of the quarterly growth rate of personal consumption in the U.S.), and we apply the same transformation to the data and to the model (i.e. growth rates and interest rates are quarterly). The growth rate of residential investment is about 6 times more volatile than the growth rate of personal consumption, while the standard deviation of nominal house price inflation is about 2 times that of CPI inflation. The model with three shocks can easily match all these standard deviations. The model can also easily match the volatility of deposit rates, credit spreads, and credit growth. If we had chosen the original Taylor parameter values, and in particular a coefficient of γ_π of 1.5, the fit to the data would have been worse. This is why we pick a slightly lower value of γ_π of 1.3. In Table 1, we also include the values for the reaction to credit growth in the augmented Taylor rule (γ_b), and the value for the reaction to credit growth in the macroprudential instrument (τ).

The last three columns of Table 2 show the variance decomposition of the main macroeconomic variables. A large share of the fluctuation on prices and real quantities is due to TFP shocks, as in most of the real business cycle literature. However, housing demand shocks are also needed to explain the higher volatility of residential investment and house prices: if we calibrated TFP shocks to match the volatility of housing variables, then the model would imply a too large volatility of personal consumption and CPI inflation. We note that the TFP and housing demand shocks have a small effect on credit growth and in particular credit spreads, which are mostly driven by the financial shock. Financial shocks explain about a sixth of CPI inflation and output gap fluctuations (where potential output is defined as the dynamics of real GDP in the model without nominal and financial frictions, so there is no counterpart in the data in Table 2). Hence, the effect of financial shocks on the macroeconomy is not negligible and policymakers might want to respond to them to stabilize the cycle. In the following section we study the appropriate policy response to each of the three shocks, and to a combination of them.

5. Simulation Results

The behavior of the model economy is examined under different policy regimes, following shocks that produce sustained rises in residential investment and house prices. The objective is to determine which policy regime is better at stabilizing the economy in the face of pressures in the housing market. In other words, we look for policies that can help prevent financial vulnerabilities, rather than policies that help pick up the pieces after a bust. The conclusions that can be drawn from this analysis depend crucially on which shocks drive the housing boom. To illustrate the importance of correctly identifying the drivers of the housing boom, we test the policy regimes using all three shocks of the model. Although asset booms can arise from changes in expectations of capital gains without any change in fundamentals, we do not model "bubbles" or "irrational exuberance." Similarly, we do not attempt to model events that trigger house price crashes.

In Section 5.1 we study the performance of simple policy rules with arbitrary coefficients, to study the role of extending the Taylor rule with an additional indicator (credit growth) or of introducing a macroprudential instrument. This allows us to better understand the change in policy in response to each of the shocks of the model, and the effects on the broader macroeconomy. Afterwards, in Section 5.2, we optimize over all the coefficients of the Taylor rule and the macroprudential instrument.

5.1. The Performance of Simple Policy Rules

In this subsection, we study how the model economy reacts to each of the three shocks when monetary and macroprudential policies change according to the different rules described in Section 3. We compare the behavior of these three simple policy regimes in Table 3. First, we study the effects of a financial shock, and show that the volatility of main variables is reduced when monetary and macroprudential policies react to credit aggregates. Next, we find that under a housing demand shock, there are welfare improvements to reacting to credit growth via monetary policy. The benefits of having the additional macroprudential instrument depend on the preferences of the policymakers. Finally, we show that when TFP shocks hit the economy, the augmented Taylor rule performs best, but introducing the additional macroprudential instrument decreases welfare.

Table 3: Performance of Simple Policy Rules (Standard Deviations)

	Financial		Housing		TFP		All Shocks	
	CPI	Gap	CPI	Gap	CPI	Gap	CPI	Gap
Taylor	0.203	0.160	0.036	0.208	0.450	0.275	0.500	0.379
Augmented Taylor	0.125	0.103	0.035	0.180	0.347	0.269	0.371	0.340
Augmented Taylor + macroprudential	0.105	0.084	0.031	0.188	0.383	0.294	0.398	0.363

Note: "CPI" is CPI inflation, "Gap" is the output gap.

5.1.1. Reaction to Financial Shocks

Figure 1 shows the responses to a financial shock (υ_t), modeled as a relaxation in lending standards that immediately reduces lending rates by 25 basis points in the baseline Taylor regime. Three paths are shown, corresponding to the three different policy regimes discussed in Section 3. In the baseline case, monetary policy is guided by the simple Taylor rule, and, with no macroprudential reaction, the financial shock causes an immediate increase in residential investment and house prices. Because banks are assumed to lower lending rates when collateral rises, the shock feeds on itself: housing demand raises house prices, collateral values increase, lending rates are lowered, and households take out more loans. This is the credit accelerator mechanism at work. In addition, lower rates also lead to higher demand for nondurable consumption goods by borrowers, pushing up CPI inflation. Some of the characteristics of a house price bust are evident in the aftermath of this shock: as financial conditions normalize, residential investment must *undershoot* for a period to bring the housing stock back to equilibrium. This process spills over to the rest of the economy, causing a temporary recession and raising volatility in all markets. The reaction of a central bank following a simple Taylor rule is straightforward: to the extent that the output gap and CPI inflation are positive following the increase in housing demand, policy rates are raised. Eventually, output and inflation stabilize.

Next we consider the augmented Taylor rule, which prompts the central bank to react directly to credit growth, in addition to the output gap and inflation. For illustration, we assume that the central bank puts an arbitrary weight of $\gamma_b = 0.3$ on changes in nominal credit growth. This rule produces greater stability across the board, as can be seen from Figure 1: the volatility

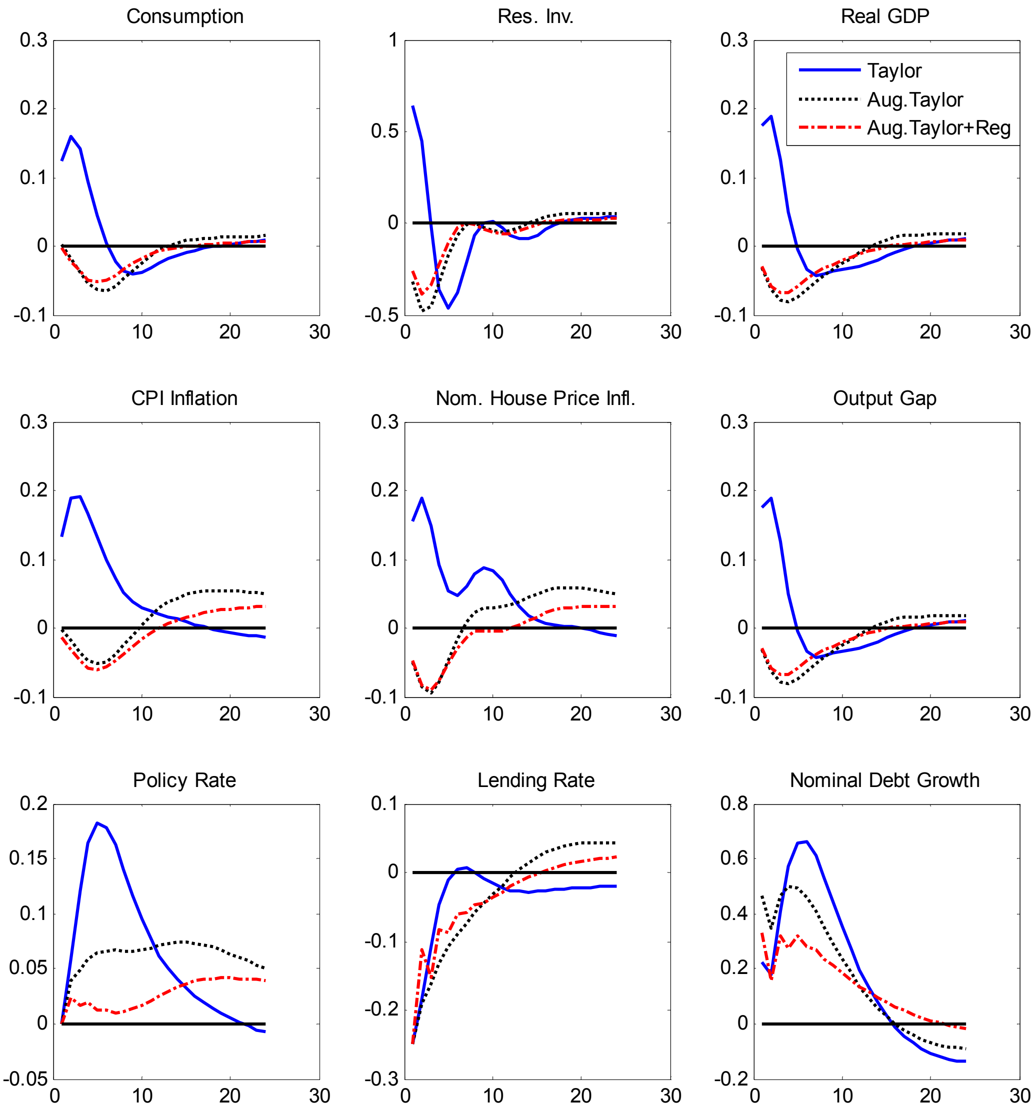

Figure 1: Effect of a Financial Shock. Note: Horizontal axis measures quarters after the shock, vertical axis are percent deviations from steady- state values.

of consumption and residential investment is lower, and there is a considerable reduction in the volatility of the output gap. House price and CPI inflation are also less volatile. Note that the volatility of interest rates is lower as well, even though the policy rule is more aggressive. This is because a model with fully forward-looking private agents, such as this one, has very strong expectations effects—households anticipate a stronger reaction from the central bank and factor it into their decision-making. The result is that monetary policy works through the threat of a stronger reaction, rather than by actually delivering that stronger reaction.

Macroeconomic stabilization is even better served under the third regime, under which the central bank complements the augmented rule with the use of the macroprudential instrument. For illustration, the growth rate of nominal credit in the macroprudential rule has also an arbitrary weight of $\tau = 0.3$, with the other weights maintained as for the augmented Taylor rule. The macroprudential rule allows policymakers to directly counter the easing of lending conditions that induces borrowers to take on more debt as house prices rise. Therefore, there is an improvement in further reducing the volatility of CPI inflation and the output gap. More interestingly, because there is a second policy instrument, monetary policy does not have to react so strongly to financial shocks. As can be see from the first two columns of Table 3, the volatility of both CPI inflation and the output gap is decreased when both monetary and macroprudential policies react to credit growth.

To summarize, adding another indicator to the monetary policy reaction function and another policy instrument can improve macroeconomic stability when the economy is hit by a financial shock. The responses hint that policy reactions guided by the standard Taylor rule are too weak in the face of loosened lending standards and credit accelerator effects, with the consequence that housing investment is insufficiently dampened.

5.1.2. Reaction to Housing Demand Shocks

Next, we study the behavior of the economy under a housing demand shock (ξ_t^D) in Figure 2. In this case, under the original Taylor rule, an increase in the demand of housing (for both savers and borrowers) leads to an increase of residential investment and house prices. In the original Taylor rule case, accelerator effects lead to a decline of lending rates, and hence, as in Iacoviello and Neri (2010), private consumption also increases when housing demand increases. Hence, the calibrated model with a conventional Taylor rule exhibits positive comovement between private consumption and residential investment. This feature typically holds in the data, due to wealth effects from higher house

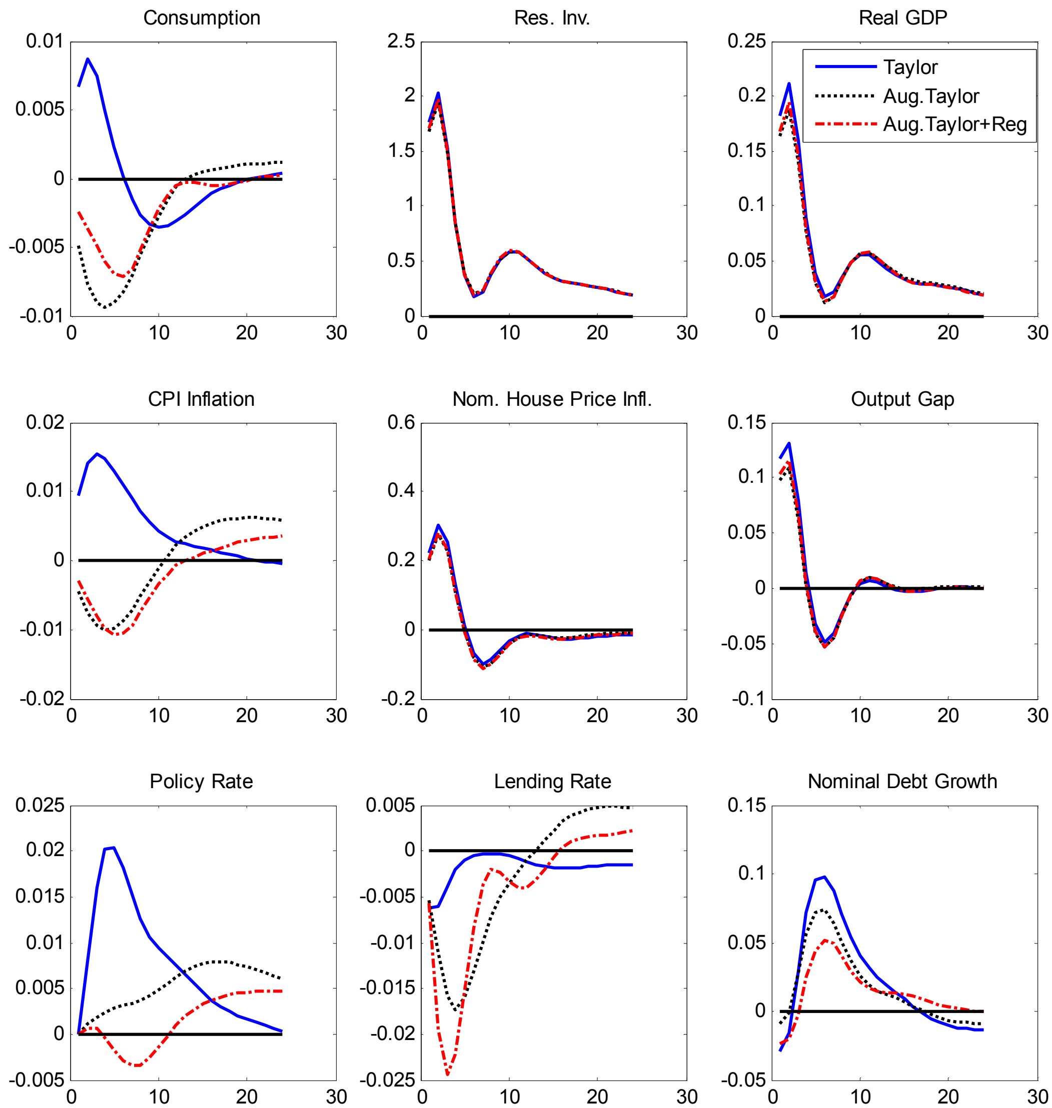

Figure 2: Effect of a Housing Demand Shock. Note: Horizontal axis measures quarters after the shock, vertical axis are percent deviations from steady- state values.

prices and better access to credit for those agents who want to borrow. These spillover effects lead to higher CPI inflation, and therefore, in the baseline, the central bank tightens monetary policy.

Extending monetary policy to include additional indicators works mostly through attenuating the impact of the spillover effects of housing to nondurable consumption, rather than cooling off the housing market directly. In the augmented Taylor rule regime, the central bank reacts to credit growth. As a result, the volatility of credit is reduced, and the accelerator effect is dampened: nondurable consumption actually decreases slightly instead of increasing. This decline in the demand for nondurables makes CPI inflation decline on impact. The effects on the output gap are modest, because the augmented Taylor regime cannot do much to reduce the volatility of residential investment, which is the main driver of the response of the output gap. Similar to the case of financial shocks, the most important channel of monetary policy is to affect expectations, and ultimately, the central bank raises interest rates by less than in the baseline case. At any rate, volatility is reduced and welfare improved when monetary policy reacts to credit (see Table 3, columns 3 and 4). In the augmented Taylor plus macroprudential regime, the volatility of all variables is very similar to that obtained without macroprudential measures. The welfare effects are ambiguous since the volatility of CPI inflation declines but the volatility of the output gap increases. Hence, the final evaluation depends on the welfare criterion of the policymaker and the relative weight that is given to the variance of the two variables. We comment on this issue below, after describing the effects of a TFP shock.

5.1.3. Reaction to Productivity Shocks

Broader and more aggressive policy regimes can improve stability in the face of financial shocks, and can also help in the face of housing demand shocks, but they raise the possibility of policy mistakes in the face of other types of shocks. This can be seen from the last set of simulations, which shows reactions to an increase in productivity in the nondurable goods sector (A_t^C) that, in the case of the original Taylor rule, delivers an immediate 1/2 percent increase in output (Figure 3).[15] The initial stages of this shock resemble a housing boom: residential investment, house prices and the demand for credit all rise, just as in the case of a financial shock. Personal consumption increases. However, the prices of consumption goods fall. Indeed, the fact that CPI inflation was

[15] Although the shock is centered on the production of nondurable consumption goods, households spend more on residential investment as well as nondurables consumption because of expectations of higher income.

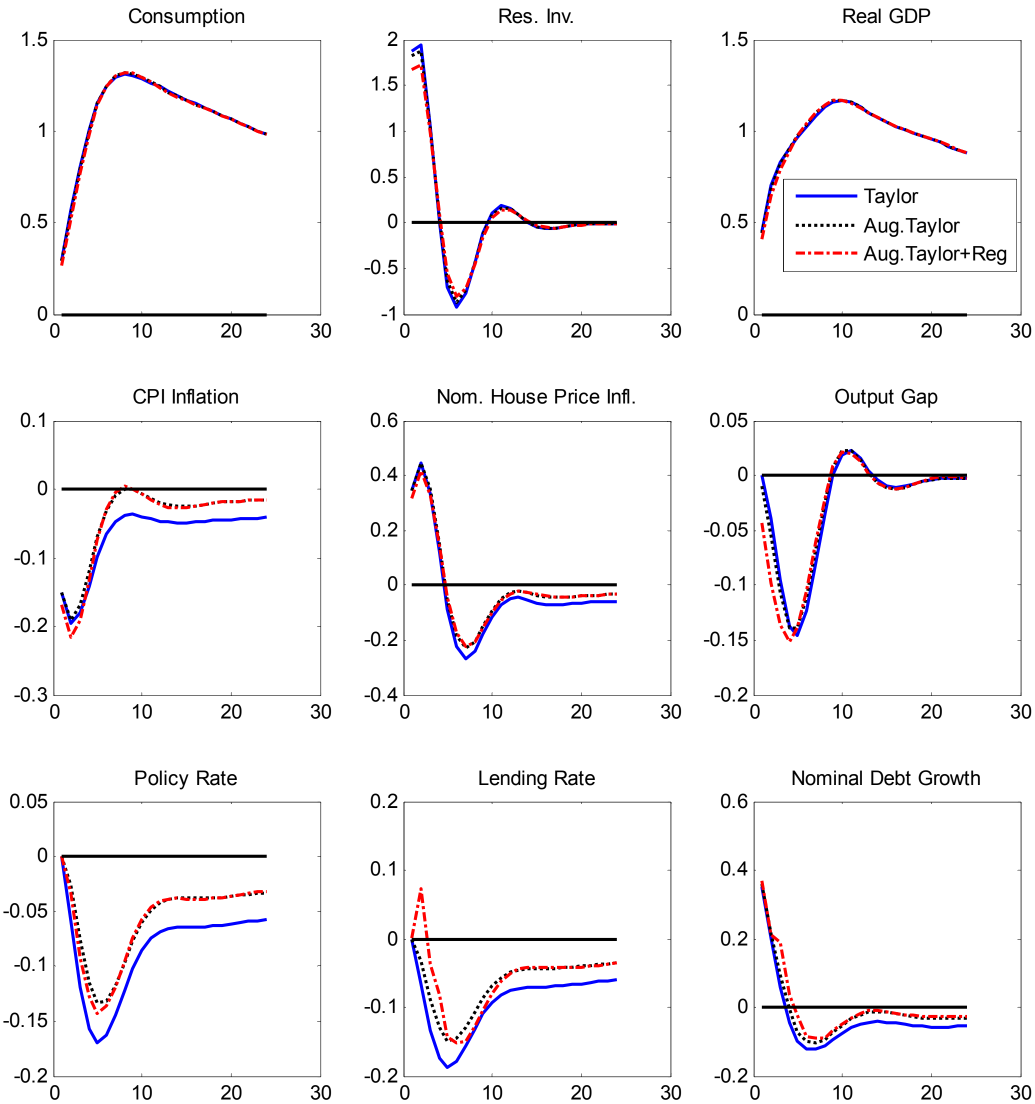

Figure 3: Effect of a Productivity Shock. Note: Horizontal axis measures quarters after the shock, vertical axis are percent deviations from steady- state values.

contained in recent years while asset prices surged led many policymakers to conclude that asset price rises were being driven by positive productivity shocks. The decline in deposit and lending rates leads to a wide-spread increase in credit growth.

Policies to suppress private sector borrowing using macroprudential policies would be misguided, as shown in Figure 3. In the augmented Taylor rule, the economy is more stable than in the baseline case–the output gap and CPI inflation decline more on impact, but they return to their steady-state values faster, and hence their volatility is lower than under the baseline case (Table 3, columns 5 and 6). However, introducing macroprudential rules, with the same parameter values as for the financial shock, accentuates downward pressure on prices (CPI) and the output gap. Because of the extra reaction to credit growth, policy is less expansionary than in the baseline case, and there is a significant increase in the lending rate. Both consumption, and especially residential investment, react by less than in the baseline. The result is that the output gap and inflation are *more* volatile, not less, compared to the policy response without macroprudential measures. In fact, output gap volatility is the largest under the augmented Taylor rule plus macroprudential regime, while CPI inflation volatility falls somewhere between the original and the augmented Taylor rules. Among the first three policy regimes—Taylor, augmented Taylor, augmented Taylor with macroprudential—the best is the augmented Taylor rule. These results suggest that policy reactions to indicators of potential financial vulnerability should be neither automatic nor rigid, since policy mistakes are possible. Therefore, it is crucial to identify what is the main source behind a house price boom, and this is a task that is not easily achievable since in the early stages of the shock housing market and credit variables behave very similarly.

5.1.4. Comparing Simple Rules

In order to compare the three different rules, we use the welfare criterion considered in equation (28). We provide robust results by considering 4 different types of policymaker, that range from mostly caring about CPI inflation fluctuations to mostly caring about the output gap. We consider four values for the relative importance of output gap fluctuations in the welfare function: a "super-dove" policymaker ($\varsigma = 10$), a dove ($\varsigma = 1$), a hawk ($\varsigma = 0.1$) and a "super-hawk" ($\varsigma = 0.01$). We compute the value of the welfare function for each type of shock, and for the three shocks, using the same calibration of the shocks as in Table 1. We rank the three regimes in Table 4.

Table 4: Ranking of Simple Policy Rules

	Financial				Housing			
	SD	D	H	SH	SD	D	H	SH
Taylor	3	3	3	3	3	3	3	3
Augmented Taylor	2	2	2	2	1	1	1	2
Augmented Taylor + macroprudential	1	1	1	1	2	2	2	1
	TFP				**All**			
	SD	D	H	SH	SD	D	H	SH
Taylor	2	3	3	3	3	3	3	3
Augmented Taylor	1	1	1	1	1	1	1	1
Augmented Taylor + macroprudential	3	2	2	2	2	2	2	2

Note: Rules ranked according to equation (28) where SD is the case for "super dove" ($\varsigma = 10$), D is for "dove" ($\varsigma = 1$), H is for "hawk" ($\varsigma = 0.1$), and SH is for "super hawk" ($\varsigma = 0.01$).

If the policymaker were able to identify the shocks and react accordingly, then it would be following different policy regimes. Under financial shocks the best policy regime is always the augmented Taylor plus macroprudential, regardless of the preferences of the policymaker. Under housing shocks, the preferred regime would be to augment the Taylor rule with a reaction to credit growth in most cases. The only exception is when the policymaker is a "super-hawk". In this case, including the macroprudential instrument would be the most preferred option. Finally, under TFP shocks the most preferred option would be the augmented Taylor rule regime. The same result holds when all shocks are considered, which is not surprising since in normal times TFP is the main driver of economic fluctuations.

Therefore, the main conclusion of this exercise is that extending monetary policy to include credit aggregates seems to be the preferred option. However, if policymakers were able to identify that the shock originates from the financial sector, or if policymakers were able to identify that the shock comes from the housing sector–and they mostly care about stabilizing CPI inflation–then the augmented Taylor rule plus macroprudential regime would be the preferred option.

5.2. Optimal Policy Rules Under Multiple Shocks

The parameters in the simple augmented and macroprudential rules used in the previous subsection were ad-hoc, and were designed to highlight which effects would be operating if the central bank were to react to additional indicators or to deploy a second macroprudential instrument which would directly affect the lending-deposit spread in the mortgage market. However, the improvement in stability from adding nominal credit to the monetary policy rule and employing the macroprudential instrument could simply indicate that, under the baseline Taylor rule, the reaction to the output gap and inflation is insufficient. In this subsection, we optimize over all the coefficients of the augmented Taylor rule plus macroprudential regime. We study optimal rules under different preference of the policymakers (different values of ς).

We also study the behavior of optimal rules under the baseline calibration for the variance of the TFP, housing demand, and financial shocks, and for alternative calibrations where the last two shocks become more important. In our baseline calibration, TFP shocks are the main drivers of fluctuations. But the relative importance of shocks driving the economy changes overtime. For instance, Justiniano and Primiceri (2008) and Fernández-Villaverde and Rubio-Ramírez (2007) document the presence of stochastic volatility in the main shocks driving the U.S. economy. The importance of financial shocks has obviously become more important during the crisis, requiring a different policy response than in the pre-crisis period. In fact, a popular view up to the summer of 2007 was that financial innovation and deregulation had lead to a new era where increased investment opportunities and diversification had lead to a decline in aggregate risk.[16] Similarly, the incidence and importance of housing demand shocks can also be time-varying. Periods of high population growth and/or immigration and changes in household formation patterns can lead to sustained large increases in the demand of housing that eventually taper off.[17] Therefore, policy responses can change as the main shocks driving an economy evolve over time.

One more remark before we present the optimization results is necessary. In several cases, when we run the optimization routine, we found that the optimal value for γ_r in the optimal Taylor rule (26) tended to go towards one. As a result, the optimization routine would deliver very large parameters for the other coefficients. When this was the case, we study first-difference rules

[16] However, other authors were emphasizing even before the crisis that financial deregulation could increase financial sector risk, even when observed measures of risk were low. See Rajan (2005) and Bernanke (2007).

[17] See Aspachs-Bracons and Rabanal (2010) for the case of Spain.

of the type:[18]

$$\frac{R_t}{R_{t-1}} = \left(\frac{P^C_{t-1}}{P^C_{t-2}}\right)^{\gamma_\pi} \left(\frac{Y_{t-1}}{Y^*_{t-1}}\right)^{\gamma_y} \left(\frac{B^B_{t-1}}{B^B_{t-2}}\right)^{\gamma_b}. \tag{29}$$

We present the results for optimal monetary policy for a value of the ς parameter ranging from 0.01 to 100 in the top panel of Table 5. Optimal monetary policy is very aggressive—the weights on the output gap and inflation are multiples of those in the standard Taylor rule and typical estimated monetary reaction functions, specially when the policymaker cares mostly about stabilizing CPI inflation (low ς). The weight on nominal credit in setting the policy rate is zero for low ς, and it becomes positive and larger as the policymaker becomes more concerned about stabilizing the output gap. First-difference rules are optimal for low or high values of ς. On the contrary, for intermediate values of ς, no-interest rate smoothing ($\gamma_r = 0$) is optimal. Crucially, however, the optimal weight on nominal credit in the macroprudential rule is not zero, and it displays a U-shaped pattern with respect to the value of ς. When the policymaker cares mostly about stabilizing inflation (low ς), the weight on the macroprudential is substantially larger than the value used in the calibrations of Section 5.1 (where we set $\tau = 0.3$). When the preferences of the policymaker put similar weight on stabilizing CPI inflation and the output gap, the optimal weight on the macroprudential instrument declines to 0.16. Afterwards, when the policymaker becomes more dovish and mostly cares about stabilizing real activity, the importance of the macroprudential instrumental becomes more important again.

In order to get a sense of what is the contribution of expanding monetary policy with credit growth and including a macroprudential instrument, in Figure 4 we present the "Taylor curves" that show what is the best available outcome (in terms of CPI inflation and output gap volatility) of using backward looking Taylor rules and macroprudential rules. We present 3 curves: (i) when the central bank optimizes over the set of parameters ($\gamma_{\pi,}\gamma_y, \gamma_r$), labelled as "optimal Taylor", (ii) when it also includes the reaction to credit growth (γ_b), label "optimal augmented Taylor", and (iii) the "optimized augmented Taylor plus macroprudential" regime, that also includes the reaction of the macroprudential instrument τ. The Taylor curves shift in when a new coefficient and/or instrument is included, showing that welfare is improved. For comparison, we also include the values of the standard deviation of CPI inflation and the output gap (with our baseline calibration) in Figure 4, that we plot with a triangle. As we can see, most of the welfare improvement comes

[18] Levin, Wieland and Williams (1999) discuss the optimality of first-difference rules in New Keynesian models.

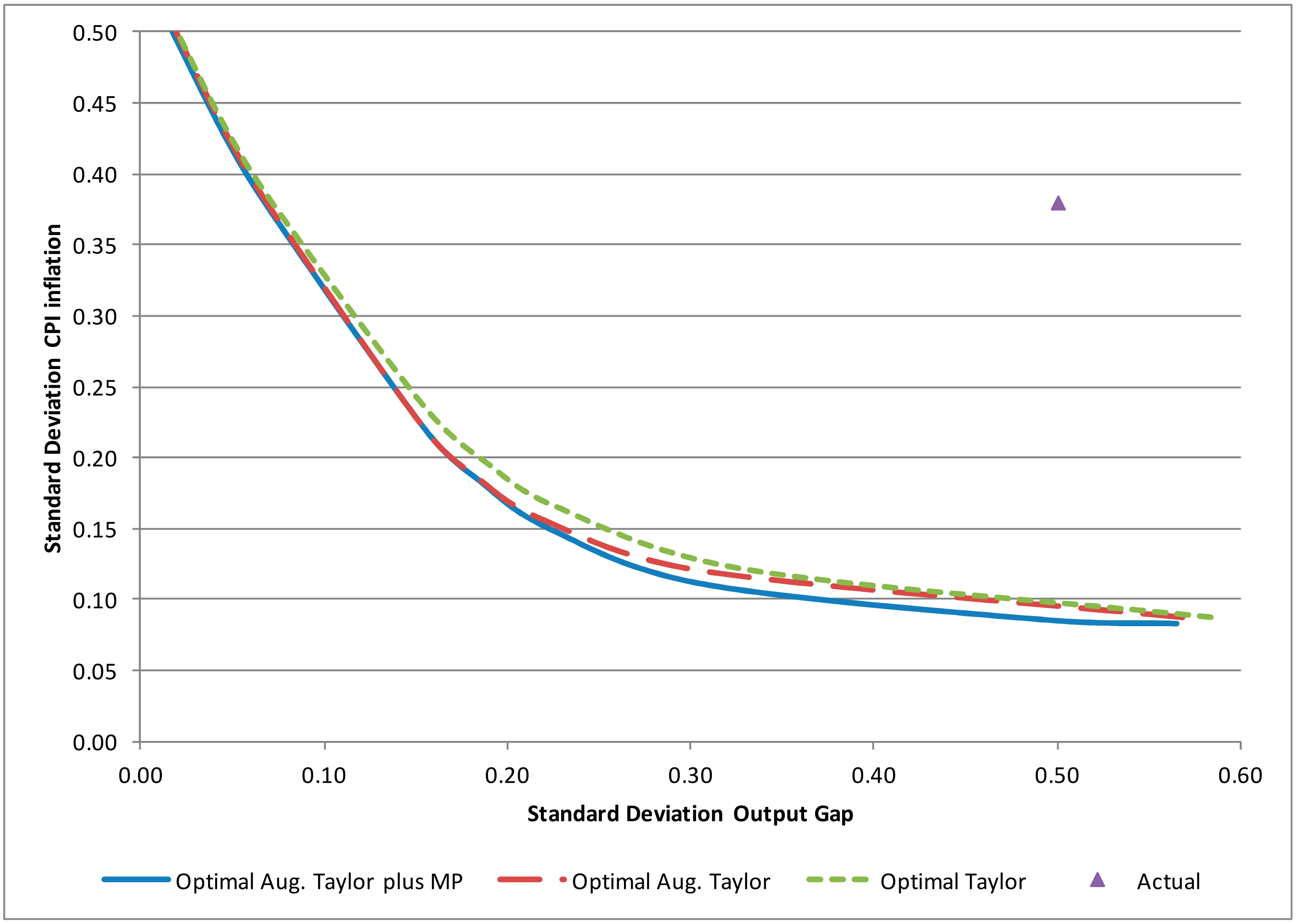

Figure 4: Taylor Curves

from optimizing the coefficients of the original Taylor rule, and welfare gains of expanding monetary and macroprudential policies are much lower. Similar results are obtained by Iacoviello (2005) and Unsal (2011).

Table 5: Optimal Policy Rules

All Shocks	γ_π	γ_y	γ_r	γ_b	τ
$\varsigma = 0.01$	71.35	1.63	FD	0.00	0.52
$\varsigma = 0.05$	11.55	1.01	FD	0.17	0.82
$\varsigma = 0.1$	10.49	1.82	FD	0.32	0.70
$\varsigma = 0.5$	4.72	3.82	0	0.51	0.16
$\varsigma = 1$	2.84	3.73	0	0.52	0.21
$\varsigma = 2$	5.13	7.45	FD	0.74	0.39
$\varsigma = 10$	2.73	8.50	FD	0.45	0.53
$\varsigma = 100$	1.77	12.19	FD	0.15	0.52
Subset of Shocks	γ_π	γ_y	γ_r	γ_b	τ
$\varsigma = 0.1$, TFP	13.9	1.93	FD	1.9	0.00
$\varsigma = 0.1$, Housing+Financial	25.09	4.60	FD	0.00	0.80
$\varsigma = 1$, TFP	2.99	3.54	0	0.73	0.00
$\varsigma = 1$, Housing+Financial	5.67	6.24	FD	0.28	0.70

Note: FD denotes that the optimal rule is a first-difference rule as in equation (29).

Optimal policy rules must strike a balance among the optimal responses to each different type of shock, and must reflect the relative importance of the shocks in driving the economy. Consequently, the case for using a macroprudential tool will depend, among other things, on the mixture of shocks facing a particular economy. In the bottom panel of Table 5, we compute optimal rules conditional on the policymaker being able to distinguish the type of shock hitting the economy. For illustration purposes, we only present the cases where the policymaker is a dove ($\varsigma = 1$) and when the policymaker is a hawk ($\varsigma = .1$). Confirming the results obtained in our simulations, we find that when the economy is hit by TFP shocks only, the optimal reaction is to not use the macroprudential instrument, while having monetary policy react to credit growth is optimal. When the economy is only hit by a combination of housing and financial shocks, then introducing the macroprudential instrument is optimal. Including credit growth in the monetary policy rule depends on whether the policymaker is a dove or a hawk. Ultimately, the optimality of deploying the macroprudential instrument will depend on the relative importance of both shocks. In "normal times" when TFP shocks drive economic fluctuations, including macroprudential measures will be welfare decreasing, as it will lead to inefficient credit rationing. But in periods where financial and

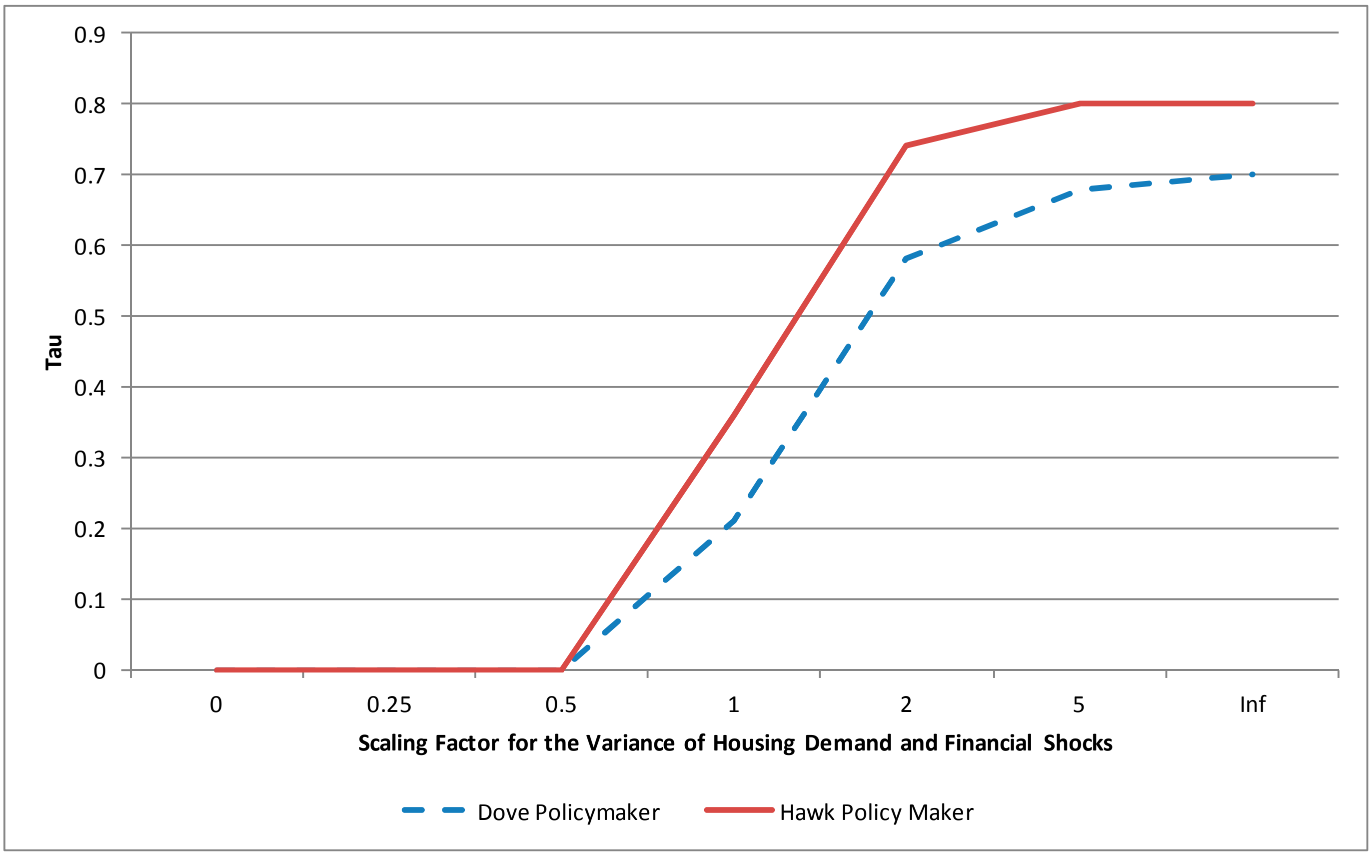

Figure 5: Weight on Macroprudential Instrument

housing variables are driven by sector-specific shocks, using macroprudential measures is useful.

Figure 5 shows how the optimal weight on changes in nominal credit in the macroprudential rule rises as financial shocks become relatively more important than productivity shocks. The exercise involves specifying a sequence of variance-covariance matrices in which the variance of the financial and housing demand shocks increases by the same proportion (ϖ), while the variance of the productivity shock is fixed at the value calibrated in Table 2. For each of the variance-covariance matrices in the sequence, the weights for all variables in the augmented Taylor and macroprudential rule regime are optimized. The calibrated case of Table 2 is $\varpi = 1$. When there are no financial or housing demand shocks ($\varpi = 0$), there is no need for the macroprudential tool. When there are only financial and housing shocks ($\varpi \rightarrow \infty$), the optimal weight on nominal credit in the macroprudential rule in this model is 0.8 when the policymaker is a hawk and 0.7 when she is a dove. The weight on macroprudential increases with the volatility of financial and housing demand shocks. Ideally, then, policymakers would be able to use different reaction functions to deal appropriately with different types of shocks as they arise, rather than reacting rigidly with fixed rules. In practice, it might be more difficult.

Overall, the qualitative results coming from the optimal monetary policy exercises reinforce the message coming from the calibrated exercises of Section 5.1. Macroprudential policy is unambiguously useful for dealing with housing demand and financial shocks, even when the central bank is free to use policy rates very aggressively. One the other hand, macroprudential policy should not be deployed when TFP shocks hit the economy. On balance, using our baseline calibration and for a wide range of policymaker's preferences, using the macroprudential tool is a more efficient reaction to loosening credit conditions than simply raising policy rates, because it tackles the problem at its root.

6. Robustness of the Results

In this section, the augmented Taylor plus macroprudential regime is re-optimized for four alternative calibrations for which, in each case, a single parameter is changed. We concentrate on those parameters that relate to the non-standard aspects of the model, to make sure that the results are robust to reasonable variations in these parameters. Several authors have suggested that housing prices are fully flexible, or at least more flexible than nondurable goods (see the discussion in Iacoviello and Neri, 2010). The first variation eliminates nominal house price rigidities, by setting θ^d and ϕ^d to zero. The second variation examines the results of using a higher value for the Frisch elasticity of labor supply, $\phi = 2$, instead of the baseline calibration of $\phi = 1$. Changes in this elasticity have an important impact on real unit labor costs and inflation dynamics. Finally, we look at the results when there are no labor reallocation costs (ι_L), which makes the model closer to a standard single-sector model.

Table 6 shows the results of the augmented Taylor plus macroprudential regimes optimized for all shocks, again under the two main cases where the policymaker is a dove ($\varsigma = 1$) and when the policymaker is a hawk ($\varsigma = .1$). Although there is a large range of values for the optimal weights on inflation and the output gap, the striking result is that the weight on nominal credit in the macroprudential rule is within the range of 0.21 to 0.79. Hence, the previous result that there is an unambiguous role for the macroprudential instrument in improving macroeconomic stability holds under reasonable variations of parameter values.

Table 6: Sensitivity Analysis of Optimal Policy Rules

All Shocks	γ_π	γ_y	γ_r	γ_b	τ
Flexible House Prices, $\varsigma = 0.1$	61.76	1.58	FD	0.00	0.71
Flexible House Prices, $\varsigma = 1$	31.20	8.20	FD	0.00	0.76
Higher Labor Elast. ($\phi = 2$), $\varsigma = 0.1$	0.70	0.37	FD	0.00	0.47
Higher Labor Elast. ($\phi = 2$), $\varsigma = 1$	5.15	0.60	FD	0.08	0.87
No Labor Reallocation Cost, $\varsigma = 0.1$	2.84	3.73	0	0.52	0.21
No Labor Reallocation Cost, $\varsigma = 1$	4.28	0.35	0	0.29	0.79

Note: FD denotes that the optimal rule is a first-difference rule as in equation (29).

7. Conclusions

Monetary policymakers in advanced economies with flexible exchange rate regimes have been guided in recent years by the principle that stabilizing inflation forms the best policy for promoting economic growth and welfare. Moreover, it was suggested that stable inflation would reduce risk premia and increase financial stability. Thus, a number of central banks have been given explicit mandates to target CPI inflation, and they have been strikingly successful in achieving this objective. But this approach has not been enough to prevent asset price and credit busts.

The results from the simulations show that there are potential benefits from aggressive monetary policy reactions to financial shocks that would otherwise generate a cycle of loosening credit conditions, overvalued housing, and over-extended households. In addition, macroprudential tools could be used to help tackle loose financial conditions. The simulations also clearly show the importance of being able to identify the shocks that are driving changes in financial conditions and asset prices. In the case of a productivity shock, for example, there is no role for a macroprudential tool. Going forward, the best case is for policymakers to be given extra tools with which to address financial shocks. Such tools might reduce the need for aggressive monetary policy reactions and should, in principle, be less disruptive to the whole macroeconomy than using policy rates. However, the characterization of the macroprudential tools in the model used in this paper is very simple and glosses over important questions about how exactly such tools would be managed and how effective they could be in actual financial systems. Hence, the results are only suggestive, and further research on the practicalities of such tools is required.

The results obtained in this paper assume that the central bank minimizes a traditional loss function in terms of the volatility of CPI inflation and the output gap. Another possibility is that central bank mandates be expanded to include explicit concern for avoiding financial vulnerabilities. As with macroprudential instruments, there are some significant practical issues that will need to be carefully assessed before a broader framework for monetary policy is implemented, and expectations about what can be achieved must be realistic. Rigid reactions to indicators such as nominal credit flows and inflexible use of policy tools will likely lead to policy mistakes, so judgment is required. Hence, implementing a broader framework for monetary policy to mitigate macrofinancial risks would further increase the importance of correctly identifying the sources of shocks driving changes in credit and asset prices. Central bankers implementing broader policies would need to explain very carefully the basis for their actions, their immediate objectives, and how their actions are consistent with longer-term objectives of price stability. Moreover, monetary and macroprudential policies would need to be coordinated, requiring greater information exchange and more consultation between monetary and supervisory authorities.

A. Appendix

A.1. Equilibrium Definition

Given the law of motion for the (log) TFP, housing demand and financial shocks defined by (55), an equilibrium for this economy is a set of allocations for savers and borrowers households, C_t, L_t^C, L_t^D, D_t, I_t, B_t, C_t^B, $L_t^{C,B}$, $L_t^{D,B}$, D_t^B, I_t^B, and B_t^B; allocations for nondurable and durable final goods and intermediate goods producers, Y_t^C, Y_t^D, $Y_t^C(i)$ and $Y_t^D(i)$, for $i \in [0,1]$; final and intermediate nondurable and durable goods prices P_t^C, P_t^D, $P_t^C(i)$ and $P_t^D(i)$, for $i \in [0,1]$; wages in both sectors, W_t^C and W_t^D; and lending and deposit rates R_t^L and R_t; such that: (i) given prices, wages and interest rates household allocations solve the households' problem; (ii) given all other final and intermediate goods prices and wages, intermediate goods producers prices and allocations solve the intermediate goods producers' problem in each sector; (iii) given intermediate goods prices, final goods producers prices and allocations solve the final goods producers' problem in each sector; (iv) given deposit rates and macroprudential rules, financial intermediaries set lending rates according to equation (12); (v) deposit rates are given by the monetary policy rule; and (vi) all goods, labor and credit markets clear.

A.2. Appendix: Linearized Conditions

This appendix provides the log-linear conditions. Lower case variables denote log-linear deviations from steady-state values. We define the relative price of durables in terms of nondurables as $Q_t = \frac{P_t^D}{P_t^C}$. Also, ω_t^i denotes deviations from the real wage from steady-state values, defined as nominal wage (W_t^i, for $i = C, D$) divided by the nondurable price level (P_t^C).

From the optimal decisions by savers we get the following:

$$q_t - \frac{c_t - \varepsilon c_{t-1}}{1-\varepsilon} + \eta(i_t - i_{t-1}) = \mu_t + \beta\eta(E_t i_{t+1} - i_t), \tag{30}$$

where $\eta = \bar{S}''(.)$,

$$[1 - \beta(1-\delta)]\,(\xi_t^D - d_t) = \mu_t - \beta(1-\delta)E_t\mu_{t+1}, \tag{31}$$

$$\varepsilon\Delta c_t = E_t\Delta c_{t+1} - (1-\varepsilon)(r_t - E_t\Delta p_{t+1}^C), \tag{32}$$

$$\frac{c_t - \varepsilon c_{t-1}}{1-\varepsilon} + [(\varphi - \iota_L)\alpha + \iota_L]\, l_t^C + (\varphi - \iota_L)(1-\alpha) l_t^D = \omega_t^C, \tag{33}$$

and

$$\frac{c_t - \varepsilon c_{t-1}}{1-\varepsilon} + [(\varphi - \iota_L)(1-\alpha) + \iota_L]\, l_t^D + (\varphi - \iota_L)\alpha l_t^C = \omega_t^D. \tag{34}$$

The same conditions for borrowers are:

$$q_t - \frac{c_t^B - \varepsilon c_{t-1}^B}{1-\varepsilon} + \eta(i_t^B - i_{t-1}^B) = \mu_t^B + \beta^B \eta(E_t i_{t+1}^B - i_t^B), \tag{35}$$

$$\left[1 - \beta^B(1-\delta)\right](\xi_t^D - d_t^B) = \mu_t^B - \beta^B(1-\delta)E_t\mu_{t+1}^B, \tag{36}$$

$$\varepsilon \Delta c_t^B = E_t \Delta c_{t+1}^B - (1-\varepsilon)(r_t^L - E_t \Delta p_{t+1}^C), \tag{37}$$

$$\frac{c_t^B - \varepsilon c_{t-1}^B}{1-\varepsilon} + \left[(\varphi - \iota_L)\alpha + \iota_L\right] l_t^{B,C} + (\varphi - \iota_L)(1-\alpha) l_t^{B,D} = \omega_t^C, \tag{38}$$

and

$$\frac{c_t^B - \varepsilon c_{t-1}^B}{1-\varepsilon} + \left[(\varphi - \iota_L)(1-\alpha) + \iota_L\right] l_t^{B,D} + (\varphi - \iota_L)\alpha l_t^{B,C} = \omega_t^D. \tag{39}$$

The budget constraint of impatient households is:

$$\begin{aligned} & C^B c_t^B + I^B(q_t + i_t^B) + R^L B^B(r_{t-1}^L + b_{t-1}^B - \Delta p_t^C) \\ = \; & B^B b_t^B + \alpha W L^B(\omega_t^C + l_t^{C,B}) + (1-\alpha) W L^B(\omega_t^D + l_t^{D,B}), \end{aligned} \tag{40}$$

where b_t^B is the deviation of the real value of credit in nondurable consumption units from its steady-state value (i.e. deviations of B_t^B/P_t^C from its steady-state value). The effective interest rate for borrowers is a spread over the riskless rate, with an exogenous markup shock (υ_t) and an endogenous component, that depends on the loan-to-value ratio for borrowers in the economy:

$$r_t^L = r_t + \kappa(b_t^B - d_t^B - q_t) - \upsilon_t + \tau(b_{t-1}^B - b_{t-2}^B + \Delta p_{t-1}^C), \tag{41}$$

where we have substituted the macroprudential rule. As long as $\tau = 0$ this instrument is not operational, otherwise it raises the costs of lending in proportion to nominal credit growth.

The relative price of housing evolves as:

$$q_t = q_{t-1} + \Delta p_t^D - \Delta p_t^C. \tag{42}$$

The production functions are given by:

$$y_t^C = a_t^C + l_t^{C,tot}. \tag{43}$$

and

$$y_t^D = l_t^{D,tot}. \tag{44}$$

And the pricing equations are given by

$$\begin{aligned} \Delta p_t^C - \varphi_C \Delta p_{t-1}^C &= \beta E_t(\Delta p_{t+1}^C - \varphi_C \Delta p_t^C) + \kappa^C \left(\omega_t^C - a_t^C\right), \text{ and} && (45) \\ \Delta p_t^D - \varphi_D \Delta p_{t-1}^D &= \beta E_t(\Delta p_{t+1}^D - \varphi_D \Delta p_t^D) + \kappa^D \left(\omega_t^D - q_t - a_t^D\right), && (46) \end{aligned}$$

where $\kappa^C = \frac{(1-\theta_C)(1-\beta\theta_C)}{\theta_C}$, and $\kappa^D = \frac{(1-\theta_D)(1-\beta\theta_D)}{\theta_D}$.

The market clearing conditions for the nondurable goods sectors read as follows:

$$y_t^C = \frac{\lambda C c_t + (1-\lambda) C^B c_t^B}{[\lambda C + (1-\lambda) C^B]}. \tag{47}$$

Aggregate investment expenditures equal production of investment goods:

$$y_t^D = \frac{\lambda \delta D i_t + (1-\lambda)\delta D^B i_t^B}{\lambda \delta D + (1-\lambda)\delta D^B}. \tag{48}$$

And the law of motion of the two types of housing stocks (for borrowers and savers) are given by:

$$\begin{aligned} d_t &= (1-\delta) d_{t-1} + \delta i_t, \text{ and} && (49) \\ d_t^B &= (1-\delta) d_{t-1}^B + \delta i_t^B, && (50) \end{aligned}$$

where hours in each sector are:

$$l_t^{C,tot} = \frac{\lambda L l_t^C + (1-\lambda) L^B l_t^{C,B}}{[\lambda L + (1-\lambda) L^B]}, \tag{51}$$

and

$$l_t^{D,tot} = \frac{\lambda L l_t^D + (1-\lambda) L^B l_t^{D,B}}{[\lambda L + (1-\lambda) L^B]}. \tag{52}$$

To close the model, we specify a monetary policy Taylor rule:

$$r_t = \gamma_r r_{t-1} + (1-\gamma_r)\gamma_\pi \Delta p_{t-1}^C + \gamma_y (y_{t-1} - y_{t-1}^*) + \gamma_b (b_{t-1}^B - b_{t-2}^B + \Delta p_{t-1}^C), \tag{53}$$

where aggregate real GDP equals:

$$y_t = \alpha y_t^C + (1-\alpha) y_t^D. \tag{54}$$

and y_t^* is the dynamics of real GDP when the economy operates under flexible prices and no financial constraints.

Finally, the TFP, housing demand and financial shocks evolve as follows:

$$\begin{aligned} a_t^C &= \rho_a a_{t-1}^C + \varepsilon_t^a && (55) \\ \xi_t^D &= \rho_d \xi_{t-1}^D + \varepsilon_t^d \\ \upsilon_t &= \rho_\upsilon \upsilon_{t-1} + \varepsilon_t^\upsilon. \end{aligned}$$

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