BANK OF ENGLAND

Working Paper No. 431
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July 2011

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Abstract

Gertler and Karadi combined financial intermediation and credit policy in a DSGE framework. We estimate their model with UK data using Bayesian techniques. To validate the fit, we evaluate the model's empirical properties. Then we analyse the transmission mechanism of the shocks, set to produce a downturn. Finally, we examine the empirical importance of nominal, real and financial frictions and of different shocks. We find that banking friction seems to play an important role in explaining the UK business cycle. Moreover, the banking sector shock seems to explain about half of the fall in real GDP in the recent crisis. A credit supply shock seems to account for most of the weakness in bank lending.

Key words: Financial friction, DSGE, Bayesian estimation.

JEL classification: C11, E44.

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The views expressed in this paper are those of the authors, and not necessarily those of the Bank of England. We are indebted to Mark Gertler and Peter Karadi for providing access to their code. We are grateful to Andrew Blake, Jagjit Chadha, Federico Di Pace, Marcelo Ferman, Mark Gertler, Peter Karadi, Giovanni Melina, Haroon Mumtaz, Matthias Paustian, Konstantinos Theodoridis and Stephen Wright, as well as seminar participants at the Bank of England, Birkbeck College, the Cambridge Conference 'New Instruments of Monetary Policy' and at the EEA 2010 for helpful comments and suggestions. The usual disclaimer applies. A version of this work is forthcoming in Chadha, J and Holly, S (eds), *Lessons for monetary policy from the financial crisis*, Cambridge University Press. This paper was finalised on 25 March 2011.

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Publications Group, Bank of England, Threadneedle Street, London, EC2R 8AH
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ISSN 1749-9135 (on-line)

Contents

Summary

Financial intermediaries play an important role in the transmission mechanism of the shocks hitting the economy, as the recent financial crisis has dramatically demonstrated. However, in the main macroeconomic literature with financial frictions, intermediation, when present, is largely a veil. Consequently, Mark Gertler and Peter Karadi introduced a model where financial intermediaries play an active role in the real economy. Their model also introduced credit policy as an additional tool for policymakers.

The aim of this paper is to estimate that model with financial intermediaries (but without credit policy) for the UK economy. In particular, we examine the capability of the model to mimic the path of financial variables. The microfoundation of the banking sector is one of the novelties of the paper; therefore, we ask whether this microfoundation has good empirical properties and whether the model reproduces the observed behaviour of financial variables. We also analyse the contribution of structural shocks to the fluctuations in the variables we examine.

The model has the following agents: households; financial intermediaries; intermediate goods firms; capital producers; retailers; and the policymaker. The set-up is pretty standard but for the financial intermediaries, where we face an agency problem. That is, the banks operate on behalf of households. As a result, their balance sheets are endogenously constrained because the assets the financial intermediaries can acquire depend positively on their equity capital.

To estimate the model, we use data on gross domestic product, investment, seasonally adjusted inflation, lending to private non-financial corporations and corporate bond spreads for the period 1979 Q2-2010 Q1.

This model exhibits a ‘financial accelerator’ mechanism because shocks affect the debt to equity ratio (‘leverage’) of financial intermediaries, which affects their ability to lend. The more leveraged they are, the larger is the impact of capital losses on the reduction in lending. This retrenchment in lending leads to a fall in banks profits. Financial intermediaries can only rebuild their profit and capital base by increasing the lending rate; therefore, the spread rises. In the face of the increase in financing cost, firms reduce their demand for loans and therefore cut back

investment and increase the utilisation rate of capital. Both investment and output suffer a protracted decline. Subdued aggregate demand feeds back to the banking sector resulting in lower profits. This, in turn, causes financial intermediaries to further tighten credit supply and raise lending spreads in order to satisfy their endogenous balance sheet constraint. Given the decline in lending volume, financial intermediaries can only try to increase profit by increasing spreads, which is likely to lead to a further fall in lending demand.

We have two main results. First, an evaluation of the model's empirical properties reveals that the fit of the estimated model is quite satisfactory, in particular for the financial variables. The results suggest that financial frictions play an important role in explaining UK business cycles. Second, the banking sector shocks explain about half of the fall in output during the recent recession. The sharp rise in spreads since the onset of the crisis can be mainly attributed to credit supply shocks, although in the last quarter in our sample, credit demand starts to play a role as well. Credit supply shocks seem to account for most of the weakness in bank lending.

1 Introduction

As Bean (2010) noted, in most DSGE models with financial frictions, financial intermediaries are simple or non-existent. However, as the current recession has shown, banks play an active role in the real economy and they are not simply a part of the amplification of the transmission mechanism. In contrast, Gertler and Karadi (2011) (GK, henceforth) presented a DSGE model with financial frictions and credit policy,[1] calibrated for the US economy. Unlike Bernanke *et al* (1999) and Kiyotaki and Moore (1997), the financial frictions directly originate in the financial sector: the financial intermediaries face an agency problem and their balance sheets are endogenously constrained. Their paper is particularly interesting because the authors emphasise the role of financial intermediaries in the transmission mechanism of the shocks. In addition, their paper is the first attempt in a DSGE framework to assess quantitatively direct credit intermediation of the type pursued by the Fed during the financial crisis as an additional tool for monetary policy. The aim of the present work is to examine the empirical properties of the GK model estimated for the UK economy: in particular, we analyse the capability of the model to mimic the path of financial variables. Bayesian estimation techniques are used to estimate the model with financial intermediaries and without credit policy.

The Bayesian DSGE approach has become very popular in recent times both in academia and among policymakers because it can address a number of key issues in business cycle analysis (see Smets and Wouters (2007), Adolfson *et al* (2007), Gertler *et al* (2008), among many others).[2] We first analyse the model's fit for the UK economy. The comparison between model and data is made along two dimensions. First, the Kalman filtered estimates of the observed variables, computed at the posterior mode of the estimated parameters, along with the actual variables. And second, the comparison of the unconditional moments, as standard in the RBC literature (see Cooley and Hansen (1995), among many others). After validating the fit of the model, impulse response functions (IRFs) are used to summarise the predictions of the model. Its baseline specification is compared to a model without respectively nominal, real and financial frictions. Finally, some policy implications are presented via IRFs analysis, when credit policy is 'at work'.

[1] Under GK's credit policy which they term 'unconventional monetary policy' , the policymaker assumes an direct intermediation role. This is clearly not the policy of quantitative easing undertaken by the Bank of England. We note that, even though we are using data to 2010 Q1, the effects of credit policy would be hard to estimate, due to the absence of such policies through most of the period.

[2] Fernández-Villaverde (2010) provides a comprehensive survey about Bayesian estimation of DSGE models.

The structure of the paper is as follows: in Section 2 the main features of the model are briefly presented. Section 3 contains a short description of the data used. Section 4 analyses the estimation procedure: calibrated parameters, prior and posterior distributions of the estimated parameters and model fit; it also provides subsample estimates. Section 5 presents the following estimation results: impulse responses to different shocks; the relative importance of different shocks; and the empirical importance of different frictions. Section 6 presents some policy implications. The final section offers some concluding remarks.

2 The model

The GK model combines three different strands of literature. First, the vast literature about financial frictions on non-financial firms, whose seminal paper is Bernanke *et al* (1999),(BGG, henceforth). Second, the smaller literature on the role of bank capital, eg Aikman and Paustian (2006), Meh and Moran (2008) and Gertler and Kiyotaki (2010). And third, the standard DSGE modelling with frictionless capital markets: Christiano *et al* (2005) and Smets and Wouters (2007) (SW, henceforth). The main novelties of the model regard the set-up of the financial intermediaries and of the policymaker.

We now briefly present the main features of the GK model. The agents in the GK model are: households, financial intermediaries (FIs), intermediate goods firms, capital producers, monopolistically competitive retailers; and the policymaker. Each household consumes, saves and supplies labour. Households do not hold capital directly; they save by lending funds to the FIs. Within each household there are two types of members at any point in time: the fraction f of the household members are workers and the fraction $(1 - f)$ are bankers. GK introduced a finite horizon for bankers in order to avoid the possibility that they can reach the point where they can fund all investment from their own capital. The turnover between bankers and workers is as follows: every banker stays banker next period with a probability θ, which is independent of history. Therefore, every period $(1 - \theta)$ bankers exit and become workers. Similarly, a number of workers become bankers, keeping the relative proportion of each type constant. The family provides its new banker with a start-up transfer, which is a small fraction of total assets, χ. Each banker manages a financial intermediary.

The households maximise utility subject to the budget constraint; the utility function is separable in consumption and labour and exhibits internal habit formation:

$$E_t \sum_{t=0}^{\infty} \beta^t \left[\ln(C_t - hC_{t-1}) - \frac{\omega}{1+\phi} L_t^{1+\phi} \right] \tag{1}$$

where $\beta > 0$, the parameter h captures habit formation, ω measures the relative weight of leisure and ϕ is the inverse of Frisch elasticity of labour supply. Financial intermediaries obtain funds from the household at the rate R_t and they lend them to firms at the market lending rate R_t^k. There is perfect information between financial intermediaries and firms and asymmetric information between financial intermediaries and households. At the beginning of the period the financial intermediary can divert a fraction λ of total assets and transfer them to her family. The cost of doing so is that the FI goes into bankruptcy. The objective of the banker is to maximise expected terminal wealth, V_t. For the lender to deposit money in the FI, the following incentive compatibility constraint should hold:

$$V_t \geq \lambda Q_t S_t \tag{2}$$

where S_t is the quantity of financial claims on non-financial firms and Q_t is the relative price of each claim. The LHS of equation **(2)** represents the loss for the FI from diverting funds, and the RHS represents the gain from doing so. When the constraint binds, GK show that the previous equation can be written as:

$$Q_t S_t = lev_t N_t \tag{3}$$

where lev_t stands for the FI leverage ratio and N_t is FI capital (or net worth). According to equation **(3)** the assets the FI can acquire depend positively on its equity capital. The agency problem introduces an endogenous capital constraint on the bank's ability to acquire assets. Total net worth is the sum of net worth of existing bankers, N^e, and net worth of new bankers, N^n. Concerning the first, net worth evolves as:

$$N_t^e = \{\theta[(R_t^k - R_{t-1})lev_{t-1} + R_{t-1}]N_{t-1}\}\exp(-e_t^n) \tag{4}$$

where R_t is the riskless interest rate on deposit, R_t^k is the lending rate and e_t^n is a shock to FI capital. Net worth of new bankers is:

$$N_t^n = \chi Q_t S_t \tag{5}$$

where χ is the fraction of total assets given to new bankers. The spread is defined as:[3]

$$\hat{SP}_t = \hat{R_{t+1}^k} - \hat{R}_t \tag{6}$$

[3]A variables with a 'hat' denotes a percentage deviation from steady state.

Each intermediate goods firm finances the acquisition of capital, K_{t+1}, by obtaining funds from the FI. The firm issues S_t state-contingent claims equal to the number of units of capital acquired and prices each claim at the price of a unit of capital Q_t:

$$Q_t K_{t+1} = Q_t S_t \tag{7}$$

Lending to firms does not involve any agency problem. However, the constraint that FIs face affects the supply of funds to intermediate firms and the lending rate. The firms maximise profits, choosing capital, labour and the utilisation rate. The production function is a standard Cobb-Douglas:

$$Y_t = A_t (u_t K_t \psi_t)^{\alpha} \ell_t^{1-\alpha} \tag{8}$$

where u_t is the utilisation rate and ψ_t is the shock to the quality of capital (which is meant to capture economic obsolescence). At the end of each period, competitive capital producing firms buy capital from intermediate goods firms and then repair depreciated capital and builds new capital. They then sell both the new and refurbished capital.

Sticky prices are introduced in the production sector by assuming monopolistic competition at the retail level as in BGG. The Phillips curve is:

$$\hat{\pi}_t = \frac{\sigma_p}{1+\sigma_p \beta} \hat{\pi}_{t-1} + \frac{\beta}{1+\sigma_p \beta} E_t\{\hat{\pi}_{t+1}\} - \frac{(1-\beta\sigma)(1-\sigma)}{(1+\sigma_p \beta)\sigma} \hat{\mu}_t \tag{9}$$

where σ is the probability of keeping prices constant and σ_p measures indexation to past inflation.

The policymaker follows a standard Taylor rule:

$$i_t = i_{t-1}^{\rho_i} \left(\pi_t^{\rho_\pi} y_t^{\rho_y} \right)^{1-\rho_i} \exp(\varepsilon_t^i) \tag{10}$$

and the following feedback rule for credit policy:

$$cp_t = cp + \nu[(R_{t+1}^k - R_t) - (R^k - R)] \tag{11}$$

$$\text{with} \quad Q_t S_{pt} = cp_t Q_t S_t$$

where $Q_t S_{pt}$ is the value of assets intermediated via the policymaker, which is a fraction, cp_t, of total assets. In steady state the fraction of publicly intermediated assets is zero. According to equation **(11)** the degree of intermediation depends on the extent that the spread deviates from its steady-state value.

Credit policy works in GK as follows: the policymaker, after obtaining funds from households at the rate R, lends the funds to non-financial firms at the market lending rate R^k. The policymaker always honours its debt so there is no agency conflict that limits the policymakers ability to obtain funds from households. In other words, the policymaker does not have a balance sheet constraint that limits its lending capacity.

In the model there are five exogenous disturbances: ε_i, the monetary policy shock; the FI capital (or bank capital) shock; the technology shock; the capital quality shock; and the government shock. And the last three shocks evolve exogenously according to the following first-order autoregressive processes:

$$x_t = \rho_x x_{t-1} + \varepsilon_t^x$$

where $\rho_x \in (0, 1)$ with $x = a, \psi, g$ and ε_t^x is an i.i.d. shock with constant variance $\sigma^2_{\varepsilon^x}$.

3 The data

To estimate the model we use quarterly UK data for the period 1979 Q2-2010 Q1. We match the following five observable variables: real GDP, real investment, CPI seasonally adjusted inflation, lending to private non-financial corporations (PNFCs) and corporate bond spread.[4] The M4 lending data show the business between UK monetary financial institutions and M4 private sector. This is broken into business with other financial corporations, PNFCs and the household sector. We consider M4 lending to PNFCs because the GK model analyses lending to PNFCs alone. The spread is calculated as the yield on BAA rated corporate bonds over maturity-equivalent risk-free rates.

To make these variables stationary, the logarithm of GDP, of investment, of lending to PNFCs and inflation are detrended with the HP filter. Inflation is calculated as the log difference of seasonally adjusted CPI in terms of quarterly annualised inflation rate. Data on the spread are demeaned and then divided by 100 to make the units compatible with the HP data. We chose this period following DiCecio and Nelson (2007). Notwithstanding that, this sample period was characterised by different monetary policy regimes (Nelson (2000) and Benati (2004)). Hence, in

[4]We use ONS quarterly series GDP (ABMI) and investment (NPQT), both seasonally adjusted and in constant 2006 prices. The lending series (LPQBC57) come from the Bank of England database and have been deflated with the GDP deflator.

Table A: Some statistical properties of the data (1979-2009)

			Cross-correlation with GDP_{t+k}				
Variable (t)	Std dev	Relative std dev	t= -4	t= -2	t= 0	t=2	t=4
Full sample							
GDP	0.0146						
Investment	0.0457	3.13	0.28	0.65	0.80	0.57	0.23
Inflation	0.0136	0.93	0.51	0.48	0.08	-0.29	-0.43
Lending	0.0540	3.70	0.35	0.44	0.39	0.16	-0.07
Spread	0.0082	0.56	0.20	0.06	-0.26	-0.36	-0.21
1993 Q1-2010 Q1							
GDP	0.0121						
Investment	0.0417	3.45	0.01	0.50	0.80	0.60	0.14
Inflation	0.0061	0.50	0.35	0.57	0.42	-0.10	-0.22
Lending	0.0516	4.26	0.34	0.60	0.55	0.28	0.03
Spread	0.0101	0.83	0.39	0.21	-0.33	-0.54	-0.32

Section 4 we compare the full-sample estimates with the post-1992 period, when inflation targeting was adopted.

Table A presents some statistical properties of the data. For the full sample, the series display different volatilities. Investment is three times more volatile than GDP. The volatility of inflation is slightly lower than that of GDP, with a relative standard deviation of inflation (std of inflation/ std of GDP) equal to 0.93. Lending to PNFCs is more volatile than investment as in Bean *et al* (2002), with a relative standard deviation of 3.7. The spread is less volatile than output, with a relative standard deviation of 0.56.

As far as cross-correlations are concerned, the data reflects the economic properties that output and investment are positively correlated, and the same applies to inflation and output. Lending to PNFCs is also procyclical. The correlation with the spread is negative; this evidence supports the countercyclicality of the spread, as in Aksoy *et al* (2009) and Gertler and Lown (1999). The evidence in Table A suggests that CPI inflation lags the cycle by approximately four quarters, as in Bean *et al* (2002). The lending series lags the cycle by approximately two quarters. These results are in line with Bean *et al* (2002), who used a different filtering technique over the sample 1970-2000.

The subsample period 1993-2010 Q1 includes not only the 'Great Moderation' but also the 'Great Contraction' (Bean (2010)). The volatility of output, investment, inflation and lending fell.

The most significant reduction regards the inflation series, whose standard deviation decreased by more than 50%. By contrast, the volatility of the spread increased almost 25% compared to the full-sample value (0.0101 versus 0.0082). The last observations of this sample include the Great Contraction. In the period 1993 Q1-2007 Q4 the volatility of the spread is 0.003, while it increased more than fourfold (0.0139) when including the period 2008 Q1-2010 Q1. The signs of the correlations are the same as those in the full sample, confirming both the cyclical and the leading characteristics of the macro series. Interestingly, the correlation between output and the spread is higher than the full-sample value.

4 Estimation

Bayesian inference begins with the prior distribution of selected parameters, which describes the available information prior to observing the data used in the estimation. Then the Kalman filter is used to calculate the likelihood function of the data. Combining prior distributions with the likelihood of the data gives the posterior kernel, which is proportional to the posterior density. The posterior distribution of the model's parameters is summarised by the mode and the mean.

4.1 Calibrated parameters

As standard in Bayesian estimation of DSGE models, some parameters are fixed in the estimation procedure (see, eg, Christiano *et al* (2010)). Most of these calibrated parameters, reported in Table B, are related to the steady-state value of variables observed in the economy. The calibrated values of the capital income share, the discount factor, the depreciation rate and the price elasticity of demand are standard in the literature. These values reproduce the ratio of investment to GDP of our data set, equal to 0.18. The elasticity of labour supply, the relative utility weight of labour and the habit persistence parameter have been calibrated such that the average hours of work is equal to 0.33, a common value in the literature. We have chosen to calibrate these parameters since our data set do not contain any information on employment and wages. The three parameters related to the financial sector are calibrated because they pin down some steady-state values of the model economy. In particular, the fraction of assets given to new bankers, the survival rate and the fraction of assets that can be diverted are, respectively, equal to 0.002, 0.94 and 0.19. Those values imply an annual steady-state spread of 118 basis points, consistently with the average value in our data set, and with a steady-state leverage ratio of 11, as

Table B: Calibrated parameters

Parameter	Value
α, capital income share	0.33
β, discount factor	0.99
δ, depreciation rate	0.025
ϵ, price elasticity of demand	6
ϕ, inverse of Frisch elasticity of labour supply	0.33
ω, relative utility weight of labour	4.01
h, habit persistence parameter	0.815
χ, fraction of assets given to the new bankers	0.002
θ, survival rate	0.94
λ, fraction of divertable assets	0.19
ν, feedback parameter for credit policy	0

in Gerali *et al* (2010). The feedback parameter in the credit policy rule, ν, is set equal to zero as GK's 'credit policy' cannot be captured in our data set (see footnote 1).

4.2 Prior and posterior distributions of the estimated parameters

The remaining parameters governing the dynamics of the model are estimated. They mostly pertain to the nominal and real frictions in the model and the exogenous shock processes.

Table C shows the assumptions for the prior distributions of the estimated parameters. The locations of the prior mean correspond to a large extent to those in previous studies on the UK economy, eg Harrison and Oomen (2010) and DiCecio and Nelson (2007).

The posterior distribution of all estimated parameters is obtained in two steps. First, the posterior mode and an approximate covariance matrix, based on the inverse Hessian matrix evaluated at the mode, is obtained by numerical optimisation on the log posterior density. Second, the posterior distribution is explored by generating draws using the Random Walk Metropolis-Hastings algorithm with a sample of 250,000 draws; see Schorfheide (2000) and SW for further details. We use the inverse gamma (IG) distribution for the standard deviation of the shocks and we set a loose prior with two degrees of freedom. We use the beta distribution for all parameters bounded between 0 and 1. For parameters measuring elasticities we use the gamma distribution, and for the unbounded parameters we use the normal distribution. However, for the parameter measuring the response to inflation in the Taylor rule we set a lower bound so that the

Table C: Prior and posterior distributions of structural parameters

	Prior distr			Posterior
Parameters	Distr	Mean	St. Dev./df	Mean
σ, Calvo parameter	Beta	0.75	0.1	0.81
σ_p, price indexation	Beta	0.5	0.2	0.11
S'', Inv. adj. costs	Gamma	5.5	0.25	5.85
ζ, elasticity of marg. deprec	Gamma	1	0.5	1.88
ρ_π, Taylor rule	Normal	1.5	0.2	1.59
ρ_y, Taylor rule	Normal	0.12	0.2	0.39
ρ_i, Taylor rule	Normal	0.87	0.1	0.64
ρ_a, persist of tech shock	Beta	0.85	0.1	0.98
ρ_k, persist of capital shock	Beta	0.5	0.1	0.40
ρ_g, persistence of gov shock	Beta	0.5	0.1	0.51
σ_a, std of tech shock	IG	0.1	2	0.02
σ_k, std of capital shock	IG	0.1	2	0.02
σ_i, std of monetary shock	IG	0.1	2	0.02
σ_n, std of FI capital shock	IG	0.1	2	0.18
σ_g, std of gov shock	IG	0.1	2	0.05

Taylor principle is satisfied. The parameter of price stickiness is assumed to follow a beta distribution with mean 0.75, which corresponds to changing prices every four quarters on average, and we set a relatively loose prior for the indexation parameter as in SW. The elasticity of the investment adjustment cost function has a prior mean of 5.5 and a relatively high standard deviation. The elasticity of marginal depreciation with respect to capital utilisation is set at 1, as in GK, and with a high standard deviation, following the previous studies on the UK economy. The Taylor rule coefficient on inflation has a normal distribution with a prior mean of 1.5 and a relatively high standard deviation, following the studies of Harrison and Oomen (2010), DiCecio and Nelson (2007) and Smets and Wouters (2007). The Taylor coefficient on the output gap is set at 0.12 with a standard deviation of 0.2; and the Taylor smoothing parameter has a prior mean of 0.87, as in Harrison and Oomen (2010) and DiCecio and Nelson (2007).

The last column of Table C shows the posterior mean of all the parameters. The estimated Calvo parameter, σ, implies that firms reoptimise on average every five quarters. The degree of price indexation, σ_p, is lower than its prior mean, similarly to the results obtained by SW for the US economy. The elasticity of the cost of changing investment is estimated to be higher than the prior, suggesting a slower response of investment to changes in the value of capital. The elasticity of marginal depreciation with respect to capital utilisation is also higher, suggesting a small response of capital utilisation to the shocks. Concerning the monetary policy reaction function parameters, the mean of the reaction coefficient to inflation is estimated to be higher than its prior distribution. There is a lower degree of interest rate smoothing, as the mean of the coefficient on the lagged interest rate is estimated to be 0.64. Monetary policy appears to react to the output gap level with a coefficient of 0.39, similar to DiCecio and Nelson (2007).

Finally, turning to the exogenous shock variables, the shock to bank capital is the most volatile. The second most volatile shock is to government. It is worth noting that in a closed-economy model government shock might also capture trade movements; its higher value could be interpreted as a signal of the exogenous disturbances from trade. The technology shock is very persistent, with a coefficient of 0.98; the persistence of the shock to the quality of capital is lower than the prior mean, with a coefficient of 0.40.

4.3 Model fit

Following Adolfson *et al* (2007), in Figure 1 we report the Kalman filtered estimates of the observed variables, computed at the posterior mode of the estimated parameters in the benchmark model along with the actual variables. The red line corresponds to the one step ahead forecasts implied by the estimated model and the blue line represents the data. Roughly speaking, these estimates correspond to fitted values in a regression. As it is evident from Figure 1, the in-sample fit of the baseline model is quite satisfactory for inflation, lending and the spread. The fit for investment improves in the last decade while that of output is overall less satisfactory. This result is not surprising for a number of reasons. First, a closed-economy model is unlikely to perfectly reproduce the GDP fluctuations for the United Kingdom, since external demand is not explicitly modelled. Second, the GK model does not incorporate unemployment or frictions in the labour market, which might be important drivers of GDP fluctuations. Third, since bank capital is explicitly included, the model is able to capture the disruption of financial intermediation, similar to what happened in the recent crisis. Indeed, the fit of the model for GDP is more satisfactory in the period after the onset of the crisis.

There seems to be a support to the empirical properties of the GK model, in particular concerning the financial variables. One of the main novelties of the GK paper is the microfoundation of the banking sector. Therefore, this microfoundation has nice empirical properties when applied to the UK economy. To further assess the conformity between the data and the model, we compare

Table D: Simulated moments

Variable	Std dev	Relative std dev
GDP	0.111	
Investment	0.368	3.32
Inflation	0.054	0.49
Lending	0.239	2.15
Spread	0.072	0.65

the moments generated by the model with the data in Table A. Table D reports some selected moments of the data and the simulated model. Overall, the table shows that the model overpredicts the volatility of output, investment and lending, which is a common problem in DSGE models (see also von Heideken (2009)). The model reproduces the relative standard deviations of investment (3.32 in the simulated model versus 3.13 in the data) and the spread (0.65 in the model versus 0.56 in the data). The relative standard deviations of lending and inflation are slightly different from the actual values (for inflation 0.49 in the model versus 0.93 in the data and for lending 2.15 in the simulated model versus 3.7). This result is not surprising given the estimates obtained in Figure 1. Notwithstanding this, the cyclical features of inflation, less volatile than GDP, and lending, more volatile than GDP, are preserved in the estimated model.

4.4 Subsample estimates

The full sample 1979-2010 includes different monetary regimes: monetary targeting in the late 1970s and early 1980s; exchange rate management, culminating in the UK membership of the ERM; the adoption of inflation targeting in October 1992. We now investigate whether the previous results are sensitive to the chosen sample. Our subsample corresponds to the inflation-targeting period. Table E compares the full-sample estimates with the post-1992 sample estimates.

The comparison between two samples reveals that the Calvo parameter has slightly increased, suggesting that the average duration of price contracts is about six quarters, a quarter more than the full-sample value. The indexation parameter reveals a higher degree of price stickiness in the recent period. Concerning the two real elasticities, the elasticity of the cost of changing investment is lower than the full-sample value and the elasticity of marginal depreciation with

Table E: Subsample estimates

Parameters	Fullsample	Subsample
Mode of estimated parameters		
σ	0.81	0.84
σ_p	0.11	0.19
S''	5.85	4.69
ζ	1.88	1.58
ρ_π	1.59	1.66
ρ_y	0.39	0.37
ρ_i	0.62	0.74
ρ_a	0.98	0.98
ρ_k	0.40	0.37
ρ_g	0.51	0.69
σ_a	0.02	0.01
σ_k	0.02	0.02
σ_i	0.02	0.01
σ_n	0.18	0.19
σ_g	0.05	0.05

respect to capital utilisation is lower as well. Therefore, for investment the real friction is reduced, while for marginal depreciation it has increased, so that the overall the presence of real frictions in the model economy has not changed significantly. The parameters in the Taylor rule seem to signal a different monetary regime: the policymaker's reaction coefficient to inflation is higher than its full-sample value, revealing that in the post-1992 sample period UK monetary policy behaviour opted for more weight on inflation. In contrast, the policymaker's reaction coefficient to the output gap has decreased. Results are quite stable as far as the volatility of the shocks is concerned. The standard error of technology and interest rate shocks have slightly fallen, while the volatility of net worth shock has slightly increased.

5 Model properties

5.1 Impulse response function

In the GK model there are five shocks: while four of them are standard in the literature (the technology, monetary, bank capital and government shock), the shock to the quality of capital is relatively new. In the GK model this last shock is meant to mimic the broad dynamics of the sub-prime crisis.

Figures 2 and 3 show the impulse response functions to four shocks. All the shocks are set to produce a downturn, as in GK. We can distinguish the transmission mechanism from the technology and monetary shocks on one hand, and the bank capital and quality of capital shocks on the other.

Contractionary technology and monetary policy shocks lead to a fall in investment; this implies a decrease in asset prices, which worsens the banks' balance sheet. Such a deterioration implies that banks push up the premium and this reduces the amount of lending, as is evident from Figure 2. The technology shock is a standard supply shock, in the sense that it has a negative effect on output and a positive effect on inflation. The interest rate shock is a standard demand shock, in the sense that it has a negative impact on both output and inflation. The shock to the quality of capital translates directly into a shock to banks' balance sheet because of the identity between capital and assets. In the GK model financial frictions are always binding and depositors require that banks do not become overleveraged. As a result, banks are forced to curtail their lending. The squeeze on credit means that firms are able to buy less capital for use in the following period. The shock to bank capital directly affects the banks' balance sheet as well: the drop in bank net worth tightens the banks' borrowing constraint because banks are leveraged.

In order to better understand the financial accelerator effect in the transmission mechanism, it is worthwhile to note that three factors drive the growth of bank profit: the size of the spread, the lending volume and the leverage. Following a sharp decline in bank net worth, banks have to cut back lending because of the balance sheet constraint. The more leveraged they are, the larger is the impact of capital losses on the reduction in lending. This retrenchment in lending leads to a fall in banks' profits. Banks can only rebuild their profit and capital base by increasing the lending rate; therefore, the spread rises as shown in the figures. In the face of the sharp increase in financing cost, firms are forced to reduce demand for loans and, therefore cut back investment and increase the utilisation rate of capital. Both investment and output suffer a protracted decline. Subdued aggregate demand feeds back to the banking sector resulting in lower profits. This, in turn, causes banks to further tighten credit supply and raise lending spreads in order to satisfy their endogenous balance sheet constraint. This is the financial accelerator effect. It can take a long time for banks to rebuild their capital back to their steady-state level. The slowdown in lending is highly persistent and substantial. And the reduction of the credit flow exacerbates the crisis. As is evident from Figure 3, both shocks are supply shocks. This finding is particularly interesting compared to the findings of GK; in their paper both the shock to the quality of capital and the shock to bank capital behave like demand shocks. Aikman and Paustian (2006) and Meh and Moran (2008) found that a negative shock to bank capital behaves like a supply shock. As Aikman and Paustian (2006) explained, the contraction in the production of intermediate goods is accompanied by higher prices, implying higher marginal costs. The increase in marginal costs is expected to persist and this results in an upward pressure on inflation.

It is not surprising that the shock to the quality of capital behaves like a supply shock, because in the GK model it affects the capital accumulation equation and, therefore, the production function, equation **(8)**.

5.2 Historical decomposition

Now we have estimated the model and studied its propagation mechanism, we can use it to quantify the relative importance of different shocks. Indeed, one advantage of having an estimated DSGE model (as opposed to a calibrated one) is that we can decompose movements in endogenous variables into that part caused by each of the shocks. More specifically, given the starting values of all the endogenous variables in the model, we can run a simulation in which one shock, say to credit supply, follows its historical path while the other shocks are set equal to zero in all periods. This simulation shows us the proportion of movements in the endogenous variables that are due to this particular shock. We can repeat this exercise for all the shocks so as to apportion movements in the endogenous variables between them all. Doing that, we can see what shocks have contributed to the movement in macro and financial variables at different stages of the business cycle.

We assume that the economy is driven by five shocks: productivity, bank capital, monetary policy, government spending, and a shock to capital quality.

We decompose output, inflation, corporate bond spreads and lending for the whole sample period. Figure 4 plots the shock decomposition for a more recent period (2006 Q1- 2010 Q1).

The first chart shows which shocks are important in explaining the sharp fall in real output by 6% in the recent crisis. Firstly, a bank capital shock in red contributes negatively to a decline in output from its trend. Since the onset of the crisis, this shock on its own would be pushing GDP 3% below its trend. Secondly, what may seem surprising is that the government expenditure shock in yellow also pushes down GDP. In fact, this is because the yellow bar here is likely to capture both shocks to government expenditure and net trade; since we apply a closed-economy model, the external sector is not explicitly modelled. We calibrate the steady-state parameters to let consumption and investment match their shares in GDP. Then we allow the share of government expenditure to pick up the rest of GDP that is not included in consumption and investment. This implies that the shock to government expenditure, in effect, reflects both shocks to government expenditure and shocks to external demand. In the recent crisis, the economy was hit by a large negative shock in external demand. The negative contribution of yellow bars indicates that the negative external demand shock is more than offsetting the expansionary effect of government spending in the early stage of the crisis. Overall, this negative effect from external demand may explain 2% of the fall in GDP. Offsetting this is the monetary policy shock.

The second chart in Figure 4 shows a historical decomposition for corporate bond spreads. Since the beginning of the crisis, corporate spreads have risen about 400 basis points from trough to peak. It is interesting to know whether this is driven by credit demand or credit supply conditions. But given we only observe the final price which reflects the equilibrium condition of demand and supply, it is very difficult to identify credit demand *versus* supply shocks in a reduced-form analysis (see Chadha *et al* (2010) for a similar identification issue applied on money demand and money supply). Nevertheless, a structural model like this offers a natural environment to study the issue. The credit supply shock is the one that originated from the financial sector and only affects banks' ability to extend credit, and in this model it includes a shock to bank net worth and a shock to the capital quality. While a shock that affects firms demand for credit, a shock to TFP, interest rate and fiscal expenditure, can be categorised as credit demand shock. The third chart in Figure 4 shows that the sharp rise in spread since the crisis can be mainly attributed to credit supply shocks, although in the most recent quarter, credit demand starts to play a role as well.

Finally, we study bank lending behaviour in the recent crisis. In particular, we ask to what extent the subdued bank lending is driven by credit supply *versus* demand factors. The last chart suggests that as much as banking sector shock (in red) and capital quality shock (in green) seem to have contributed positively to bank lending before the crisis, they act to drag down bank lending significantly since the onset of the crisis. These two shocks together seem to explain most of the weakness in bank lending.

5.3 Model comparison

The introduction of a large number of frictions raises the question of which of those are really necessary to capture the dynamics of the data. Bayesian estimation techniques can address this type of issue. As illustrated by Chang *et al* (2002), the marginal data density can be interpreted as maximum log-likelihood values; it provides an indication of the overall likelihood of the model given the data.

In this section, we examine the contribution of each of the frictions to the marginal likelihood of the model. In particular, we analyse three types of frictions: nominal frictions (price stickiness, price indexation), real frictions (investment adjustment, capital utilisation) and financial frictions. Table F presents the estimates of the mode of the parameters and the marginal likelihood when each friction is drastically reduced one at a time. We also analyse the robustness of the parameters under the different specifications.

In order to make a meaningful comparison with the model without financial frictions (no ' FF'), we use four observables for all the models described in Table F and, therefore, four structural shocks in the model economy. Unlike the BGG framework, removing financial frictions in the GK model is not obtained by setting a certain parameter equal to zero. We have calculated again the equilibrium conditions for the standard DSGE model, where the banking sector has been removed. There is no spread variable and no shock to bank capital in the model 'no FF' , so the spread is not used as observable in the Bayesian estimation procedure. For comparison, the first column reproduces the baseline estimates (mode of the posteriors) and the marginal likelihood based on the Laplace approximation for the model.

Concerning nominal frictions, we reduced the Calvo probability to 0.1, so that on average a firm reoptimises its price every quarter. The marginal likelihood of the model is reduced to 1,122, while in the baseline model it is 1,231. A lower degree of price stickiness does not have a great impact on the mode of the parameters, which are quite stable across the two models.

Removing price indexation to past inflation, that is setting $\sigma_p = 0$, implies a moderate reduction of the marginal likelihood (to 1,224). The values of the estimated parameters are substantially stable under this different model specification. Concerning real frictions, removing the investment adjustment costs implies a considerable deterioration in the marginal likelihood (to 1,087). The parameter most affected by the significant reduction of the elasticity of adjustment cost is the persistence of the technology shock, whose mode decreases. The presence of variable capital utilisation is examined by setting the value of the elasticity of depreciation with respect to capital utilisation to 3.5. A larger ζ implies that variation in capital utilisation is more costly (in terms of higher depreciation rate) and, thus, capital utilisation varies less. Therefore, the elasticity of the marginal depreciation with respect to capital utilisation is a measure of how variable the capital utilisation rate can be. In the standard RBC model, the value of this parameter tends to infinity: the cost of changing the utilisation rate is very high and cost-minimising firms decide not to vary the utilisation rate at all. Removing this friction is not costly in terms of marginal likelihood, which increases slightly to 1,244. This result is in line with SW. As far as nominal and real frictions are concerned, the most important friction in terms of empirical performance of the model is the investment adjustment costs parameter, similarly to SW. The last column of Table F presents the results for the model without financial frictions (FF). The marginal likelihood reveals that the model without FF has the worst empirical performance (marginal likelihood 1,076). Given the significant deterioration of the marginal likelihood, the data clearly favour the model with financial frictions in the UK economy. The parameters most affected are the Calvo parameter and the standard deviations of the technology and government shocks, whose modes have increased.

6 Credit policy

The GK model has been estimated without credit policy: the feedback parameter of equation **(5)** has been set equal to zero. We now solve the GK model using the estimated parameters of Table C and setting the feedback parameter in the credit policy equal to two different values: $\nu = 10$ and $\nu = 50$. In the GK paper $\nu = 10$ corresponds to an intervention by the central bank roughly in line with what has occurred in practice in the United States. When $\nu = 50$ the intervention by the policymaker is more aggressive. In this experiment, therefore, the policymaker is now implementing both the Taylor rule and the credit policy. Thus, the policymaker might offset the contraction shown in Figures 2 and 3 with the non-standard measure, aimed to increase liquidity provisions.

Table F: The importance of the different frictions

	Base	$\sigma = 0.1$	$\sigma_p = 0$	$S'' = 0.1$	$\zeta = 3.5$	no FF
Marginal likelihood						
	1231	1122	1224	1087	1244	1076
Mode of estimated parameters						
σ, Calvo parameter	0.80	0.10	0.80	0.83	0.81	0.85
σ_p, price indexation	0.15	0.15	0	0.16	0.15	0.16
S'', Inv. adj.costs	6.00	6.00	6.00	0.10	6.00	5.99
ζ, elasticity of marg. depr.	1.90	1.90	1.90	1.90	3.5	1.91
ρ_π, Taylor rule	1.65	1.66	1.65	1.66	1.65	1.65
ρ_y, Taylor rule	0.31	0.29	0.30	0.40	0.37	0.28
ρ_i, Taylor rule	0.75	0.73	0.76	0.60	0.76	0.77
ρ_a, persist of tech shock	0.93	0.89	0.94	0.82	0.94	0.85
ρ_k, persist of capital shock	0.51	0.51	0.51	0.43	0.51	0.53
ρ_g, persist of gov shock	0.48	0.48	0.48	0.49	0.48	0.50
σ_a, std of tech shock	0.02	0.03	0.01	0.03	0.02	0.06
σ_k, std of capital shock	0.04	0.03	0.03	0.04	0.04	0.05
σ_i, std of monetary shock	0.01	0.02	0.01	0.01	0.01	0.03
σ_g, std of gov shock	0.05	0.05	0.05	0.05	0.05	0.08

Figure 5 reports this experiment. We have analysed the response of output to the two 'financial' shocks: the quality of capital and bank capital. The case of an interest rate shock has not been examined, because it is unlikely that the policymaker would increase interest rates and at the same time decide to inject credit in the economy to offset the recession. The same rationale applies to the government shock. The black line is the response of the variable in the absence of the credit policy. The grey line represents the response of the corresponding variable when $\nu = 10$ and the red line corresponds to $\nu = 50$. The intervention by the policymaker makes the crisis less severe in both cases. In the case of the shock to the quality of capital we have reported in Figure 5 the impulse responses of output, inflation, lending and the spread. The moderate intervention by the policymaker, $\nu = 10$, corresponds to the injection of 7% of the value of total capital stock. And the more aggressive intervention, $\nu = 50$, corresponds to the injection of 11%. The credit policy significantly affects the reaction of the spread, as is evident in the figure. The modest rise in the spread attenuates the financial accelerator mechanism described in Section 5. As a result, the intervention by the policymaker reduces the tightening of lending and the contraction of output. The effect on inflation in significantly small. The more aggressive intervention further moderates the contraction.

For the net worth shock, a moderate intervention corresponds to the injection of 5% of the value of the total capital stock. The more aggressive intervention, $\nu = 50$, corresponds to the injection of 7%. The contraction of output is lower in the presence of credit policy, but is slightly more persistent. The impact of credit policy on inflation is less prominent. The credit policy reduces the contraction of lending. As expected, the spread is significantly reduced when credit policy is at work; given the financial accelerator mechanism explained in the previous section, the moderate rise in the spread implies a lower contraction in lending and a lower fall in banks' profits.

In the United Kingdom, there is evidence that asset purchases by the central bank helped to restore liquidity in various funding markets and in turn reduced funding costs for banks. Consequently, such asset purchases would help to reduce private sector borrowing costs, which is the aim of the credit policy modelled in the paper. Moreover, in addition to preventing considerably more serious systemic problems in the banking sector, it is likely that the authorities' direct recapitalisation of UK banks has also helped to restore bank lending by helping banks to rebuild their balance sheets.

7 Conclusions

We have estimated Gertler and Karadi's model incorporating financial intermediation and frictions for the UK economy, using Bayesian techniques. The fit of the model is quite satisfactory, in particular for the financial variables. The estimation suggests that financial frictions play an important role in explaining UK business cycles. The historical decomposition suggests that the banking sector shocks explain around half of the fall in real output from its trend in the most recent crisis. Credit supply shocks seems to explain most of fall in bank lending and rises in lending spreads.

The paper finds that financial factors have played a significant role both in the systematic component of business cycle behaviour and also in the recent recession. Therefore, financial frictions cannot be ignored in setting systematic monetary policy nor in dealing with recovery from recession.

Figure 1: Fit of the model

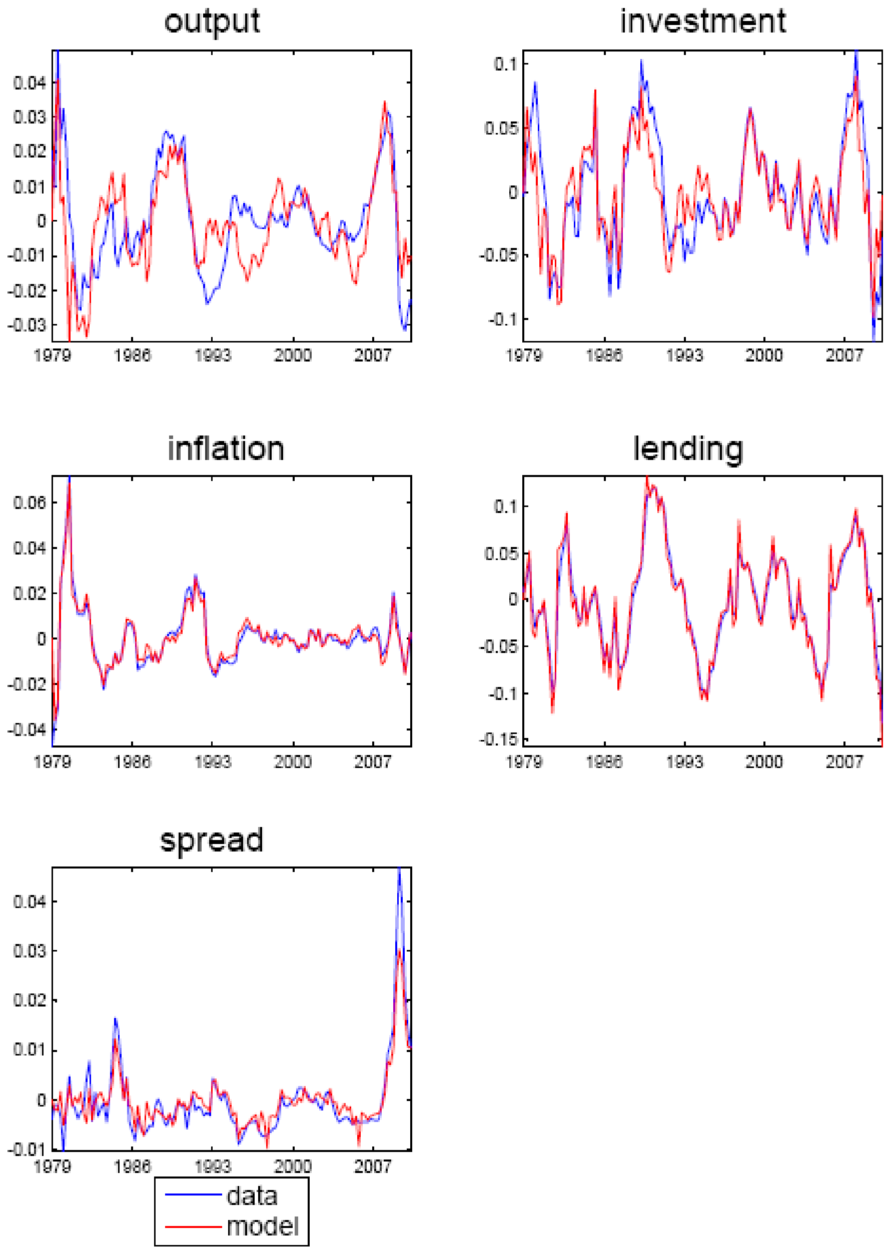


Figure 2: Estimated IRFs to a technology shock and interest rate shock. Standard error of shocks are both 2%.

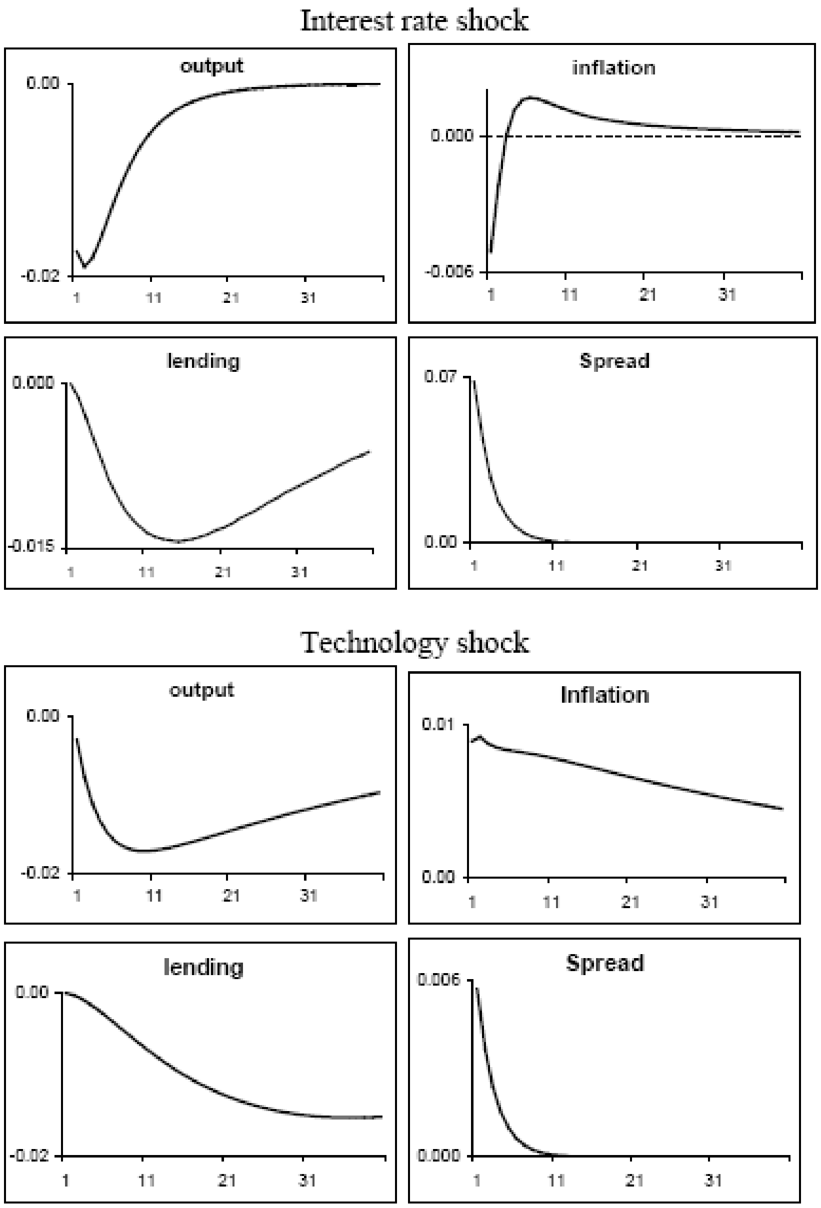


Figure 3: The estimated IRFs to a shock to the quality of capital and to a shock to bank capital. Standard errors of shocks are 2% and 18% respectively.

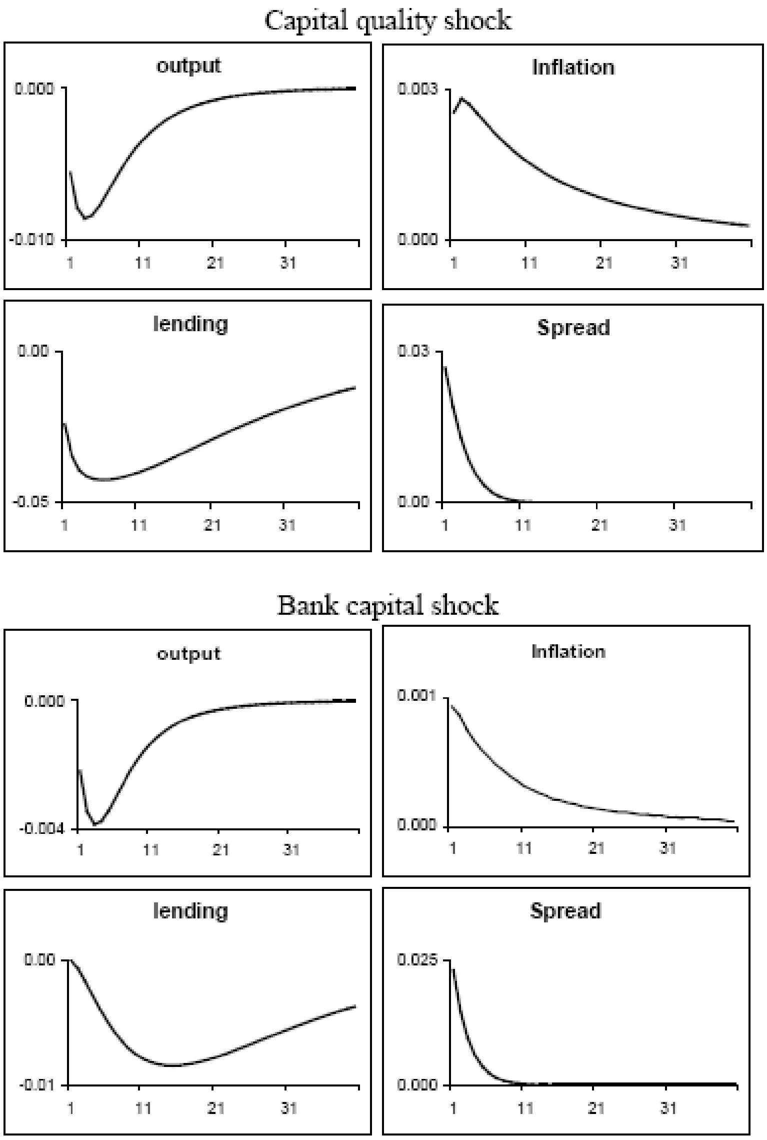


Figure 4: Historical decomposition

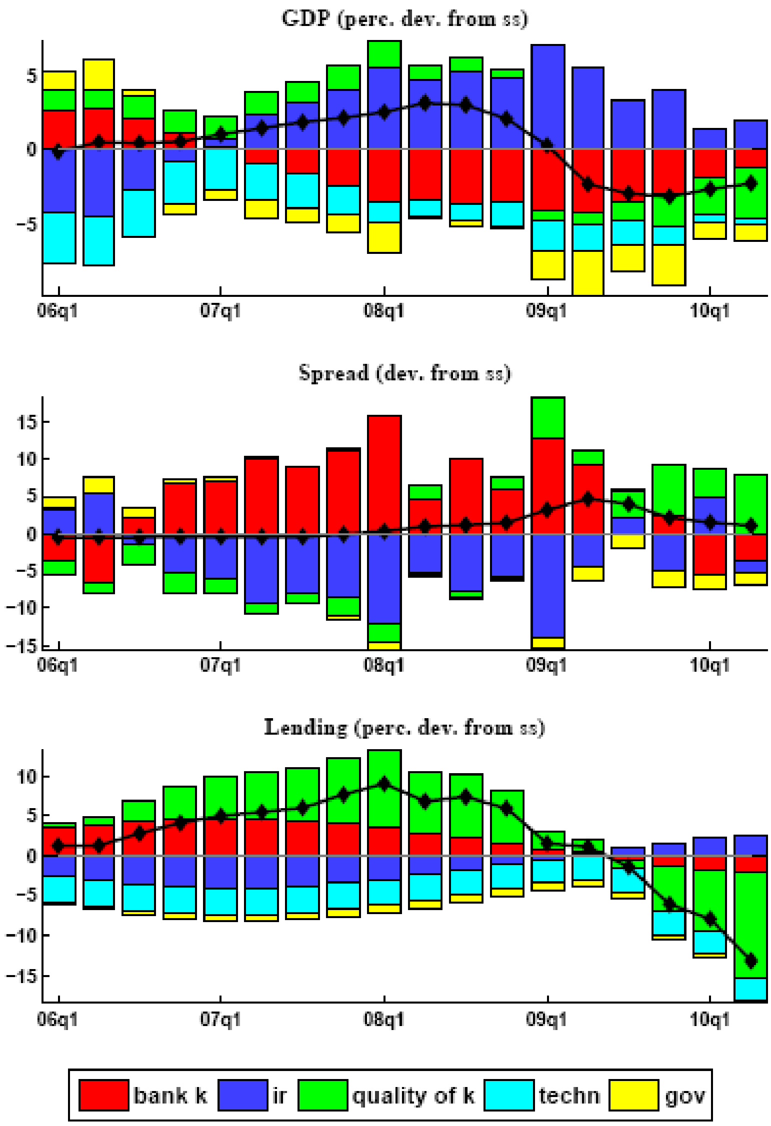
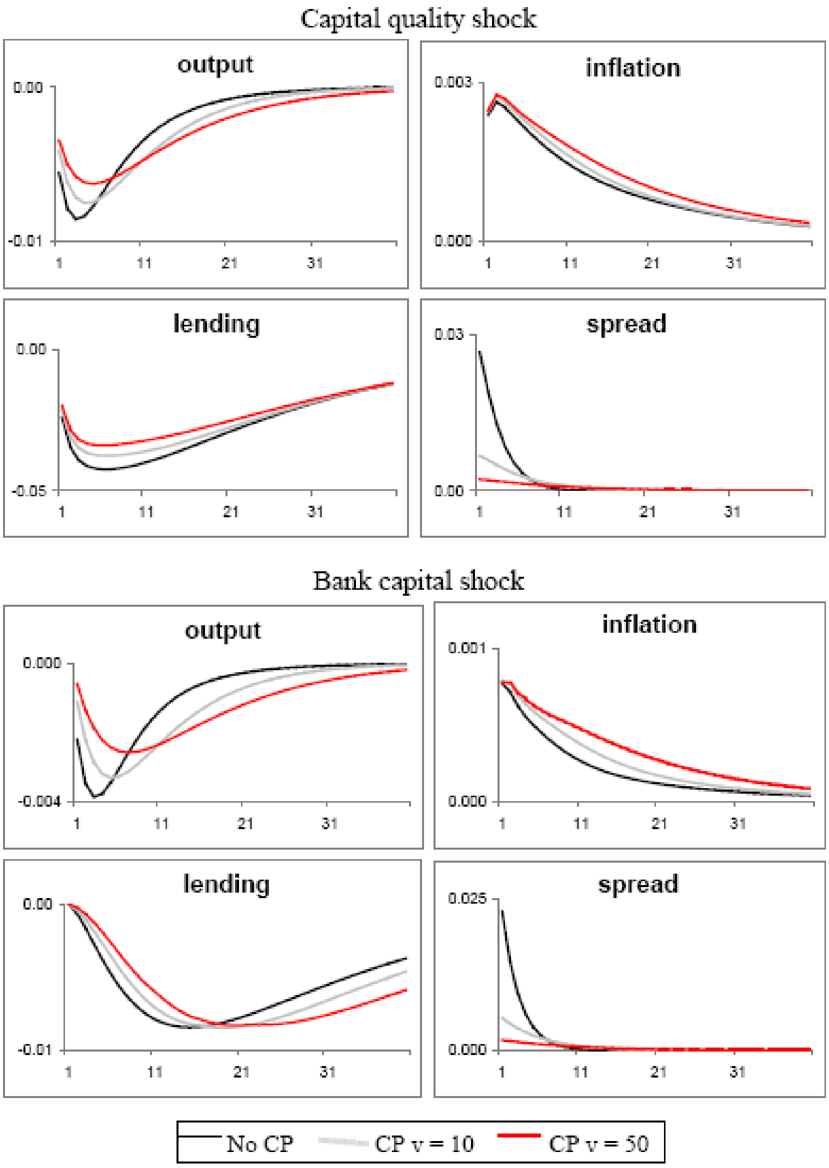


Figure 5: Estimated IRFs with and without credit policy



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