Financial intermediaries in an estimated DSGE model for the UK *

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Abstract

Gertler and Karadi (2009) combined financial intermediation and unconventional 'monetary policy'(i.e., direct lending to financial institutions) in a DSGE framework. First, we estimate their model with UK data using Bayesian estimation techniques. To validate the fit of the estimated DSGE model, we provide an evaluation of the model's empirical properties. Then, we analyse the transmission mechanism of the shocks, set to produce a downturn. Finally, we deal with some key issues in business cycle analysis: we examine the empirical importance of nominal, real and financial frictions and of different shocks. Our main findings are that the data strongly favour a model with financial frictions for the UK economy; the sharp rise in spread since the recent

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crisis can be mainly attributed to credit supply shocks; and the credit policy might help to make the simulated contraction less severe.

1 Introduction

Gertler and Karadi (2009) (GK, henceforth) presented a DSGE model with financial frictions and unconventional monetary policy (in the form of direct lending to financial institutions), calibrated for the US economy. Differently from Bernanke et al. (1999) and Kiyotaki and Moore (1997), the financial frictions directly originate in the financial sector and financial intermediaries play an active role in the transmission mechanism. The financial intermediaries face an agency problem and their balance sheets are endogenously constrained.

Their paper is particularly interesting for three main reasons: first, the authors have emphasized the role of financial intermediaries in the transmission mechanism of the shocks. Second, their paper is the first attempt to quantitatively assess central bank intermediation as an additional tool for monetary policy in a DSGE framework. And finally, the model tried to capture the key elements of the sub-prime crisis.

As Bean (2009) 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 in the amplification of the transmission mechanism.

The question 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 the financial variables. Bayesian estimation techniques are used to estimate the model with financial intermediaries and without unconventional monetary policy.[1]

The Bayesian DSGE approach has become very popular in recent times both in the academia and central banks because it can address a number of key issues in business cycle analysis (see Smets and Wouters (2007), Adolfson

[1] GK's unconventional monetary policy consists in the direct lending to financial institutions so that the central bank assumes an intermediation role. While the UK government pursued such policies during the financial crisis, this is clearly not the policy of Quantitative Easing undertaken by the Bank of England. We note that, even though we are using data from 1979 to 2009Q2, the effects of what GK describe as unconventional monetary policy would be hard to estimate, due to the absence of such policies through most of the period.

et al. (2007), Gertler et al. (2008), among many others).[2]
We first analyse the model fit for the UK economy. The comparison between the model fit and the data will be made along two dimensions: the Kalman filtered estimates of the observed variables, computed at the posterior mode of the estimated parameters in the model, 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, its baseline specification is compared with a model without respectively nominal, real and financial frictions. Impulse response functions are used to summarize the predictions of the model for the UK economy.
Finally, some policy implications are presented via IRFs analysis, when unconventional monetary policy is 'at work'.
The structure of the paper is as follows: in section 2 the main equations 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 discusses the empirical importance of different frictions. Section 5 presents the impulse responses to different shocks; it provides subsample estimates and it quantitatively analyses the relative importance of different shocks. Section 6 presents some policy implications. The final section offers some concluding remarks and future lines of research.

2 The linearised 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 less vast literature on the role of bank capital, e.g. Aikman and Paustian (2006), Meh and Moran (2008) and Gertler and Kiyotaki (2009). And third, the standard DSGE modelling with frictionless capital markets: Christiano, Eichenbaum and Evans (2005) and Smets and Wouters (2007), (SW, henceforth).
The agents in the GK model are: households, financial intermediaries (FIs), intermediate goods firms, capital producers, monopolistically competitive retailers; *and* the central bank.

[2] Fernández-Villaverde (2009) provides a comprehensive survey about Bayesian estimation of DSGE models.

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 have introduced a finite horizon for bankers in order to avoid 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 becomes 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 total assets, χ. Each banker manages a financial intermediary.

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. The following incentive compatibility constraint should hold for the lender to deposit money in the FI:

$$V_t \geq \lambda Q_t S_t \tag{1}$$

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 (1) 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:

$$Q_t S_t = \phi_t N_t \tag{2}$$

where ϕ stands for the FI leverage ratio and N_t is FI capital (or net worth). According to equation (2) 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:

$$N_t^e = \{\theta[(R_t^k - R_{t-1})lev_{t-1} + R_{t-1}]N_{t-1}\}\exp(-\varepsilon_{n,t}) \tag{3}$$

where R_t is the riskless interest rate on deposit, R_t^k is the lending rate and $e_{n,t}$ is a shock to FI capital.
Each intermediate-good 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:

$$Q_t K_{t+1} = Q_t S_t \tag{4}$$

Lending to firms does not involve any agency problem. However, the constraint that FIs face (equation 2) affects the supply of funds to intermediate firms and the lending rate.
The Central Bank conducts both conventional and unconventional monetary policy: a standard Taylor rule (see equation LL-13) and the following feedback rule for credit policy:

$$cp_t = cp + \nu[(R_{t+1}^k - R_t) - (R^k - R)] \tag{5}$$

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

where $Q_t S_{ct}$ is the value of assets intermediated via the central bank, which is a fraction, cp_t, of total assets. Under steady state the fraction of publicly intermediated assets is zero.
Unconventional monetary policy works in GK as follows: the CB, after obtaining funds from households at the rate R, lends the funds to the FIs at the market lending rate R^k, which in turn lend to firms at the same rate. Therefore, there is no effect on the FI balance sheet. The central bank always honours its debt so there is no agency conflict that limits central banks ability to obtain funds from households. In other words, the central bank does not have a balance sheet constraint that limits its lending capacity.
In terms of main linearised equations, variables without time subscripts denote steady-state values, and the circumflex denotes a percentage deviation from steady state.
The incentive constraint can be written as:

$$\hat{S}_t + \hat{Q}_t - S\hat{cp}_t = \hat{lev}_t + \hat{N}_t \tag{LL-1}$$

where cp stands for credit policy.
Total net worth is:

$$\hat{N}_t = \frac{N^e}{N}\hat{N}_t^e + \frac{N^n}{N}\hat{N}_t^n \tag{LL-2}$$

The spread is defined as:

$$\hat{SP}_t = \hat{R^k_{t+1}} - \hat{R}_t \tag{LL-3}$$

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

$$\beta h E_t[\hat{c}_{t+1}] = (1 + \beta h^2)\hat{c}_t - h\hat{c}_{t-1} + (1 - h)(1 - \beta h)\hat{mu}_t \tag{LL-4}$$

where $\beta > 0$, mu stands for marginal utility and h captures habit formation. The labour supply is

$$\phi\hat{\ell}_t = \hat{w}_t + \hat{mu}_t \tag{LL-5}$$

where ϕ is the inverse of Frisch elasticity of labour supply.
The net worth of existing bankers, N^e, is:

$$\hat{N}^e_t = \hat{N}_{t-1} + \hat{z}_t - \varepsilon^n_t \tag{LL-6}$$

where ε^n_t is the bank capital shock and z is the gross growth rate of net worth.
The production function is a standard Cobb-Douglas with variable capital utilization. The demand for capital is:

$$\hat{R}^k_t + \hat{q}_{t-1} = \frac{1}{R^k}\left[\delta'(U)(\hat{y}_t - \hat{k}_t - \hat{u}_t - \hat{\mu}_t) + \hat{\psi}_t + \hat{q}_t\right] \tag{LL-7}$$

where u is the utilization rate, μ is the mark-up and ψ is the shock to the quality of capital (which is meant to capture economic obsolescence).
The labour demand can be written as:

$$\hat{w}_t = -\hat{\mu}_t + \hat{y}_t - \hat{\ell}_t \tag{LL-8}$$

The condition for optimal capital utilization is:

$$(1 + \zeta)\hat{u}_t = -\hat{\mu}_t + \hat{y}_t - \hat{k}_{t-1} - \hat{\psi}_t \tag{LL-9}$$

where ζ is the elasticity of marginal depreciation with respect to capital utilization.
The capital accumulation equation is:

$$\hat{k}_t = (1 - \delta)\hat{k}_{t-1} + \hat{\psi}_t - \delta'(U)\hat{u}_{t-1} + \delta\hat{I}_{t-1} \tag{LL-10}$$

GK introduce net investment, I_t^a, that is the investment used for the construction of new capital goods:

$$\hat{I}_t^a = \hat{I}_t - \delta\prime K \hat{u}_t - \delta \hat{k}_t \quad \text{(LL-11)}$$

The Phillips curve is:

$$\hat{\pi}_t = \frac{\sigma_p}{1+\sigma_p\beta}\hat{\pi}_{t-1} + \frac{\beta}{1+\sigma_p\beta}E_t\{\hat{\pi}_{t+1}\} - \frac{(1-\beta\sigma)(1-\sigma)}{(1+\sigma_p\beta)\sigma}\hat{\mu}_t \quad \text{(LL-12)}$$

where σ is the probability of keeping prices constant and σ_p measures indexation to past inflation.
The Taylor rule can be expressed as:

$$\hat{i}_t = \rho_i \hat{i}_{t-1} + (1-\rho_i)(\rho_\pi \hat{\pi}_t + \rho_y \hat{y}_t) + \varepsilon_{i,t} \quad \text{(LL-13)}$$

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

$$A_t = \rho_a A_{t-1} + \varepsilon_t^a$$

$$\psi_t = \rho_k \psi_{t-1} + \varepsilon_t^k$$

$$g_t = \rho_g g_{t-1} + \varepsilon_t^g$$

where $\rho_i \in (0,1)$ with $i = a, k, g$ and ε_t^i is an i.i.d. shock with constant variance $\sigma_{\varepsilon^i}^2$.[3]

3 The data

To estimate the model we use quarterly UK data for the period 1979Q1-2009Q2 and we match the following five observable variables: real GDP (y), real consumption (consump), CPI seasonally adjusted inflation (sa inf), lending to private non-financial corporations (PNFCs) and corporate bond spread.[4]

[3] The system of all linearised equations is available upon request.
[4] Data come from the Bank of England database.

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. The reason why we are considering M4 lending to PNFCs is that the GK model is analysing lending to PNFCs only.

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 consumption and of the stock of lending to PNFCs have been detrended with the HP filter. Inflation is calculated as log difference of seasonally-adjusted CPI. Data on lending have been deflated with the GDP deflator. Data on the spread have been divided by 100 to make the units compatible with the HP data.

We have chosen this period following DiCecio and Nelson (2007). Notwithstanding, this sample period has been characterized by different monetary policy regimes (Nelson (2006) and Benati (2004)). Hence, in section 5 we compare the full-sample estimates with the post-1992 period, when inflation targeting has been adopted.

Table 1 presents some statistical properties of the data; as far as the full sample is concerned, the series display different volatilities: the volatility of consumption is slightly higher than that of output,[5] which is higher than that of inflation. The relative standard deviations of consumption (consum/GDP) is 1.06; while the relative standard deviations of inflation (infl/GDP) is 0.74. Lending to PNFCs is more volatile than output. The spread is less volatile than output, with a relative standard deviation of 0.59.

As far as cross correlations are concerned, the data reflects the intuitive economic properties that output and consumption 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 (Aksoy et al. (2009), among others). Moreover, Gertler and Lown (1999) have found that the corporate bond spread seems to lead movements in the output by 1-2 years.[6] They found higher values of correlation between output and the spread, compared to those in table 1; notwithstanding, the negative correlation confirms that the spread leads output.

[5] In contrast to US and the euro area, in UK consumption is slightly more volatile than output (Bean et al. (2002)).

[6] A rise in the spread signals a subsequent decline in output, consistently with the GK model.

All these results are in line with Bean et al. (2002), who used a different filtering technique over the sample 1970-2000.
The subsample period 1993-2009Q2 includes not only the 'Great Moderation'but also the 'Great Contraction'(Bean (2009)). The volatility of output, consumption and inflation fell considerably. On the contrary, the volatility of the spread has increased; the last 6 observations of this sample includes the Great Contraction. In the period 1993-2007Q4 the volatility of the spread is 0.0032, while it triplicates when including the period 2008-2009Q2. And in general, the volatility of all the series is lower for the period 1993-2007, as expected.
The sign of the correlations are generally the same as those in the full sample. Interestingly, the values of the correlation between output and the spread is higher than the full sample value.

			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	0.0141						
consump	0.0150	1.06	0.35	0.57	0.85	0.56	0.24
inflation	0.0104	0.74	0.23	0.25	0.33	0.15	-0.26
lending	0.0515	3.65	0.34	0.33	0.34	0.11	-0.09
spread	0.0083	0.59	0.15	0.04	-0.36	-0.26	-0.11
1993-2009Q2							
GDP	0.0112						
consump	0.0083	0.74	-0.01	0.16	0.78	0.51	-0.03
inflation	0.0035	0.31	0.05	0.22	0.38	0.27	-0.30
lending	0.0462	4.13	0.26	0.33	0.46	0.19	0.02
spread	0.0104	0.93	0.35	0.18	-0.54	-0.38	-0.13

Table 1: Some statistical properties of the data (1979-2009)

4 Estimation

Bayesian inference starts out from setting the prior distribution of selected parameters; the prior 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 summarized 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, e.g., Smets and Wouters (2007)). We have chosen to calibrate the parameters we think are weakly identified by the observable variables used; most of these parameters are related to the steady state value of variables observed in the actual economy. Table 2 reports the calibrated parameters.

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. The feedback parameter in the credit policy rule, ν, is set equal to zero because what GK describe as unconventional monetary policy cannot be captured in our dataset (see footnote 1). The parameter χ refers to the fraction of assets given to new bankers; when estimating this parameter the posterior distribution coincides with the prior. This is an indication that our dataset is not informative for the purpose of its identification, hence we use the same calibrated value of GK.

The elasticity of labour supply has been calibrated as the dataset do not contain any information on employment and wages. The value of this parameter is set equal to 0.33, as in GK.

Parameter	**Value**
α, capital income share	0.33
β, discount factor	0.99
δ, depreciation rate	0.025
ϵ, price elasticity of demand	11
ν, the feedback parameter for credit policy	0
χ, fraction of assets given to the new bankers	0.003
ϕ, inverse of Frisch elasticity of labour supply	0.33

Table 2: Calibrated parameters

4.2 Prior and posterior distribution of the estimated parameters

The remaining 18 parameters, which mostly pertain to the nominal and real frictions in the model as well as the exogenous shock processes, are estimated. Table 3 shows the assumptions for the prior distributions of the estimated parameters. The location of the prior distribution corresponds to a large extent to that in SW for U.S. data and that in Adolfson et al. (2007) for Euro area data.

We use the inverse gamma (IG) distribution for the standard deviation of the shocks and we set a loose prior with 2 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 Taylor principle is satisfied.

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 optimization on the log posterior density. Second, the posterior distribution is subsequently 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. The results are reported in the last two columns of Table 3, which shows the posterior mode and mean of all the parameters.

Parameters	Prior distr			Posterior	
	Distr	Mean	St. Dev./df	Mode	Mean
σ, Calvo parameter	Beta	0.7	0.05	0.67	0.67
σ_p, price indexation	Beta	0.5	0.05	0.50	0.49
S'', Inv. adj. costs	Gamma	5.48	0.05	5.48	5.56
ζ, EDCU	Gamma	1	0.1	1.00	0.96
h, habit parameter	Beta	0.7	0.1	0.58	0.58
θ, survival rate	Beta	0.952	0.05	0.966	0.966
λ, divertable assets	Beta	0.25	0.05	0.21	0.18
ρ_π, Taylor rule	Normal	1.5	0.1	1.51	1.49
ρ_y, Taylor rule	Normal	0.125	0.1	0.12	0.12
ρ_i, Taylor rule	Normal	0.5	0.1	0.50	0.50
ρ_a, persist of tech shock	Beta	0.85	0.1	0.93	0.94
ρ_k, persist of capital shock	Beta	0.5	0.1	0.51	0.51
ρ_g, persistence of gov shock	Beta	0.5	0.1	0.57	0.57
σ_a, std of tech shock	IG	0.2	2	0.02	0.02
σ_k, std of capital shock	IG	0.1	2	0.03	0.02
σ_i, std of monetary shock	IG	0.1	2	0.02	0.02
σ_n, std of FI capital shock	IG	0.1	2	0.22	0.26
σ_g, std of gov shock	IG	0.1	2	0.06	0.06

Table 3: Prior and posterior distributions of structural parameters

Overall, the dataset are quite informative on the parameters. The shock to the FI capital is the most volatile. The technology shock is persistent; the persistence of the shock to the quality of capital is lower than the calibrated value of GK. This is not surprising because in the GK model this shock tries to capture the current crisis.

The estimates of the main behavioural parameters also reveal that the dataset is informative. The estimated Calvo parameter implies that firms reoptimise on average every three quarters. The degree of price indexation is close to its prior. The elasticity of the cost of changing investment is estimated to be close to that assumed *a priori*, suggesting a slow response of investment to changes in the value of capital. The elasticity of marginal depreciation with respect to capital utilization (0.96) is slightly lower than assumed a priori, suggesting a higher response of capital utilization to the shocks. The habit formation parameter is lower than assumed a priori. The financial parameters are respectively λ and θ; the first parameter is equal to 0.18, slightly less to

the value of 0.25. The parameter θ is equal to 0.966, implying a steady state leverage ratio of about 10; it is worth noting that GK set this value equal to 4, which is substantially lower than the leverage ratio of FIs in UK.
Finally, turning to the monetary policy reaction function parameters, the mean of the reaction coefficient to inflation is estimated to be close to its prior distribution. There is a considerable degree of interest rate smoothing, as the mean of the coefficient on the lagged interest rate is estimated to be 0.51. Monetary policy appears to react to the output gap level (0.124).

4.3 Model fit

Following Adolfson et al. (2007), in Figure 2 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. Roughly speaking, these estimates correspond to fitted values in a regression. As it is evident from the figure, the in-sample fit of the baseline model is quite satisfactory for all the variables, very satisfactory for the financial variables and consumption. This first check seems to support the emprical properties of the GK model, in particular concerning the financial variables.
To further assess the conformity between the data and the model, we compare the moments generated by the model with the data in table 1. Table 4 reports some selected moments of the data and the simulated model. Overall, the table shows that the model overpredicts the volatility of output, consumption and lending, which is a common problem in DSGE models (see also von Heideken (2009)). The model reproduces the relative standard deviations of consumption (1.24 in the simulated model versus 1.06 in the data) and lending (3.41 versus 3.57). The relative standard deviations of inflation and the spread are slightly lower than the actual values (for inflation 0.3 in the simulated model versus 0.7 and for the spread 0.33 versus 0.59).

Variable	std dev	relative std dev
GDP	0.088	
consumption	0.109	1.24
Inflation	0.026	0.30
lending	0.30	3.41
spread	0.029	0.33

Table 4: Simulated moments

4.4 Model comparison

Similarly to SW, 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. In this section, we examine the contribution of each of the frictions to the marginal likelihood of the DSGE model. In particular, we analyse three types of frictions: nominal frictions, real frictions and financial frictions. Table 5 presents the estimates of the mode of the parameters and the marginal likelihood when each friction (price stickiness, price indexation, investment adjustment, habit formation, capital utilization, and credit frictions) is drastically reduced one at a time. For comparison, the first column reproduces the baseline estimates (mode of the posterior) and the marginal likelihood based on the Laplace approximation for the model.

Concerning nominal frictions, we have reduced the Calvo probability to 0.1 and the marginal likelihood of the model is significantly reduced to the value of 1580, while in the baseline model it is 1743. The parameters more affected are the habit formation, whose mode is higher, and the persistence of the technology shock, whose mode has increased. A lower degree of price stickiness does not have a great impact on the other parameters.

Price indexation also plays an important role in terms of marginal likelihood, which decreases to the value of 1432 in the model without price indexation.

Concerning real frictions, removing the investment adjustment costs implies a considerable deterioration in terms of marginal likelihood, whose value becomes 1347. The parameters most affected are the habit parameter, the persistence of the technology shock and the standard error of the government shock, whose mode increases.

Reducing habit formation is less costly in terms of marginal likelihood; most of the parameters are not affected, but the standard error of the bank capital shock which slightly increases.

The presence of variable capital utilization is examined by setting the value of the elasticity of depreciation with respect to capital utilization to 2.5. A larger ζ implies that variation in capital utilization is more costly (in terms of higher depreciation rate) and, thus, capital utilization varies less. Therefore, the elasticity of the marginal depreciation with respect to capital utilization is a measure of how variable the capital utilization rate can be. In the standard RBC model, the value of this parameter tends to infinity: the cost of changing the utilization rate is very high and therefore cost-minimising firms decide not to vary utilization rate at all. Removing this friction implies that the marginal likelihood of the model decreases, and the parameters most affected are the Calvo probability and the standard error of the bank capital shock.

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. Price stickiness and price indexation are also important.

The last column of table 5 presents the results for the model without financial frictions (FF). Differently from the BGG framework, removing financial frictions in the GK model is not obtained by simply setting a certain parameter equal to zero. We have calculated again the equilibrium conditions in the GK model, where the banking sector has been removed. The model without the financial frictions consists of 18 equations (instead of the 29 equations of the baseline model).

For the purpose of model comparison, the data on the marginal likelihood reveal that the model without FF has the worst empirical performance. The deterioration of the marginal likelihood is of the order of 740. Therefore, the data clearly favour the model with financial frictions in the UK economy.

The Calvo parameter and the habit formation parameter are the most affected, while removing the financial frictions does not have a significant impact on the other parameters.

	Base	$\sigma = 0.1$	$\sigma_p = 0$	$S'' = 0.1$	$h = 0.1$	$\zeta = 2.5$	no FF
Marginal likelihood							
	1743	1580	1432	1347	1704	1617	1003
Mode of estimated parameters							
σ	0.67	0.10	0.70	0.61	0.66	0.57	0.81
σ_p	0.50	0.50	0.01	0.49	0.52	0.51	0.51
S''	5.48	5.48	5.48	0.10	5.49	5.48	5.48
ζ	1.00	1.00	1.03	1.01	1.01	2.5	0.99
h	0.58	0.65	0.51	0.67	0.1	0.59	0.73
θ	0.966	0.954	0.949	0.957	0.955	0.955	—
λ	0.21	0.19	0.23	0.20	0.20	0.23	—
ρ_π	1.51	1.51	1.51	1.51	1.50	1.53	1.53
ρ_y	0.12	0.11	0.13	0.16	0.14	0.06	0.12
ρ_i	0.50	0.48	0.59	0.50	0.45	0.44	0.49
ρ_a	0.93	0.99	0.97	0.99	0.89	0.92	0.96
ρ_k	0.51	0.47	0.58	0.47	0.49	0.46	0.43
ρ_g	0.57	0.52	0.49	0.56	0.52	0.60	—
σ_a	0.02	0.02	0.02	0.02	0.02	0.02	0.05
σ_k	0.03	0.02	0.03	0.02	0.02	0.02	0.13
σ_i	0.02	0.01	0.02	0.02	0.06	0.02	0.04
σ_n	0.22	0.18	0.22	0.21	0.31	0.33	—
σ_g	0.06	0.04	0.03	0.22	0.04	0.04	—

Table 5: The importance of the different frictions

5 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.
Figures 2 and 3 show the mean impulse response functions to four shocks. All the shocks are set to produce a downturn, as in GK. We can distinguish the transmission mechanism between 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 determine a fall in investment; this implies a decrease in the asset prices, which deteriorates the banks balance sheet. Such a deterioration implies that banks push up the

premium and this reduces the amount of lending, as 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 in a shock to the bank 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 over-leveraged; 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 financial accelerator effect in the transmission mechanism, it is worthwhile to note that there are 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 impact of capital losses on reduction in lending is. 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 face of the sharp increase in financing cost, firms are forced to reduce demand for loans, 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 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. And this is the financial accelerator effect. Given both lending volume and leverage decline, banks can only try to increase profit by increase spreads, which is likely to lead further fall in lending demand. It can take a long time for banks to rebuild their capital back to their steady state level. Reflected in lending, the figures show that the slow-down in lending is highly persistent.

As 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), Meh and Moran (2008) and

Gilchrist et al. (2009) 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 this shock affects the capital accumulation equation and, therefore, the production function.

5.1 Subsample estimates

The full sample 1979-2009 includes different monetary regimes: the monetary targeting in the late 1970s and early 1980s; the 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; the chosen subsample corresponds to the inflation targeting period. Table 6 compares the full sample estimates with the post-1992 sample estimates.

Parameters	Full-sample	Subsample
Mode of estimated parameters		
σ	0.67	0.65
σ_p	0.50	0.51
S''	5.48	5.48
ζ	1.00	1.01
h	0.58	0.57
θ	0.966	0.955
λ	0.21	0.21
ρ_π	1.51	1.56
ρ_y	0.12	0.09
ρ_i	0.50	0.47
ρ_a	0.93	0.97
ρ_k	0.51	0.43
ρ_g	0.57	0.59
σ_a	0.02	0.02
σ_k	0.03	0.02
σ_i	0.02	0.02
σ_n	0.22	0.29
σ_g	0.06	0.04

Table 6: Subsample estimates

The comparison between two samples reveals that the Calvo and indexation parameters and the elasticities are quite stable. Concerning the financial parameters, while the mode of the parameters measuring the fraction of divertable asset is the same, the survival rate is lower. This different value implies that the steady state leverage ratio is 14 in the subsample, higher than the full sample value. Therefore, according to these estimates, UK financial intermediaries have increased their leverage ratio in the post-1992 period.

The parameters in the Taylor rule seem to signal a different monetary regime: the central bank'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. The contrary happens to the central bank's reaction coefficient to output gap, which has decreased.

Results are mixed as far as the volatility of the shocks is concerned. The standard error of capital quality and government shocks have slightly fallen, while the volatility of net worth shock has increased. This higher volatility might capture the recent financial crisis and the ‘Great Contraction ’period.

5.2 Historical decomposition

Once we estimated model and studied its propagation mechanism, we now can use it to quantify the relative importance of different shocks. For example, we can analyse what role the shock from financial sector has played in the dynamics of main variables since the on sight of the crisis.

Hence, we perform a historical decomposition of the dynamics of the main macro and financial variables of the UK. To do this, we fix the parameters at their posterior mode, and then use Kalman smoother to get the values of the innovations for each shock.

Figure 4 and 5 show the results. For output, the historical decomposition suggest that banks' balance sheet shock (in red) explains more than half of the fall in output since the start of the crisis, and a negative TFP shock (in turquoise) also played an important role. The bank capital shock in the model affects the real economy mainly through investment. In fact, the decomposition of this variable shows that the bank capital shock drives up investment in great stability years, and pushes it down during the crisis.

Since the beginning of the crisis, bank lending has been weak and corporate spreads have risen about 400bps from trough to peak. It is interesting to know whether this is driven by weak credit demand or weak credit supply. But it is very difficult to identify credit demand versus supply shocks. The structured model like this give us a natural environment to study this question. 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 (in green). While a shock that affects firms demand for credit, a shock to TFP, interest rate (in dark blue)and fiscal expenditure (in yellow), can be categorised as credit demand shock. Figure 5 shows that the sharp rise in spread since the crisis can be mainly attributed to credit supply shocks, although in the most recent quarter, weak demand starts to play a role as well.

The technology and interest rate shocks explain the greatest fraction in the total variation in inflation, whereas the financial shocks play a minor role. The fact that over the sample period shown in figure 5, 2001-2009, monetary policy is a dominant source of movements in inflation in not surprising, given the previous estimates of the previous section, which show that the monetary policy responds quite aggressively to inflation.

6 Credit policy

The GK model has been estimated without unconventional monetary 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 3 and setting $\nu = 10$. Therefore, the Central Bank is now implementing both conventional and unconventional monetary policy: the Taylor rule and the credit policy in the form of direct lending to financial institutions.

The Central Bank might offset the contraction shown in figures 2 and 3 with the non-standard measure, aimed to increase liquidity provisions.

Figure 6 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 interest rate shock has not been examined, because it is very unlikely that the Central Bank increases interest rate and at the same time decides to inject credit in the economy to offset the recession.

The black line is the response of the variable in the absence of the credit policy; while the grey line represents the response of the corresponding variable with credit market intervention.

The intervention by the Central Bank makes the crisis less severe in both cases. In the case of net worth shock, the contraction of output is lower in the presence of unconventional monetary policy, but it is slightly more persistent. Central bank intermediation reduces inflation and the contraction of lending. As expected, the spread is significantly reduced when unconventional monetary 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.

In the case of the shock to the quality of capital we have reported the same variables: output, inflation, lending and the spread. Credit policy is beneficial not only in terms of contraction of output, but also in terms of inflation, lending and the spread. In particular, the intervention by the Central Bank reduces the tightening of lending. These results might be particular interesting because in the GK model the shock to the quality of capital tries to capture the broad dynamics of the sub-prime crisis. The Central Bank intervention directly aimed at reducing the spread weakens the financial accelerator mechanism.

Similarly to what GK obtain in their calibrated model, the credit policy significantly moderates the contraction.

7 Conclusions

We have estimated the model by Gertler and Karadi using Bayesian techniques for the UK economy.
The fit of the model is quite satisfactory, but further research is needed to match exactly the relative standard deviations. The data strongly favour the model with financial frictions in the UK economy compared to models without nominal/real/financial frictions.
The policy experiment has shown that the intervention by policymakers in the form of injecting credit in the economy (which is not the policy of Quantitative Easing pursued by the Bank of England) significantly moderates the contraction.
As a future research, it would be interesting to simulate in the GK model a 'zero lower bound' scenario and analyse the effects of an increase in government spending.

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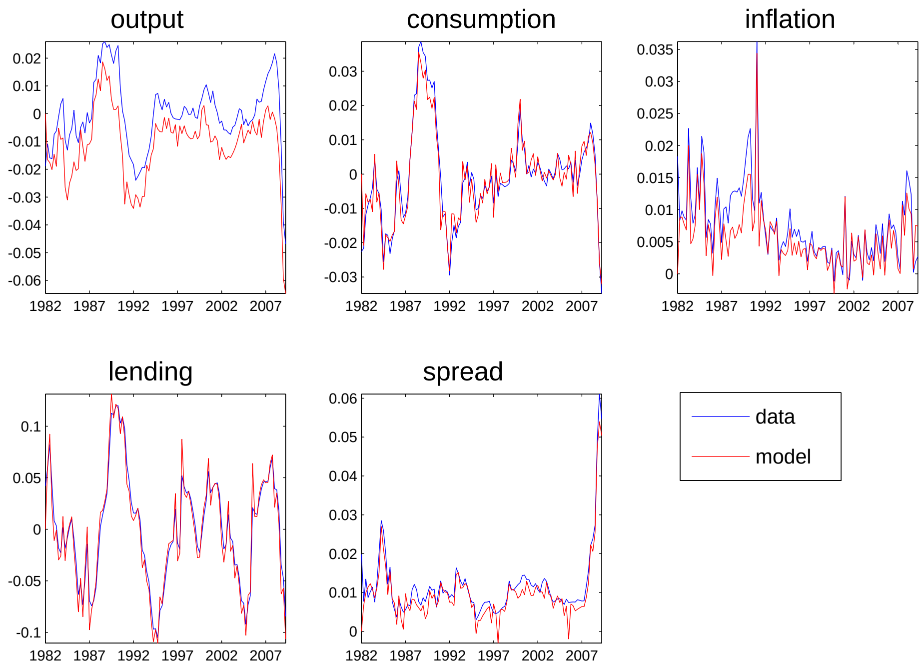

Figure 1: Fit of the model

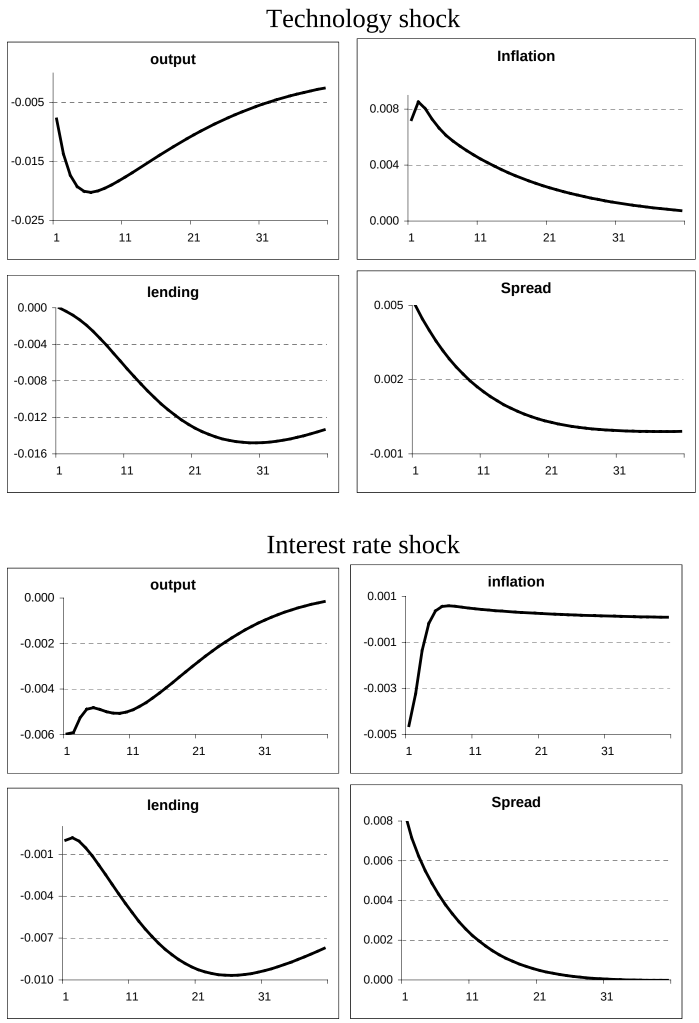

Figure 2: The estimated IRFs to a technology shock and to interest rate shock.
The standard error of technology shock is 2%. The standard error to the interest rate is 2% as well.

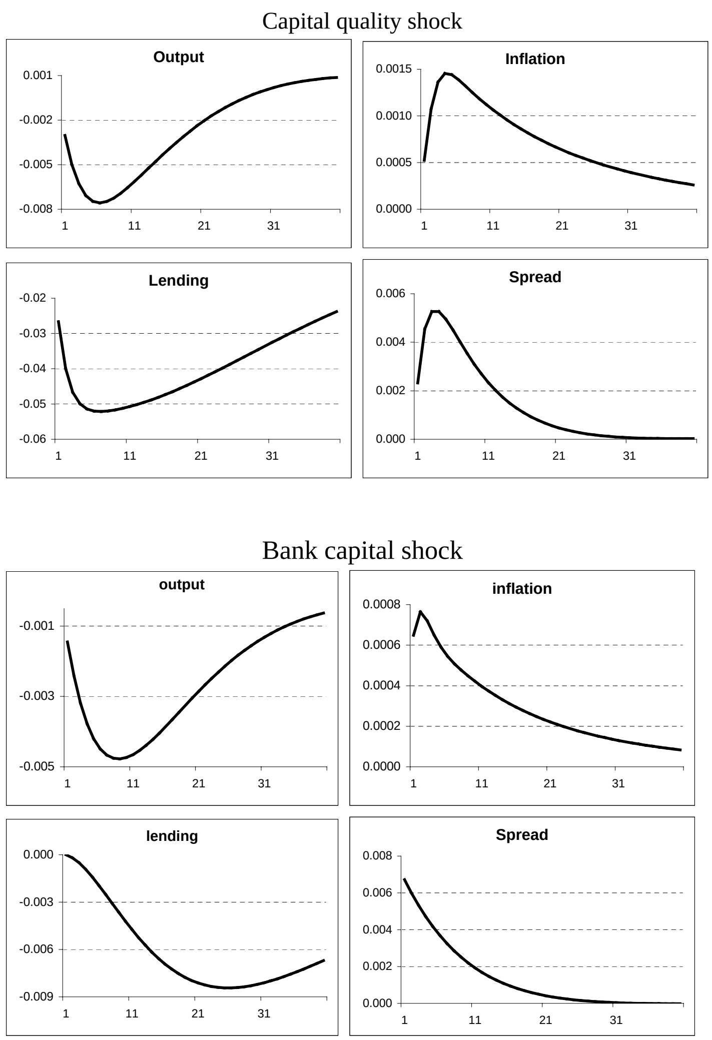

Figure 3: The estimated IRFs to a shock to the quality of capital and to a shock to bank capital.

The standard error of the shock to the quality of capital is 6%. The standard error to the FI capital shock is 26%.

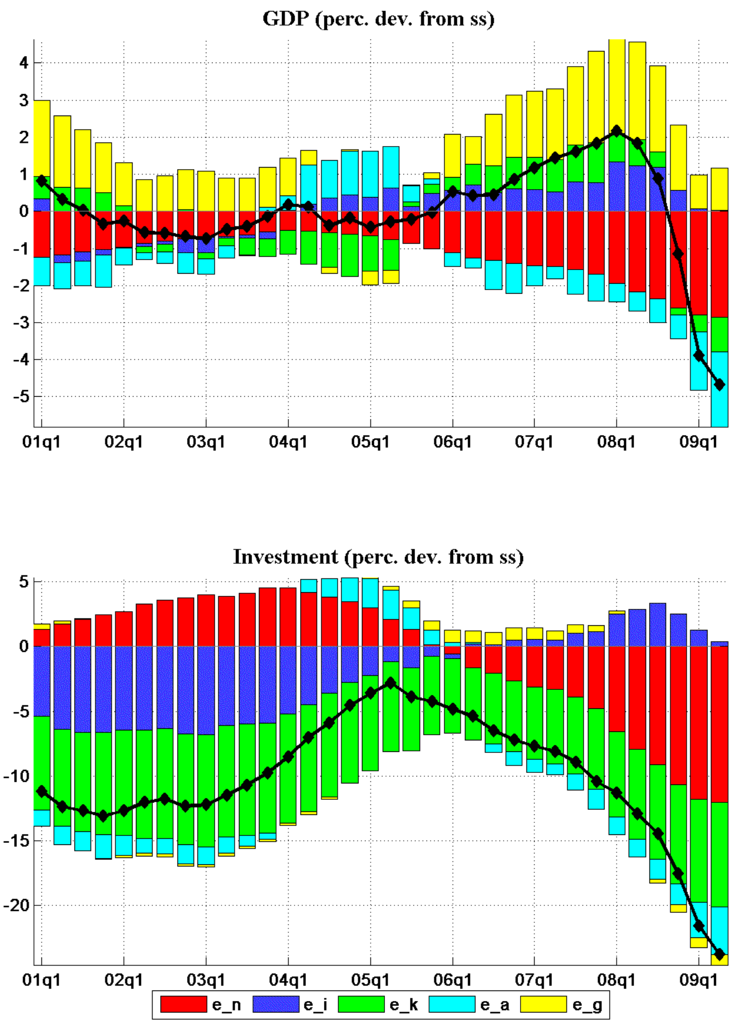

Figure 4: Historical decomposition

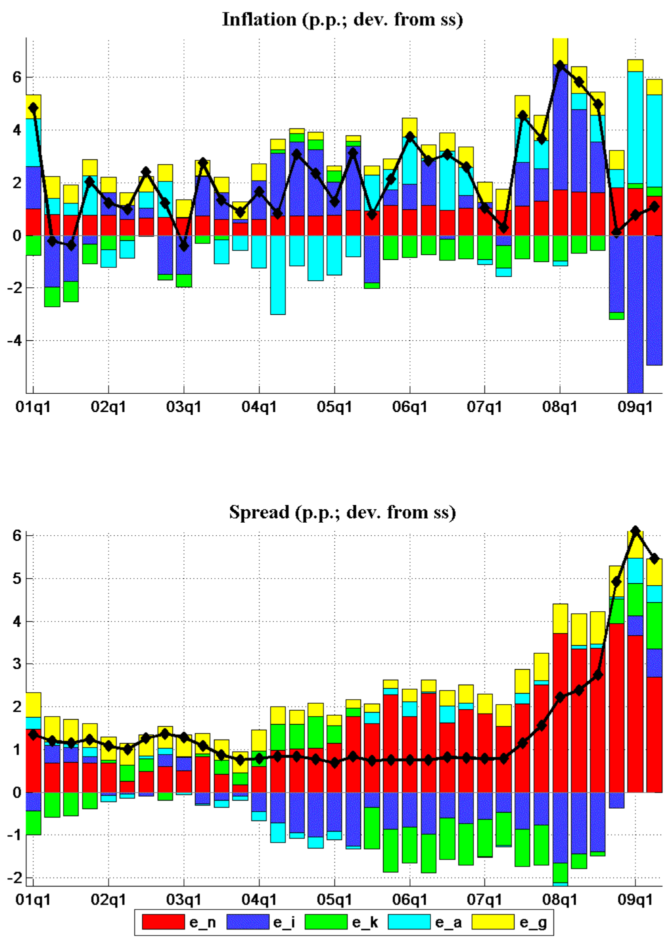

Figure 5: Historical decomposition.

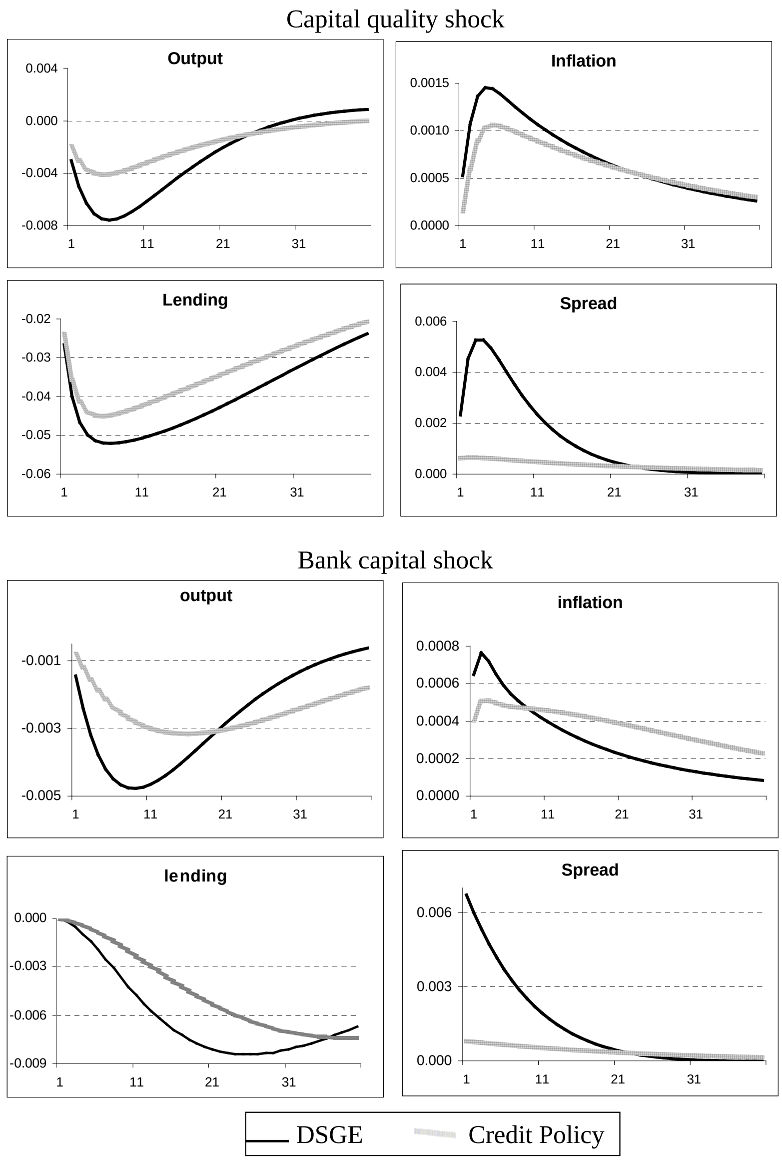

Figure 6: The estimated IRFS with and without credit policy.