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Abstract

The goal of this paper is to present the dynamic stochastic general equilibrium (DSGE) model developed and used at the Federal Reserve Bank of New York. The paper describes how the model works, how it is estimated, how it rationalizes past history, including the Great Recession, and how it is used for forecasting and policy analysis.

Key words: DSGE models

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Contents

1 Introduction

The goal of this paper is to present the FRBNY DSGE model, that is, the dynamic stochastic general equilibrium (DSGE) model developed and used at the Federal Reserve Bank of New York. The paper describes how the model works, how it is estimated, how it rationalizes past history including the Great Recession, and how it is used for forecasting and policy analysis. Models, unless they are very simple, are often perceived as black boxes. This problem is particularly prevalent for DSGE models which are necessarily complicated to capture the fundamentally dynamic relationships in the economy as well as the general equilibrium forces that drive most macroeconomic variables. In addition, the Bayesian techniques used for the estimation of these models may seem mysterious. We are providing here a fairly detailed description of the FRBNY DSGE model. Such a description is necessarily somewhat technical. However, to make sure that most readers understand the key features of the model, we complement the model description with more intuitive discussions of the model's ingredients and implications.

The FRBNY DSGE model is a medium scale, one-sector dynamic stochastic general equilibrium model. It builds on the neo-classical growth model by adding nominal wage and price rigidities, variable capital utilization, costs of adjusting investment, habit formation in consumption, and credit frictions. The core of the model is based on the work of Smets and Wouters (2007), and Christiano et al. (2005), and includes credit frictions as in the financial accelerator model developed by Bernanke et al. (1999). The actual implementation of the credit frictions follows closely Christiano et al. (2009).

The model is perturbed by a set of exogenous shocks, which are the fundamental sources of macroeconomic fluctuations. These shocks are identified by matching the model dynamics with the following quarterly data series: real GDP growth, core PCE inflation, the labor share, aggregate hours worked, the effective federal funds rate (FFR), and the spread between Baa corporate bonds and 10-year Treasury yields. In addition, we use data on federal funds rate expectations as measured by OIS rates, starting in 2008Q4, i.e., when the policy rate hit the zero lower bound. The parameters of the model are estimated on data from 1984Q1 to 2013Q1 using Bayesian methods as presented for instance in An and Schorfheide (2007) and Del Negro and Schorfheide (2010).

DSGE models have a number of key advantages over alternative models, as discussed e.g., in Sbordone et al. (2010). First, by being built on microeconomic foundations, these models make clear how economic agents' current decisions depend on their expectations about uncertain future outcomes. Second, the general equilibrium feature of these models imply an important interaction between policy actions and households or firms' behavior. Moreover, the clear specification of the stochastic shocks allows one to identify the source of economic fluctuations.

The fact that DSGE modelers can readily take advantage of progress in academic research by incorporating new features and new inference procedures into their models is arguably another key advantage of DSGE models relative to alternative approaches. This also means however that DSGE models evolve over time to keep up with advances in research, and the FRBNY DSGE model is no exception. What we present here is therefore just a snapshot of the model at this point in time. In spite of the fact that this model will continue to evolve over time, it seemed worthwhile to document where we currently stand.

The remainder of the paper is as follows. Section 2 describes the model, first at a general level and then more in detail. Section 3 elaborates on the estimation procedure, including the use of anticipated monetary policy shocks to model forward guidance. Section 4 discusses the prior information on the model's parameters, which is based in large part based on the calibration literature, and their posterior distribution. Section 5 illustrates the estimated model's transmission mechanism, with particular emphasis on the propagation of anticipated policy shocks. Section 6 provides the model's interpretation of the Great Recession. Section 7 shows the model's forecasts as of June 2013, and elaborates on how this structural model can be used to interpret the outlook. The model's forecasts are distinct from the FRBNY staff forecasts. Section 8 provides an assessment of the model's real time forecasts over the past three years. Finally, section 9 concludes.

2 The DSGE Model

This section is structured as follows. We first describe the general features of the model by introducing its main economic units and briefly discussing their role, the various frictions that affect their interrelationships, and the source of exogenous disturbances. Next we detail the microfoundations of the model — the form of preferences, technology, and constraints and the shock processes — and present the optimization problem of each set of agents. Solving these optimization problems result in optimal decision rules that describe the behavior of each set of agents. Rather than attempting to solve the full set of model equations, we proceed by performing a log-linear approximation to all equilibrium conditions. We describe at the end of the section the set of log-linearized equilibrium conditions, which are needed to reproduce our results.

2.1 General Features of the Model

The economic units in the model are households, firms, banks, entrepreneurs, and the government. Figure 1 illustrates the interactions among these units, the model frictions and the shocks that affect the economy's dynamics.

Households supply labor services to firms. The utility they derive from leisure is subject to a random disturbance, which we call "labor supply" shock, since it captures exogenous movements in labor supply due to factors such as demographics and labor market imperfections (this shock is sometimes also referred to as a "leisure" shock). Frictions in the labor market take the form of nominal wage rigidities. These frictions imply that various shocks affect hours worked. Households also choose how much to consume and to save. Their savings take the form of deposits into banks and purchases of government bonds. Households' preferences for consumption incorporate habit persistence, a characteristic that affects their consumption smoothing decisions.

Monopolistically competitive firms produce intermediate goods, which a competitive firm aggregates into a single final good that is used for both consumption and investment. The production function of intermediate producers is subject to "total factor productivity" (TFP) shocks. Frictions in the intermediate goods markets take the form of nominal price rigidities. Together with wage rigidities, this friction allows demand shocks to be a source of business cycle fluctuations, as countercyclical mark-ups induce firms to produce less when demand is low. Firms' optimal price setting implies that inflation evolves in the model according to a standard, forward-looking New Keynesian Phillips curve, which determines inflation as a function of marginal costs, expected future inflation, and "mark-up" shocks. Mark-up shocks capture exogenous changes in the degree of competitiveness in the intermediate goods market. In practice, these shocks capture also unmodeled inflationary pressures, such as those arising from fluctuations in commodity prices.

Financial intermediation involves two actors, *banks* and *entrepreneurs*, whose interaction captures imperfections in financial markets. These agents should not be interpreted in a literal sense, but rather as a device for modeling credit frictions. Banks collect deposits from households and lend to entrepreneurs. Entrepreneurs use their own wealth and loans from the banks to acquire capital, which they rent to intermediate good producers. Entrepreneurs are subject to idiosyncratic disturbances that affect their ability to manage capital. Consequently, their revenues may not be high enough to repay their borrowing, in which case they default. Banks protect themselves against default risk by pooling loans to all entrepreneurs and charging them a spread over the deposit rate. The spread varies both endogenously, as a function of the entrepreneurs' leverage, as well as exogenously on the basis of entrepreneurs' riskiness. In particular, mean-preserving changes in the volatility of entrepreneurs' idiosyncratic shocks lead to variations in the spread, to compensate banks for expected losses from defaults. We refer to these exogenous movements in risk as "spread" shocks. Spread shocks, which capture various disturbances to the financial intermediation process, affect entrepreneurs' borrowing costs, altering their demand for capital, and hence investment.

Capital producers transform general output into capital goods, which they sell to the entrepreneurs. The production of new capital is subject to convex adjustment costs, making the production of capital goods more costly in periods of rapid investment growth. It is also subject to exogenous changes in the "marginal efficiency of investment" (MEI). These MEI shocks capture exogenous movements in the productivity of new investments in generating new capital. A positive MEI shock implies that fewer resources are needed to build new capital, leading to higher real activity and inflation, with an effect that persists over time. Such MEI shocks reflect both changes in the relative price of investment versus consumption goods as well as financial market imperfections that are not reflected in movements of the spread (Justiniano et al. (2010)).

Finally, the *government* sector comprises a monetary authority that sets short-term interest rates according to a Taylor-type rule and a fiscal authority that sets public spending and collects lump-sum taxes. Exogenous changes in government spending are called "government" shocks; more generally, these shocks capture exogenous movements in aggregate demand.

2.2 The Model Microfoundations

Here we lay out preferences and constraints of each of the economic units of the model, describe their optimization problems and formalize the interactions between them.

Households and labor aggregators. There is a continuum of households indexed by $j \in [0,1]$. Households have identical preferences, which are separable in consumption, leisure, and real money balances. Their objective function is

$$E_t \sum_{s=0}^{\infty} \beta^s \left[log(C_{t+s}(j) - hC_{t+s-1}(j)) - \frac{\varphi_{t+s}}{1+\nu_l} L_{t+s}(j)^{1+\nu_l} + \frac{\chi}{1-\nu_m} \left(\frac{M_{t+s}(j)}{Z_{t+s}P_{t+s}} \right)^{1-\nu_m} \right], \quad (1)$$

where $C_t(j)$ is consumption, $L_t(j)$ is labor supply (total available hours are normalized to one), and $M_t(j)$ is money holdings. Habit persistence in consumption is captured by the parameter h. Real money balances enter the utility function as a ratio to the (stochastic) trend growth of the economy Z_t, so that real money demand relative to Z_t is stationary. Since money balances enter separably, and policy is described by an interest rate rule, the "demand for money" only determines households' cash holdings without affecting the determination of other variables in the model. In addition, since we do not use money balances as an observable in the estimation, we will subsequently ignore it.

Households' preferences are subject to a stochastic preference shifter φ_t which affects the marginal utility of leisure, and captures more generally exogenous changes in labor supply driven for instance by demographic changes. We assume that this shifter follows an exogenous process defined below, and refer to innovations to this process as *labor supply shocks*. Household j chooses $\{C_t(j), L_t(j), M_t(j), B_t(j), D_t(j)\}_{t=0}^{\infty}$ to maximize the expected utility (1) subject to the following budget constraint, written in nominal terms

$$\begin{aligned} P_{t+s}C_{t+s}(j) + B_{t+s}(j) + D_{t+s}(j) + M_{t+s}(j) \leq R_{t+s-1}B_{t+s-1}(j) + R^d_{t+s-1}D_{t+s-1}(j) \\ + M_{t+s-1}(j) + \Pi_{t+s} + W_{t+s}(j)L_{t+s}(j) + T_{t+s} + Tr_{t+s}, \quad (2) \end{aligned}$$

where $B_t(j)$ is holdings of government bonds and $D_t(j)$ represents deposits in the banking sector. R_t is the gross nominal interest rate on government bonds, R^d_t is the gross nominal interest rate on bank deposits, Π_t is the per-capita profit the household receives from owning the firms (we assume that households pool their firm shares so that they all receive the same profits), $W_t(j)$ is the nominal wage, T_t are lump-sum transfers (or taxes, if negative) from the government, and Tr_t are net per-capita lump-sum transfers from the entrepreneurs (discussed later).

We assume that households have access to a full menu of state-contingent securities, although to simplify the notation we do not explicitly add these securities to the budget constraint. Because of this assumption, all households choose the same consumption, money demand, bond holdings and bank deposits. The choice of hours worked can however differ across households, since they will face different wages in equilibrium.

The labor input supplied to the intermediate goods producers, L_t, is a composite of all the labor services supplied by each household j. We assume the existence of competitive labor aggregators (or "employment agencies") which combine individual households' labor into an aggregate L_t, sold to the intermediate goods producers

$$L_t = \left[\int_0^1 L_t(j)^{\frac{1}{1+\lambda_w}} dj \right]^{1+\lambda_w}. \tag{3}$$

The parameter $\lambda_w \in (0, \infty)$ affects the elasticity of substitution between differentiated labor services.

The first-order condition of the employment agencies' problem leads to the following labor demand schedule $L_t(j)$ for labor services of household j:

$$L_t(j) = \left(\frac{W_t(j)}{W_t} \right)^{-\frac{1+\lambda_w}{\lambda_w}} L_t, \tag{4}$$

where $W_t(j)$ is the wage paid to $L_t(j)$ and W_t is the aggregate wage, defined as

$$W_t = \left[\int_0^1 W_t(j)^{\frac{1}{\lambda_w}} dj \right]^{\lambda_w}. \tag{5}$$

Every household has market power and chooses its nominal wage subject to the demand constraint (4). However, we assume nominal wage rigidity à la Calvo (1983): in every period, each household has a probability $1 - \zeta_w$ of choosing its wage freely. The households that cannot do so simply increase $W_t(j)$ by the steady-state growth rate of aggregate wages (equal to steady state inflation π_* times the growth rate of the economy e^γ). Instead, households that can optimize at time t choose a wage $\widetilde{W}_t(j)$ to maximize:

$$E_t \sum_{s=0}^{\infty} (\zeta_w \beta)^s \left[-\frac{\varphi_{t+s}}{1+\nu_l} L_{t+s}(j)^{1+\nu_l} \right], \tag{6}$$

subject to the budget constraint (2), the labor demand equation (4), and the indexation rule

$$W_{t+s}(j) = (\pi_* e^{\gamma})^s \widetilde{W}_t(j), \tag{7}$$

for $s = 1, ..., \infty$.

Final good producers. The competitive final good producing firms combine intermediate goods $Y_t(i)$ using the technology

$$Y_t = \left[\int_0^1 Y_t(i)^{\frac{1}{1+\lambda_{f,t}}} di \right]^{1+\lambda_{f,t}}. \tag{8}$$

Profit maximization implies that the demand for intermediate goods is

$$Y_t(i) = \left(\frac{P_t(i)}{P_t} \right)^{-\frac{1+\lambda_{f,t}}{\lambda_{f,t}}} Y_t. \tag{9}$$

Combining (9) with the zero profit condition, yields the price of the composite good is obtained as

$$P_t = \left[\int_0^1 P_t(i)^{-\frac{1}{\lambda_{f,t}}} di \right]^{-\lambda_{f,t}}. \tag{10}$$

We indicate by $\lambda_{f,t}$ the net mark-up that intermediate goods producers would like to charge over marginal costs. This desired mark-up varies exogenously over time and we refer to the innovations to this process as *mark-up shocks*. A higher $\lambda_{f,t}$ corresponds to a more inelastic demand, which leads optimizing firms to charge a higher markup, and hence higher prices.

Intermediate good producers. A continuum of firms indexed by i produce differentiated intermediate goods by combining capital and labor via a common Cobb-Douglas production function with capital elasticity α

$$Y_t(i) = K_t(i)^{\alpha} (Z_t L_t(i))^{1-\alpha}, \tag{11}$$

where Z_t represents exogenous technological progress, which we assume to be non-stationary. We model the growth rate of productivity $z_t = \ln(Z_t/Z_{t-1})$ as a stationary exogenous process with mean γ, and refer to the innovations to this process ϵ_t^z as *productivity shocks*.

The intermediate goods producers hire labor and rent capital in competitive markets and face an identical nominal wage, W_t, and rental rate for capital, R_t^k. The profit function for each firm i is therefore

$$P_t(i)Y_t(i) - W_t L_t(i) - R_t^k K_t(i). \tag{12}$$

Following Calvo (1983), we assume that in every period a fraction $(1-\zeta_p)$ of the intermediate goods producers optimize their prices and the remainder ζ_p adjusts prices to steady state inflation π^*. The firms that are able to optimize choose prices $\tilde{P}_t(i)$ to maximize the expected discounted sum of future profits:

$$\Xi_t^p(\tilde{P}_t(i) - MC_t)Y_t(i) + \mathbb{E}_t \sum_{s=1}^{\infty} \zeta_p^s \beta^s \Xi_{t+s}^p (\tilde{P}_t(i)\pi_*{}^s - MC_{t+s})Y_{t+s}(i)$$

subject to

$$Y_{t+s}(i) = \left(\frac{\tilde{P}_t(i)\pi_*{}^s}{P_{t+s}} \right)^{-(1+\frac{1}{\lambda_{f,t+s}})} Y_{t+s}.$$

where $\pi_t \equiv \frac{P_t}{P_{t-1}}$, MC_t is firms' nominal marginal cost, and $\beta^s \Xi_{t+s}^p$ is a discount factor (Ξ_t^p is the Lagrange multiplier associated with the households' nominal budget constraint).

Capital producers. Capital producers are competitive firms that purchase an amount of capital x from entrepreneurs at the beginning of the period. During the period, they buy an amount I of general output from the final goods producers, and transform it into new capital via the technology:

$$x' = x + \mu_t \left(1 - S\left(\frac{I_t}{I_{t-1}} \right) \right) I_t, \tag{13}$$

so that x' is the new stock of capital, which they sell back to entrepreneurs at the end of the same period. I_t is investment spending and $S(\cdot)$ is the cost of adjusting investment, with $S'(\cdot) > 0$, $S''(\cdot) > 0$. The exogenous process μ_t affects the efficiency by which a foregone unit of consumption contributes to capital accumulation, and its innovations are labeled "marginal efficiency of investment" (MEI) shocks. Capital producers choose investment to maximize their profits, expressed in terms of consumption goods,

$$\Pi_t^k = \frac{Q_t^k}{P_t}(x' - x) - I_t, \tag{14}$$

where Q_t^k is the price of capital.

Entrepreneurs and Banks. There is a continuum of entrepreneurs indexed by e. Each entrepreneur buys installed capital $\bar{K}_{t-1}(e)$ from the capital producers at the end of period $t-1$ using her own net worth $N_{t-1}(e)$ and a loan $B_{t-1}^d(e)$ from the banking sector, so that:

$$Q_{t-1}^k \bar{K}_{t-1}(e) = B_{t-1}^d(e) + N_{t-1}(e), \tag{15}$$

where net worth is expressed in nominal terms. In the next period she rents capital to intermediate good producing firms, earning a rental rate R_t^k per unit of effective capital. In period t an idiosyncratic shock $\omega_t(e)$, i.i.d. across entrepreneurs and over time, may increase or shrink entrepreneurs' capital. We denote by $F_{t-1}(\omega)$ the cumulative distribution function of ω at time t, which is assumed to be known at time $t-1$. After observing the shock, the entrepreneur chooses a level of capital utilization $u_t(e)$ by paying a cost in terms of general output equal to $a(u_t(e))$ per-unit-of-capital. At the end of period t the entrepreneur sells the depreciated capital to the capital producers.

Entrepreneurs' revenues (net of utilization cost) in period t are therefore:

$$\omega_t(e)\tilde{R}_t^k(e)Q_{t-1}^k\bar{K}_{t-1}(e) \tag{16}$$

where

$$\tilde{R}_t^k(e) = \frac{R_t^k u_t(e) + (1-\delta)Q_t^k - P_t a(u_t(e))}{Q_{t-1}^k} \tag{17}$$

is the gross nominal return to capital for entrepreneurs, and δ is the capital depreciation rate. Since the choice of the utilization rate, given by $R_t^k/P_t = a'(u_t(e))$, is independent of the amount of capital purchased and of the ω_t shock, we drop the index e from the return $\tilde{R}_t^k$ in what follows.

The debt contract undertaken by the entrepreneur in period $t-1$ consists of the triplet $(B_{t-1}^d(e), R_t^c(e), \bar{\omega}_t(e))$ where $B_{t-1}^d(e)$ is the entrepreneur's debt, $R_t^c(e)$ represents the contractual interest rate, and $\bar{\omega}_t(e)$ is a 'bankruptcy' threshold: for realizations $\omega_t(e) < \bar{\omega}_t(e)$ the entrepreneur defaults on her debt. The threshold is therefore defined by the equation:

$$\bar{\omega}_t(e)\tilde{R}_t^k Q_{t-1}^k \bar{K}_{t-1}(e) = R_t^c(e)B_{t-1}^d(e). \tag{18}$$

The model features a representative bank that collects deposits from households, on which it pays an interest rate R_t^d, and lends to entrepreneurs. Loan contracts are subject to costly state verification: verification costs are a fraction μ^e of the amount the bank extracts from the entrepreneur in case of bankruptcy. The bank's zero profit condition implies that:

$$[1 - F_{t-1}(\bar{\omega}_t(e))]\, R_t^c(e)B_{t-1}^d(e) + (1-\mu^e)\int_0^{\bar{\omega}_t(e)} \omega dF_{t-1}(\omega)\tilde{R}_t^k Q_{t-1}^k \bar{K}_{t-1}(e) = R_{t-1}^d B_{t-1}^d(e) \tag{19}$$

Entrepreneurs' expected profits (before the realization of the shock ω_t) can be written as:

$$\int_{\bar{\omega}_t}^{\infty} \left[\omega_t(e)\tilde{R}_t^k Q_{t-1}^k \bar{K}_{t-1}(e) - R_t^c(e) B_{t-1}^d(e)\right] dF_{t-1}(\omega_t(e)). \tag{20}$$

We assume that entrepreneurs choose the amount of capital and the level of debt in order to maximize their expected net worth, subject to the financing constraint (19).

Aggregate entrepreneurs' equity evolves according to:

$$V_t = \int_{\bar{\omega}_t}^{\infty} \omega_t(e)\tilde{R}_t^k Q_{t-1}^k \bar{K}_{t-1}(e) dF_{t-1}(\omega_t) - [1 - F_{t-1}(\bar{\omega}_t(e))] R_t^c(e) B_{t-1}^d(e). \tag{21}$$

We assume that each period a fraction $1-\gamma^e$ of entrepreneurs exits the economy while the fraction γ^e continues operating. Exiting entrepreneurs consume a fraction Θ of their total net worth upon exit and the remaining net worth is transferred as a lump sum to the households. Each period new entrepreneurs enter and receive a net worth transfer W_t^e. Because W_t^e is small, this exit and entry process ensures that entrepreneurs do not accumulate enough wealth to be able to self-finance their activity and hence escape the financial friction. Aggregate entrepreneurs' net worth therefore evolve as:

$$N_t = \gamma^e V_t + W_t^e, \tag{22}$$

and net transfers from entrepreneurs to households are equal to

$$Tr_t = (1-\Theta)(1-\gamma^e)V_t - W_t^e. \tag{23}$$

The idiosyncratic random disturbances to entrepreneurs' capital productivity, $\omega_t(e)$, represent disruptions to financial intermediation in the model. We assume that

$$\log \omega_t(e) \sim N(m_{\omega,t-1}, \sigma_{\omega,t-1}^2),$$

where $m_{\omega,t-1}$ is such that $\mathbb{E}\omega_t(e) = 1$, and the standard deviation $\sigma_{\omega,t}$ follows an exogenous process. A (mean-preserving) increase in volatility increases the perceived riskiness of borrowers, and hence increases the cost of capital (relative to the risk-free rate), given entrepreneurs' leverage. We therefore refer to innovations to the volatility process $\sigma_{\omega,t}$ as *spread shocks.*

Monetary Policy. The central bank follows a standard feedback rule according to which the interest rate responds to deviations of inflation from target and to deviations of output growth from its steady state:

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\rho_R} \left[\left(\Pi_{j=0}^{3}\frac{\pi_{t-j}}{\pi_*}\right)^{\psi_\pi} \left(\frac{Y_t}{Y_{t-4}}e^{-4\gamma}\right)^{\psi_Y}\right]^{1-\rho_R} e^{\epsilon_t^R}\ \Pi_{k=1}^{K} e^{\epsilon_{k,t-k}^R}. \tag{24}$$

In (24) R is the steady state (gross) nominal interest rate, π_* is the inflation target, $\Pi_{j=0}^{3}\pi_{t-j}$ is the 4-quarter gross inflation rate, $\frac{Y_t}{Y_{t-4}}$ is the 4-quarter gross growth rate of output, and $e^{4\gamma}$ is the gross annualized steady-state growth rate of the economy; ψ_π and ψ_y are the central bank's reaction coefficients, and ρ_R captures persistence in the reaction function. $\epsilon_{R,t}$ is a *monetary policy shock,* where $\epsilon_t^R \sim N(0, \sigma_r^2),\ i.i.d.$, and $\epsilon_{k,t-k}^R$ are *anticipated policy shocks.* The latter are policy shocks which are known to agents at time $t-k$, but affect the policy rule k periods later, that is, at time t. We assume that $\epsilon_{k,t-k}^R \sim N(0, \sigma_{k,r}^2),\ i.i.d.$ The purpose of introducing anticipated policy shocks is to constrain the path of the interest rate, which may be needed to enforce the zero lower bound constraint and/or to implement policymakers' 'forward guidance' on the future path of the interest rate.

Fiscal Policy. Fiscal policy is fully Ricardian so that the timing of taxes does not affect the equilibrium. Public spending is determined exogenously as a time-varying fraction of aggregate output

$$G_t = (1 - 1/g_t)Y_t, \tag{25}$$

where government spending g_t follows an exogenous process, and we refer to the innovations to this process, ϵ_t^g, as *demand shocks*, with $\epsilon_t^g \sim N(0, \sigma_g^2),\ i.i.d.$.

Market clearing. Combining the government's and households' budget constraints with the zero profit condition of final goods producers and employment agencies yields the aggregate resource constraint

$$C_t + I_t + a(u_t)\bar{K}_{t-1} = \frac{1}{g_t}Y_t. \tag{26}$$

The optimization conditions of the model result in dynamic relationships among macroeconomic variables. Together with market clearing conditions, they completely characterize the equilibrium behavior of the model economy.

2.3 The Model in Log-linear Form

The model has a source of non-stationarity in the process for technology Z_t, which has a unit root. Hence consumption, investment, capital, real wages and output inherit stochastic growth. To solve the model we first rewrite its equilibrium conditions in terms of stationary variables and solve for the non-stochastic steady state of the transformed model. Then we take a log-linear approximation of the transformed model around its steady state. This approximation generates a set of log-linear equations, which we solve to obtain the model's state-space representation, using the method of Sims (2002). We then use the state-space representation in the estimation procedure.

Below we list the log-linear equations of the model. We follow the usual convention of denoting log-deviations from steady state with hatted variables: for any stationary variable x_t, $\widehat{x}_t \equiv \log(x_t/x_*)$, where x_* denotes its steady state value. The steady state itself is a function of the model's parameters. Equations describing the mapping between parameters and steady state variables are available upon request.

The *Consumption Euler Equation* that characterizes the optimal allocation of consumption over time is given by

$$\hat{\xi}_t = \hat{R}_t + \mathbb{E}_t[\hat{\xi}_{t+1}] - \mathbb{E}_t[\hat{z}_{t+1}] - \mathbb{E}_t[\hat{\pi}_{t+1}], \tag{27}$$

where $\hat{R}_t$ is the gross nominal interest rate on government bonds, and $\hat{\xi}_t$ is the marginal utility of consumption.

The *Marginal Utility of Consumption* ξ_t evolves according to

$$(e^\gamma - h\beta)(e^\gamma - h)\hat{\xi}_t = -\ (e^{2\gamma} + \beta h^2)\hat{c}_t + he^\gamma \hat{c}_{t-1} \ - \ he^\gamma \hat{z}_t + \beta he^\gamma \mathbb{E}_t[\hat{c}_{t+1}] \ + \beta he^\gamma \mathbb{E}_t[\hat{z}_{t+1}],$$

where $\hat{c}_t$ is consumption, e^γ is the steady-state (gross) growth rate of the economy and h captures habit persistence in consumption.

The *Capital Stock* follows

$$\hat{\bar{k}}_t = -(1 - \frac{i_*}{k_*})\hat{z}_t + (1 - \frac{i_*}{k_*})\hat{\bar{k}}_{t-1} + \frac{i_*}{k_*}\hat{\mu}_t + \frac{i_*}{k_*}\hat{\imath}_t, \tag{28}$$

where $\hat{\bar{k}}_t$ is installed capital, $\hat{z}_t$ is the growth rate of productivity, i_* and k_* are steady state investment and the level of capital, respectively, and $\hat{\mu}_t$ is the exogenous process that affects the efficiency by which a foregone unit of consumption contributes to capital utilization.

The *Effective Capital* $\hat{k}_t$ is in turn given by

$$\hat{k}_t = \hat{u}_t - \hat{z}_t + \hat{\bar{k}}_{t-1}, \tag{29}$$

where $\hat{u}_t$ is the level of capital utilization.

Capital Utilization is given by

$$r_*^k \hat{r}_t^k = a''(u)\ \hat{u}_t, \tag{30}$$

where r_*^k is the steady state rental rate of capital and the function $a(u)$ captures the utilization cost.

The *Optimal Investment* decision satisfies the Euler equation

$$\hat{i}_t = \frac{1}{1+\beta}\mathbb{E}_t[\hat{\imath}_{t-1} - \hat{z}_t] + \frac{\beta}{1+\beta}\mathbb{E}_t[\hat{\imath}_{t+1} + \hat{z}_{t+1}] + \frac{1}{(1+\beta)S''e^{2\gamma}}\hat{q}_t^k + \frac{1}{(1+\beta)S''e^{2\gamma}}\hat{\mu}_t, \tag{31}$$

where $\hat{i}_t$ is investment, $S(.)$ is the cost of adjusting capital, with S' and $S'' > 0$, and $\hat{q}_t^k$ is the price of capital.

The *Realized Return on Capital* is given by:

$$\hat{\tilde{R}}_t^k - \hat{\pi}_t = \frac{r_*^k}{r_*^k + (1-\delta)}\hat{r}_t^k + \frac{(1-\delta)}{r_*^k + (1-\delta)}\hat{q}_t^k - \hat{q}_{t-1}^k, \tag{32}$$

where δ is the rate of capital depreciation, π_t is the inflation rate, whose evolution is described below, $\hat{r}_t^k$ is the capital rental rate and $\hat{q}_t^k$ is the price of capital.

The *Expected Excess Return on Capital* (or 'spread')

$$\mathbb{E}_t\left[\hat{\tilde{R}}_{t+1}^k - \hat{R}_t\right] = \zeta_{sp,b}\left(\hat{q}_t^k + \hat{\bar{k}}_t - \hat{n}_t\right) + \tilde{\sigma}_{\omega,t} \tag{33}$$

can be expressed as a function of the entrepreneurs' leverage (i.e., the ratio of the value of capital to nominal net worth) and exogenous fluctuations in the volatility of the entrepreneurs' idiosyncratic productivity, $\tilde{\sigma}_{\omega,t} \equiv \zeta_{sp,\sigma_\omega}\hat{\sigma}_{\omega,t}$. The parameter $\zeta_{sp,b}$ is the elasticity of the spread with respect to leverage, and ζ_{sp,σ_ω} is the elasticity of the spread with respect to the volatility of the spread shock.

The *Entrepreneurs' Net Worth,* $\hat{n}_t$, evolves according to

$$\hat{n}_t = \zeta_{n,\tilde{R}^k}\left(\hat{\tilde{R}}_t^k - \hat{\pi}_t\right) - \zeta_{n,R}\left(\hat{R}_{t-1} - \hat{\pi}_t\right) + \zeta_{n,qK}\left(\hat{q}_{t-1}^k + \hat{\bar{k}}_{t-1}\right)$$
$$+ \zeta_{n,n}\hat{n}_{t-1} - \gamma^e\frac{v_*}{n_*}\hat{z}_t - \frac{\zeta_{n,\sigma_\omega}}{\zeta_{sp,\sigma_\omega}}\tilde{\sigma}_{\omega,t-1}, \tag{34}$$

where $\zeta_{n,\tilde{R}^k}$, $\zeta_{n,R}$, ζ_{n,q^K}, $\zeta_{n,n}$, and ζ_{n,σ_ω} are the elasticities of net worth to the return on capital, the nominal interest rate, the cost of capital, net worth itself and the volatility σ_ω, respectively, and γ^e is the fraction of entrepreneurs who survive each period.

The evolution of the *Aggregate Nominal Wage* is then given by

$$\hat{w}_t = \hat{w}_{t-1} - \hat{\pi}_t + \frac{1-\zeta_w}{\zeta_w}\hat{\tilde{w}}_t, \tag{35}$$

where ζ_w is the fraction of workers who cannot adjust their wages in a given period and $\hat{\tilde{w}}_t$ is the optimal wage chosen by workers that can freely set it, or optimal reset wage.

The *Optimal Reset Wage* follows

$$\begin{aligned}(1+\nu_l\frac{1+\lambda_w}{\lambda_w})\hat{\tilde{w}}_t \; + \; (1+\zeta_w\beta\nu_l(\frac{1+\lambda_w}{\lambda_w}))\hat{w}_t = \\ \zeta_w\beta(1+\nu_l\frac{1+\lambda_w}{\lambda_w})\mathbb{E}_t[\hat{\tilde{w}}_{t+1}+\hat{w}_{t+1}] \; + \; \hat{\varphi}_t \; + \; (1-\zeta_w\beta)(\nu_l\hat{L}_t - \hat{\xi}_t) \\ + \; \zeta_w\beta(1+\nu_l\frac{1+\lambda_w}{\lambda_w})\mathbb{E}_t[\hat{\pi}_{t+1}+\hat{z}_{t+1}],\end{aligned}$$

where $\hat{\varphi}_t$ is a stochastic preference shifter affecting the marginal utility of leisure and λ_w is the parameter that determines the elasticity of substitution between differentiated labor services.

The optimal price-setting decision yields a *Phillips Curve* equation

$$\hat{\pi}_t = \beta\mathbb{E}_t[\hat{\pi}_{t+1}] + \frac{(1-\zeta_p\beta)(1-\zeta_p)}{\zeta_p}\hat{mc}_t + \frac{1}{\zeta_p}\tilde{\lambda}_{f,t}, \tag{36}$$

where $\hat{\pi}_t$ is inflation, $\hat{mc}_t$ is nominal marginal cost, β is the discount factor, and ζ_p is the Calvo parameter, representing the fraction of firms that cannot adjust their prices each period. $\tilde{\lambda_{f,t}}$ is the following re-parametrization of the cost-push shock $\lambda_{f,t}$: $\tilde{\lambda_{f,t}} = [(1-\zeta_p\beta)(1-\zeta_p)\lambda_f/(1+\lambda_f)]\lambda_{f,t}$, where λ_f is the steady state value of the markup shock.

The *Marginal Cost (or labor share)* satisfies

$$\hat{mc}_t = (1-\alpha)\hat{w}_t + \alpha\hat{r}_t^k, \tag{37}$$

where α is the output elasticity to capital and $\hat{r}_t^k$ is the capital rental rate.

The *Production Function* is given by

$$\hat{y}_t = \alpha\hat{k}_t + (1-\alpha)\hat{L}_t, \tag{38}$$

where the *Capital-Labor Ratio* satisfies

$$\hat{k}_t = \hat{w}_t - \hat{r}_t^k + \hat{L}_t. \tag{39}$$

The *Resource Constraint* is

$$\hat{y}_t = \hat{g}_t + \frac{c_*}{c_* + i_*}\hat{c}_t + \frac{i_*}{c_* + i_*}\hat{\imath}_t + \frac{r_*^k k_*}{c_* + i_*}\hat{u}_t, \tag{40}$$

where $\hat{y}_t$ is output and $\hat{g}_t$ is government spending.

Finally, the *Policy Rule* is

$$\hat{R}_t = \rho_R \hat{R}_{t-1} + (1-\rho_R)\left(\psi_\pi \sum_{j=0}^{3} \hat{\pi}_{t-j} + \psi_y \sum_{j=0}^{3}(\hat{y}_{t-j} - \hat{y}_{t-j-1} + \hat{z}_{t-j})\right) + \epsilon_t^R + \sum_{k=1}^{K} \epsilon_{k,t-k}^R, \tag{41}$$

where $\sum_{j=0}^{3} \hat{\pi}_{t-j}$ is 4-quarter inflation expressed in deviation from the Central Bank's objective π_* (which corresponds to steady state inflation), $\sum_{j=0}^{3}(\hat{y}_{t-j} - \hat{y}_{t-j-1} + \hat{z}_{t-j})$ is the 4-quarter growth rate of real GDP expressed in deviation from steady state growth, ϵ_t^R is the standard contemporaneous policy shock, and the terms $\epsilon_{k,t-k}^R$ are anticipated policy shocks, known to agents at time $t-k$.

2.4 The Exogenous Processes

The exogenous processes $\widehat{z}_t, \widehat{\varphi}_t, \tilde{\lambda}_{f,t}, \hat{\mu}_t, \tilde{\sigma}_{\omega,t}$ and $\hat{g}_t$ are assumed to follow AR(1) processes with autocorrelation parameters denoted by $\rho_z, \rho_\varphi, \rho_{\lambda_f}, \rho_\mu, \rho_{\sigma_\omega}$, and ρ_g, respectively. The innovations to these processes are structural shocks driving the model dynamics. They are assumed to be normally distributed with mean zero and a standard deviation denoted by $\sigma_z, \sigma_\varphi, \sigma_{\lambda_f}, \sigma_\mu, \sigma_{\sigma_\omega}$, and σ_g, respectively. The remaining structural shocks are the monetary policy shocks, both unanticipated, ϵ_t^R, and anticipated, $\epsilon_{k,t-k}^R$, all assumed *i.i.d.*

3 Estimation and Data

The solution to the approximate log-linear model presented above yields the following state-space representation:

$$s_t = \mathcal{T}(\theta)s_{t-1} + \mathcal{R}(\theta)\epsilon_t, \tag{42}$$

and

$$y_t = \mathcal{D}(\theta) + \mathcal{Z}(\theta)s_t. \tag{43}$$

Equation (42) summarizes the evolution over time of the model's state vector s_t, which comprises both the endogenous and exogenous variables appearing in the log-linearized equilibrium conditions and the equations describing the evolution of the exogenous processes. The matrices $\mathcal{T}(\theta)$ and $\mathcal{R}(\theta)$ are functions of the vector of all model parameters θ, and ϵ_t is the vector of structural shocks: $\epsilon_t = (\epsilon_t^z, \epsilon_t^\varphi, \epsilon_t^{\lambda_f}, \epsilon_t^\mu, \epsilon_t^{\sigma_{\omega,t}}, \epsilon_t^g, \epsilon_t^R)'$. Specifically, the vector ϵ_t is composed of the seven exogenous shocks discussed in the previous section: a productivity shock ϵ_t^z, a labor shock ϵ_t^φ, a marginal efficiency of investment (MEI) shock ϵ_t^μ, a government policy shock ϵ_t^g, a price mark-up shock $\epsilon_t^{\lambda_f}$, a spread shock $\epsilon_t^{\sigma_{\omega,t}}$, and a monetary policy shock ϵ_t^R.

Expression (43) is a system of measurement equations which maps the vector of states s_t into the vector of observables y_t. The variables included in y_t are: 1) the annualized growth rate of real GDP per capita, where the real gross domestic product is computed as the ratio of nominal GDP (SAAR) to the chain-type price index from the BEA;[1] 2) the log of labor hours, measured as per capita hours in non-farm payroll; 3) the log of the labor share, computed as the ratio of total compensation of employees to nominal GDP, from the BEA; 4) the annualized rate of change of the core PCE deflator (PCE excluding food and energy, but including purchased meals and beverages), seasonally adjusted; 5) the effective federal funds rate, percent annualized, computed as the quarterly average of daily data; and 6) the spread between the Baa corporate bond yield and the yield on 10 year Treasuries.[2] The elements of the matrices $\mathcal{D}(\theta)$ and $\mathcal{Z}(\theta)$ are described in appendix A.

We estimate the vector of model parameters θ with data from 1984Q1 to 2013Q1 using Bayesian methods as described in Del Negro and Schorfheide (2010) and An and Schorfheide (2007), applied to the state-space representation of equations (42) and (43).

Starting in 2008Q3 (one period before the implementation of the zero lower bound for the nominal interest rate) we incorporate FFR market expectations, as measured by OIS

[1] Per capita variables are obtained dividing aggregate variables by the civilian non-institutionalized population over 16. We HP-filter the population series in order to smooth out the impact of Census revisions.

[2] Haver mnemonics for the data are as follows: Real GDP (GDP@USECON/JGDPUSECON); Labor Hours (LHTNAGRA@USECON); Labor share (YCOMP@USECON/GDP@USECON); Core PCE deflator (JCXFE@USNA); FFR (FFED@DAILY); Civilian non-institutionalized population over 16 (LN16N@USECON); Baa (FBAA@USECON); 10yT (FCM10@USECON).

rates, into our outlook following the approach described in Section 5.4 of Del Negro and Schorfheide (2013).[3] Specifically, we take FFR expectations up to K quarters ahead into account by augmenting the measurement equations (43) with expectations for the policy rate:

$$\begin{aligned} FFR^{e}_{t,t+k} &= 400\left(\mathbb{E}_t \widehat{R}_{t+k} + \ln R_*\right) \\ &= 400\left(\mathcal{Z}_R(\theta)\mathcal{T}(\theta)^k s_t + \mathcal{D}_R(\theta)\right), \quad k = 1,..,K \end{aligned} \tag{44}$$

where $FFR^{e}_{t,t+k}$ are the market's expectations for the FFR k quarters ahead, $\mathcal{Z}_R(\theta)$ and $\mathcal{D}_R(\theta)$ are the rows of $\mathcal{Z}(\theta)$ and $\mathcal{D}(\theta)$, respectively, corresponding to the interest rate, and R_* is the gross steady state nominal interest rate. The observation equation (44) contains valuable information for the estimation of the state of the economy: market expectations of continued low interest rates may reflect either a relatively weak economy or accommodative monetary policy. We express the anticipated shocks in recursive form by augmenting the state vector s_t with K additional states $\nu^R_t, \ldots, \nu^R_{t-K}$ whose law of motion follows[4]

$$\begin{aligned} \nu^R_{1,t} &= \nu^R_{2,t-1} + \epsilon^R_{1,t} \\ \nu^R_{2,t} &= \nu^R_{3,t-1} + \epsilon^R_{2,t} \\ &\vdots \\ \nu^R_{K,t} &= \epsilon^R_{K,t}. \end{aligned} \tag{45}$$

We also augment the vector of shocks ϵ_t in equation (42) with the anticipated shocks $[\epsilon^R_{1,t}, .., \epsilon^R_{K,t}]'$ and re-solve the model to compute the matrices $\mathcal{T}(\theta)$ and $\mathcal{R}(\theta)$ appropriately.[5] The standard deviation of the anticipated shocks is estimated using post-2008Q3 data.[6]

[3]Del Negro et al. (2012) describe some of the issues associated with using anticipated policy shocks to perform policy counterfactuals based on forward guidance.

[4]It is easy to verify that $\nu^R_{1,t-1} = \sum_{k=1}^{K} \epsilon^R_{k,t-k}$, that is, $\nu^R_{1,t-1}$ is a "bin" that collects all anticipated shocks that affect the policy rule in period t.

[5]Note that we make the – arguably counterfactual – assumption that the anticipated shocks are independent from one another. Campbell et al. (2012) forcefully argue, based on their own findings as well as Gürkaynak et al. (2005)'s, that anticipated shocks follow a factor structure.

[6]Effectively we estimate the DSGE model assuming a structural break in 2008Q3: our assumption is that the Fed begins to use forward guidance only after this date.

4 Priors and Posterior Estimates for the DSGE Model Parameters

Table 1 shows the priors and posteriors for the DSGE model parameters. The top section shows the prior for the policy rule parameters, namely the inflation target π_*, the responses of interest rates to inflation (ψ_π) and economic activity (ψ_y) – 4-quarter output growth in the baseline specification – in the policy rule, persistence (ρ_r), and variance of i.i.d. policy shocks, (σ_r). The prior on π_* is centered at 2% in light of the Fed's long run inflation objective. Its posterior is slightly higher than 2%, reflecting the fact that inflation has been higher on average than 2% in our sample.[7] The priors on ψ_π and ψ_y are centered at 2 and 0.2 respectively, and imply a fairly strong response to inflation and a moderate response to output. The posterior means of these parameters are generally in line with the prior means, although the posterior for ψ_π is quite tighter than the prior (with 90% bands roughly between 1.9 and 2.4), indicating that the data are in agreement with a relatively strong reaction to inflation in the interest feedback rule. The prior on the degree of inertia ρ_r is centered at 0.5 and is quite wide. The posterior estimates indicate a substantial degree of inertia (they are centered at 0.8, with relatively tight bands), in line with the results in the literature. The prior on the variance of the *i.i.d.* policy shocks σ_r is centered at 0.2.

Priors on nominal rigidities parameters ζ_p (prices) and ζ_w (wages) are shown in the second panel of Table 1. We have considered two priors, as in Del Negro and Schorfheide (2008). "Low Rigidities" (loosely calibrated at Bils and Klenow (2004) values of average duration less than 2 quarters), and "High Rigidities" (duration about 4 quarters). The latter fits the data better according to marginal likelihood criteria. Indeed the posterior distributions for both ζ_p and ζ_w are higher than the prior, at about 0.9.

Priors on remaining parameters are shown in the bottom two panels of Table 1. The priors on "Endogenous Propagation and Steady State"are generally chosen as in Del Negro and Schorfheide (2008). The prior for the habit persistence parameter h is centered at 0.7, which is the value used by Boldrin et al. (2001). The prior for a'' implies that in response to

[7] In future model developments we plan to include in the model a time-varying inflation target. In order to provide information on the public's assessment of this time varying target we also plan to add the long run inflation expectations to the list of observables, following the approach in Del Negro and Schorfheide (2013).

a 1% increase in the return to capital, utilization rates rise by 0.1 to 0.3%. These numbers are considerably smaller than the value used by Christiano et al. (2005). The 90% interval for the prior distribution on ν_l implies that the Frisch labor supply elasticity lies between 0.3 and 1.3, reflecting the micro-level estimates at the lower end, and the estimates of Kimball and Shapiro (2003) and Chang and Kim (2006) at the upper end. We use a pre-sample of observations from 1959Q3-1984Q1 to choose the prior means for the parameters that determine steady states.

For the credit frictions the key parameters are the elasticity of the spread with respect to leverage, $\zeta_{sp,b}$, the survival rate for the entrepreneurs, γ^e, and the steady state default rate, $F(\bar{\omega})$. The last two are calibrated while the former is estimated. Following Gilchrist et al. (2009), we set γ^e to 0.99. We set $F(\bar{\omega})$ to imply an annualized default rate of 3%, as in Bernanke et al. (1999). The prior for the spread elasticity, $\zeta_{sp,b}$, is a beta distribution with mean 0.05 (as in Bernanke et al. (1999)) and standard deviation of 0.02. The steady state spread has a Gaussian prior with mean 2 and standard deviation of 0.5, in annual percentage terms.

The priors on the persistence of the exogenous processes are chosen as in Del Negro and Schorfheide (2008). The priors on the standard deviations of the shocks are chosen so that the overall variance of the endogenous variables is close to that observed in the pre-sample 1959Q3–1984Q1, informally following the approach in Del Negro and Schorfheide (2008).

5 The Transmission Mechanism and the Variance Decomposition

In this section, we illustrate some of the key economic mechanisms at work in the model's equilibrium. We do so with the aid of the impulse response functions and variance decompositions of the shocks hitting the economy, which we report in Figures 2 to 11.

We start the discussion from the shock most closely associated with the Great Recession and the severe financial crisis that characterized it: the spread shock. As discussed above, this shock stems from an increase in the perceived riskiness of borrowers, which induces banks to charge higher interest rates for loans, thereby widening credit spreads. As a result of this increase in the expected cost of capital, entrepreneurs' borrowing falls, hindering their ability to channel resources to the productive sector via capital accumulation. The model identifies this shock by matching the behavior of the ratio of the Baa corporate bond yield to the 10-year Treasury yield, and the spread's comovement with output growth, inflation, and the other observables.

Figure 2 shows the impulse responses of the variables used in the estimation to a one-standard-deviation innovation in the spread shock. An innovation of this size increases the observed spread by roughly 35 basis points and keeps it elevated for several quarters afterward (bottom right panel). This dynamic profile is not too dissimilar from what was observed in occasion of the Great Recession and its aftermath, when tighter financial conditions persisted long after the official end of the recession, and arguably continue today, at least for some borrowers.

This persistent increase in spreads leads to a reduction in investment and consequently to a reduction in output growth (top left panel) and hours worked (top right panel). The fall in the level of hours is fairly sharp in the first year and persists for many quarters afterwards, leaving the labor input not much higher than at its trough four years after the impulse. Of course, the effects of this same shock on GDP growth, which roughly mirrors that on the level of hours, are more short-lived. Output growth returns to its steady state level about two years after the shock hits, but it barely moves above it after that, implying a painfully slow catch up of the level of GDP with its previous trend. The persistent drop in the level of economic activity due to the spread shock also leads to a prolonged decline in real marginal costs — which in this model map one-to-one into the labor share (middle left panel) — and, via the New Keynesian Phillips curve, in inflation (middle right panel). Finally, policymakers endogenously respond to the change in the inflation and real activity outlook by cutting the federal funds rate (bottom left panel).

On average, the spread shock plays a limited role in fluctuations, as shown by the variance decompositions in Figure 11. Exogenous changes in the spread account for no more than 10/15% of the variance of all variables — including the spread itself! — at any horizon. In this respect, the Great Recession stands out as a very unusual event in our sample, due to a very large and unlikely realization of the spread shock, as discussed in more detail in the next section. In light of the impulse responses discussed above, which feature an extremely gradual recovery of the real economy from this shock, the unusual "spread intensity" of the Great Recession might help to explain the slow and halting nature of the lackluster recovery that has followed it.

Very similar considerations hold for the MEI shock, which represents a direct hit to the "technological" ability of entrepreneurs to transform investment goods into productive capital, rather than an increase in their funding cost. Although the origins of the spread and MEI shocks are different, the fact that they both affect the creation of new capital implies very similar effects, but with opposite sign, on the observable variables, as shown by the impulse responses in Figure 3. In particular, a positive MEI shock also implies a very persistent increase in investment, output and hours worked, as well as in the labor share and hence inflation. The key difference between the two impulses, which is also what allows to tell them apart empirically, is that the MEI shock leaves spreads little changed (bottom right panel). Moreover, MEI shocks play a fairly large role in fluctuations, accounting for between 10% and 25% of the variance of the variables reported in Figure 11.

The TFP shock is another crucial shock in the model, with large contributions to the variance of output, hours, the spread and (to a somewhat lesser extent) inflation and the nominal interest rate. Unlike for the spread shock, this predominance is evident both unconditionally (Figure 11) and during the Great Recession, but much less over the course of the recovery.

As shown in Figure 4, a positive TFP shock has a large and persistent effect on output growth, even if the response of hours is muted in the first few quarters, and slightly negative on impact, as in the data (see Galí (1999)). This muted response of hours is due to the presence of nominal rigidities, which prevent aggregate demand from expanding sufficiently to absorb the increased ability of the economy to supply output. With higher productivity, marginal costs and thus the labor share fall, leading to lower inflation. The policy rule specification implies that this negative correlation between inflation and real activity, which is typical of supply shocks, produces countervailing forces on the interest rate, which as a result moves little.

The last structural shock that plays a relevant role in the current economic environment is the mark-up shock, whose impulse response is depicted in Figure 5. This shock is an exogenous source of inflationary pressures, stemming from changes in the market power of intermediate goods producers. As such, it leads to higher inflation and lower real activity, as producers reduce supply to increase their desired markup. The effects of markup-shocks are significantly less persistent than those of the other prominent supply shock in the model, the TFP shock. GDP growth falls on impact after mark-ups increase, but returns above average after about one year, thus restoring the original level of output over the horizon of the simulation. Inflation is sharply higher for a couple of quarters, leading to a temporary spike in the nominal interest rate, as monetary policy tries to limit the pass-through of the shock to prices. Unlike in the case of TFP shocks, however, hours fall immediately, mirroring the behavior of output.

The IRFs of the labor supply shock are depicted in Figure 6. This disturbance stands at the opposite end of the spectrum with respect to the spread shock, in the sense that its role in fluctuations is quite pronounced on average, but negligible in the last few years. Labor shocks, which capture changes in households' taste for leisure/work, are responsible for about 20% of the fluctuations in most of the variables included in Figure 11. Their dynamics feature a fairly persistent fall in hours worked (Figure 6), which triggers a fall in output, but an increase in wages and the labor share, with the attendant inflationary pressures and positive response of policy rates.

Finally, Figure 7 reports the IRFs of the government spending shock, which plays a very limited quantitative role in the model, accounting for less than 5% of the fluctuations of all variables, except at very short forecast horizons. In terms of dynamics, this shock boosts GDP growth in the very short run, and hours for a few quarters, generating some mild inflationary pressures that are kept in check by a rise in interest rates.

5.1 Policy Shocks: Anticipated and Unanticipated

Policy shocks deserve a separate treatment from the other structural disturbances in the model, due to the presence of both standard (i.e. unanticipated) and less common, 'anticipated' shocks, which are known to agents in advance of their realization. Anticipated shocks capture expected deviations of the interest rate from the setting implied by the policy rule, which can occur in two different circumstances. First, such deviations are a way of capturing in a linear model the contractionary effect of the zero lower bound on the nominal interest rate, which prevents the policy rate from being negative when the policy rule would otherwise dictate that it be. Second, anticipated shocks can capture communication on the part of the central bank—the so-called "forward guidance"—whose objective is to shift expectations of the future federal funds rate away from what would be implied by the historical policy rule, for instance towards a more accommodative stance of policy, as is the case currently (see Del Negro et al. (2012)).

Figure 8 reports the responses of the key variables to an unanticipated, negative 50 bps monetary shock. The dynamics are those familiar from many VAR and DSGE studies. The fall in the interest rate, which only gets reabsorbed over the course of two years, due mostly to the persistence of the policy rule, leads to a sizable expansion in the real economy, with hours increasing in a humped shaped pattern, by roughly 0.5% at the peak, and output growth higher by 0.7% on impact, but returning to steady state in about one year. The labor share also rises, with a similar pattern to that of hours, but its increase is more muted, leading to a relatively modest, but fairly persistent increase in inflation. The spread falls on impact, but it recovers afterward; its movements, however, are overall negligible.

Anticipated shocks have similar qualitative dynamics, in the sense of leading to an expansion in real activity and to more inflation, but with some peculiarities due to their effect on expectations. Figures 9 and 10 plot IRFs for monetary policy shocks anticipated four and eight quarters ahead, to give a flavor of the quantitative impact of anticipation. Shocks anticipated at different horizons within the range considered in our exercises have similar characteristics. The first feature that stands out in both responses is that an anticipated negative shock (i.e. one that is expected to bring the interest rate down in the future), leads to higher interest rates now. This is because the lower future interest rate has a stimulative effect already today—agents are forward looking in the model. As a result, the policy rate rises endogenously on impact in reaction to these positive real developments, as well as in response to the associated higher inflation, as per the model's Taylor rule. Nevertheless, the economy continues to expand as the actual shock draws near and in fact it does not react when the interest rate actually falls, since this development is old news at that point.

Another notable feature of the dynamics associated with these disturbances is that shocks that occur in the future can have larger effects than contemporaneous ones of the same magnitude (all three policy shocks are -50 bps in the figures). For instance, a shock anticipated 4 quarters ahead has a larger impact on GDP growth and hours than the contemporaneous shock (compare Figures 9 and 10), although the effect on these variables is somewhat smaller for the 8-quarter-ahead shock. However, the impact on inflation is larger, the longer is the anticipation horizon, since the effect on the labor share is more persistent, even if it is smaller on impact. As a result, inflation, which discounts all feature developments in unit labor costs, is higher immediately.

6 Developing a Narrative: from the Great Recession to a Sluggish Recovery

In the previous section we have described the key mechanisms determining the equilibrium evolution of the model. This transparent framework enables us to identify the source of the past fluctuations and the current outlook for key economic indicators in terms of the exogenous processes described above. In this section we describe how the model 'explains' the evolution of output growth, core PCE inflation and the federal funds rate (FFR) during the Great Recession and what are the drivers behind their mean forecast through 2016. Through the lenses of the model, the evolution of the economy since 2007 is driven by two main forces. On the one hand, disruptions in the financial sector depressed aggregate demand and employment, producing a sharp economic downturn and a sluggish recovery. On the other hand, monetary policy played an important role in supporting the economy by providing stimulus both by conventional measures at the onset of the recession and by the use of forward guidance afterwards.

The importance of each shock for output growth, core PCE inflation, and the federal funds rate (FFR) from 2007 on is quantified in Figure 12. In each of the three panels the solid line (black for realized data, red for the mean forecast) shows the variable in deviation from its steady state (for output growth and inflation, the numbers are quarter-to-quarter annualized). The bars represent the contribution of each shock to the deviation of the variable from steady state, that is, the counterfactual values of output growth, inflation, and the federal funds rate (in deviations from the mean) obtained by setting all other shocks to zero. By construction, for each observation the bars do in principle sum to the value on the solid line. (To be precise, we do not show in the figure the contribution of the state at the beginning of the sample on the subsequent evolution of the variables, as this deviation from steady state contributes only modestly to short-term economic fluctuations.) The shock decomposition and model forecasts shown in the figure are obtained using data up to 2013Q1, the quarter for which we have the most recent GDP release, as well as the federal funds rate and spread data for 2013Q2 (we use the average realizations for the quarter up to the forecast date). In order to capture the effect of forward guidance, the federal funds rate expectations in the model are constrained to be equal to market expectations for the federal funds rate (as measured by OIS rates) until 2015Q2. Finally, we estimate the standard deviation of the anticipated shocks as in Campbell et al. (2012), but we only use post-2008Q4 data. The model forecasts represented by the red lines are distinct from the FR

The Great Recession was characterized by a severe financial crisis that impaired the flow of credit, depressing aggregate demand and employment. The presence of credit intermediation frictions enables the FRBNY DSGE model to capture key dimensions of these events, attributing an important part of the economic downturn to the spread shock, which reflects higher perceived riskiness of borrowers and causes disruptions in financial intermediation. In fact, Figure 12 shows that spread shocks (measured by the dark purple bars) explain about half of the drop in output growth and inflation during the recession. As we discussed, this shock works through the model by increasing the expected cost of capital and reducing entrepreneurs' borrowing: hence it decreases their capital accumulation and their ability to channel resources to the productive sector. Figure 14 plots the standardized innovations (that is, the innovations measured in standard deviation units) of the shocks in the model, from 2007 on. The figure shows that realizations of the spread shock are indeed positive in the early part of the Great Recession, with large spikes in late 2007 and particularly in 2008Q4, in the aftermath of the Lehman collapse.

Other shocks also contributed to the Great Recession. Figure 12 shows that TFP shocks (dark red bars) played an important role in the decline of output, particularly in 2008. As revealed in Figure 14, TFP shocks were indeed largely negative during this period, reflecting disruptions in production for given factor inputs. However, productivity shocks cannot fully account for the Great Recession because a drop in productivity leads to an increase in inflation, rather than the decline that was observed. This is evident from Figure 4, which shows the impulse responses to a one-standard-deviation positive TFP shock. One can infer from this figure that a negative one-standard deviation TFP shock would lead to a substantial drop in output but also to an increase in inflation. Moreover, because of nominal rigidities, the impact response of hours worked to the negative shock in productivity is very small, if not positive.

"Labor supply" shocks (pink bars) have not been major driver of the Great Recession, as they cannot replicate the observed comovement between inflation and output during this episode. As we discussed (see also Figure 6) positive labor supply shocks (exogenous inward shifts in labor supply, possibly due to unmodeled labor market imperfections) lead to a decline in output and hours, but to an increase in inflation. This is because firms' marginal costs rise following a contraction in labor supply.

Monetary policy shocks played an important countervailing role during the recession (orange bars). Offsetting the negative effect of spread shocks and TFP shocks, monetary policy contributed to lifting GDP growth by more than two percentage points in late 2007 and in the first half of 2008, by sharply reducing the Federal funds rate. As shown in the bottom panel, the reduction in the federal funds rate observed in the recession was much larger than explained by the contraction in inflation and output growth. Hence, the model identifies a series of negative monetary policy shocks as the primary drivers of the rate's sharp decline by the end of 2008. The large drop in interest rates boosted output growth and, albeit with a lag, had a positive effect on inflation.

Moving past the Great Recession, Figure 12 shows that the economy continues to be affected by the headwinds from the financial crisis. These are captured initially by the effects of the spread shocks and later by MEI shocks (azure bars), which maintain the recovery subdued, real marginal costs low, and inflation consequently low. Accommodative monetary policy, and particularly forward guidance about the future path of the federal funds rate (captured here by anticipated policy shocks) has played an important role in counteracting the financial headwinds, and in lifting up output and inflation.

In more detail, the role played by spread and MEI shocks is quite evident in the shock decomposition for inflation and interest rates, which shows that MEI, and to a lesser extent, spread shocks play a key role in keeping these two variables below steady state. This feature of the DSGE forecast is less evident for real output growth, as the contribution of MEI shocks seems small, particularly toward the end of the forecast horizon, and the contribution of spread shocks is negligible (and positive). However, recall that a small, but still negative, effect on output *growth* implies that the effect of the MEI shocks on the *level* of output is getting *larger*, even several quarters after the occurrence of the shock. Similarly, the fact that the growth impact of spread shocks is positive but very small implies that the level of output is very slowly returning to trend. This is evident in the protracted effect of spread and MEI shocks on aggregate hours, shown in the impulse responses of Figures 2 and 3, respectively, and discussed above. In turn, the fact that economic activity is well below trend pushes inflation and consequently interest rates (given the Fed's reaction function) below steady state.

After the end of the Great Recession, monetary policy continued to stimulate output growth from mid 2009 to late 2012 through anticipated monetary policy shocks, representing the use of forward guidance. Since shocks at different horizons interact with one another, it is difficult to assess their overall impact. It is therefore more useful to show their cumulative impact, as shown by the orange bars in Figure 12. One can see that the cumulative impact of policy shocks on the interest rate is currently very small, implying that the level of the interest rate is not too far from that implied by the estimated policy rule. Later in the forecast horizon the impact of these shocks becomes larger, and reaches almost one percentage point in 2015: the impact of the forward guidance, combined with the interest rate smoothing component of the policy, which limits quarter-to-quarter adjustments, implies that the renormalization path is lower than that implied by the estimated rule.

Despite the important role played by policy shocks in pushing inflation and output upward both in the immediate aftermath of the recession and in the current period, the impact of policy on the *level* of output has started to wane by the end of 2012. This implies that the effect of policy on *growth* is actually negative after that, which explains why growth is still at or below trend by the end of 2016. This is partly because the stimulative effect of the forward guidance is front-loaded, and hence has the largest impact when it is first implemented.

Finally, given the weak outlook for marginal costs, the model attributes much of the rise in core inflation in 2011 and in early 2012 to price mark-up shocks. Increases in mark-ups in our monopolistically competitive setting push inflation above marginal costs and reduce output. Figure 5 shows that mark-up shocks capture large but transitory movements in inflation, such as those due to oil price fluctuations. However with the moderation in energy prices since then, mark-up shocks have had much smaller effects on inflation in recent quarters, and play almost no role in the inflation forecasts. Since output is returning to trend following mark-up shocks, these actually contribute positively to output growth from 2013 onward.

7 The Forecast Distributions

The previous section described the model forecast for key economic variables. An additional advantage of using structural economic models for forecasting and policy analysis is the ability to produce an entire forecast distribution, which reflects uncertainty about both structural parameters and the state of the economy. Figure 13 presents quarterly forecasts for output growth, core PCE inflation and the federal funds rate. In the graphs, the black line represents data, the red line indicates the mean forecast, and the shaded areas mark the uncertainty associated with our forecasts as 50, 60, 70, 80 and 90 percent probability intervals. Output growth and inflation are expressed in terms of percent annualized rates, quarter to quarter. The interest rate is the annualized quarterly average. The bands reflect both parameter uncertainty and shock uncertainty.

As discussed above, the model still projects a lackluster recovery in economic activity, with output growth in the neighborhood of 2 percent throughout the forecast horizon. There is moderate uncertainty around the real GDP forecasts; for example the 70 percent bands cover the interval -1.7 to 5.2 percent in 2014. Concerning the core PCE inflation forecast, the model predicts a very slow return to the long-run FOMC target over the forecasting horizon: indeed, according to the mean forecast, inflation is still below 2 percent in 2017. The 70 percent probability bands for inflation in 2014, 2015, and 2016 are within the 0.6-2.8 percent interval, implying that the model places high probability on inflation realizations below the long-run FOMC target.

8 An Assessment of the Model's Real-Time Forecasts, 2010-2012

In this section we discuss the real-time forecasts from the FRBNY-DSGE model starting from March 2010, when we began producing forecasts, and provide a broad assessment of how the DSGE model has fared so far in terms of forecasting accuracy. The forecasts have been produced roughly eight times a year, about two weeks before each Federal Open Markets Committee meeting, and have all been published in internal documents. We should emphasize that the model specification has changed over time, reflecting model developments. For instance, financial frictions which, as discussed above, play a crucial role in explaining the

Great Recession and in shaping the current forecast, were introduced in 2011. Concerning our assumptions about monetary policy, the horizon for which we use market-based observations on FFR expectations in order to take forward guidance into account has changed over time.

We present two sets of graphs. Figure 16 shows, for the period 2010-2012, three vintages of the annualized quarterly forecasts for output growth and core PCE inflation from the DSGE model. For comparison, the figure shows also the median forecast of the Federal Reserve Bank of Philadelphia's Survey of Professional Forecasters (SPF), indicated by red lines. We report the last forecast vintage generated for each year so that SPF forecasts have the longest possible forecast horizon. Importantly, all vintages of SPF forecasts are produced after the DSGE forecast is produced; hence the DGSE econometricians are always at an informational disadvantage relative to the other forecasters.

We show two types of DSGE forecasts. The first, which we refer to as "unconditional" forecasts and which are indicated by dark blue lines are constructed as described in the previous section, by using the most recently-available released data, including up-to-date spread and FFR data. The second forecast, which we refer to as "conditional" and which is indicated by light blue lines incorporates the FRBNY staff nowcast for the current quarter, and treats it as actual data. (The forecast is conditioned on the FRBNY staff nowcast in the spirit of Doan et al. (1984), hence the adjective "conditional"). This second forecast partly overcomes the informational disadvantage mentioned above (see the discussion in Del Negro and Schorfheide (2013)).

Figure 17 shows the rolling progression over time of forecasts for year-over-year output growth and Q4/Q4 core PCE inflation in 2011, 2012, and 2013. We show these yearly forecasts because they allow for a comparison with SPF forecasts for longer horizons than the quarterly forecasts.

From both sets of figures we can see that in the periods considered the FRBNY-DSGE output growth forecasts have been comparable to, if not better than, the median SPF forecasts. To some extent the SPF has been overly optimistic about growth, especially in the medium-long term, as professional forecasters have been repeatedly forecasting a relatively rapid closing of the output gap which opened in the aftermath of the financial crisis. Conversely, the DSGE model has been consistently predicting a very slow recovery following financial shocks, as discussed at length in previous sections. As a consequence, we can see from Figure 17 that for each of the years considered, the SPF has initially produced an overly optimistic forecast, which, as time passes and more information is accumulated, converges to where the DSGE model had been all along. (Note that the apparent mis-forecasting in 2012 by all models is due to the July 2013 comprehensive NIPA revision which revised up the growth rate of real GDP from 2.2% to 2.8%.) However, the DSGE model continues to predict rather weak growth forecasts several years after the financial crisis, and we suspect that these weak forecasts may partly result from the DSGE model "overfitting" the crisis.

The DGSE model, on the other hand, under-forecasted inflation in 2011 and early 2012, partly because it missed the effect of commodity prices on core inflation, and partly because the weak activity forecast within the model naturally translate into a weak inflation forecast. We can see, however, that in late 2012 and 2013, after the effect of commodity prices waned, inflation has fallen and is now broadly in line with, say, the DSGE model forecasts made in 2010.

9 Conclusion

In this paper, we presented the FRBNY DSGE model and discussed how it is used for forecasting and to interpret the recent history. At the FRBNY, the model has also been used for policy analysis, for example as discussed in Del Negro et al. (2012). In addition, we have used the model to evaluate the impact on the outlook of adopting monetary policy rules that differ from the historical one.

We have focused our discussion on one model only. We are well aware that in presence of model misspecification one would want to consider multiple models (see Geweke and Amisano (2012)). These models may differ in terms of their underlying assumptions, estimation procedures, and degrees of theoretical coherence (as measured by the tightness with which the cross-equations are imposed, e.g. see Del Negro and Schorfheide (2004)). This is an important direction for future research and modeling work within a central bank.

In terms of modelling, there are many directions in which the model could be enriched or adjusted, to make it an even more useful tool for day-to-day monetary policy analysis. In particular, it would be desirable to include a more fully developed model of the labor market, which would account for the unemployment rate, given the importance of this variable in the policy debate. Incorporating a more fundamental role for financial intermediation, in particular as a potential source of economic instability, as well as developing the asset pricing implications of the model, would also help it better answer some of the questions often on the minds of policymakers.

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Table 1: Prior and Posterior for the DSGE Model Parameters

Parameters	Prior Mean	Prior Stdd	Post Mean	90% Lower Band	90% Upper Band
Policy Parameters					
π_*	2.000	0.250	2.392	2.128	2.651
ψ_π	2.000	0.250	2.132	1.869	2.384
ψ_y	0.200	0.100	0.253	0.151	0.360
ρ_r	0.500	0.200	0.800	0.763	0.836
σ_r	0.200	4.000	0.139	0.124	0.156
Nominal Rigidities Parameters					
ζ_p	0.750	0.100	0.878	0.853	0.904
ζ_w	0.750	0.100	0.902	0.870	0.933
Other "Endogenous Propagation and Steady State" Parameters					
α	0.330	0.020	0.351	0.346	0.356
a''	0.200	0.100	0.286	0.119	0.452
h	0.700	0.050	0.730	0.671	0.790
S''	4.000	1.500	4.013	2.986	5.056
ν_l	2.000	0.750	1.310	0.502	2.052
r_*	1.500	1.000	0.305	0.046	0.557
γ	2.750	0.500	1.726	1.331	2.095
g_*	0.300	0.100	0.185	0.086	0.282
$\zeta_{sp,b}$	0.050	0.020	0.081	0.048	0.112
SP_*	2.000	0.500	1.112	0.738	1.474
ρs and σs					
ρ_z	0.400	0.250	0.473	0.344	0.607
ρ_ϕ	0.750	0.150	0.308	0.188	0.428
ρ_{λ_f}	0.750	0.150	0.500	0.400	0.606
ρ_μ	0.750	0.150	0.994	0.989	1.000
ρ_g	0.750	0.150	0.931	0.849	0.999
ρ_{σ_w}	0.750	0.150	0.960	0.931	0.991
σ_z	0.300	4.000	0.778	0.686	0.867
σ_ϕ	3.000	4.000	29.082	13.474	44.661
σ_{λ_f}	0.200	4.000	0.084	0.069	0.098
σ_μ	0.750	4.000	0.356	0.271	0.438
σ_g	0.500	4.000	0.226	0.178	0.271
σ_{σ_w}	0.050	4.000	0.084	0.074	0.093

Note: The values reported for the parameters π_*, r_*, γ, and SP_* are expressed in annualized terms. The following parameters are fixed: $\delta = 0.025$, $\nu_m = 2$, $\lambda_w = 0.3$, $\chi = 0.1$, $\lambda_f = 0.15$, $F(\bar{\omega}) = 0.0075$, $\gamma^e = 0.99$.

Figure 1: Model Structure

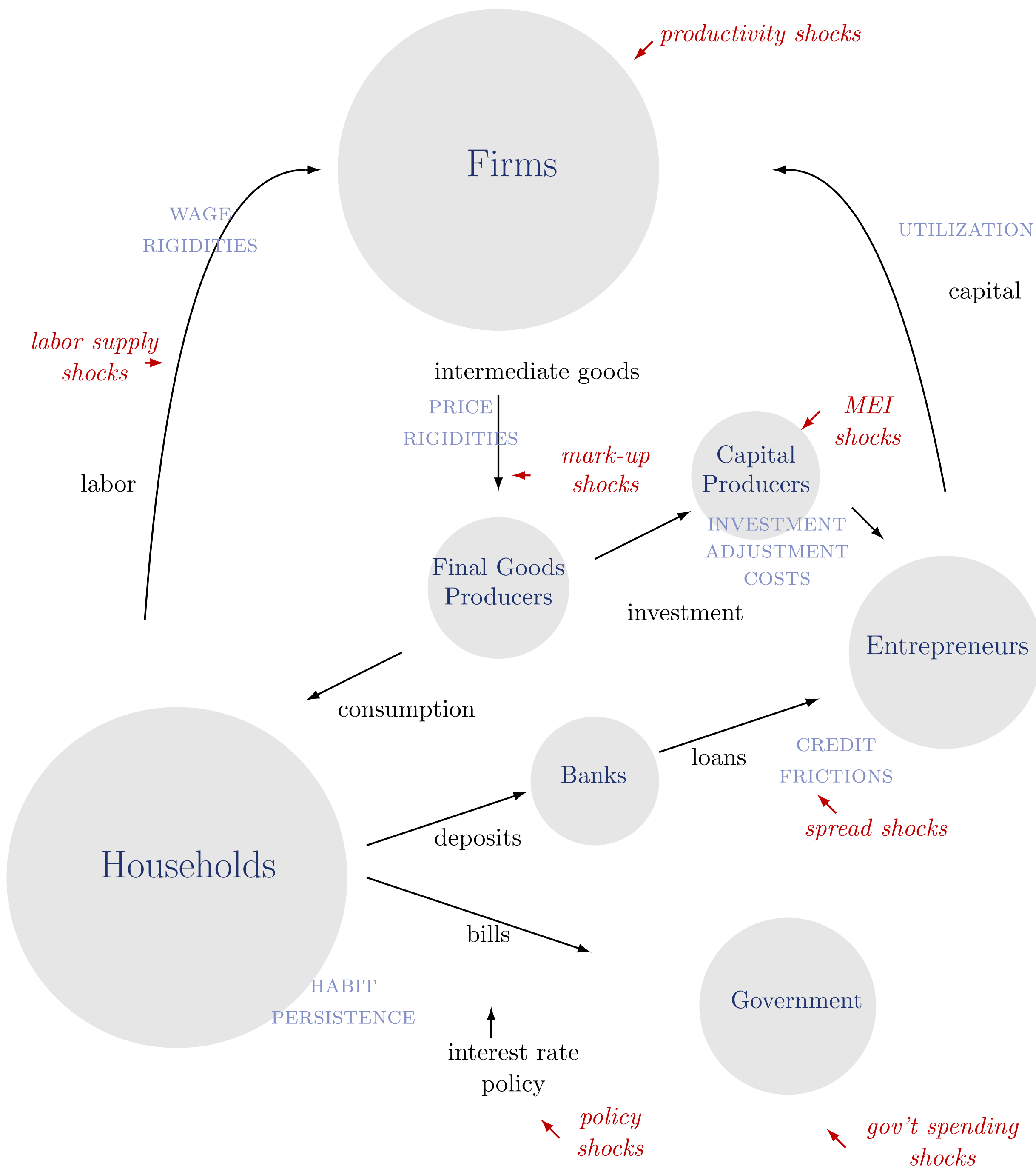


Figure 2: Responses to a Spread Shock

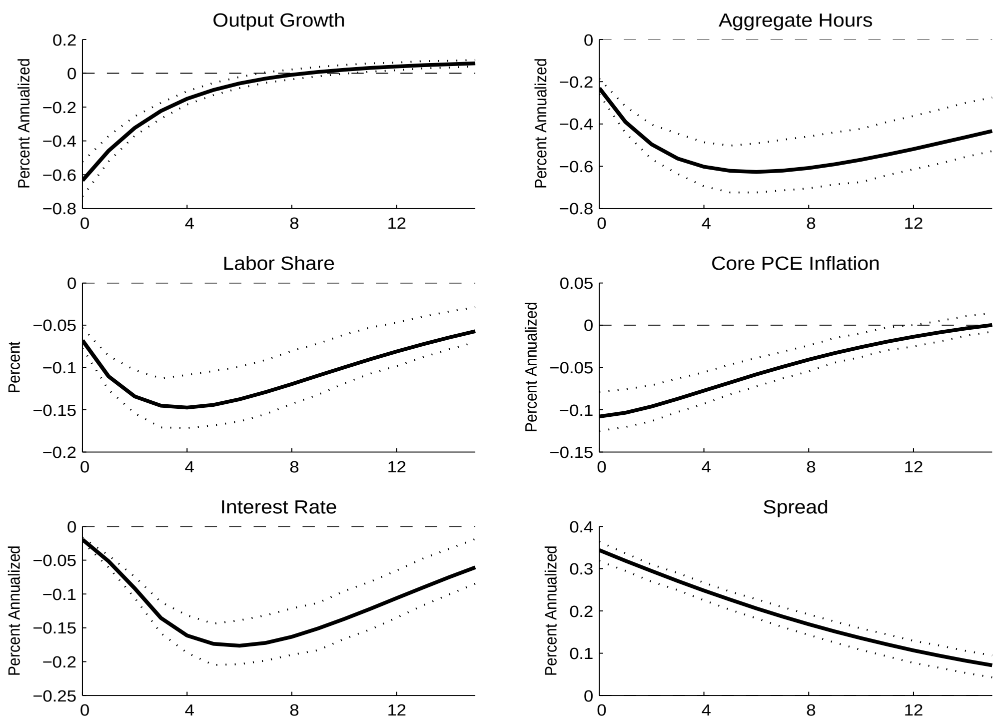


Figure 3: Responses to an MEI Shock

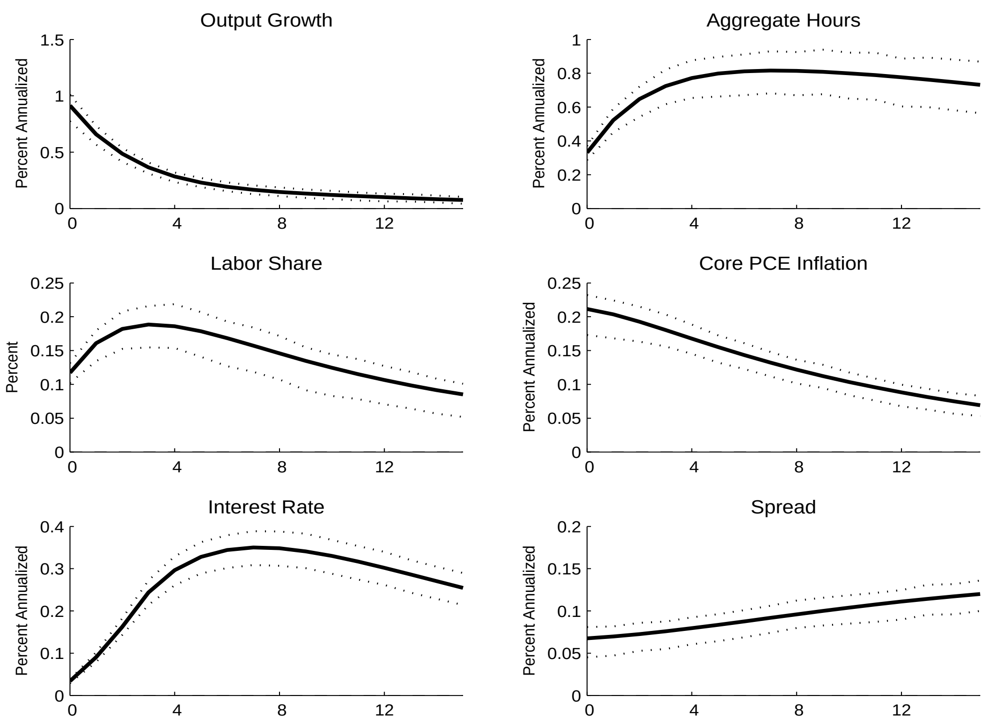


Figure 4: Responses to a TFP Shock

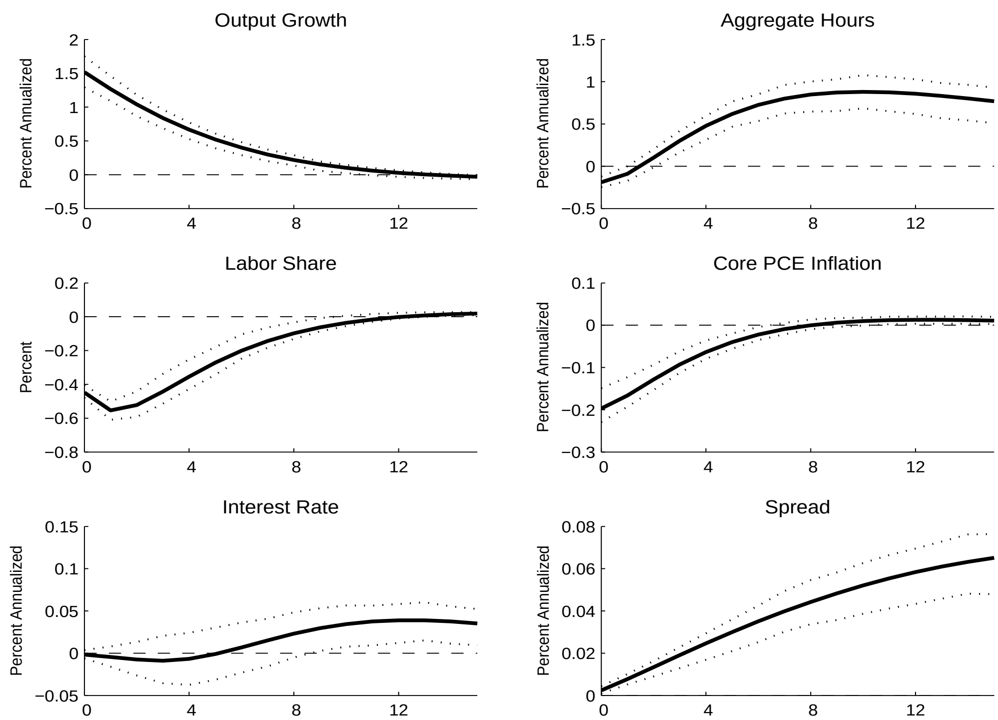


Figure 5: Responses to a Mark-up Shock

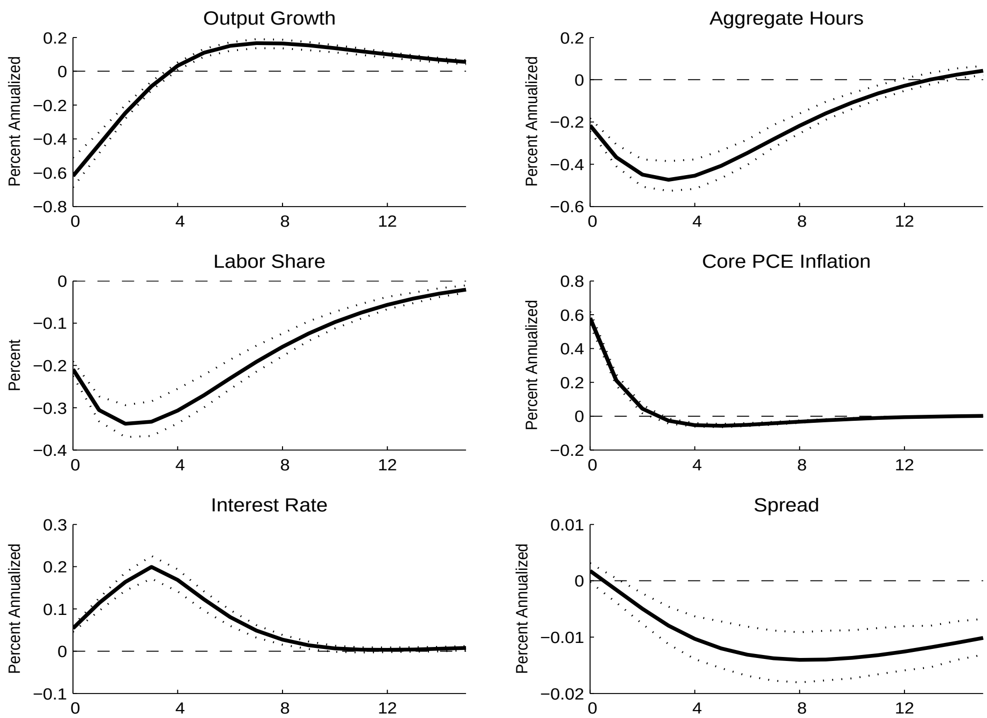


Figure 6: Responses to a Labor Supply Shock

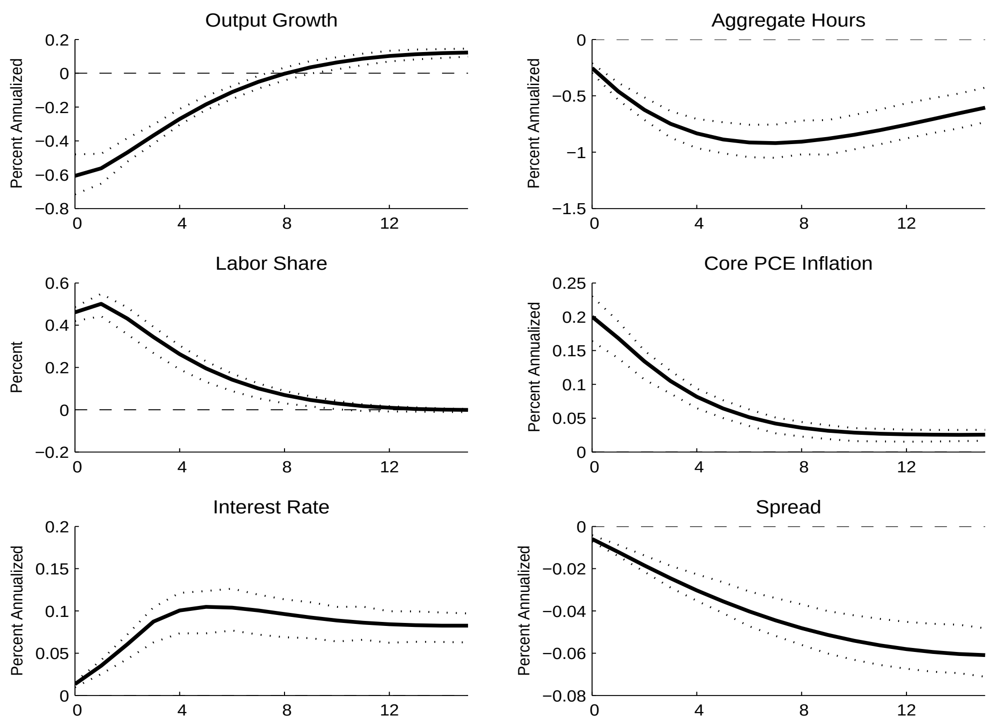


Figure 7: Responses to a Government Spending Shock

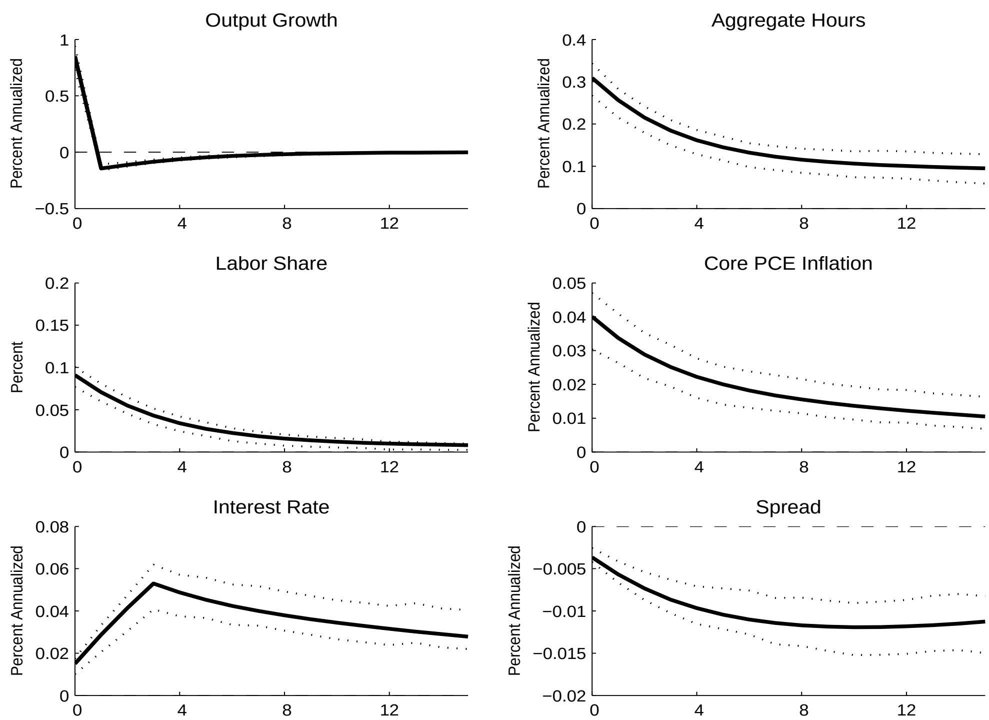


Figure 8: Responses to a Monetary Policy Shock (-50 bps)

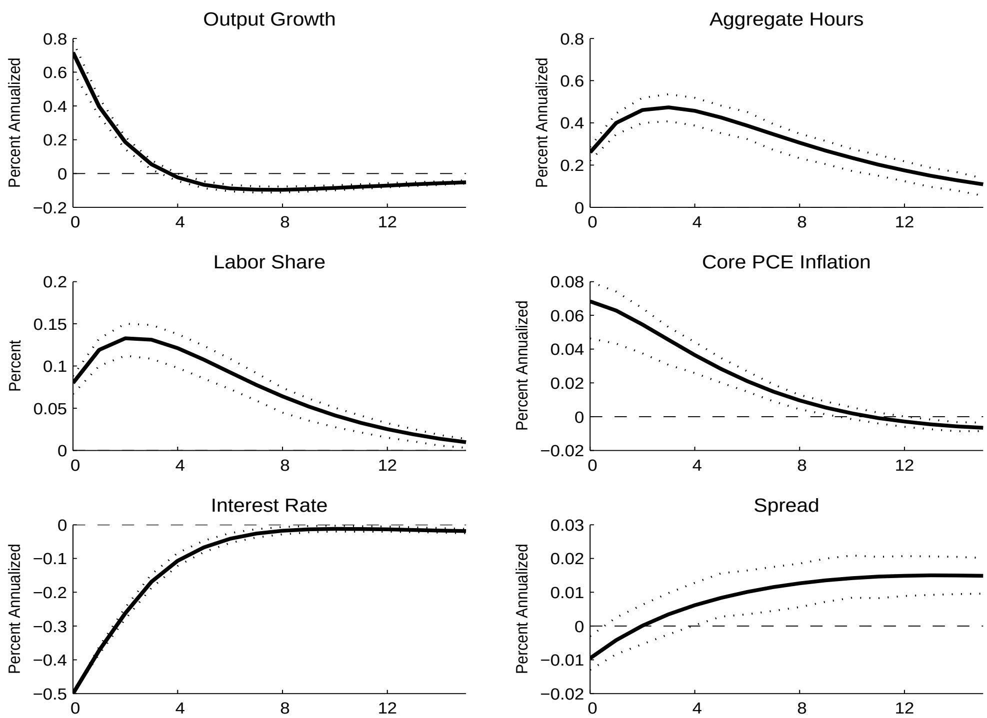


Figure 9: Responses to a 4Q Ahead Anticipated Monetary Policy Shock (-50 bps)

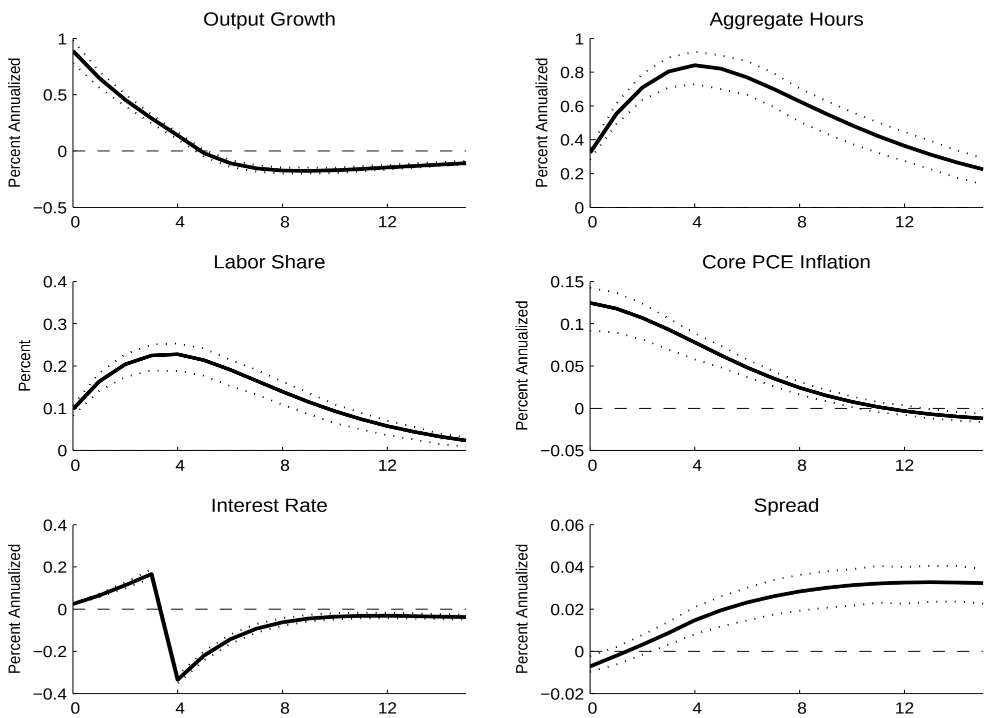


Figure 10: Responses to a 8Q Ahead Anticipated Monetary Policy Shock (-50 bps)

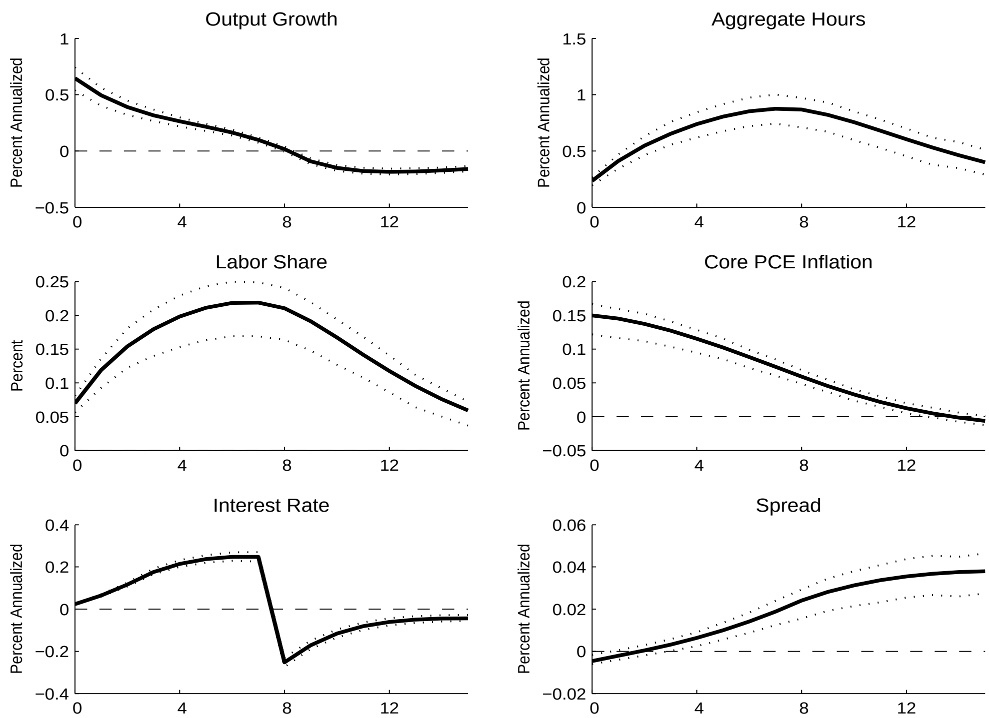


Figure 11: Variance Decomposition

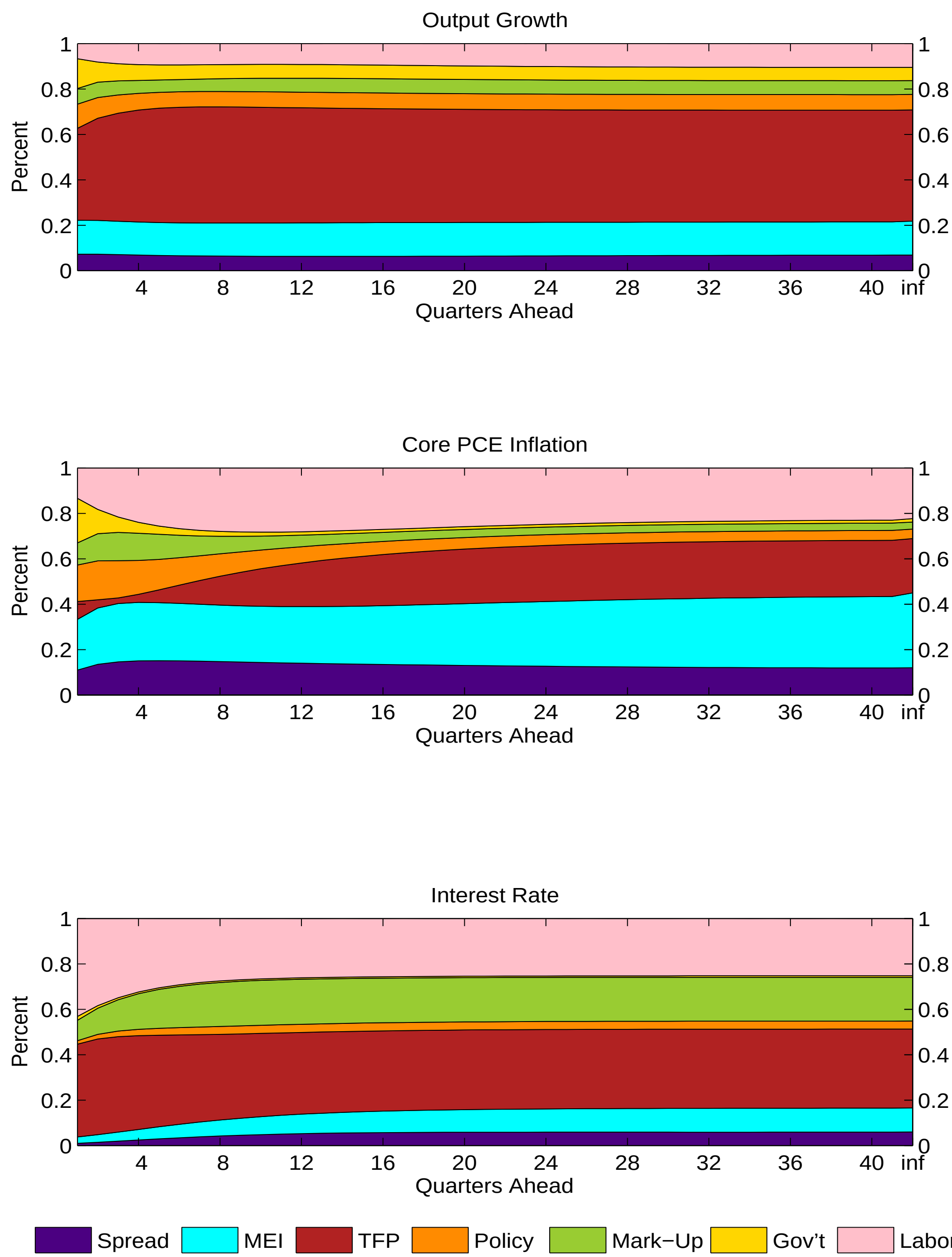
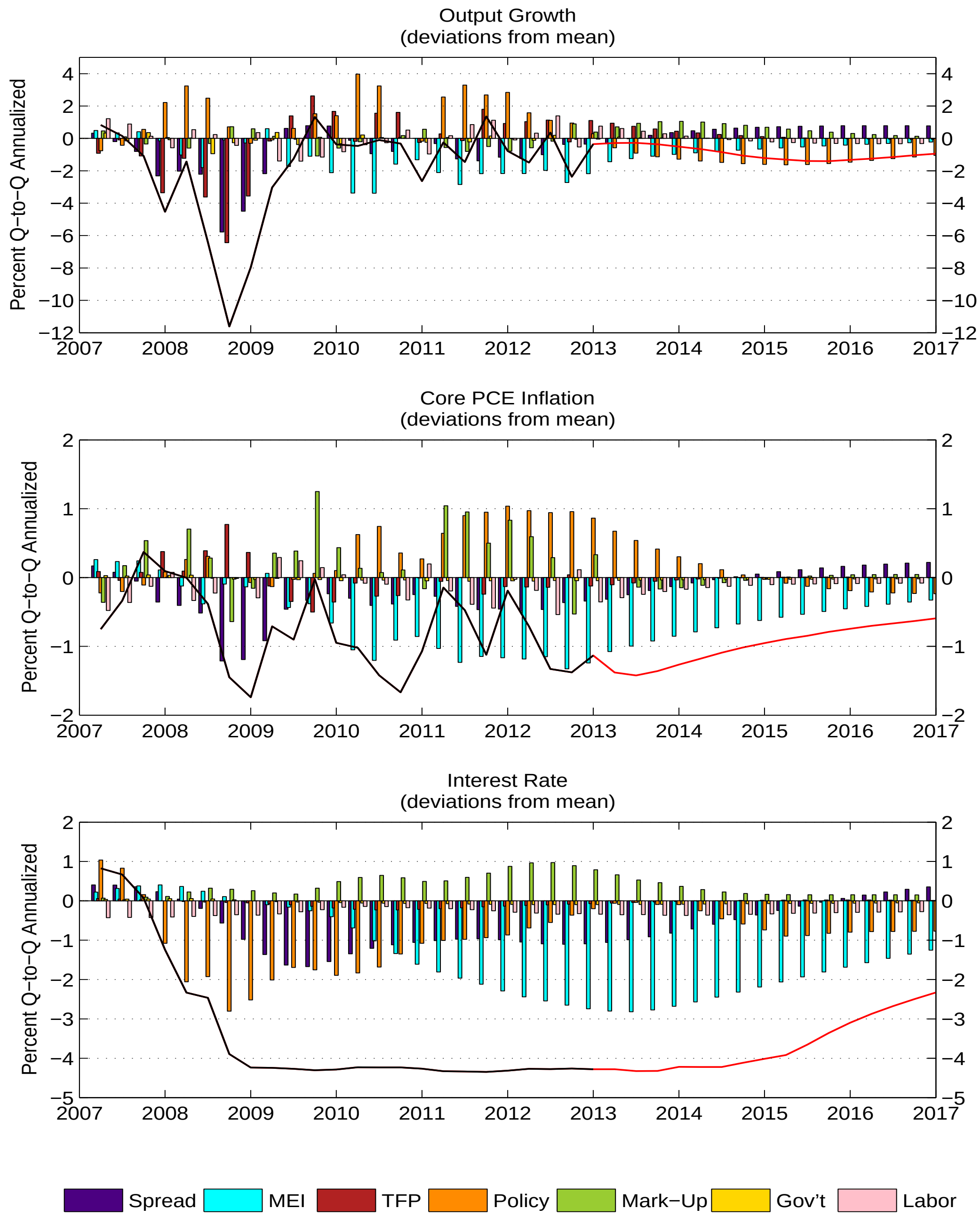
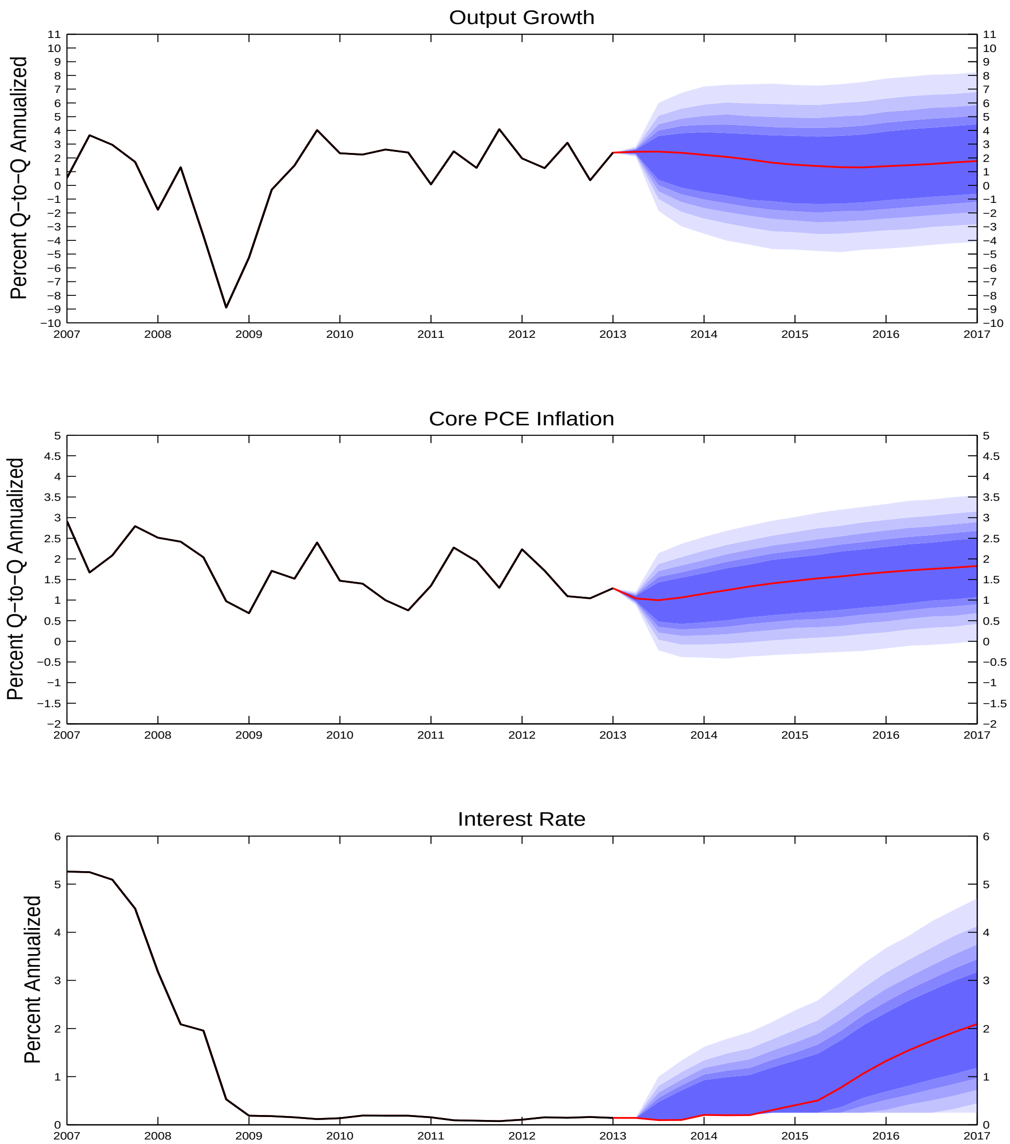


Figure 12: Shock Decomposition



The shock decomposition is presented for the realized data as well as the forecast. The solid lines (black for realized data, red for mean forecast) show each variable in deviation from its steady state. The bars represent the shock contributions; specifically, the bars for each shock represent the counterfactual values for the observables (in deviations from the mean) obtained by setting all other shocks to zero.

Figure 13: Forecasts



Black lines indicate data, red lines indicate mean forecasts, and shaded areas mark the uncertainty associated with our forecast as 50, 60, 70, 80, and 90 percent probability intervals.

Figure 14: Shock Histories

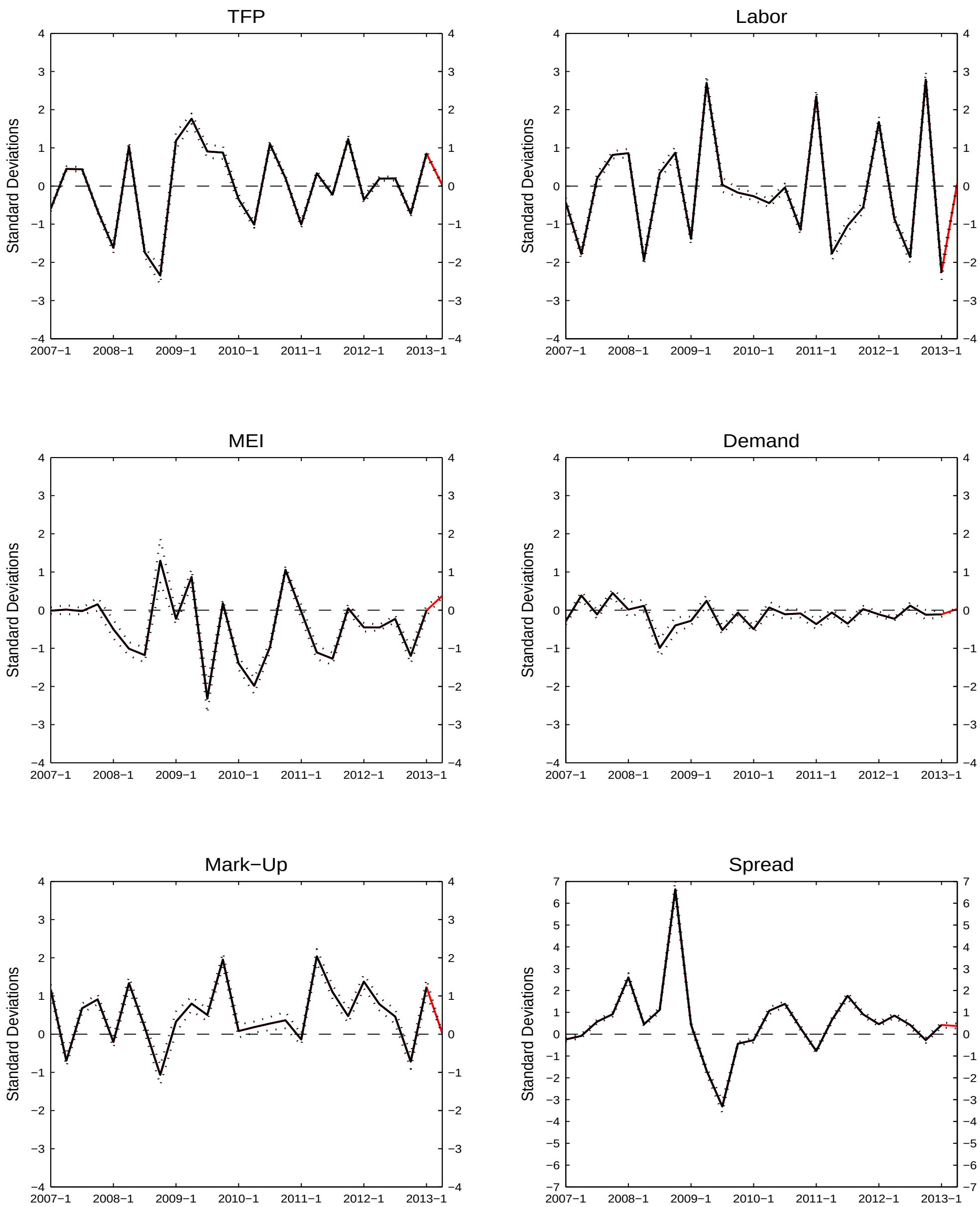


Figure 15: Anticipated Shock Histories

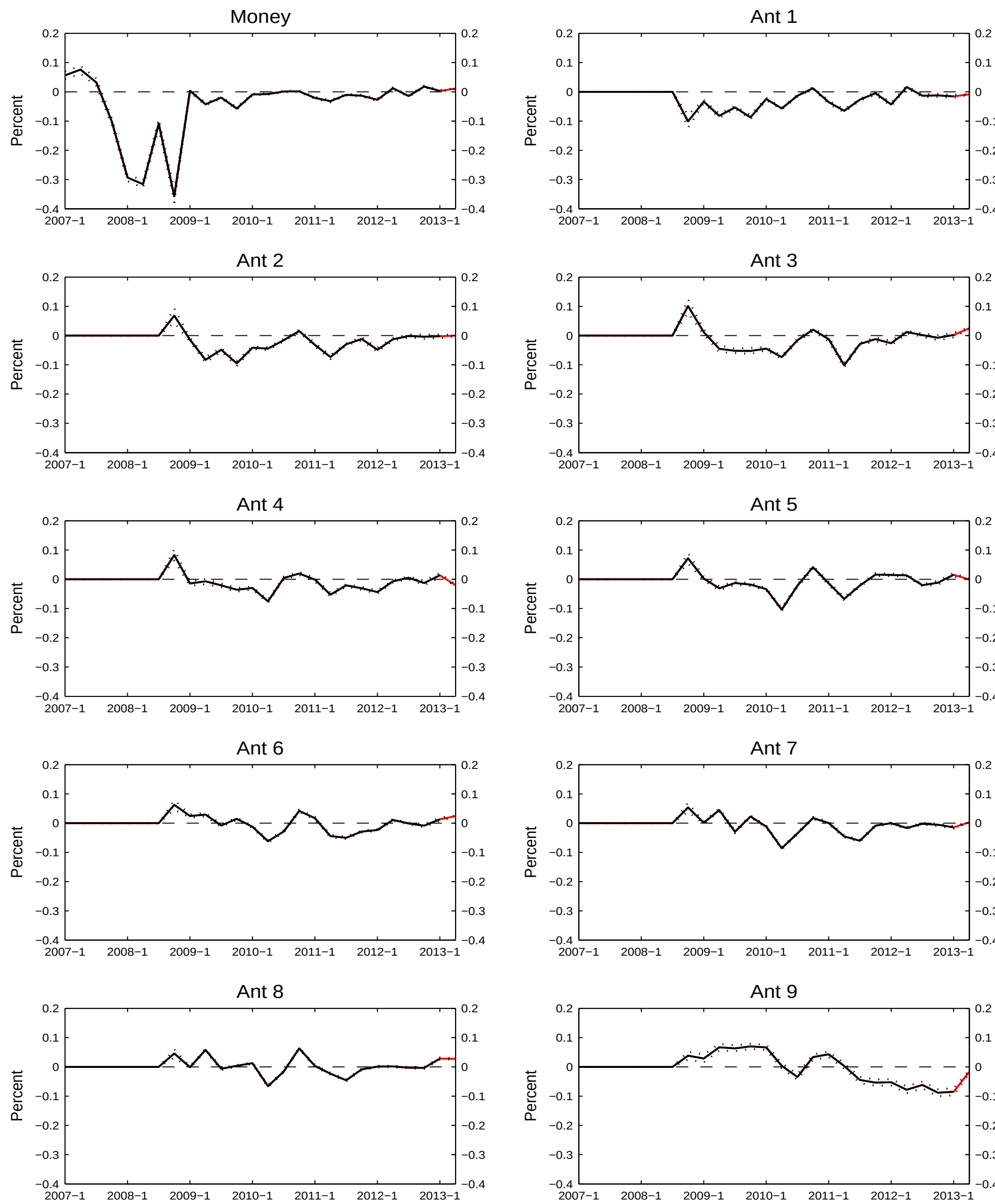
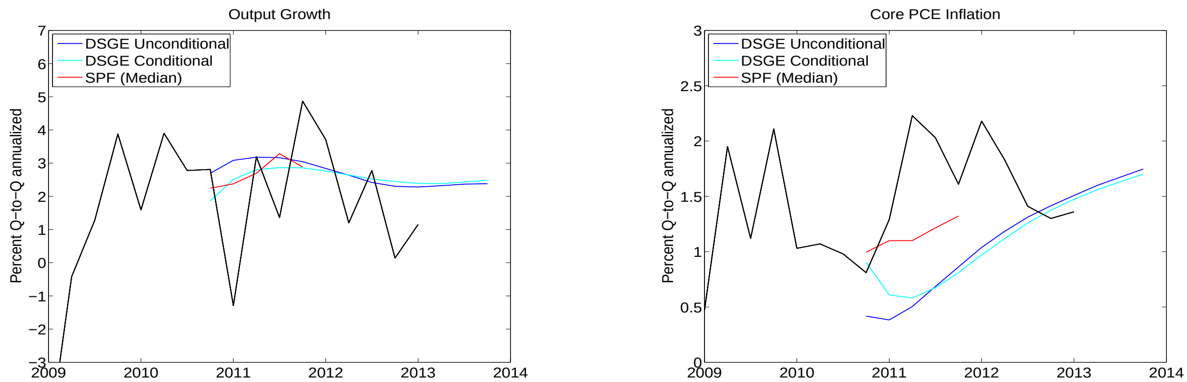
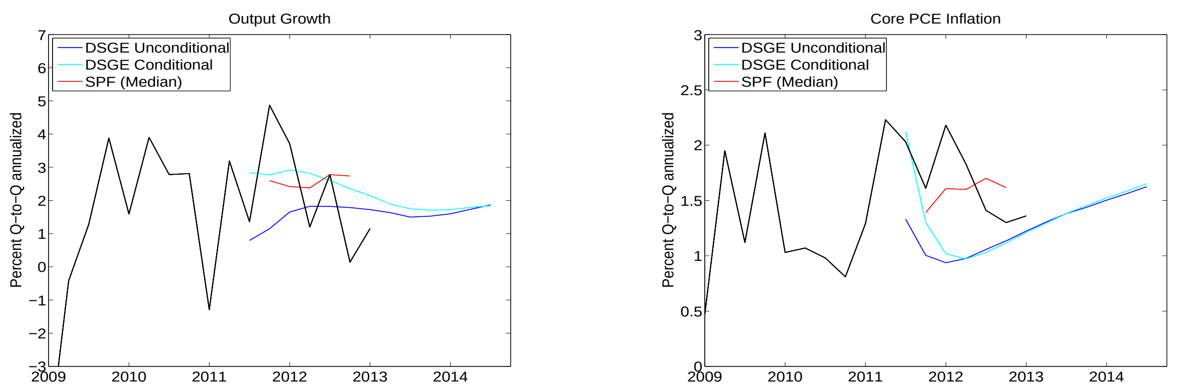


Figure 16: Real-Time Forecasts

November 2010



October 2011



November 2012

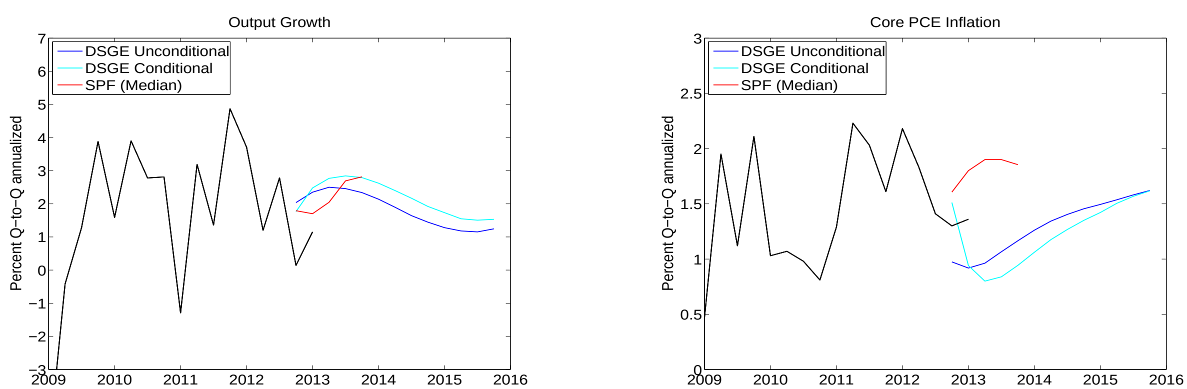
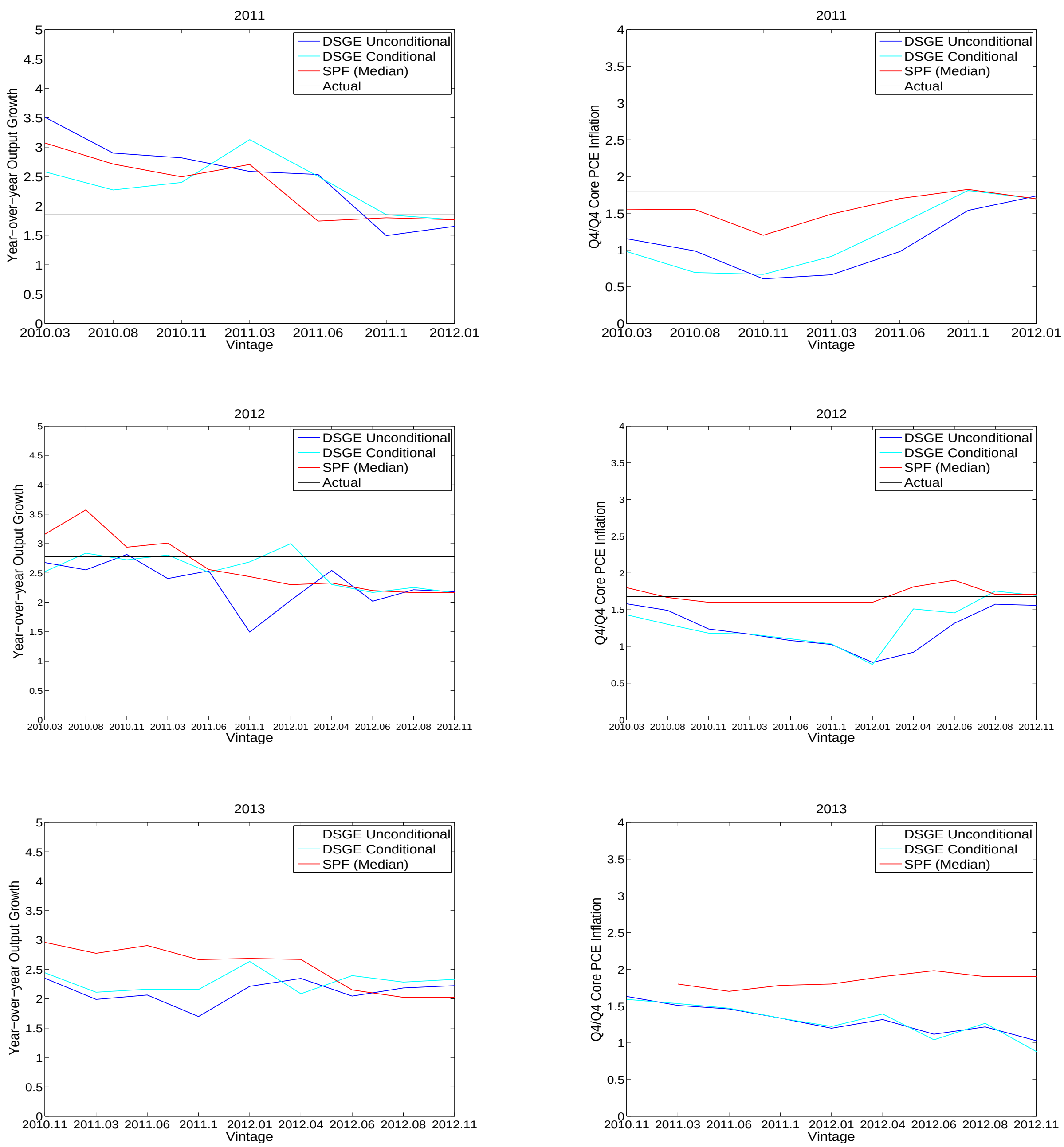


Figure 17: Real-Time Forecast Progression

Year-over-year Output Growth Q4/Q4 Core PCE Inflation



A Measurement Equations

The system of measurement equations (43) is specified as follows:

Real output growth (%, annualized)	$400(\ln Y_t - \ln Y_{t-1})$	$=$	$400(\widehat{y}_t - \widehat{y}_{t-1} + z_t + \gamma)$
Hours Worked (%)	$100 \ln L_t$	$=$	$100(\widehat{L}_t + \ln L^{adj})$
Labor Share (%)	$100 \ln LS_t$	$=$	$100(\widehat{L}_t + \widehat{w}_t - \widehat{y}_t + \ln LS_*)$
Inflation (%,annualized)	π_t^{core}	$=$	$400(\widehat{\pi}_t + \ln \pi_*)$
Interest Rate (%,annualized)	FFR_t	$=$	$400(\widehat{R}_t + \ln R_*)$,
Spread (%,annualized)	SP_t	$=$	$400(\mathbb{E}_t \left[\widehat{\tilde{R}}^k_{t+1} - \hat{R}_t \right] + SP_*)$,

where the parameter L^{adj} captures the units of measured hours worked. In the estimation, it has a prior mean of 253.5, with a standard deviation of 5.