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Do We Really Know that U.S. Monetary Policy was Destabilizing in the 1970s?*

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June 25, 2019

Abstract

The paper re-examines whether the Federal Reserve's monetary policy was a source of instability during the Great Inflation by estimating a sticky-price model with positive trend inflation, commodity price shocks and sluggish real wages. Our estimation provides empirical evidence for substantial wage-rigidity and finds that the Federal Reserve responded aggressively to inflation but negligibly to the output gap. In the presence of non-trivial real imperfections and well-identified commodity price-shocks, U.S. data prefers a determinate version of the New Keynesian model: monetary policy-induced indeterminacy and sunspots were not causes of macroeconomic instability during the pre-Volcker era.

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1 Introduction

The Great Inflation was one of the defining macroeconomic chapters of the twentieth century. From the late 1960s and throughout the 1970s, the U.S. economy experienced both turbulent business cycle fluctuations as well as unprecedented high and volatile rates of inflation. By 1979 inflation hovered above 15 percent. Since the seminal works by Clarida et al. (2000) and Lubik and Schorfheide (2004), a dominant narrative of this historical episode attributes the macroeconomic fluctuations and elevated inflation to poorly designed monetary policy: the Federal Reserve’s weak response to inflation generated equilibrium multiplicity and the resulting instability and sunspot shocks nourished further inflation movements. On the other hand, Gordon (1977) and Blinder (1982), among others, have singled out cost-push shocks – mainly arising from spikes in the prices of food and oil – as the principal causes of the 1970s’ stagflation.¹ Such cost-push shocks are largely absent from the more recent studies of the Great Inflation that focus on the interplay of monetary policy and indeterminacy.

This paper aims to re-examine these two views by estimating a sticky-price model to which we add three key factors that are often put forward as distinctive features of the Great Inflation period: positive trend inflation (Coibion and Gorodnichenko, 2011, and Ascari and Sbordone, 2014), commodity price shocks and real wage rigidity (Blanchard and Galí, 2010, and Blanchard and Riggi, 2013). In this version of a Generalized New Keynesian (GNK) economy, commodity price disturbances and wage rigidity generate a strong negative correlation between inflation and the output gap, thereby confronting the monetary authority with a difficult trade-off.² This trade-off is important as it explains why our estimates of the Taylor rule parameters – in particular, a very weak response to the output gap and strong response to inflation and output growth – are different from the ones obtained by other studies of the Great Inflation. As in Hirose et al. (2017), we employ Bayesian techniques featuring the Sequential Monte Carlo (SMC) sampling algorithm of Herbst and Schorfheide (2014) to uncover the posterior distribution of the model’s parameters over the entire

¹See also Blinder and Rudd (2012) for a recent resurrection of this line of thought and Barsky and Kilian (2001) for a critical evaluation.

²Following Ascari and Sbordone (2014), we use the term GNK to refer to the New Keynesian model loglinearized around a positive steady-state inflation rate.

parameter space.³ This upgrade is particularly relevant given the discontinuity that arises in the posterior distribution along the boundary between the determinacy and indeterminacy regions of the model. We estimate the artificial economy using quarterly observations on six key macroeconomic variables that are essential to properly identify cost-push shocks and their propagation as well as wage dynamics.

Our central claim is that we can rule out indeterminacy as a source of instability during the Great Inflation period. The underlying mechanism to this result is connected to monetary policy, in particular to the central bank's response to inflation and the output gap, as well as to the degree of wage sluggishness. We also take into account positive trend inflation as it alters the dynamics of the GNK model and makes price-setting firms more forward-looking, which effectively flattens the Phillips Curve. This flattening changes the parametric region of indeterminacy. As a result, adhering to the Taylor Principle is no longer sufficient to rule out indeterminacy. Moreover, weak responses of nominal interest rate setting to output gap variations and strong responses to output growth stabilize the economy (see Ascari and Ropele, 2009, and Coibion and Gorodnichenko, 2011). In fact, these upshots conjoin to our estimated Taylor Rule for the Pre-Volcker period: it is active with respect to inflation as in Hirose et al. (2017) but, at the same time, it entails a weaker response to the output gap and a stronger one to output growth. Our interpretation is that the central bank's response reflects the aforementioned trade-off between inflation and output gap stabilization in the presence of oil price shocks. An important element for this trade-off is a certain degree of real wage rigidity, a factor that has also been found important for understanding other macroeconomic puzzles.⁴ Along these lines, we make two contributions. First, we provide new theoretical insight regarding how wage sluggishness dampens the effect of trend inflation on equilibrium instability. Second, in the context of our estimated model, we find evidence for high degree of rigidity once we use wage data to identify wage dynamics. Then the estimated Tay-

³See also Ascari et al. (2019) for a different approach to estimation using SMC that relies on particle learning.

⁴See, for example, Barsky et al. (2015), Blanchard and Galí (2010), Blanchard and Riggi (2013), Hall (2005), Jeanne (1990), Michaillat (2012) and Uhlig (2007). Beaudry and DiNardo (1991) and others find micro-evidence along these lines. However, Basu and House (2016) suggest that a considerable portion of this rigidity disappears when accounting for heterogeneity.

lor Rule involves a more active response to inflation, a stronger response to output growth and a close to non-existent response to the output gap. This combination is key for our determinacy result during the Pre-Volcker era.

When we estimate our model over the Great Moderation period, the interest rate responses to inflation and output growth almost double, while trend inflation falls considerably. These patterns are consistent with the findings of Coibion and Gorodnichenko (2011) and Hirose et al. (2017). We also find that the Federal Reserve moved its focus away from responding to headline inflation toward core inflation (Mehra and Sawhney, 2010), implying a less contractionary response of monetary policy to oil price shocks. Finally, wages became more flexible during the Great Moderation period and therefore oil price shocks were no longer as stagflationary as in the 1970s, which is in line with Blanchard and Gali's (2010) hypothesis as to why the 2000s are so different from the 1970s.

Our paper stands in line with Lubik and Schorfheide (2004) who, while building on Clarida et al. (2000), were the first to estimate a small-scale model with price frictions to find that the Federal Reserve's passive response to inflation resulted in sunspot equilibria in the 1970s.⁵ Hirose et al.'s (2017) study takes into consideration the role of positive trend inflation in a small-scale sticky-price model and, like Coibion and Gorodnichenko (2011), they show that the Federal Reserve's policy still induced sunspot equilibria.⁶ All of these existing empirical investigations of the link between monetary policy and equilibrium stability have sidestepped the explicit treatment of commodity price fluctuations and the policy trade-off that these disturbances can generate. Nicolò (2018) estimates a medium-scale model with cost push shocks similar to Smets and Wouters (2007) but abstracts from trend inflation. In addition, we also model commodity price shocks in a more explicit way which allows us to use particular observables that sharpen their identification. There are several studies of oil's role from a general equilibrium perspective. Natal (2012) considers an alternative mechanism to real wage rigidity through which oil price shocks can create a policy trade-off. His approach relies on the interaction between monopolistic competition

⁵Ascari et al. (2019) take an alternative path that involves temporarily explosive paths.

⁶Arias et al. (2019) work off a medium-scale model with trend inflation but only estimate the Great Moderation period.

and the substitutability of oil. Nakov and Pescatori (2010) and Bjørnland et al. (2018) study the role of oil in driving the Great Moderation. Lastly, Blanchard and Riggì (2013) and Bodenstein et al. (2008) also examine the role of wage stickiness in the presence of oil price disturbances. More concretely, the former examines structural changes in the economy that have modified the transmission mechanism of oil shocks and the latter addresses optimal monetary policy design in the presence of commodity price shocks. Thus, neither of these papers has examined whether or not monetary policy was a source of indeterminate equilibria and, therefore, instability during the Great Inflation.

2 Model

The artificial economy is a GNK model with a commodity product that we interpret as oil.⁷ The economy consists of monopolistically competitive wholesale firms that produce differentiated goods using labor and oil. These goods are bought by perfectly competitive firms (retailers) that weld them together into the final good that can be consumed. People rent out their labor services and labor markets are characterized by wage rigidity. Firms and households are price takers on the market for oil.

2.1 People

The economy is populated by a representative agent whose preferences over consumption C_t and hours worked N_t are ordered by

$$E_0 \sum_{t=0}^{\infty} \beta^t d_t \left[\ln \left(C_t - h\tilde{C}_{t-1} \right) - \nu_t \frac{N_t^{1+\varphi}}{1+\varphi} \right]$$

where E_t is the expectations operator conditioned on time t information, β represents the discount factor, $h\tilde{C}_{t-1}$ is external habit in consumption taken as exogenous by the agent where $0 \leq h < 1$, and φ is the inverse of the Frisch labor supply elasticity. Disturbances to the discount factor are denoted by preference shocks d_t while ν_t stands for shocks to the disutility of labor. Both disturbances follow AR(1) processes:

$$\ln d_t = \rho_d \ln d_{t-1} + \epsilon_{d,t}$$

⁷The economy boils down to a variant of Blanchard and Galí (2010) when approximated around a zero inflation steady state. The Appendix provides details of the model.

and

$$\ln \nu_t = \rho_\nu \ln \nu_{t-1} + \epsilon_{\nu,t}.$$

Here $\epsilon_{d,t}$ and $\epsilon_{\nu,t}$ are independently and identically distributed, $N(0, \sigma_d^2)$ and $N(0, \sigma_\nu^2)$ respectively. Consumption is a Cobb-Douglas basket of domestically produced goods $C_{q,t}$ and imported oil $C_{m,t}$

$$C_t = \Theta_\chi C_{m,t}^\chi C_{q,t}^{1-\chi} \quad 0 \leq \chi < 1, \quad \Theta_\chi \equiv \chi^{-\chi}(1-\chi)^{-(1-\chi)}.$$

where χ is the elasticity of oil in consumption. We denote the core consumer price index by $P_{q,t}$, the price of oil by $P_{m,t}$ and the headline consumer price index is then given by

$$P_{c,t} \equiv P_{m,t}^\chi P_{q,t}^{1-\chi}. \quad (1)$$

People sell labor services to wholesale firms at the nominal wage W_t . They have access to a market for one-period riskless discount bonds B_t at the interest rate R_t . All profits Π_t flow back to households and the budget constraint in period t is given by

$$W_t N_t + B_{t-1} + \Pi_t \geq P_{q,t} C_{q,t} + P_{m,t} C_{m,t} + \frac{B_t}{R_t}.$$

Then, the agent's first-order conditions imply

$$\frac{d_t}{P_{c,t}(C_t - hC_{t-1})} = \beta E_t \frac{R_t d_{t+1}}{P_{c,t+1}(C_{t+1} - hC_t)}$$

and

$$\frac{W_t}{P_{c,t}} = \nu_t N_t^\varphi (C_t - hC_{t-1}). \quad (2)$$

2.2 Firms

Two kinds of firms exist. Perfectly competitive final good firms produce the homogeneous good Q_t by choosing a combination of intermediate inputs $Q_t(i)$ subject to a Constant Elasticity of Substitution production technology. With $P_{q,t}(i)$ as the price of the intermediate good i and ε as the elasticity of substitution between any two differentiated goods, the demand for good i is given by

$$Q_t(i) = \left(\frac{P_{q,t}(i)}{P_{q,t}} \right)^{-\varepsilon} Q_t. \quad (3)$$

There is a continuum of intermediate goods producers using labor N_t and (imported) oil M_t . Each firm i produces according to the production function

$$Q_t(i) = M_t(i)^\alpha [A_t N_t(i)]^{1-\alpha} \quad 0 \leq \alpha < 1$$

in which α is the share of oil in production and A_t denotes non-stationary labor-augmenting technology that follows

$$\ln A_t = \bar{g} + \ln A_{t-1} + \epsilon_{g,t}.$$

Here, \bar{g} stands for the steady-state gross rate of technological change and $\epsilon_{g,t}$ is independently and identically distributed $N(0, \sigma_g^2)$. Cost minimization implies that the firm's demand for oil is

$$M_t(i) = \frac{\alpha}{\mathcal{M}_t^P(i)} \frac{Q_t(i)}{s_t} \frac{P_{q,t}(i)}{P_{q,t}} \quad (4)$$

where $\mathcal{M}_t^P(i)$ is the firm's gross markup of price over marginal cost and $s_t \equiv \frac{P_{m,t}}{P_{q,t}}$ is the real price of oil which follows

$$\ln s_t = \rho_s \ln s_{t-1} + \epsilon_{s,t}$$

with $\epsilon_{s,t}$ independently and identically distributed $N(0, \sigma_s^2)$. Aggregating over all i and defining $\Delta_t \equiv \int_0^1 \left(\frac{P_{q,t}(i)}{P_{q,t}}\right)^{-\varepsilon} di$ as the measure of relative price dispersion, (4) becomes

$$M_t = \frac{\alpha}{\mathcal{M}_t^P} \frac{Q_t}{s_t} \Delta_t^{\frac{\varepsilon-1}{\varepsilon}}$$

where the average gross markup is $\mathcal{M}_t^P \equiv \int_0^1 \mathcal{M}_t^P(i) di$. Next, combining the cost minimization condition and the production function yields the factor price frontier:

$$\left(\frac{W_t}{P_{c,t}}\right)^{1-\alpha} \mathcal{M}_t^P = \mathcal{C} A_t^{1-\alpha} s_t^{-\alpha-\chi(1-\alpha)} \Delta_t^{-\frac{1}{\varepsilon}}$$

where \mathcal{C} is a constant that depends on α and χ . The intermediate goods producers face a constant probability $0 < 1 - \xi < 1$ of being able to adjust prices to $P_{q,t}^*(i)$ to maximize expected discounted profits

$$E_t \sum_{j=0}^{\infty} \xi^j \Lambda_{t,t+j} \left[\frac{P_{q,t}^*(i)}{P_{q,t+j}} Q_{t+j}(i) - \frac{W_{t+j}}{(1-\alpha)P_{q,t+j} A_{t+j}^{1-\alpha}} \left(\frac{(1-\alpha)P_{m,t+j}}{\alpha W_{t+j}} \right)^\alpha Q_{t+j}(i) \right]$$

subject to the demand schedule (3) where $\Lambda_{t,t+j}$ is the stochastic discount factor. The first-order condition for the relative price $p_{q,t}^*(i) \equiv \frac{P_{q,t}^*(i)}{P_{q,t}}$ is

$$p_{q,t}^*(i) = \frac{\varepsilon}{(\varepsilon - 1)(1 - \alpha)} \frac{E_t \sum_{j=0}^{\infty} \xi^j \Lambda_{t,t+j} \frac{W_{t+j}}{P_{q,t+j} A_{t+j}^{1-\alpha}} \left[\frac{(1-\alpha)P_{m,t+j}}{\alpha W_{t+j}} \right]^\alpha \left[\frac{P_{q,t}}{P_{q,t+j}} \right]^{-\varepsilon} Q_{t+j}}{E_t \sum_{j=0}^{\infty} \xi^j \Lambda_{t,t+j} \left[\frac{P_{q,t}}{P_{q,t+j}} \right]^{1-\varepsilon} Q_{t+j}}.$$

Finally, the condition that trade is balanced yields a relation between aggregate consumption C_t , gross output Q_t and gross domestic product Y_t :

$$P_{c,t}C_t = P_{q,t}Q_t - P_{m,t}M_t = \left(1 - \frac{\alpha}{\mathcal{M}_t^P} \Delta_t^{\frac{\varepsilon-1}{\varepsilon}} \right) P_{q,t}Q_t = P_{y,t}Y_t$$

where $P_{y,t}$ is the GDP deflator implicitly defined by

$$P_{q,t} \equiv (P_{y,t})^{1-\alpha} (P_{m,t})^\alpha.$$

2.3 Monetary policy

The central bank adjusts the short-term nominal interest rate R_t according to the Taylor-type rule

$$\frac{R_t}{\bar{R}} = \left(\frac{R_{t-1}}{\bar{R}} \right)^{\rho_R} \left(\left[\left(\frac{\pi_{c,t}}{\bar{\pi}} \right)^\tau \left(\frac{\pi_{q,t}}{\bar{\pi}} \right)^{1-\tau} \right]^{\psi_\pi} \left[\frac{Y_t}{Y_t^*} \right]^{\psi_x} \left[\frac{Y_t/Y_{t-1}}{\bar{g}} \right]^{\psi_g} \right)^{1-\rho_R} e^{\varepsilon_{R,t}}. \quad (5)$$

Here \bar{R} is the steady state gross nominal interest rate and $\bar{\pi}$ denotes the central bank's inflation target (which is also the steady state level of inflation, i.e. trend inflation). Mehra and Sawhney (2010) suggest that the Federal Reserve used different inflation measures to inform policy decisions. In the model, this translates into the central bank responding to a convex combination of headline and core inflation rates governed by the weight $0 \leq \tau \leq 1$. The coefficients ψ_π , ψ_x and ψ_g dictate the central bank's response to the inflation gap, output gap and output growth respectively. Following Blanchard and Galí (2007) and Blanchard and Riggi (2013), the output gap here measures the deviation of actual GDP from its efficient level Y_t^* , defined as the allocation under flexible prices and perfect competition in goods and labor markets.⁸ The policy rule further allows for interest rate smoothing via $0 \leq \rho_R < 1$. Policy shocks $\varepsilon_{R,t}$ are independently and identically distributed $N(0, \sigma_R^2)$.

⁸Blanchard and Riggi (2013) point out that in a model with real wage rigidities, the flexible-price output gap may fluctuate a lot with respect to oil price changes. In contrast, the welfare-relevant output gap moves much less, follows more of a smooth time trend, and it appears to be what the Federal Reserves looks at.

2.4 Real wage sluggishness

Departing from the above, we allow for real wage rigidities. Such rigidities have been found to be important in understanding the macroeconomic effect of oil price shocks (Blanchard and Galí, 2010, and Blanchard and Riggi, 2013), news shocks (Barsky et al., 2015), the behavior of labor markets (Hall, 2005, Michaillat, 2012) and asset markets (Uhlig, 2007) and the propagation of monetary policy shocks (Jeanne, 1990). We follow these insights and let wages adjust only partially, representing frictions not explicitly considered here. As pointed out by Blanchard and Galí (2007), this parsimonious formulation of wage rigidity entails micro-founded makeups without the need to confine to a particular one. Wage sluggishness modifies the intratemporal optimality condition (2) to

$$\frac{W_t}{P_{c,t}} = \left(\frac{W_{t-1}}{P_{c,t-1}} \right)^\gamma (\nu_t N_t^\varphi (C_t - hC_{t-1}))^{1-\gamma} \quad 0 \leq \gamma < 1$$

where γ determines the degree of rigidity, which will be a key parameter in the estimation. This modification looks after the possibility that model estimations with a flexible wage specification ascribe wage dynamics to shocks when instead those dynamics are more accurately modelled as frictions. That is, we let the data decide and if it prefers the original micro-founded specification, the estimation procedure remains free to select a value of γ close to zero.

2.5 Equilibrium dynamics

New Keynesian models are prone to indeterminacy and this is particularly the case in versions with trend inflation. Real wage rigidity affects the dynamic properties of the economy as well. To show this, Figure 1 plots the indeterminacy regions of the linearized model in the $\psi_\pi - \gamma$ space for various levels of trend inflation.⁹ In the absence of any real wage rigidity, i.e. $\gamma = 0$, the minimum responsiveness to inflation required to generate determinacy rises with trend inflation. Ascari and Ropele (2009) show that trend inflation makes price-setting firms more forward-looking which then flattens the New Keynesian Phillips Curve (in the inflation-marginal costs plane).

⁹When constructing Figure 1, the policy rule is $\widehat{R}_t = \psi_\pi \widehat{\pi}_t$ and parameters are set at $\beta = 0.99$, $\varepsilon = 11$, $\xi = 0.75$, $\varphi = 1$, $h = 0$ and $\alpha = \chi = 0$.

Therefore, the central bank needs to respond more strongly to inflation in order to generate a reduction in output that would generate a given reduction in inflation. You can see this expansion of the indeterminacy region to the right in Figure 1. Real wage rigidity partially undoes this effect and the minimum responsiveness to inflation ψ_π required for equilibrium uniqueness decreases. In the figure the impact of wage rigidity on indeterminacy translates into a downwardly sloping boundary. The intuition goes as follows. Assume a sudden increase in inflation expectations that usually sets off sunspot events. In the standard New Keynesian model, ruling out these self-fulfilling expectations requires the central bank to increase the short-run rate to drive up the real interest rate – the Taylor Principle. This then contracts output and lowers inflation, and therefore sunspot beliefs are no longer consistent in equilibrium. With trend inflation and a flatter Phillips Curve, the central bank is required to be more aggressive to keep indeterminacy in check. However, in a model with real wage rigidity, there is an additional channel at play, namely the endogenous increase in wage markup. As the real interest rate goes up, the wage markup (defined as the ratio of real wages to the marginal rate of substitution) increases endogenously due to the sluggish adjustment of real wages. An increase in wage markup reduces aggregate employment and therefore aggregate output and inflation. As a result, the central bank does not need to respond to inflation as strongly as otherwise it would have to in the absence of real wage rigidity.¹⁰

3 Model solution and econometric strategy

To solve the rational expectations system with indeterminacy, we follow the methodology of Lubik and Schorfheide (2003). The full set of solutions to the linear rational expectations model under indeterminacy entails the system of transition equations

$$\varrho_t = \Phi(\theta)\varrho_{t-1} + \Phi_\varepsilon(\theta, \widetilde{M})\varepsilon_t + \Phi_\zeta(\theta)\zeta_t,$$

where ϱ_t is the vector of endogenous variables, θ is the vector of the model's parameters, ε_t is the vector of fundamental shocks, and $\Phi(\theta)$, $\Phi_\varepsilon(\theta, \widetilde{M})$ and $\Phi_\zeta(\theta)$ are appropriately defined coefficient matrices.¹¹ Indeterminacy alters the solution in two

¹⁰If trend inflation is zero, Araújo's (2009) result of no effect of real wage rigidity holds.

¹¹Under determinacy, the solution boils down to a VAR, i.e. $\varrho_t = \Phi^D(\theta)\varrho_{t-1} + \Phi_\varepsilon^D(\theta)\varepsilon_t$.

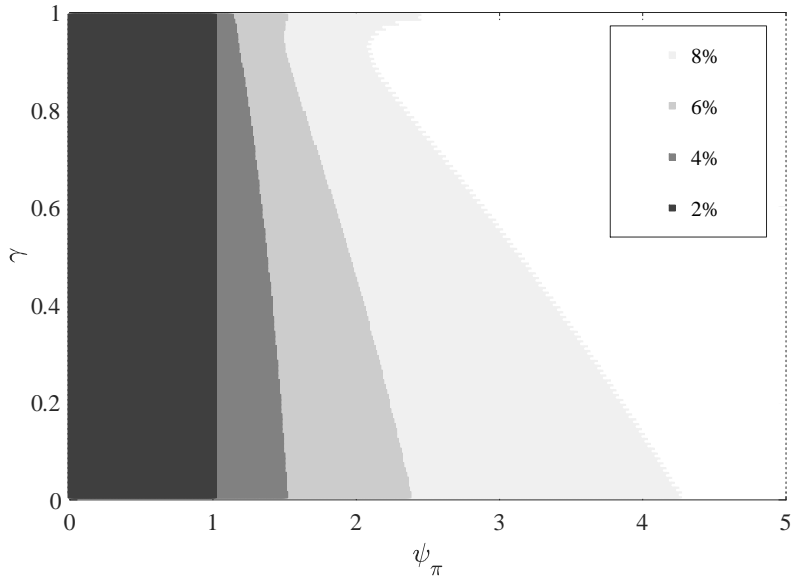


Figure 1: Indeterminacy zones (shaded)

distinct ways. First, purely extrinsic disturbances, i.e. the sunspots ζ_t , hit the economy. These sunspot shocks satisfy $\zeta_t \sim \text{i.i.d. } \mathbf{N}(0, \sigma_\zeta^2)$. Second, the propagation of fundamental shocks is no longer uniquely pinned down and this multiplicity is captured by the (arbitrary) elements of \widetilde{M} . Following Lubik and Schorfheide (2004), we replace \widetilde{M} with $M^*(\theta) + M$ and set the prior mean for M equal to zero in the subsequent empirical analysis. This strategy selects $M^*(\theta)$ such that the responses of the endogenous variables to fundamental shocks are continuous at the boundary between the determinacy and the indeterminacy regions. Analytical solution for the boundary in the current model is infeasible. We therefore resort to a numerical procedure to find the boundary by perturbing the parameter ψ_π in the monetary policy rule.¹² In Section 8.3, we will present the robustness of our results with regards to alternative perturbations.

3.1 Bayesian estimation with the Sequential Monte Carlo algorithm

We use Bayesian techniques to estimate the model parameters and to test for indeterminacy using posterior model probabilities. We follow Hirose et al. (2017) by

¹²See also Hirose (2014) as well as Justiniano and Primiceri (2008).

employing the Sequential Monte Carlo algorithm of Herbst and Schorfheide (2014) to produce an accurate approximation of the posterior distribution.¹³ In models like ours that contain determinacy and indeterminacy regions, the likelihood function is susceptible to exhibit multiple modes and a discontinuity at the parametric boundary. These irregularities prove to be a challenge for standard Markov chain Monte Carlo techniques (such as the Random Walk Metropolis Hastings algorithm) and these standard techniques often fail to explore the entire parameter space. The SMC algorithm circumvents this problem by building a sequence of posterior distributions through steadily tempering the likelihood function. Accordingly, we are able to estimate the model simultaneously over the determinacy and indeterminacy regions.¹⁴ The likelihood function is given by

$$p(\mathbf{X}_T|\theta_S, S) = 1\{\theta_S \in \Theta^D\}p^D(\mathbf{X}_T|\theta_D, D) + 1\{\theta_S \in \Theta^I\}p^I(\mathbf{X}_T|\theta_I, I).$$

Here, θ_S stands for the parameters of model S . Θ^D , Θ^I are the determinacy and indeterminacy regions of the parameter space, $1\{\theta_S \in \Theta^S\}$ is the indicator function that equals 1 if $\theta_S \in \Theta^S$ and zero otherwise where $S \in \{D, I\}$. \mathbf{X}_T denotes observations through period T and $p^D(\mathbf{X}_T|\theta_D, D)$ and $p^I(\mathbf{X}_T|\theta_I, I)$ are the likelihood functions under determinacy and indeterminacy. The SMC algorithm constructs a particle approximation of the posterior distribution by building a sequence of tempered posteriors defined as

$$\Pi_n(\theta_S) = \frac{[p(\mathbf{X}_T|\theta_S, S)]^{\phi_n} p(\theta_S|S)}{\int_{\theta_S} [p(\mathbf{X}_T|\theta_S, S)]^{\phi_n} p(\theta_S|S) d\theta_S}$$

with $p(\mathbf{X}_T|\theta_S, S)$ denoting the likelihood function, $p(\theta_S|S)$ the prior density, and ϕ_n the tempering schedule that slowly increases from zero to one determined by

$$\phi_n = \left(\frac{n-1}{N_\phi-1} \right)^\delta$$

where δ controls the shape of the tempering schedule. The algorithm generates weighted draws from the sequence of posteriors $\{\Pi_n(\theta)\}_{n=1}^{N_\phi}$, where N_ϕ is the number of stages. At any stage, the posterior distribution is represented by a swarm of

¹³Farmer et al. (2015) and Bianchi and Nicolò (2019) use alternative strategies to estimate models with indeterminacy.

¹⁴Lubik and Schorfheide's (2004) test for indeterminacy separately estimates the model for each parametric region. In our application, we monitor that the SMC's exploration is indeed crossing the boundary between the regions.

particles $\{\theta_n^i, W_n^i\}_{i=1}^N$, where W_n^i is the weight associated with θ_n^i and N denotes the number of particles. The algorithm involves three main steps. First, in the *correction* step, the particles are re-weighted to reflect the posterior density in iteration n . Next, in the *selection* step, any particle degeneracy is eliminated by resampling the particles. Liu and Chen (1998) propose a rule-of-thumb measure of this degeneracy as the reciprocal of the uncentered variance of the particles, called the effective sample size (ESS). We use systematic resampling whenever $ESS < \frac{N}{2}$. Finally, in the *mutation* step, the particles are propagated forward using a Markov transition kernel to adapt to the current bridge density by using one step of a single-block Random Walk Metropolis Hastings algorithm. In the first stage, i.e. when $n = 1$, ϕ_1 is zero and so the prior density serves as an efficient proposal density for $\Pi_1(\theta)$. Therefore, the algorithm is initialized by drawing the initial particles from the prior. The idea is that the density of $\Pi_n(\theta)$ may be a good proposal density for $\Pi_{n+1}(\theta)$. In our estimation, the tuning parameters N , N_ϕ and δ are fixed *ex ante*. We use $N = 10000$ particles and $N_\phi = 200$ stages and set δ at 2 following Herbst and Schorfheide (2015).

3.2 Calibration

We calibrate a subset of the model parameters to avoid identification issues. The discount factor β is set to 0.99, the steady state markup at ten percent, i.e. $\varepsilon = 11$, and the inverse of the labor-supply elasticity to one. Following the computations in Blanchard and Galí (2010), we calibrate the shares of oil in production and consumption to $\alpha = 0.015$ and $\chi = 0.023$ for the first and $\alpha = 0.012$ and $\chi = 0.017$ for the second sample period. The autoregressive parameter of the commodity price shock is fixed at $\rho_s = 0.995$ to model the commodity price being very close to a random walk (as in the data) yet retaining stationarity (Blanchard and Riggi, 2013).

3.3 Prior distributions

We estimate all remaining parameters. The specifications of the prior distributions are summarized in Table 1 and are in line with Smets and Wouters (2007) and Hirose et al. (2017).¹⁵ The prior for the parameter determining the central bank's

¹⁵The inverse gamma priors are of the form $p(\sigma|\nu, \varsigma) \propto \sigma^{-\nu-1} e^{-\frac{\nu\varsigma^2}{2\sigma^2}}$ where $\nu = 4$ and $\varsigma = 0.38$ for all shocks but commodity prices. For commodity price shock $\varsigma = 3.81$. The prior predictive

responsiveness to inflation ψ_π follows a gamma distribution centred at 1.10 with a standard deviation of 0.50, while the response coefficients to both the output gap and output growth are centred at 0.125 with standard deviation 0.10. We use Beta distributions for the degree of interest rate smoothing ρ_R , the weight on headline inflation in the Taylor rule τ , the Calvo probability ξ , the real wage rigidity γ , the habit persistence in consumption h , the persistence of the discount factor shock and the labor supply shock. For the standard deviations of the innovations, the priors for all but one follow an inverse-gamma distribution with mean 0.50 and standard deviation 0.20. The exception is the standard deviation of the oil price shocks. We center its prior distribution at 5.00 with a standard deviation of 2.00 to account for the higher volatility of these disturbances. The priors of M follow a standard normal distribution as in Lubik and Schorfheide (2004). Our choice of priors leads to a prior predictive probability of determinacy of 0.51 and indicates no prior bias toward either determinacy or indeterminacy.

3.4 Data

We estimate the model using quarterly observations on six aggregate U.S. variables. The vector of observables X_t contains the quarterly growth rates of real per-capita GDP (GDP), the consumer price index (CPI), the core consumer price index ($CoreCPI$), real wages and the level of the Federal Funds rate expressed in percent on a quarterly basis (FFR). Justiniano et al. (2013) find that most high frequency variations of the wage series are measurement errors and argue that ignoring this fact may lead to erroneous inference. We follow their approach by matching the model's wage variable to two measures of hourly labor income, allowing for errors in their measurement, along the lines of Boivin and Giannoni (2006).¹⁶ Matching the model's wage to two measures of the return to labor improves the ability to isolate the high frequency idiosyncrasies specific to each series, from a common component that is more likely to represent genuine macroeconomic forces. Wage data are *hourly compensation for the Nonfarm Business sector for all persons (NHC)* and *average hourly earnings of production and non-supervisory employees (HE)* which we both deflate

probability of determinacy is 0.51.

¹⁶See also Doko Tchatoka et al. (2017).

by the CPI to obtain measures for real wages. Then the measurement equation is

$$X_t = \begin{bmatrix} 100\Delta \log GDP_t \\ 100\Delta \log CPI_t \\ 100\Delta \log CoreCPI_t \\ FFR_t \\ 100\Delta \log(NHC_t/CPI_t) \\ 100\Delta \log(HE_t/CPI_t) \end{bmatrix} = \begin{bmatrix} g^* \\ \pi^* \\ \pi^* \\ R^* \\ g^* \\ g^* \end{bmatrix} + \begin{bmatrix} \mathbf{I}_4 & \mathbf{O} \\ \mathbf{O} & \mathbf{\Lambda} \end{bmatrix} \begin{bmatrix} \widehat{g}_{y,t} \\ \widehat{\pi}_{c,t} \\ \widehat{\pi}_{q,t} \\ \widehat{R}_t \\ \widehat{g}_{w,t} \\ \widehat{g}_{w,t} \end{bmatrix} + \begin{bmatrix} \mathbf{0} \\ \mathbf{e}_t \end{bmatrix}$$

where $g^* = 100(\bar{g} - 1)$ is the quarterly steady-state net output growth rate, $\pi^* = 100(\bar{\pi} - 1)$ is the steady-state net inflation rate and $R^* = 100(\bar{R} - 1)$ stands for the steady-state net interest rate. Furthermore, $\widehat{g}_{y,t}$ denotes the growth rate of output, $\widehat{\pi}_{c,t}$ is consumer price inflation, $\widehat{\pi}_{q,t}$ is core consumer price inflation, $\widehat{g}_{w,t}$ is the growth rate of real wages and \widehat{R}_t denotes the nominal interest rate. Hatted variables stand for log deviations from the steady state. $\mathbf{\Lambda} = \text{diag}(1, \lambda)$ is a 2×2 diagonal matrix of factor loadings relating the latent model concept of real wage growth to the two indicators and $\mathbf{e}_t = [e_{NHC,t}, e_{HE,t}]' \sim i.i.d.(\mathbf{0}, \mathbf{\Sigma})$ is a vector of serially and mutually uncorrelated indicator-specific measurement errors, with $\mathbf{\Sigma} = \text{diag}(\sigma_{NHC}^2, \sigma_{HE}^2)$. We jointly estimate the parameters $(\mathbf{\Lambda}, \mathbf{\Sigma})$ of the measurement equation along with the structural parameters. Our prior distributions for the loadings and measurement errors are $\lambda \sim N(1.00, 0.50)$ and $\sigma_{NHC}^2, \sigma_{HE}^2 \sim IG(0.10, 0.20)$. The estimation is conducted over two sample periods: 1966:I to 1979:II and 1984:I to 2008:II. This separation aligns with the monetary policy literature as it looks at the pre-Volcker and the Great Moderation periods individually. We exclude the years of the Volcker disinflation as in Lubik and Schorfheide (2004). We do not demean or detrend any series.

4 Was U.S. monetary policy destabilizing in the 1970s?

We find that the answer is no. Table 2 reports the marginal data densities of our estimated model as well as the posterior probabilities of determinacy for both sample periods.¹⁷ The posterior probability of determinacy is calculated as the fraction

¹⁷ The SMC algorithm delivers a numerical approximation of the marginal data density as a by-product in the correction step (see Herbst and Schorfheide, 2015).

Table 1: Prior Distributions and Posterior Parameter Estimates

Name	Density	Prior Mean (std. dev.)	Posterior Mean (pre-1979) [90% interval]	Posterior Mean (post-1984) [90% interval]
ψ_π	Gamma	1.10 (0.50)	1.51 [1.25,1.78]	3.09 [2.50,3.66]
ψ_x	Gamma	0.125 (0.10)	0.03 [0.00,0.07]	0.11 [0.03,0.20]
ψ_g	Gamma	0.125 (0.10)	0.33 [0.10,0.53]	0.62 [0.38,0.82]
ρ_R	Beta	0.50 (0.20)	0.68 [0.59,0.78]	0.73 [0.65,0.78]
τ	Beta	0.50 (0.20)	0.58 [0.32,0.84]	0.14 [0.05,0.23]
π^*	Normal	1.00 (0.50)	1.37 [1.07,1.64]	0.97 [0.81,1.11]
R^*	Gamma	1.50 (0.25)	1.53 [1.19,1.85]	1.46 [1.24,1.71]
g^*	Normal	0.50 (0.10)	0.45 [0.34,0.57]	0.17 [0.11,0.26]
ξ	Beta	0.50 (0.05)	0.60 [0.53,0.66]	0.61 [0.54,0.67]
γ	Beta	0.50 (0.20)	0.89 [0.83,0.94]	0.46 [0.26,0.63]
h	Beta	0.50 (0.10)	0.38 [0.28,0.50]	0.24 [0.16,0.33]
ρ_d	Beta	0.70 (0.10)	0.76 [0.66,0.86]	0.84 [0.78,0.90]
ρ_ν	Beta	0.70 (0.10)	0.86 [0.74,0.97]	0.99 [0.97,0.99]
σ_s	Inv-Gamma	5.00 (2.00)	17.31 [14.60,20.00]	20.14 [17.79,22.31]
σ_g	Inv-Gamma	0.50 (0.20)	0.49 [0.35,0.64]	0.43 [0.31,0.54]
σ_r	Inv-Gamma	0.50 (0.20)	0.30 [0.25,0.36]	0.17 [0.15,0.20]
σ_d	Inv-Gamma	0.50 (0.20)	1.84 [1.33,2.37]	1.21 [0.90,1.47]
σ_ν	Inv-Gamma	0.50 (0.20)	0.38 [0.25,0.49]	0.74 [0.53,0.98]
σ_ζ	Inv-Gamma	0.50 (0.20)	0.44 [0.21,0.68]	0.47 [0.22,0.73]
$M_{s,\zeta}$	Normal	0.00 (1.00)	-0.01 [-1.55,1.67]	-0.10 [-1.80,1.50]
$M_{g,\zeta}$	Normal	0.00 (1.00)	0.00 [-1.54,1.68]	-0.11 [-1.73,1.39]
$M_{r,\zeta}$	Normal	0.00 (1.00)	0.01 [-1.57,1.62]	0.03 [-1.59,1.60]
$M_{d,\zeta}$	Normal	0.00 (1.00)	0.08 [-1.50,1.74]	0.06 [-1.49,1.70]
$M_{\nu,\zeta}$	Normal	0.00 (1.00)	0.01 [-1.60,1.64]	0.06 [-1.48,1.70]
λ	Normal	1.00 (0.50)	1.05 [0.66,1.43]	0.30 [0.16,0.43]
σ_{NHC}^2	Inv-Gamma	0.10 (0.20)	0.36 [0.19,0.51]	0.66 [0.55,0.77]
σ_{HE}^2	Inv-Gamma	0.10 (0.20)	0.47 [0.33,0.63]	0.38 [0.32,0.44]

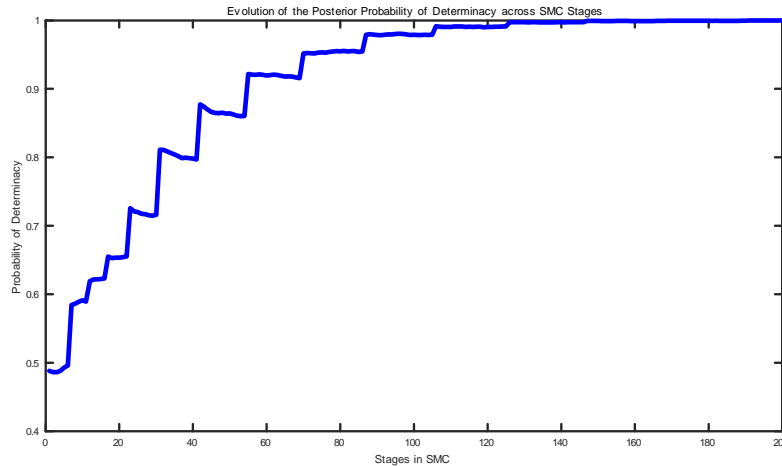


Figure 2: Evolution of the posterior probability. The estimation involves six observables and is performed for the 1966:I to 1979:II period.

of the draws in the final stage of the SMC algorithm that generate determinate equilibrium. The main result of our paper is that pre-Volcker monetary policy did not generate indeterminacy. Determinacy prevailed in the turbulent 1970s as well as during the Great Moderation. In each episode, the posterior distribution puts all its mass in the determinacy region. Figure 2 plots the evolution of the posterior probability of determinacy across the 200 stages of the SMC algorithm for the pre-Volcker period.¹⁸ As the particles are re-weighted and their values modified at each stage, this tempering of the likelihood function gradually moves the approximation to the posterior distribution from its prior level towards the probability that is reported in the first row of Table 2. This finding differs strikingly from Lubik and Schorfheide (2004), Hirose et al. (2017) and Nicolò (2018).

4.1 What drove determinacy?

Our diagnosis of the Seventies may be surprising and a natural question that arises is: what drove it? To shed light on this issue, the fourth column in Table 1 reports the posterior means and 90 percent highest posterior density intervals for the pre-Volcker period, based on 10000 particles from the final importance sampling. Let us focus on the monetary policy parameters first. The steady-state annualized inflation rate

¹⁸Note that in the first stage, the prior probability of determinacy is around 0.5 in line with our priors such that a-priori the test is unbiased.

Table 2: Determinacy versus Indeterminacy

	Log-data density	Probability of determinacy
1966:I-1979:II	-279.27	1
1984:I-2008:II	-275.71	1

Notes: According to the prior distributions, the probability of determinacy is 0.51.

is around 5.5 percent during this period. The response to inflation was active, i.e. greater than one, which echoes Orphanides (2004) and parallels Hirose et al. (2017). However, our estimated interest rate reactions to the output gap and to output growth differ from Hirose et al. (2017). In particular, we find that the Federal Reserve was barely responding to output gap fluctuations and that it was instead reacting strongly to output growth. As shown by Coibion and Gorodnichenko (2011), these two features tend to stabilize GNK economies. In fact, the combination of a strong response to inflation together with an insignificant reaction to the output gap holds the key to our result that the US economy was likely in the determinacy region even during the 1970s.

To connect with existing work and better understand which features of our econometric strategy lead to our interpretation of the Great Inflation, we now consider a sequence of special cases of our empirical model and report the findings in Tables 3 and 4. To begin with, we shut down oil in the model by calibrating the shares of oil in consumption and production to zero ($\alpha = \chi = 0$). The model then features only one concept of inflation and we therefore set the weight of headline inflation in the policy rule equal to one ($\tau = 1$). We further set the degree of real wage rigidity to zero ($\gamma = 0$) and turn off the labor supply disturbances. This artificial economy thus boils down to a simple GNK model with positive trend inflation and three fundamental shocks (discount factor, technology and monetary policy) similar to Hirose et al. (2017). We estimate this specification using only three standard observables: output growth, the Federal Funds rate and inflation (Headline CPI). The first row in Table 3 confirms that the estimation favors the models's indeterminate version in the pre-Volcker period, although we obtain a somewhat lower probability of indeterminacy

Table 3: Determinacy versus Indeterminacy (1966:I - 1979:II)

	Log density	Prob. of det.
GNK, 3 obs $(g_{y,t}, R_t, \pi_{c,t}) [\alpha, \chi, \gamma = 0; \tau = 1]$	-118.02	0.07
GNK, 3 obs $(g_{y,t}, R_t, \pi_{c,t}) [\alpha, \chi = 0; \tau = 1]$	-118.90	0.20
GNK with Oil, 3 obs $(g_{y,t}, R_t, \pi_{c,t}) [\tau = 1]$	-118.22	0
GNK with Oil, 4 obs $(g_{y,t}, R_t, \pi_{c,t}, \pi_{q,t})$	-157.12	0.80
GNK with Oil, 6 obs $(g_{y,t}, R_t, \pi_{c,t}, \pi_{q,t}, \Delta w_t^{NHC}, \Delta w_t^{HE})$	-279.27	1

Notes: The state-space models are (from top to bottom): i) Basic GNK model estimated with three observables; ii) GNK model featuring wage rigidity estimated with three observables; iii) GNK model with oil and wage rigidity estimated with three observables; iv) GNK with oil and wage rigidity estimated with four observables (i.e. two inflation measures); v) GNK with oil and wage rigidity estimated with six observables (i.e. two wage series). Parameters in square brackets are calibrated. "obs" denotes the number of observables which are indicated in parentheses.

than Hirose et al. (2017).¹⁹

Having bridged the gap with existing studies, we now sequentially add one feature at a time until we end up again with our original model. To begin with, we introduce real wage rigidity by specifying an agnostic prior Beta (0.5, 0.2) for γ and we estimate this model with only three observables. You can see from the third column in Table 4 that the degree of real wage rigidity is not properly identified and the posterior distribution of γ is similar to the prior. The posterior probability of determinacy increases slightly to 20 percent (second row of Table 3). This finding is consistent with our previous discussion regarding how real wage rigidity affects the determinacy region (see Figure 1).

We then turn on oil by resetting the values of α and χ to their benchmark calibrations. This setup gives us a New Keynesian model with sluggish wages and micro-founded cost-push shocks, features that are reminiscent of the environment in the 1970s, yet are missing in existing empirical investigations on indeterminacy. We

¹⁹Our model also features homogenous labor (as in Ascari and Sbordone, 2014), while Hirose et al. (2017) assume firm-specific labor. Moreover, they use a different measure of inflation (GDP deflator) to estimate their model.

also switch on labor supply disturbances. For now, we continue to use only three observables in the estimation (hence we calibrate τ at one). The third row of Table 3 shows that data now strongly prefers indeterminacy for the pre-Volcker period. The decline in the posterior probability of determinacy reflects the lower wage rigidity that is obtained when we include persistent labor supply shocks. Looking at the fourth column in Table 4, we observe that the standard deviation of oil price shocks σ_s is virtually indistinguishable from the prior suggesting identification issues: using only one inflation measure does not provide sufficient information to pin down commodity price shocks.

Hence, we next simultaneously treat both headline and core inflation as observables and our dataset now includes four variables. This step enables a tight identification of oil-price shocks or more generally commodity price shocks (see equation 1). We also estimate the weight τ in the policy rule as it can now be identified. The fourth row of Table 3 shows that the probability of determinacy rises considerably. Moreover, as anticipated, the innovation to the oil-price shock σ_s is now well identified: the posterior mean is one order of magnitude larger than the prior mean.

The last step deals with the degree of wage sluggishness γ which is a key parameter in our artificial economy. As Blanchard and Galí (2007) argue, the presence of real wage rigidity generates a trade-off between stabilizing inflation and the output gap in response to supply-side disturbances. Moreover, Blanchard and Riggi (2013) document that real wage rigidity plays a fundamental role in the propagation of oil price shocks. To sharpen the identification of this rigidity parameter, we next add real wage data, i.e. we employ all six observables to estimate the model. This step then gives us our benchmark setup again. As already argued above, the pre-Volcker period is then best characterized by determinacy and, as you can see in the sixth column of Table 4, by a high degree of real wage rigidity.

Figure 3 shows the evolution of the dynamics in the $\psi_\pi - \psi_x$ space for four estimation setups for the pre-Volcker period.²⁰ The panel in the North West corner represents the results from the basic GNK model estimated with the three standard observables (similar to Hirose et al. 2017), while our baseline results are visible in the

²⁰We report specifications i), iii), iv) and v) from Table 3.

Table 4: Parameter Estimates (1966:I-1979:II)

	GNK $\gamma = 0$ 3 obs	GNK 3 obs	GNK-Oil 3 obs	GNK-Oil 4 obs	GNK-Oil 6 obs
ψ_π	0.96 [0.87,1.11]	0.96 [0.76,1.16]	0.94 [0.75,1.12]	1.16 [0.93,1.35]	1.51 [1.25,1.78]
ψ_x	0.10 [0.00,0.22]	0.14 [0.00,0.27]	0.23 [0.00,0.42]	0.15 [0.00,0.31]	0.03 [0.00,0.07]
ψ_g	0.09 [0.00,0.17]	0.11 [0.01,0.21]	0.11 [0.01,0.21]	0.14 [0.01,0.26]	0.33 [0.10,0.53]
ρ_R	0.41 [0.28,0.53]	0.44 [0.29,0.59]	0.48 [0.36,0.61]	0.50 [0.35,0.64]	0.68 [0.59,0.78]
τ	1	1	1	0.65 [0.43,0.88]	0.58 [0.32,0.84]
π^*	1.40 [1.07,1.72]	1.43 [1.14,1.71]	1.34 [1.00,1.69]	1.38 [1.09,1.70]	1.37 [1.07,1.64]
R^*	1.54 [1.21,1.85]	1.57 [1.30,1.83]	1.50 [1.19,1.79]	1.55 [1.23,1.84]	1.53 [1.19,1.85]
g^*	0.46 [0.31,0.62]	0.49 [0.33,0.65]	0.51 [0.36,0.65]	0.51 [0.37,0.65]	0.45 [0.34,0.57]
ξ	0.50 [0.43,0.60]	0.50 [0.42,0.59]	0.54 [0.46,0.61]	0.57 [0.48,0.65]	0.60 [0.53,0.66]
γ	0	0.51 [0.17,0.90]	0.33 [0.07,0.60]	0.30 [0.04,0.59]	0.89 [0.83,0.94]
h	0.38 [0.27,0.48]	0.47 [0.28,0.51]	0.37 [0.27,0.49]	0.31 [0.21,0.41]	0.38 [0.28,0.50]
ρ_d	0.83 [0.73,0.92]	0.78 [0.65,0.90]	0.70 [0.54,0.86]	0.68 [0.53,0.83]	0.76 [0.66,0.86]
ρ_ν	—	—	0.69 [0.53,0.86]	0.72 [0.56,0.87]	0.86 [0.74,0.97]
σ_s	—	—	5.43 [2.12,8.45]	17.03 [14.44,19.58]	17.31 [14.60,20.00]
σ_g	1.49 [1.17,1.80]	1.57 [1.19,1.93]	1.51 [1.17,1.86]	1.26 [0.95,1.73]	0.49 [0.35,0.64]
σ_r	0.32 [0.25,0.38]	0.31 [0.24,0.38]	0.30 [0.25,0.36]	0.31 [0.24,0.38]	0.30 [0.25,0.36]
σ_d	0.96 [0.76,1.16]	0.56 [0.31,0.85]	0.40 [0.20,0.60]	0.86 [0.35,1.31]	1.84 [1.33,2.37]
σ_ν	—	—	0.36 [0.19,0.53]	0.45 [0.22,0.69]	0.38 [0.25,0.49]
σ_ζ	0.53 [0.20,0.85]	0.51 [0.20,0.82]	0.46 [0.21,0.74]	0.50 [0.20,0.82]	0.44 [0.21,0.68]
$M_{s,\zeta}$	—	—	-1.19 [-2.28,-0.46]	-0.12 [-1.40,1.58]	-0.01 [-1.55,1.67]
$M_{g,\zeta}$	0.94 [-0.76,2.28]	0.61 [-0.97,1.91]	0.78 [-0.37,1.95]	0.10 [-1.46,1.67]	0.00 [-1.54,1.68]
$M_{r,\zeta}$	0.18 [-1.29,1.68]	0.09 [-1.60,1.65]	0.39 [-1.16,2.06]	0.10 [-1.50,1.70]	0.01 [-1.57,1.62]
$M_{d,\zeta}$	0.07 [-1.69,1.75]	0.16 [-1.60,1.95]	-0.16 [-1.89,1.46]	0.02 [-1.36,1.92]	0.08 [-1.50,1.74]
$M_{\nu,\zeta}$	—	—	-0.23 [-1.82,1.52]	-0.02 [-1.62,1.56]	0.01 [-1.60,1.64]
λ	—	—	—	—	1.05 [0.66,1.43]
σ_{e_1}	—	—	—	—	0.36 [0.19,0.51]
σ_{e_2}	—	—	—	—	0.47 [0.33,0.63]