TOWARDS A RULE-BASED APPROACH TO MONETARY POLICY EVALUATION IN SUB-SAHARAN AFRICA

Stephen A. O’Connell¹
Eugene M. Lang Research Professor
Swarthmore College

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ABSTRACT I review the 3-equation AS/IS/MP model that is at the core of the dynamic stochastic general equilibrium (DSGE) models in use within central banks in the industrial countries. Monetary policy rules play a central role in these models, and alternative rules can be compared in terms of their implications for the economy’s dynamic adjustment to shocks. I discuss the advantages of DSGE modeling in low-income countries and show how interest-rate rules can be adapted to reflect the balance-sheet instruments widely used among African countries. I also identify features of the African economic environment that are poorly captured by existing models, including a large and volatile food sector, imperfect capital mobility, and a credit channel for monetary policy. To illustrate the DSGE approach, I develop a model in which food supply shocks play a key role in inflation dynamics. I show that private storage can generate serial correlation of food price inflation when food price shocks are serially uncorrelated.

¹ Eugene M. Lang Research Professor, Swarthmore College, USA (steve_oconnell@swarthmore.edu). I thank my discussant Andrew Feltenstein, and also Christopher Adam and Peter Montiel, for useful insights, and Andrew Berg, Rafael Portillo and Derya Unsal for a preview of their ongoing research on monetary targeting in low-income countries. Any errors or omissions are my own responsibility.
1. **INTRODUCTION**

A long revolution in macroeconomic thinking has boiled itself down into an elegant 3-equation model in which a central bank policy rule anchors inflation expectations and stabilizes the real economy in the short run (Woodford 2003, Gali and Gertler 2008). This small dynamic stochastic general equilibrium (DSGE) model expresses what Mankiw (2006) and others call the “new neoclassical synthesis” in macroeconomics. It is the workhorse of the inflation targeting literature and is part of the policy evaluation toolkit of a growing number of central bank research departments in industrial and emerging-market economies (Berg, Karam and Laxton 2006). Within these institutions it forms the core of larger-scale but still low-order DSGE models that operate alongside their older AS/AD counterparts and perform many of the same functions, from counterfactual policy analysis to forecasting (Tovar 2008).

Like any new research technology, DSGE modeling is technically demanding, at least at the frontier, and is still in the process of proving its worth. Outside of South Africa, DSGE model are not yet used much in SSA. They have had very little imprint on AERC research to date, whether in the bi-annual workshops or in sponsored dissertations. There are suspicions in some quarters that DSGE techniques not ready for prime time, at least in Africa.\(^2\)

I believe that this situation is going to change rapidly. The use of DSGE techniques is becoming much more accessible as practical experience accumulates and appropriate software tools become available. Despite its drawbacks, the use of small-scale DSGE models has a lot to recommend it in the African context. This is especially true as more African central banks take on elements of inflation targeting, including an emphasis on policy coherence, transparency, forecasting, and communication with the public.

In this paper I introduce the basic DSGE model, focusing particularly on the role played by the monetary policy rule in determining the macroeconomic properties of the system. I then adopt an African perspective and ask what insights these small-scale DSGE models can already deliver and where they will need further development if they are to be as useful in the African

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\(^2\) As recently as a year ago, I was in contact with a bilateral donor regarding a technical assistance program that would be housed within an African central bank. I was told that no proposal with the initials DSGE in it could possibly be funded by this donor.
context as they have been among the advanced economies. I ignore issues of estimation and model validation, even though these are dynamic research areas in the broader literature, in order to focus on how these models are specified and calibrated, what kinds of question they can handle, and where their shortcomings lie. My main message is that this is a promising time for AERC researchers – including graduates of the collaborative masters and PhD programs, who are well represented within African central banks and academic departments – to take up DSGE methods and begin to apply them to African monetary policy challenges.

2. DSGE PRELIMINARIES

The closed-economy IS/AS/MP model, which I will refer to below as the ‘core DSGE’, consists of three equations: a forward-looking IS curve relating aggregate spending to the real interest rate and other variables, a new Keynesian Phillips curve describing the aggregate supply (AS) side of the economy, and a monetary policy (MP) rule describing how the central bank reacts to developments in the economy. Our focus below will be on the monetary policy rule, but of course the content of a desirable rule depends on how the rest of the economy behaves. Some sense of DSGE themes and variations can be gained by contrasting two recent versions:

Woodford (2003), chapter 4

\begin{align*}
\text{(AS-W)} & \quad \pi_t &= \beta E_t[\pi_{t+1}] + \varphi \tilde{Y}_t \\
\text{(IS-W)} & \quad \dot{Y}_t &= E_t[\tilde{Y}_{t+1}] - \sigma(i_t - E_t[\pi_{t+1}] - \bar{r}) + \epsilon_t^\gamma \\
\text{(MP)} & \quad i_t &= f(E_t[\pi_{t+1}], \pi_t, \dot{Y}_t, ...) \\
\text{(Definition)} & \quad \dot{Y}_t &= \tilde{Y}_t - \tilde{Y}_t^n \\
\text{(Shocks)} & \quad \text{Distributional assumptions on exogenous shock processes \( \tilde{Y}_t^n \) and \( \epsilon_t^\gamma \)}
\end{align*}

Freedman and Laxton (2009)

\begin{align*}
\text{(AS-FL)} & \quad \pi_t &= \lambda E_t[\pi_{t+1}] + (1 - \lambda)\pi_{t-1} + \varphi \tilde{Y}_t + \epsilon_t^\pi \\
\text{(IS-FL)} & \quad \dot{Y}_t &= \rho \tilde{Y}_{t-1} - \sigma(i_t - E_t[\pi_{t+1}] - \bar{r}) + \epsilon_t^\gamma \\
\text{(MP)} & \quad i_t &= f(E_t[\pi_{t+1}], \pi_t, \dot{Y}_t, ...)
\end{align*}
Distributional assumptions on exogenous shock processes $\varepsilon^\pi_t$ and $\varepsilon^\nu_t$.

Here $\pi$, $Y$, $i$ and $r$ are the inflation rate, real GDP, the nominal interest rate, and the real interest rate, respectively; $\lambda$, $\varphi$, $\rho$ and $\sigma$ are constants to be determined by calibration or estimation; and $E_t$ denotes an expected value or conditional forecast made by the private sector in the course of determining its behavior. An over-bar (e.g., $\bar{\pi}$) denotes a baseline value. The notation “~” denotes the difference between the log of a variable and its log along the baseline path (see below); these variables are interpreted as percentage deviations from the baseline.

Woodford (2003) is the seminal work on the theory of monetary policy rules; his version is the ‘canonical’ one in which the behavior of the private sector is built up from strict optimizing foundations (see also Gali and Gertler 2008). Freedman and Laxton (2009) take Woodford as a point of departure, but build in a set of practical compromises designed to improve the empirical performance of the model (see also Berg, Karam and Laxton 2006). In each case $y = Y - Y^*$ is the GDP gap, defined as the difference between actual GDP and the ‘natural’ level of GDP, defined as the level that would occur if all wages and prices were perfectly flexible. The Freedman-Laxton version specifies the full model in terms of the gap, so a separate definitional equation is not needed.

These two models share the hallmark features of the DSGE approach. First, the IS and AS curves are built up from the first-order conditions of intertemporal optimization problems. The IS curve, for example, is a consumption Euler equation in which $\sigma$ is the intertemporal elasticity of substitution. DSGE exercises are therefore less likely to fall prey to the Lucas critique than exercises built in reduced-form econometric evidence, because their underlying parameters are structural in the sense of Lucas (1976). This means that the reduced form of a DSGE automatically changes when the structure of the shocks or the behavior of policymakers changes. Second, private-sector behavior is explicitly forward-looking. Expected values of future variables appear in the model wherever they play a role in determining current behavior. Monetary policy, in these models, is a problem of managing expectations (Woodford 2003).
The presence of expectational terms means that these models are underdetermined in the absence of a theory of how expectations are formed. The FL model, for example, comprises 3 equations to determine the 4 endogenous variables, $\pi_t$, $\hat{y}_t$, $i_t$, and $E_t[\pi_t]$. The additional restriction comes from assuming that expectations are ‘rational’ or model-consistent, so that $E_t[\pi_{t+1}]$ is the mathematical expectation of next-period’s inflation, conditional on information available at time $t$.

Both core DSGEs are linear in their variables, and this is no coincidence. In contrast to perfect-foresight models, where agents foresee the future perfectly, in the stochastic case the actions of private-sector agents cannot be determined by just solving the underlying nonlinear difference equations numerically and deriving a single, once-for-all path for the variables in the model. Instead what has to be solved for is a set of optimal feedback rules in which decision variables are determined in each period conditional on what has occurred in the past and what is known about the distribution of future shocks. These behavioral rules can readily be solved for when the model is linear, but not (in general) when it is nonlinear. A preliminary step, therefore, involves linearizing the nonlinear model around some reference path. The standard approach is to use the deterministic steady state of the model.

The way DSGE models are derived and solved has three important implications. The first is that the model has to be represented in a form that has a steady state. Underlying deterministic or stochastic trends are therefore not being modeled in this approach; agents are determining their behavior around the trend path of the economy. The levels of all variables can be recovered *ex post*, by adding back the stochastic and/or deterministic trends (see Griffoli 2007). The second is that the variables being modeled in the DSGE are not levels, but deviations from steady-state values (the underlying variables are typically expressed in logs, so that the deviations are scaled by steady-state levels); the linear approximation is useful only if these variables stay reasonably small. The third is that these models are very easy to scale up: a 10-equation linear rational expectations model is no more difficult to solve than a 3-equation version. Free software now exists, in fact, that will take a set of nonlinear equations as input
(e.g., the underlying nonlinear Euler equation that led to (IS-W)) and – with sufficient guidance from the analyst – do the rest, from linearization to simulation to estimation.³

Beyond these similarities, the differences between these two versions suggest one set of directions in which practitioners have ‘built out’ from the core DSGE: the FL version incorporates a set of features that simplify the exposition and/or better incorporate important empirical regularities (I will return below to the other major set of directions, which involve incorporating structural features like international financial mobility, trade, fiscal linkages, and imperfect credit markets, that are missing from the core specification). In particular:

- The Freedman/Laxton version of the new Keynesian Phillips curve satisfies the natural rate hypothesis (NRH), while the canonical Woodford version does not. To see this, compute the sum of coefficients on all leads and lags of inflation on the right-hand side of the Phillips curve: in the FL version this sum is 1, implying the absence of a long-run tradeoff between inflation and the GDP gap, while in the Woodford version it is \( \beta < 1 \). Woodford’s is the theoretically purer version; (AS-W) is the first-order condition from a model of optimal price-setting by producers of differentiated products, a fraction of which get to change their prices each period. The discount rate emerges because producers have to balance the current benefit of setting marginal revenue equal to marginal cost – the source of the GDP gap term – against the discounted cost of having a future price level that is misaligned with the prices being set by their competitors. But \( \beta < 1 \) means that the Woodford version violates the NRH. Long-run values satisfy

\[
\bar{\pi} = \left[ \frac{1-\beta}{\varphi} \right] \bar{y},
\]

allowing policymakers to choose a bit more output than the flex-price level in the long run. Freedman and Laxton’s version does satisfy the NRH, and in that sense probably better captures the empirical consensus among central bankers and macroeconomists. For the workhorse model of inflation targeting, it may seem surprising that this point has not been of much interest. To date the DSGE literature has focused much more on how to manage a given target inflation rate than on what that

³ DYNARE, developed by Michel Juillard, is very widely used and can be downloaded for free from www.dynare.org. Dynare routines run in Matlab (www.mathworks.com), which is unfortunately not free but may be accessible to researchers employed by universities or central banks, via site licenses.
target should be (Woodford 2003 is an exception). Once a target is chosen, of course, the steady state level of the GDP gap is tied down and this difference between the two versions disappears.

- Freedman and Laxton take greater liberties with the theory by incorporating lagged inflation in their Phillips curve. They do this to accommodate the evidence from estimated Phillips curves that inflation has an inertial component – i.e., a backward-looking component that does not adjust in response to the current state of the economy. The source of this backward-looking component can be institutional – the use of nominal wage contracts, for example – or behavioral – if a fraction of price-setters relies only on past inflation rates in forming expectations. The parameter $\lambda$ lies between zero and 1; it can be calibrated, estimated, or treated as a free parameter to be varied, depending on the nature of the exercise. The degree of inertial inflation affects the transmission mechanism of exogenous shocks and monetary policy actions, and therefore the output costs of strict inflation targeting.

- The Woodford version of the Phillips curve does not include a cost shock $\varepsilon_t$, while the Freedman/Laxton version – like most empirical Phillips curves in the literature – does. The reason the canonical new Keynesian Phillips curve (AS-W) does not include a cost shock term is that the whole range of supply-side shocks emphasized in the real business cycle literature – shocks to labor supply, intermediate input costs, and productivity, for example – are already captured in the time-varying value of natural output. This has important implications: it implies that any monetary policy that succeeds in stabilizing the output gap in (AS-W) will stabilize inflation, and vice-versa. Blanchard and Gali (2007) call this feature of the new Keynesian Phillips curve the ‘divine coincidence’. Their argument is that real-side distortions in the economy are often assumed to have a fixed proportional impact on GDP – so that the difference between the natural level of output and the efficient or ‘first-best’ level of output is the same as the GDP gap, up to a constant. Under these conditions there is no policy
conflict between a policy that seeks only to stabilize inflation and a policy that cares also about stabilizing the welfare-relevant GDP gap. The Freedman/Laxton version, by contrast, includes shocks that drive a wedge between inflation and the welfare-relevant GDP gap. Like inertial inflation, these shocks create a policy tradeoff between inflation goals and output-stabilization goals. The empirical counterpart to these shocks is unclear, since the theory suggests that only shocks that alter the relationship between natural and efficient output should appear – i.e., shocks that change the degree of distortions in the economy. Conventional supply shocks (e.g., oil prices) do not qualify by this criterion unless they interact with other frictions to alter the impact of distortions on GDP (Blanchard and Gali 2007).

- Note finally that in the Woodford version the IS curve refers to GDP, rather than to the GDP gap. The (IS-W) curve can of course be rewritten in terms of the GDP gap, as

\[ \tilde{y}_t = E_t[\tilde{y}_{t+1}] - \sigma(t_t - E_t[\pi_{t+1}]) + u^y_t, \]

where \( u^y_t = \delta^y + E_t[\tilde{y}^n_{t+1}] - \tilde{Y}_t^n \), but this adjustment is not trivial; it means that alongside the traditional demand-side shocks that would normally be assumed to drive \( \delta^y \) in (IS-FL), the disturbance term in (IS-W) is also a function of supply-side shocks that affect the equilibrium real rate of interest.

3. **MP AND THE LOGIC OF POLICY RULES**

The third equation of the core DSGE is a monetary policy rule. The dominant specifications by far are variants of the Taylor rule (Taylor 1993), in which the central bank adjusts a policy interest rate in response to the observed GDP gap and the deviation of inflation – or an inflation forecast – from a medium-term target. The equation Taylor estimated was

\[ (MP-TR) \quad i_t = \bar{I} + \phi_r(\pi_t - \bar{\pi}) + \phi_y y_t \]

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4 An alternative interpretation is that the output gap in the FL case is simply the gap between \( Y \) and its steady-state level; in that case for \( \lambda = 1 \), (AS-FL) is identical to (AS-W) if we define the inflation shock as \( \delta^* = -\varphi Y^*_t \). But this would have implications for the interpretation of the IS shock in (IS-FL), and would add a shock to (MP-TR) as well.
where $y_t$ is the deviation of real GDP from a deterministic trend, $\pi$ is an inflation target, and $\bar{\pi} = \pi + \pi_0$ is the nominal interest rate consistent with the inflation target and a steady-state real interest rate of $\pi$.

Taylor found that the values $\phi_\pi = 1.5, \phi_y = 0.5$ gave a good description of US policy in the post-Volcker period, suggesting that the Fed paid attention both to an underlying inflation target and to deviations of output from trend. The condition $\phi_\pi > 1$ implied an aggressive response to inflationary developments: the Fed would increase the policy interest rate more than point-for-point with inflation – thereby raising the real interest rate and contracting aggregate demand – unless the rise in inflation were accompanied by a slump in GDP. This condition is known as the ‘Taylor Principle’; subsequent theoretical work showed that it is a necessary condition in a forward-looking economy for an interest rate rule to succeed in generating a determinate price level (Woodford 2003).

The policy rules in DSGEs are often adapted to allow for the observed tendency of many central banks to smooth interest rates over time; denoting the Taylor rule interest rate by $i_t^\pi$, this might take the form $i_t = \delta i_t^\pi + (1 - \delta) i_{t-1}$, where $\delta$ is between 0 and 1.

**What happened to MV = PY?**

In the core DSGE, the monetary policy rule replaces what used to be the monetary equilibrium condition – the LM curve – in earlier models. From the perspective of central banking in Africa, this must seem the oddest feature of the model. Few African central banks use an interest rate as their policy instrument or operational target; the majority, by far, are on reserve-money programs in which balance sheet operations are the instrument and base money is the operational target. More fundamentally still, most central banks continue to use broader monetary aggregates as their intermediate targets, within a version of the IMF’s financial programming model (IMF 2008). Monetary equilibrium therefore plays a central role in policy thinking within Africa, and remains the focal point of intense discussion between central bank officials and visiting IMF teams. The new neoclassical synthesis is “Keynesian macroeconomics without the LM curve” (Romer 2000). How can these models be relevant?
There are two responses to this concern; both suggest that the DSGE approach is of greater relevance for African central banks than it first appears. The first is that while the relevant methods were developed for advanced economies, their relevance for emerging-market economies grew during the 1990s as central banks in these economies emerged from systems of fiscal dominance and financial repression, moved towards greater exchange rate flexibility, and placed greater emphasis on inflation as an intermediate target of policy. African central banks are engaged in a similar process. Outside of the CFA zone, which continues to operate a hard peg, central banks in Africa now have similar policy goals and institutional protections, at least de jure, as those in more advanced economies. Two African central banks (South Africa and Ghana) have adopted FFIT; and many more have adopted indicative targets for inflation along with other elements of inflation targeting. As the analytical core of the inflation targeting literature, the DSGE approach should therefore be of intense interest to African central banks.

A second and more immediate response, however, is that these models can be adapted to varied institutional circumstances without losing their central insights. The case for a monetary policy rule, after all, is much broader than the case for any particular rule. To see how differences in instruments and operating procedures can be accommodated, consider a traditional money demand function of the form

\[ \tilde{m}_t = \gamma \bar{y}_t - \rho i_t. \]

where \( m \) is real money balances. A money demand function like this can be derived alongside the consumption behavior represented in the IS curve. Nominal money growth, in turn, satisfies the definitional equation \( \tilde{\mu}_t = \tilde{m}_t - \bar{m}_{t-1} + (\pi_t - \bar{\pi}). \) Monetary equilibrium – obtained by equating \( \tilde{m} \) in these two expressions – therefore gives us an expression for the money growth consistent with any interest rate rule. The Taylor rule (MP-TR), for example, generates the following expression for nominal money growth.\(^5\)

\(^5\) After replacing \( y \) in the empirical Taylor Rule with \( \bar{y}. \)
where the coefficients are given by \( \delta_\pi = 1 - \rho \phi_\pi \) and \( \delta_\gamma = \gamma - \rho \phi_\gamma \).

The Taylor rule can therefore be implemented as an interest rate rule, leaving the money stock to be determined endogenously, or as a money growth rule, leaving the interest rate to be determined endogenously. Equation (2) is of course more complicated than a financial-programming rule, which in this context might take the form \( \mu_t = \bar{\pi} \); by contrast, equation (2) embodies a policy response to the past equilibrium error \( \hat{\pi}_{t-1} \) as well as to the current state of the economy. But in a DSGE environment the two rules can be compared in terms of what they imply for macroeconomic outcomes.

**The logic of policy rules**

The logic of policy rules is rooted in a set of intellectual developments that grew out of the Great Inflation and that both facilitated and responded to the emergence of inflation targeting as a new framework for monetary policy. Three propositions acquired growing acceptance among industrial-country economists starting in the mid-1970s. The first was that the greatest contribution monetary policy could make to economic welfare was to provide an environment of price stability. This meant that low inflation should receive first priority among the objectives of monetary policy. In this fundamental sense – ironically, given the disappearance of monetary equilibrium – the core DSGE embodies the intellectual triumph of monetarism (Goodfriend 2007). Second, since price- and wage-setting decisions were forward-looking, a necessary condition for price stability was that expected prices be stable. This re-cast monetary policy as a problem of managing private-sector expectations. Third, because expectations were

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6 This section draws on O’Connell 2009.
7 Meltzer (2005) dates the US Great Inflation from 1965 to 1984. Globally, inflation peaked first among industrial countries, then emerging-market economies. Africa’s Great Inflation ended in the second half of the 1990s: among countries with independent currencies, the number of countries with annual inflation above 40% peaked at 11 in 1995 (O’Connell 2009).
8 Two key ideas, in turn, drove this new monetarist consensus: the natural rate hypothesis of Friedman and Phelps, and critique of discretionary policy by Kydland and Prescott (see Freedman and Laxton 2009). Walsh (2010) provides a detailed treatment. On the empirical side, evidence began to accumulate starting in the 1980s, on the deleterious effects of high inflation on long-run growth. For low-income countries, however, the empirical case for very low inflation remains weak; see for example Khan and Senhadji (2001).
information-inclusive, they reflected the private sector’s active assessment of how policymakers were likely to respond to macroeconomic developments. This suggested that any systematic component of central bank behavior – expressed as a reaction function linking variables the private sector could observe to policy actions by the central bank – would ultimately be understood through repeated observation, and incorporated into private sector expectations. Moreover, it was not just past behavior that mattered; the intentions of policymakers could be constrained by institutional design. Innovations like the granting of legal independence to the central bank, or even the appointment of a conservative central bank governor with protected tenure, could transform the relationship between instruments and targets: a credible disinflation, for example, in which the private sector was convinced early on that policy would be consistent with low inflation, could reduce inflation much faster, and at lower cost in terms of real economic activity, than if expectations were calculated only on past observations.

Taken together these developments produced a revolution in the design and conduct of monetary policy. The watershed events, arguably, were the Volcker disinflation of 1979-84, accomplished at much lower cost than was previously thought possible, and the formal adoption of inflation targeting by the Reserve Bank of New Zealand in 1989. By the late 1990s, economists and central bankers worldwide were in agreement that good policy consisted in the exercise of what Bernanke and Mishkin (1997) and others called ‘constrained discretion.’ Reflecting this consensus and driving it forward, the number of advanced and emerging-market central banks practicing full-fledged inflation targeting (FFIT) rose from zero in 1989 to 27 by 2008.

The Fed is not a formal inflation targeter, but the Taylor rule gives operational content to the concept of constrained discretion. Constraint operates through the Taylor principle, which anchors inflation expectations by guaranteeing an aggressive policy response to inflation. Discretion operates through the allowance for other policy objectives, provided that these are consistent with anchoring inflation expectations; the Taylor rule allows a countercyclical role for policy, consistent with a desire to stabilize real GDP around its natural level. It soon became clear that in macro models incorporating price rigidities and forward-looking expectations, this
disciplined approach – if credible – was not only adequate to anchor expectations, but also generated highly favorable combinations of inflation and output volatility (Woodford 2003). No central bank lives by rules alone, but during the 1990s Taylor-type rules displaced alternative representations of monetary policy in the macro literature and acquired an important role in the internal discourse of advanced-country and emerging-market central banks (Berg, Karam and Laxton 2006).

4. USING THE DSGE FRAMEWORK

A DSGE can be solved and simulated once values for the unknown parameters are determined. Calibration remains the dominant approach: steady-state values are drawn from actual observation where relevant; the structural parameters that make up the coefficients of the model are tied down using microeconomic evidence; and the stochastic process for shocks is either postulated de novo or, where the shocks are readily identifiable (e.g., terms of trade shocks), estimated using standard time series techniques.

A great advantage of the calibrated DSGEs over econometric evaluations is the absence, in many African countries, of extended runs of good macroeconomic data – or, where the data are available, of extended periods within a given policy environment. Quarterly data on the real economy are typically not available at all. These data limitations of course limit the scope for empirical validation of DSGEs, but the same is of course true of any macroeconomic model; the advantage of a DSGE is that a disciplined and potentially useful specification can be constructed without the advantage of reliable time series econometrics.9

With its steady-state values and coefficients determined, the solution to a DSGE is a reduced-form equation relating the vector of endogenous variables $x_t$ to its own lagged values and the vector $u_t$ of innovations to the exogenous shock processes:

$$x_t = \sum_{i=1}^{k} A_i x_{t-i} + \Phi u_t.$$  

9 Bayesian estimation of the parameters is becoming popular (e.g., Smets and Wouters 2003) and can now be done within Dynare. To my knowledge, the first estimated DSGE for an African country was Peiris and Saxegaard (2008).
Econometric policymaking is of course often analyzed directly using reduced-form VAR systems that superficially resemble (3). The tremendous advantage of DSGEs is that they are structural in the sense of Lucas (1976): the coefficient matrices in (3) are functions of all of the coefficients in the model, and will change when any of these coefficients change.

A monetary policy rule, from this perspective, is a choice among alternative reduced forms for the economy: it shapes the coefficient matrices \( \Gamma \) and \( \Phi \) and therefore influences how the economy responds to shocks.

Once the variances of its innovations have been specified, the solved DSGE can be simulated to generate two types of output useful for policy evaluation. The first is the impulse responses of the system. These are the time paths of endogenous variables in response to one-unit shocks to the innovations. Figure 1, for example, builds directly on Freedman and Laxton (2009), using the DSGE laid out above with parameter values \( \lambda = \varphi = \rho = \sigma = 0.5 \) and the two shocks assumed to be independently and identically distributed with mean zero and variance 1. Backward-looking components in (AS-FL) and (IS-FL) give this economy considerable inertia, so monetary policy has a non-trivial task in anchoring inflation expectations. Freedman and Laxton use impulse responses to illustrate the difference between ‘good’ and ‘bad’ monetary policy. A ‘good’ policy is assumed to satisfy the Taylor rule

\[
i_t = \bar{r} + E_t[\pi_{t+1}] + 0.5(\pi_t - \pi) + 0.5\bar{y}_t.
\]

This embodies an aggressive response to inflation along with a countercyclical response to the GDP gap. They contrast this with a ‘bad’ monetary policy that barely satisfies the Taylor principle \( (\phi_{\pi} = 0.001) \) and ignores real activity \( (\phi_y = 0) \).

I have incorporated a third policy into this comparison, which with considerable oversimplification I will denote a ‘financial programming’ policy. The monetary block of a financial program seeks to limit the growth of the nominal money stock to the amount by which

\[\text{But note that } \Phi_u \text{ is not a vector of innovations to the } x \text{ variables as in a standard VAR. The vector } u \text{ contains only as many elements as there are stochastic shocks in the DSGE.}\]

\[\text{11 These parameter values are for illustration purposes only; for a small-scale DSGE calibrated to an African economic environment see } Adam \text{ et al. (2009); see also Barnichon and Peiris (2008).}\]
nominal money demand would rise if the program target for inflation were met. I consider the simplest possible version, one that allows no corrections for temporary deviations of GDP from its growth path. Recalling that underlying trends have been swept out of the model, the ‘FP’ policy rule is therefore:

\[(\text{MP-FP}) \quad \mu_t = \bar{\pi} \]

Figure 1 shows impulse responses of the system to shocks to desired spending – including responses of the 20-quarter ahead model-consistent forecast of inflation, \(E_t[\pi_{t+20}]\), as a measure of the degree to which inflation expectations remain anchored. Comparing ‘good’ with ‘bad’, the differences are stark. Equation (4) succeeds in fully anchoring inflation expectations, while the ‘bad’ policy allows them to become unhinged for an extended period. The other impulse responses show a uniformly worse macroeconomic performance under the ‘bad’ policy. Output displays a large cumulative deviation from the flexible-price equilibrium, while inflation rises more both on impact and over time.

The impulse responses implied by the FP rule, interestingly, are not much different from those implied by the Taylor rule (the example shown uses money demand equation (1), with an income elasticity of \(\gamma = 1\)). The reason for this is that while constant money growth has the ‘look’ of a passive monetary policy it may in fact imply a highly active stance. The implied interest rate rule – inverting equation (1) and imposing (MP-FP) – is

\[(5) \quad i_t = \bar{i} + \rho^{-1}(\pi_t - \bar{\pi}) + \rho^{-1}\tilde{y}_t - \tilde{m}_{t-1}. \]

The stance of policy therefore depends on the interest semi-elasticity of money demand (Poole 1970). In our example, \(\rho = 0.5\), which yields an interest semi-elasticity of 0.005 and \(\rho^{-1} = 2\). Equation (5) satisfies the Taylor principle (with a vengeance), as well as incorporating a strongly countercyclical response to the GDP gap. This interest semi-elasticity is very low by industrial-country standards, however – a value for the USA might be closer to 0.05, which would not satisfy the Taylor principle and would produce significantly wider macroeconomic fluctuations.
under a money-growth rule, as indicated in Figure 2. This underscores the relevance of econometric evidence on key parameters, whether drawn from the country in question or from structurally similar countries.\textsuperscript{12}

Note that shifting to MP-FP quietly restores the LM curve, while remaining within the new neoclassical paradigm. The DSGE literature will of course continue to be dominated by interest rate rules, given their prominence in industrial and emerging-market economies. But modeling portfolio behavior directly is likely to be crucial for making sense of African policy challenges, regardless of its relevance – which in any case may be changing, in the wake of the global financial crisis\textsuperscript{13} – for industrial-country applications.

To underscore the last point, notice that while I have called (5) an ‘interest rate rule’, the central bank in question is using a money instrument. It is not obvious – or necessary – that equation (5) could even be implemented. A policy interest rate may not even exist, or the short-term interest rate over which the central bank has some control may have tenuous links to the interest rates that matter for spending and policy behavior. For the specification to be valid, what matters is that some interest rate exists – perhaps a shadow rate in a widespread informal credit market – that serves simultaneously as the opportunity cost of current spending in terms of future spending and (in nominal terms) as the opportunity cost of holding money. If this assumption is a poor match to reality, the appropriate response is presumably to model the IS and LM behavior more carefully while retaining a faithful description of the instruments actually in use by the central bank.

The second type of output generated by the solved DSGE is the moments of the variables. If the simulated model is linear, these can be calculated exactly; if the analyst has taken a higher-order approximation to the underlying nonlinear model the moments have to be constructed empirically by simulating the model repeatedly for random draws from the distribution of shocks. Once again, since the parameters of the solution depend on the

\textsuperscript{12} For an ongoing project I recently reviewed the empirical literature on money demand in Tanzania. It is not possible on the basis of past estimates to reject the hypothesis that the interest elasticity of demand for M1 and M2 is zero. On the other hand, there is evidence of substitution between money and goods, and money and foreign currency.
\textsuperscript{13} The global financial crisis activated the zero bound on nominal interest rates among industrial countries and induced a shift towards quantitative easing. A convincing treatment of exit strategies may require giving portfolio behavior and the banking sector more prominence than in most current models.
monetary policy rule, rules can be compared in terms of how they transmit exogenous volatility into volatility in the endogenous variables.

The most striking feature of policy rules that succeed in anchoring inflation expectations is their impact in improving the policy tradeoffs that central bankers face. When expectations are anchored, market participants treat nominal price adjustments as real price adjustments. The amount of nominal adjustment required to achieve any desired change in relative prices is therefore smaller. This reduces the ‘pass-through’ of shocks to wages and prices while enhancing the impact of monetary policy actions. The result is that a central bank that succeeds in anchoring expectations can achieve a strictly better combination of nominal and real volatility than when expectations are not anchored. These impacts have played a central role in the inflation targeting literature, where the output cost of disinflation appears to be somewhat smaller, and the pass-through of exchange-rates, oil prices, and global food prices to domestic prices somewhat weaker, for inflation-targeting central banks than for non-targeting central banks (e.g., Mishkin and Schmidt-Hebbel 2007, Habermeier et al. 2009). Identifying these effects is of course difficult, given that the data cover a period in which all central banks placed increasing emphasis on inflation control and – until the oil and food price shocks of 2006-08 – global inflation pressures were relatively mild; a recent paper by Brita and Bystedt (2010), for example, finds that in contrast to the previous consensus these improvements among inflation-targeting countries are not statistically significant.

Table 1 provides an illustration of these effects by comparing the volatilities of the endogenous variables under the three rules. The two that anchor expectations achieve lower volatilities across the board. Column 4 of the table says that no dominance argument can be made between the ‘Good’ TR policy and the FP policy. A plausible loss function would favor FP, however, because in this very simple context its superior performance on inflation comes at virtually no cost in terms of real volatility. The low interest elasticity is partly responsible for this, but a feature widely viewed as the chief drawback of a money-growth rule is also absent in this comparison: equation (1) assumes that the money demand equation holds exactly. If liquidity preference were instead subject to stochastic shocks – an $\varepsilon^m_t$ term in equation (1) – the

---

14 One manifestation of this is that credibility flattens the slope of the Phillips curve.
comparison would move in favor of the Taylor rule. As emphasized by Poole (1970), money demand shocks are accommodated automatically under an interest rate policy that ignores such shocks. A money growth policy, in contrast, is not robust to unobserved money demand shocks: with money growth held fixed, a shift in the LM curve feeds through to interest rates and aggregate demand. Column 5 emphasizes this point. I incorporate a money demand shock in equation (1), with a standard deviation of 5 percent (consistent with estimates of long-run money demand in Tanzania), and then re-run the ‘good’ and ‘FP’ simulations. The FP’s superior inflation performance persists, but now at the cost of very substantial real volatility.

The search for ‘optimal’ rules of course requires a metric for comparing multi-dimensional outcomes. While the most natural approach is arguably to appeal to the utility function that was used to derive private-sector behavior (see Woodford 2003), in practice this is not often done. More heuristic approaches are typically used, with implicit or explicit reference to a loss function defined over the variances of selected macroeconomic variables – e.g., inflation and the GDP gap – around their long-run trends. If the analyst is prepared to specify a particular quadratic loss function (e.g., as a second-order approximation to an intertemporal welfare function), linearity of the underlying DSGE implies that the optimal monetary policy rule is itself linear; in this case its parameters can be determined using dynamic programming techniques (McCandless 2008).

5. ADDRESSING AFRICAN POLICY CHALLENGES

In practical applications, the modeling challenge – along with plausible calibration – is to build out from the core in a way that reflects important characteristics of the economy being studied. I briefly focus on each of the three blocks (IMP, AS, IS), asking in each case how the relevant block of the DSGE can be adapted to features of the African policy environment. In the process I argue in favor of open-economy DSGEs that accommodate balance sheet instruments and money-growth targets, imperfect capital mobility, an important role for the banking sector, and a large and volatile food sector.
Note that opening the economy introduces the nominal exchange rate as an important new variable (the real exchange rate follows through a definitional equation and plays a potentially important role in the IS curve). At least one new equation is required to accommodate the exchange rate. The standard approach is to assume high capital mobility, which yields an interest parity condition that equates the domestic interest rate to the sum of an exogenous ‘world’ interest rate and the rate of expected depreciation of the home currency. Interest rate policies may therefore exert an important portion of their impact through the exchange rate. A flexibly-specified DSGE with these properties is set out in Berg, Karam and Laxton (2006), who make a strong case for its use in emerging-market countries.

Notice, however, that the assumption of high capital mobility takes foreign exchange operations off the table as an instrument of monetary policy. In a classic proposition of international macroeconomics, high capital mobility forces a choice between controlling the interest rate (or equivalently, as we saw earlier, the money stock), or controlling the exchange rate; the monetary authority cannot do both, even in the short run. The assumption of high capital mobility preserves a central feature of the closed-economy DSGE, which is a shortage of instruments (one) relative to objectives (at least two: inflation and real stability).

**Balance sheet instruments and imperfect capital mobility**

Most African central banks use balance sheet operations (transactions in government securities and/or foreign exchange) rather than a policy interest rate as their main policy instruments and, as I emphasized earlier, monetary aggregates rather than the inflation rate or an inflation forecast as intermediate targets. Moreover, they appear to have some latitude for reconciling exchange rate objectives with other policy objectives, at least in the short term, suggesting that capital mobility, while probably on the increase, is far from perfect.

In a study of central bank responses to external shocks coming from aid and the terms of trade, O’Connell et al. (2007) forego a Taylor rule altogether and specify central bank reaction functions in terms of operations in government securities and foreign exchange. The steady-state rate of crawl of the exchange rate must of course be consistent with the inflation target, and reserve policy must be specified in such a way as to return the level of reserves,
eventually, to an underlying reference path. But the model allows for a full range of exchange rate policies, from a purely floating exchange rate to a predetermined crawl. Bond operations, in turn, can be used to sterilize foreign exchange interventions or, more generally, to support the achievement of money growth targets. They use the resulting model to search for ‘robust’ rules, defined loosely as rules that deliver favorable combinations of volatility in inflation, real GDP, and the real exchange rate, in the face of exogenous shocks.

Modeling central bank operations this way requires an explicit account of portfolio behavior; in effect, an ‘LM’ curve is needed as a bridge between the quantity instruments deployed by the central bank and the interest rate that governs private spending. O’Connell et al. (2007) assume that the capital account is closed, but that currency substitution is active. The demand for domestic money therefore depends both on the interest rate and on the rate of expected depreciation, consistent with empirical evidence for low-income Africa. The main finding from this research is that currency substitution brings out a strong complementarity between fiscal flexibility and floating exchange rates. If fiscal dominance lingers, so that shocks to aid or the terms of trade aid alter seigniorage requirements, the resulting portfolio substitution can create extreme volatility in exchange rates, with strong transmission to domestic economic activity. In this setting, unsterilized foreign exchange intervention proves an effective way of accommodating external volatility.

**Modeling money targets**

I emphasized above that an interest-rate rule can be implemented as a money-growth rule, or vice-versa. In ongoing research, Berg et al. (2010) are developing and estimating DSGEs that zeros in on the choice between *ex ante* targets for interest rates and for monetary aggregates in Africa. These models allow a serious role for money demand behavior and pay careful attention to role of incomplete information. In contrast with the Taylor rules studied above, these models assume, realistically, that operational targets for interest rates and/or monetary aggregates have to be formulated in advance, without knowledge of the current state of the economy. In this situation, while any interest-rate target implies a money-growth target that is equivalent *ex ante*, unobserved shocks will unavoidably drive a wedge, *ex post*, between the
monetary authority’s performances with respect to the two targets. Policymakers then have to choose – still without knowing the current state of the economy – whether to place greater weight on their interest rate target or their money target. As suggested above, this decision will come down in part to the relative importance of portfolio shocks: the greater the volatility from that quarter, the less allegiance policymakers will wish to place on money growth targets. DSGEs are well adapted to this kind of exercise; as a set of difference equations, their dynamic structure can easily be adapted to reflect the data and information lags that confront policymakers.

**Understanding the inflation process**

The new Keynesian Phillips curve is the intellectual centerpiece of the new neoclassical synthesis. It was developed to describe economies in which wage/price rigidities are widespread and a large share of output fluctuations come from aggregate demand. At bottom, however, the DSGE methodology is a toolkit rather than a specific structure or set of parameters. Its basic message is that the characteristics of a good monetary policy rule depend on the nature of the inflation process.

From this perspective it is remarkable how much is still to be learned about how wages and prices are set in African countries. The industrial-country literature is likely to be of little help, because the structural features of African countries differ in potentially important respects:

- The informal sector is large
- The formal sector is dominated by the public sector
- Rain-dependent agriculture is a large share of GDP, so supply shocks are prevalent
- Imperfectly traded food constitutes a large portion of the consumption basket

Consider the implications of these observations for the Phillips curve. The parameter $\varphi$, which gives the short-run slope of the Phillips curve in $(AS-W)$, depends on two underlying parameters: the frequency with which price-setters adjust their prices, and the elasticity of
marginal cost with respect to output (Gali and Gertler 2008). It is not obvious how to guide plausible choices for African economies. A natural approach may be to disaggregate, if these features differ sharply across sectors; O’Connell et al. (2007), for example, assume that price rigidities are restricted to the nontraded goods sector, mimicking long-standard practice in open-economy macro models. The dual structure of African economies suggests, however, that a more important disaggregation may be between formal and informal activities, and/or between the rural (food-exporting) and urban (food-importing) sectors.

One advantage of the DSGE approach is therefore to pose a sharp set of researchable questions about the inflation process. Is the informal sector in Africa a flex-price, flex-wage sector? Does widespread underemployment – and labor mobility – imply a highly elastic marginal cost schedule, or are these influences overwhelmed by other sources of supply-side rigidity? Do exchange rates pass through rapidly into the prices of traded goods? Do food price shocks create wage push in the urban formal sector? The content of an appropriate policy rule depends on the answers to these questions. Suppose, for example, that the formal sector is a sideshow relative to a dominant informal economy in which the costs of changing prices are small enough that prices are effectively flexible. In this case actual output tracks ‘natural’ output and monetary policy has no stabilization role at all. Strict inflation targeting – whether implemented using an interest rate instrument or a money base instrument – is appropriate.

Barnichon and Peiris (2008) estimate hybrid versions of the aggregative Phillips curve for 17 African countries and find that in contrast to a flex-price benchmark their constructed measures of the output gap have a non-trivial and statistically significant impact on inflation. This impact persists after controlling for transitory supply shocks (using rainfall). Their Phillips curves also include, however, a measure of excess money supply, constructed as the residual from a cointegrated money demand equation. This is also statistically significant and, if anything, more important than the output gap in accounting for observed variation in inflation. These results are consistent with coexistence of sticky-price and flex-price inflation dynamics, but also, possibly, with a lingering impact of fiscal dominance on inflation expectations.
Incorporating food price shocks

Further progress in understanding the inflation process in African countries will require a food/non-food disaggregation, given the size of the food sector and the highly divergent behavior of prices in the two sectors (Durevall and Ndung’u 2001). Given the focused analytical demands of DSGE modeling, this effort is likely to draw on the work of agricultural economists and CGE modelers, who have built up a base of microeconomic evidence on how rural markets behave and on their general equilibrium interactions with other markets. To illustrate some of the potential payoffs of the DSGE approach, I focus briefly here on two widely-observed features of food markets in low-income countries: Engel’s Law and private grain storage.

To incorporate Engel’s Law I follow Matsuyama (1992) in assuming that food demand is subject to a subsistence requirement $Z \geq 0$. Total spending $Y_t$ is therefore divided between food and non-food in order to maximize the within-period utility function $U(C_{Ft}, C_{Nt}) = (C_{Ft} - Z)^\xi C_{Nt}^{1-\xi}$, where $\xi$ is between zero and 1. The resulting within-period demand functions display constant shares in above-subsistence spending; food demand, for example, satisfies $P_{Ft}(C_{Ft} - Z) = \xi \cdot (P_{Ft}Y_t - P_{Ft}Z)$. As before, the IS curve describes intertemporal behavior. But since utility flows only from above-subsistence consumption, interest-sensitive smoothing behavior applies only to that subset of total spending. The counterpart to IS-W is therefore

\[
\dot{Y}_t = E_t[\hat{Y}_{t+1}] - \frac{\sigma}{\eta} (\dddot{r}_{t+1} - \hat{r}_t) - \frac{a}{\eta} (E_t[\hat{p}_{t-1}] - \hat{p}_t) + \epsilon_t Y
\]

where $\theta = \tilde{Y}/(\tilde{Y} - \tilde{p}\tilde{Z}) > 1$, $\theta$ is the share of food in total spending and $p = P_{Ft}/P$ is the ratio of the price of food to the overall CPI.

Equation (6) differs from the conventional IS curve in two ways. First, the subsistence requirement reduces the response of total spending to movements in the real interest rate (an implication of $\theta > 1$). This effect is larger the closer the population is to subsistence; the dampening impact of poverty on the interest elasticity of saving was noted by Asea and Reinhart (1996) in an AERC plenary session more than a decade ago. Second, expected movements in the relative price of food now play a role in the IS curve. The reason for this is that the real interest rate relevant for intertemporal smoothing applies only to above-
subsistence requirements and therefore places a smaller weight on food than the overall real interest rate \((\xi < \theta)\). The new term in (6) adjusts the conventional real interest rate accordingly; notice that when \(Z = 0\) this term disappears (as does the elasticity correction, since \(\theta = 1\)).

The Appendix presents a simple DSGE that incorporates equation (6) along with the other adjustments necessary to accommodate a minimal general-equilibrium treatment of the food sector. In Figures 3 and 4 I use this model to address an empirical puzzle from Loening, Durevall and Birru (2009). In a careful study of monthly inflation in Ethiopia, these authors find that although non-food prices are stickier than food prices – consistent with a greater prevalence of nominal rigidities in the non-food sector – it is the food sector that displays greater inflation inertia, in terms of the dependence of current inflation on past inflation. Indexation and administered pricing are absent in both sectors, so the source of this finding is unclear.

Figure 3 suggests that the core DSGE, when disaggregated to accommodate a large, flex-price food sector, simply re-poses the puzzle.\(^{15}\) Figure 3 shows the impulse responses to a transitory food supply shock equal to 10 percent of normal output. The supply shock produces a sharp increase in food prices, and the real interest rate rises temporarily as well, as households attempt – unsuccessfully, of course, since the economy is closed – to smooth their consumption over time. Overall inflation rises on impact, and non-food inflation displays the inertia seen in our earlier examples, as generated by the backward-looking elements in expectations and spending. But food inflation displays no inertia at all. As indicated in Table 2, this feature is apparent in the implied autocorrelations of these variables (these reflect the full structure of shocks – in the present case, shocks to food supply and aggregate spending, with standard deviations of 10 and 2.5 percent, respectively).

In Figure 4, I allow traders and households to engage in food storage. They are therefore in a position to respond to market signals during the period of a food supply shock. These

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\(^{15}\) For parameter assumptions see the notes to Figure 3. I use the Freedman/Laxton version as in the earlier examples, and continue to assume a closed economy. The latter assumption is grossly in line with Loening et al. (2009), who find that although both food and non-food prices respond eventually to movements in world prices, there are large and persistent deviations associated with food supply shocks. The wide bands within which domestic prices appear to fluctuate are consistent with high internal transport costs.
signals unambiguously reduce the return to storage, because the high real interest rate makes storage costly while food prices – having risen sharply – are expected to fall. Food supply therefore falls by less, in the presence of storage, than it otherwise would. As noted by Muth (1961) – in the paper that established the concepts and methods of what would later become DSGE modeling – this smoothing role of competitive storage increases the serial correlation of food price inflation (and, of course, of food consumption). Figure 4 shows the impact of this in a sharp increase in the short-run persistence of food versus non-food inflation. In Table 2, reduced-form autocorrelations in food inflation now stretch well past the first lag, with negative higher autocorrelations generated by the return of stocks to baseline levels.

There are of course many issues to be explored here, including the zero bound on storage and the role of international trade. But even within its simple confines, the example generates sharp questions that can be taken back to the data. For example, how is a food supply shock transmitted to the non-food sector? In Figure 3, non-food output falls initially. This recalls Cardoso’s 1981 two-sector analysis, a classic of the Latin American structuralist literature. But when storage is incorporated, non-food output rises on impact. In both cases, these initial impacts are reversed over time, so that in the storage case, the Cardoso pattern emerges with a one-period lag.

Credit in the transmission mechanism

I have been emphasizing portfolio behavior as an important fulcrum of monetary policy management in African countries. The elegance of the core DSGE also depends, however, on a tight set of links between the short-term interest rate controlled by the central bank and the long-term rates that influence spending behavior. These links are largely absent in low-income countries, where securities markets are thin or absent altogether, and where they exist, are concentrated at the short end of the maturity spectrum.

When financial frictions rule out arms-length forms of finance, banks become the dominant source of external finance and central bank credit to the banking system – rather than open-market operations in securities markets – becomes the main instrument of monetary policy. Agénor and Montiel (2008) analyze the impact of changes in the refinance
rate and show that it depends on the full financial structure of the economy, including the
dominant forms of collateral, the extent of dollarization, and the banking system’s access to
foreign borrowing. These features are likely to play a role in the next generation of DSGEs
developed for low-income economies.

6. CONCLUSIONS

DSGE models already occupy a prominent place within the research departments of central
banks in the industrial and emerging-market economies. Conditions in these environments are
favorable for the successful use of these models: the macroeconomic data are good, the
stylized facts of the business cycle are known, the research base that can be drawn upon for
calibration is strong, and the research community is deep. These conditions cannot be relied on
in low income countries, and the natural inference may be that rule-based evaluation of
monetary policy, using DSGE methods, can wait. I disagree. This is an exciting time to develop
DSGE applications that reflect African economic conditions and respond to African policy
challenges. These methods are no longer new-fangled and arcane, and their comparative
advantage is arguably strongest in environments of structural change and weak data, where
traditional time series methods are often unsatisfying. They force the analyst to be serious
about the structure of stochastic shocks, the nature of the inflation process, and the constraints
on monetary policy. A research culture that embodies these attitudes can be a critically
important support to any monetary policy framework. I hope AERC researchers will take up the
many opportunities these methods offer for policy-relevant research.
APPENDIX

The 9-equation DSGE model below builds out from the Woodford model described in the text. The food (F) sector is assumed to clear continuously via price movements, while the non-food (N) sector is characterized by a standard new Keynesian Phillips curve. Food demand is subject to a subsistence requirement of \( Z > 0 \), which generates Engel’s Law. The share of food output in GDP in the non-stochastic steady state is \( \theta \), and the share of food in above-subistence consumption is \( \xi \leq \theta \). The model determines the vector \( \mathbf{y} = [\pi_N, \tilde{\pi}_N, \tilde{\pi}, i, \pi, \tilde{p}, \tilde{y}_F, \tilde{c}_F, \tilde{s}] \). To generate Figures 3 and 4, I incorporated inertia into the Phillips curve as in (AS-FL) and used the backward-looking version of the IS curve as in (IS-FL).

A two-sector version of Woodford (2003)

\[
\begin{align*}
\pi_{Nt} - \tilde{\pi}_N &= E_t[\pi_{Nt+1} - \tilde{\pi}_N] + \varphi \tilde{\pi}_N \quad \text{(Phillips curve for N-goods)} \\
\tilde{y}_t &= E_t[\tilde{y}_{t+1}] - \frac{\sigma}{\theta} (i_t - E_t[\pi_{t+1}] - \tilde{\pi}) + \frac{\sigma(\theta - \xi)}{\theta} (E_t[\tilde{p}_{t+1}] - \tilde{p}_t) + \epsilon_t^y \quad \text{(IS curve)} \\
i_t &= \tilde{r} + \pi_{Nt} + \phi_i (\pi_{Nt} - \tilde{\pi}) + \phi_y \tilde{y}_N \quad \text{(Monetary policy rule)} \\
\pi_t - \tilde{\pi} &= \pi_{Nt} - \tilde{\pi}_N + \theta (\tilde{p}_t - \tilde{p}_t-1) \quad \text{(Headline inflation)} \\
\tilde{y}_t &= \theta \tilde{y}_F + (1 - \theta) \tilde{y}_N \quad \text{(Definition of aggregate output)} \\
\tilde{c}_F &= \frac{\xi}{\theta} \tilde{y}_t - \frac{(1-\theta)\xi}{\theta} \tilde{p}_t \quad \text{(Demand for food)} \\
\tilde{s}_t &= \alpha \cdot [(1-\theta) (E_t[\tilde{p}_{Ft+1}] - \tilde{p}_F) + (E[\pi_{t+1}] - \tilde{\pi}) - (i_t - \tilde{i})]. \quad \text{(Food storage behavior)} \\
\tilde{c}_F &= \tilde{y}_F^n + \frac{\gamma}{(1-\gamma)} [\tilde{s}_t - \tilde{s}_{t-1}] \quad \text{(Food market clearing)} \\
\tilde{y}_F^n &= \epsilon_{Ft} \quad \text{(Stochastic process for food output)}
\end{align*}
\]

where \( \alpha \geq 0 \) measures the sensitivity of food stocks to expected arbitrage gains. Note that I have excluded the inflation shock in the Phillips curve, so the simulated model has an IS shock and a food supply shock. For a detailed derivation of this model, see O’Connell (2010).
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Figure 1. Impulse responses to $\varepsilon_t^Y$ using the Freedman/Laxton (2009) core DSGE

Notes: The DSGE is as specified in the ‘FL’ equations given in the text; the monetary policy rule is equation (4). ‘Good’ and ‘bad’ policy are as specified by Freedman and Laxton (2009) and explained in the text. ‘FP’ denotes the ‘financial programming’ rule (MP-FP). Expected inflation is the 20-quarter-ahead expected value of inflation. The interest semi-elasticity of money demand is 0.005.

Table 1. Standard deviations under alternative policy rules

<table>
<thead>
<tr>
<th>Variable</th>
<th>‘Good’</th>
<th>‘Bad’</th>
<th>‘FP’</th>
<th>w/o $\varepsilon^m$</th>
<th>w/ $\varepsilon^m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflation</td>
<td>1.83</td>
<td>18.08</td>
<td>0.97</td>
<td>0.53</td>
<td>0.93</td>
</tr>
<tr>
<td>GDP gap</td>
<td>0.84</td>
<td>1.30</td>
<td>0.91</td>
<td>1.08</td>
<td>2.70</td>
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<tr>
<td>Interest rate</td>
<td>2.15</td>
<td>17.84</td>
<td>1.55</td>
<td>0.72</td>
<td>2.18</td>
</tr>
<tr>
<td>Real money balances</td>
<td>10.58</td>
<td>88.85</td>
<td>1.16</td>
<td>0.11</td>
<td>0.19</td>
</tr>
<tr>
<td>Money growth</td>
<td>10.16</td>
<td>24.26</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Expected inflation (+20)</td>
<td>0.00</td>
<td>9.94</td>
<td>0.00</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Notes: Columns 1-3 compare simulated standard deviations under the 3 rules, without a money demand shock. The last 2 columns show ratios of standard deviations, with and without the money demand shock.
Figure 2. Impulse responses with more interest-elastic money demand

Notes: These runs are identical to those of Figure 1, except that the interest semi-elasticity of money demand is 0.05 rather than 0.005.
Figure 3. Impulse responses to a food-supply shock

Notes: The model appears in the Appendix. In this run, the coefficient in the food-storage equation is set to zero.

Table 2. Simulated autocorrelations

<table>
<thead>
<tr>
<th>Version</th>
<th>Inflation rate</th>
<th>1st</th>
<th>Autocorrelation</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without</td>
<td>Non-food</td>
<td>0.6822</td>
<td>0.3114</td>
<td>0.0706</td>
<td>-0.0282</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Food</td>
<td>-0.4801</td>
<td>0.0047</td>
<td>-0.0210</td>
<td>0.0318</td>
<td></td>
</tr>
<tr>
<td>With</td>
<td>Non-food</td>
<td>0.4334</td>
<td>0.2137</td>
<td>0.1704</td>
<td>0.1490</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Food</td>
<td>0.2755</td>
<td>-0.1785</td>
<td>-0.2628</td>
<td>-0.1456</td>
<td></td>
</tr>
</tbody>
</table>

Notes: The model appears in the Appendix. The standard deviations of the IS shock and food supply shock are 2.5 and 10 percent, respectively.
Figure 4. Impulse responses to a food-supply shock, with competitive food storage

Notes: The model appears in the Appendix. In this run, the coefficient in the food-storage equation is set to 10.