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Towards Macroprudential Stress Testing: Incorporating Macro-Feedback Effects

by Ivo Krznar and Troy Matheson

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Towards Macroprudential Stress Testing: Incorporating Macro Feedback Effects

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Abstract

Macro-feedback effects have been identified as a key missing element for more effective macro-prudential stress testing. To fill this gap, this paper develops a framework that facilitates the analysis of both the direct effects of macroeconomic shocks on the solvency of individual banks and feedback effects that allow for the amplification and propagation of shocks that can result from bank deleveraging and credit crunches. The framework ensures consistency in the key relationships between macroeconomic and financial variables, and banks' balance sheets. This is accomplished by embedding a standard stress-testing framework based on individual banks' data in a semi-structural macroeconomic model. The framework has numerous applications that can strengthen stress testing and macro financial analysis. Moreover, it provides an avenue for many extensions that address the challenges of incorporating other second-round effects important for comprehensive systemic risk analysis, such as interactions between solvency, liquidity and contagion risks. To this end, the paper presents some preliminary simulations of feedback effects arising from the link between the liquidity and solvency risk.

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Keywords: stress testing, macro feedback effects, solvency risk, credit crunch.

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CONTENTS

TABLES

I. Introduction

Stress tests are widely used to analyze the resiliency of banking systems. These tests nearly always rely on exogenous macroeconomic scenarios, behavioral ad-hoc assumptions related to individual banks, and reduced-form relationships that map the macroeconomic scenarios into various forms of risks, including those related to the solvency positions of individual banks. A potential shortfall with these stress tests is that they do not adequately capture the macro-feedback effects stemming from the impact of banks' solvency problems on the real economy, which can amplify and propagate the effects of shocks.

Given their system-wide focus and importance in identifying risks in the banking sector, macroprudential stress tests should go beyond the current practice of assessing the impact of macroeconomic shocks on individual banks' solvency by better incorporating macro-feedback effects that capture the impact of banks' balance sheets on the real economy.[1] Since the global financial crisis, a variety of structural, semi-structural, and reduced-form models with real-financial linkages have been developed to analyze the interplay between the real economy and the financial sector at the *aggregate* level.[2] These models provide consistent macroeconomic frameworks with feedback loops between real and financial sectors that can be used as inputs into standard stress-testing frameworks. However, these models do not explicitly incorporate linkages between *individual* banks balance sheets and the real economy. Indeed, this issue has been identified as a key missing element for more effective macro-prudential stress tests.[3] The framework developed in this paper aims to address this issue.

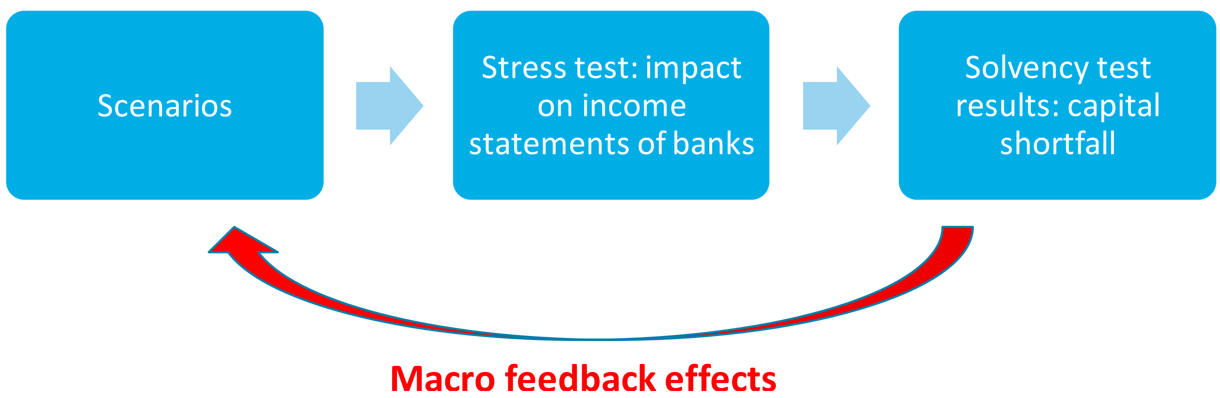
The framework essentially embeds a standard stress-testing framework based on individual banks' data in a semi-structural macroeconomic model. The framework allows for endogenous linkages between the real economy and the banking sector to better analyze the impact of macroeconomic shocks on the balance sheets of individual banks and it allows for feedback effects from banking-sector solvency shocks to the real economy (Figure 1). At the same time, it ensures consistency in the relationships between macroeconomic and financial variables and individual banks' balance sheets.

[1] In addition to macro feedback effects, macroprudential tests need to integrate liquidity, contagion risks into the solvency stress tests, capture spillovers to other financial sectors and incorporate reactions of banks and policy. See, for example, Alfaro and Drehmann (2009), Montes, and Trucharte Artigas (2012), Burrows and others (2012), Demekas (2015), IMF (2012), Constâncio (2015), BIS (2015), Vazquez, Tabak, Souto (2012).

[2] See Darracq Paries and other (2011), Christiano and others (2011), Clerc and other (2015) for various versions of a DSGE model with a banking sector. See Gray and others (2013) for GVAR models with real-financial linkages.

[3] See for example, Demekas (2015), IMF (2012), Constâncio (2015).

Figure 1. The Idea of the Paper



The framework has numerous applications that can strengthen stress testing and enhance macro financial analysis.

- *Strengthening stress testing.* The framework can be used to capture and analyze the importance of the macro-feedback effects for the health of individual banks, the overall banking sector, and the real economy. It can also generate scenarios that ensure that the linkages between all variables are taken into account in a consistent way to accommodate endogenous feedback effects.

- *Strengthening macro-financial analysis.* The framework is a tool that can be used to model and assess macro financial linkages. In particular, the framework can be used to generate baseline and stress scenarios in a consistent way and can strengthen systemic risk analysis by estimating the effects of the banking sector's solvency on the real economy—a key element of any systemic risk analysis. The model can also be used to extract business and credit cycles that can be used to inform risk analysis, and enhance understanding of the linkages between the real economy and the banking sector. This includes measuring the impact of financial variables on the real economy and vice versa, both through historical shock decompositions and impulse responses. Lastly, the model allows for the analysis of the impact of micro- and macro-prudential capital measures on the banking sector and the real economy, including their impact on monetary policy. Overall, the framework can be used to support the IMF's recent efforts to mainstream macro-financial analysis into bilateral surveillance.[4]

The paper proceeds as follows. Section II reviews related literature and section III describes the semi-structural macroeconomic model that embeds a simple stress-testing framework. The model is illustrated using macroeconomic and banking data for Brazil in section IV. The

[4] See IMF (2017).

results of the stress test are not an assessment of the current state of the Brazilian banking sector but an illustration of how the model can be used and outputs it can produce. Also, for illustrative purposes, the model's output is examined for a baseline scenario only and banking sector variables are presented at the aggregate level.[5] Section V provides some avenues that can further enhance FSAP stress testing and bilateral surveillance and caveats of the model. Section VI concludes.

II. Related Literature

The literature related to stress-testing models that incorporate feedback effects from the financial sector to the real economy remains is very limited. Nevertheless, there are a few papers related to the subject that are worth mentioning.

- The Bank of Korea's (2012) systemic risk assessment model for macro-prudential policy links the decline in the capital ratios of individual banks to lower credit supply and higher borrowers' probabilities of default that bring about second-round "credit crunch" losses. However, the model does not explicitly take account of the transmission of banking sector shocks to the real economy.

- The Bank of Japan's (2014) macroeconomic stress tests incorporate macro-feedback effects from adverse shocks in the financial sector through higher lending rates. Higher lending rates result from a worsening of non-banking sector balance sheets and lower credit supply resulting from a credit crunch. Despite a comprehensive credit risk module in the stress testing framework, the model is not fully based on theoretical considerations and does not take account of all key macroeconomic relationships. For example, the framework only focuses on dynamics of real output, without taking into account endogenous feedback loops within the macro module, such as the responses of inflation and interest rates to output. The framework is also based on equation-by-equation estimation with ordinary-least squares and suffers from simultaneity problems. Due to both of these issues, the framework would face challenges in generating consistent macroeconomic scenarios and stress-testing simulations. Another shortfall of this model is that some of the banks' important income statement items are not explicitly modeled (e.g., non-interest income, realized and unrealized gains/losses on securities holdings).

- Kida (2008) develops a model that incorporates the transmission of banking sector solvency shocks to the real economy. However, the macro module that is developed only consists of an equation linking output growth to credit growth and is thus not well suited for designing macroeconomic scenarios and projections. Moreover, the entire framework is calibrated, implying that the existence of the macro-feedback effects is imposed rather than estimated.

- Gray and others (2013) use a contingent claims analysis embedded in a global vector autoregressive model to study the endogenous interactions between risks in the banking

[5] For the baseline scenario, the projections for Brazil in the model specification without stress-testing framework and are consistent with the 2016 April World Economic Outlook projections that existed at the time of writing.

sector, the corporate sector, the sovereign, and output and credit growth. However, the risk indicators used to measure the credit risk of institutions are derived based on equity prices rather than based on accounting principles which makes it difficult to disentangle the precise source of vulnerabilities. Moreover, the market price based indicators are sensitive to short-term swings in market perceptions that may have little to do with fundamentals, and cannot be applied to countries or entities with limited or no market price data.

- Many DSGE models have been complemented with a stress-testing exercise to analyze how a solvency shock would affect the real economy.[6] However, the solvency shock in these models typically derive from credit quality problems only, and the models are not formally linked to the stress-testing frameworks.

III. Model

In this section, a simple stress-testing model is embedded in a semi-structural macro model to fully capture endogenous macro-feedback effects. The modeling framework aims to combine the granularity of stress-testing exercises based on individual bank data with the general equilibrium nature of macroeconomic models based on aggregate data. The overall framework consists of two modules linked by using the concept of credit crunch (Figure 2):

- **Macro module.** This part of the framework is a variant of the models developed in Carabenciov and others (2008) and Krznar and Matheson (2017). This class of models is typically used to understand past economic developments and to produce scenarios and forecasts. The model characterizes an open economy where the relationships between the variables are determined by theoretical and empirical considerations. It describes the joint determination of output, inflation, unemployment, interest rates, credit, financial conditions, foreign demand, and the real exchange rate.

- **Stress testing module.** A simple version of the balance sheet-based approach[7] to stress testing is used to assesses the solvency of banks through changes in net income and risk-weighted assets. The set of panel regression models describe the behavior of the individual banks' income and expenses to key variables from the macro module. Some specifications of the model also allow for the endogenous reaction of banks' incomes and expenses to changes in their capital buffers. Dividend distribution and Basel III phase-ins and phase-outs are also taken into account, and new share issuance and share buy backs are not considered.

- **Credit equation: the link between the modules.** Panel credit equations link individual banks' capital (from the stress-testing module) to bank credit and output (from the macro

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[6] See Darracq Paries and others (2011), Dees and others (2017) and references in footnote 2.

[7] See for example, Schmieder and others (2011).

module) based on the concept of a credit crunch.[8] This bank credit channel derives from the failure of the Modigliani-Miller propositions.[9] Theoretical and empirical literature have shown that the Modigliani-Miller propositions usually do not hold, implying that issuing new equity is costly, which in turn affects credit supply—undercapitalized banks may raise the capital adequacy or targeted leverage ratio by cutting back on lending rather than raising equity, hurting economic growth.[10]

The framework, incorporating macro and stress testing module, is estimated using Bayesian methods and data for Brazil ranging from the beginning of 1999q1 to 2016q2. Appendices A and B provide more details on the macro module specifications used and the parameter estimates. The stress-testing module uses publicly-available, consolidated data from the financial reports of Brazil's six largest banks. The data were adjusted for mergers and acquisitions by the banks included in the stress test.[11]

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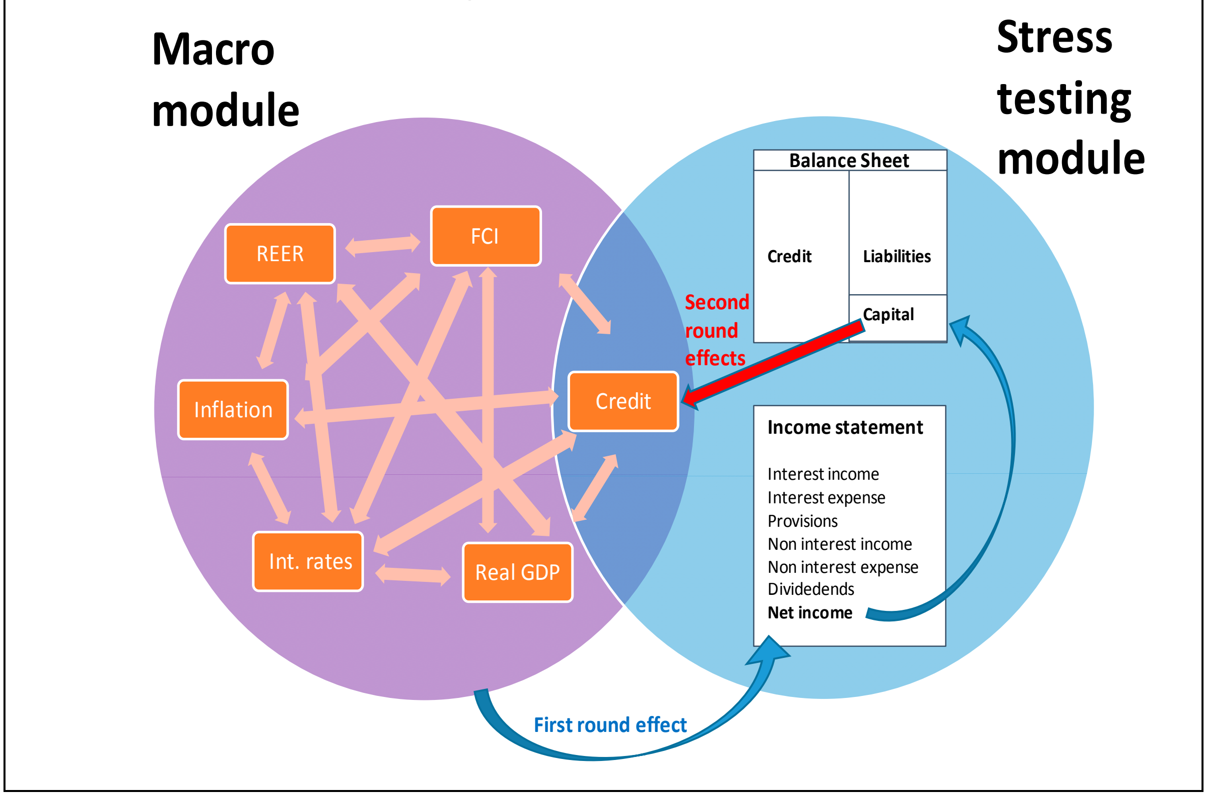
[8] The effect of changes in bank capital on loan supply is a key determinant of the linkage between financial conditions and real activity (Berrospide and Edge, 2010). Other real-financial linkages between capital and output have been identified in DSGE models with a banking sector. For example, Christiano, Motto and Rostagno (2010) model bank-funding channels where lending rates depend on banks' funding costs, banks' probability of default, and the credit worthiness of non-financial companies. In Darracq and others (2011), banks increase lending spreads when they are hit by solvency shocks.

[9] In a Modigliani-Miller world the level of bank capital (and banks' financial structure) is irrelevant to total cost of funding and lending.

[10] In general, capital has an effect on lending if breaking the regulatory capital threshold is costly and if banks cannot easily issue new equity. Empirical literature has shown that these two conditions hold. Jimenez and others (2009) find that under tight conditions a capital crunch led to credit crunch in Spain. Aiyar and others (2014) find that banks cut lending in response to tighter capital requirements in the U.K. Brun and others (2013) find a strong negative effect of capital requirements on lending. Gambacorta and Marques-Ibanez (2011) show that banks with weaker capital positions restricted the loan supply more strongly during the global financial crisis. Adrian and Shin (2010) show that banks manage their assets to maintain constant bank capital ratios, which suggests that capital has a magnified effect on assets and lending with the scaling factor equal to the leverage ratio. Carlson and others (2011) find that there was a significant relationship between capital ratios and bank lending during the global financial crisis. Bridges and others (2014) find that capital requirements affect lending with heterogeneous responses in different sectors. De Nicolo (2015) suggests that the negative short-run and long-run impact of an increase in capital requirements on bank lending and real activity is large. Others have found that the effects of capital shocks on loan growth is modest (Berrospide and Edge, 2010). Calza and Sousa (2005) find threshold effects related to the impact of credit conditions on the real economy. Cingano and others (2013) find that firms' investment in Italy is highly sensitive to bank credit and that credit shocks can have a significant impact on broader economic activity. Barone and others (2016) find that the real effects of credit crunch in Italy are concentrated among small firms. Dimelis and others (2013) find that a strong dependence of euro area firms' credit growth on credit expansion before the crisis and that post 2008, the credit crunch affected only slow-growth firms operating in the domestic economy. Meeks (2014) finds that unanticipated increases in capital requirements lower lending, raise credit spreads, and reduce aggregate expenditure.

[11] For more details on the stress testing module, see the Brazil 2016 Staff Report and Selected Issues paper on stress testing.

Figure 2. The Framework



A. Macro Module

The macroeconomic model is an extension of the model described in Krznar and Matheson (2017) that incorporates panel credit equations to provide linkages with the stress-testing model. Total credit extended by public and private banks are modelled separately to account for differences in their behavior in Brazil.[12] The equations assume that public and private credit fluctuations are driven by the business cycle and the bank capital ratio relative to the supervisory threshold:

$$c_{it}^{pb} = v_1 c_{it-1}^{pb} + v_2 y_{t-1} + \epsilon_{it}^{c^{pb}} \quad (1)$$

$$c_{it}^{pr} = \tau_1 c_{it-1}^{pr} + \tau_2 y_{t-1} + \epsilon_{it}^{c^{pr}} \quad (2)$$

where the banks are classified as being either public or private and for each bank i in each category, c_{it}^{pb} is the real public credit gap and c_{it}^{pr} is the real private credit gap, y_t is the output gap, and $\epsilon_{it}^{c^{pb}}$ and $\epsilon_{it}^{c^{pr}}$ are shocks to credit supply unrelated to past aggregate demand and past credit adjustments:

[12] The behavior of credit extended by public banks has differed from that private banks, partially due to public credit being used as a counter-cyclical policy instrument, particularly after the 2008 global financial crisis.

$$\epsilon_{it}^{c^{pb}} = \nu_3 K_{it}^{pb} + E_{it}^{c^{pb}} \tag{3}$$

$$\epsilon_{it}^{c^{pb}} = \tau_3 K_{it}^{pr} + E_{it}^{c^{pr}} \tag{4}$$

where K_{it}^{pb} public bank i's capital buffer (its capital ratio relative to the supervisory threshold) and K_{it}^{pr} is private bank i's capital buffer and $E_{it}^{c^{pb}}$ and $E_{it}^{c^{pr}}$ are white-noise shocks to real credit for each type of bank.[13] Thus, an individual bank is assumed to set its desired level of credit based on past levels of economic activity (demand), past levels of credit, and the current level of its capital ratio relative to the supervisory threshold. Since banks cannot immediately adjust credit levels (for example, due to an inability to recall credit that has already been extended), it is assumed that credit levels are slow to adjust to output fluctuations. A strong/weak economy and strong/weak capital buffers leads to strong/weak credit.

Each bank's capital buffer, K_{it}, is defined as the capital ratio deviation from a time-varying regulatory requirement, K_t^*, and its historical capital buffer above the regulatory requirement, $\overline{K}_i$:[14]

$$K_{it} = CAPITAL_{it} - (K_t^* + \overline{K}_i) \tag{5}$$

where $CAPITAL_{it}$ is common equity tier 1 capital ratio, K_t^* is the regulatory capital requirement, and $\overline{K}_i$ is each bank's historical capital buffer, i.e., the capital buffer each bank has maintained above the regulatory requirement on average over history. The regulatory requirement follows a random walk process:[15]

$$K_t^* = K_{t-1}^* + \varepsilon_t^{K^*} \tag{6}$$

As in Krznar and Matheson (2017), an equation for financial conditions is also included to take into account broader financial shocks (in addition to bank credit) that can affect the corporate sector and economic activity more generally. These financial conditions are also assumed to affect funding spreads and the solvency position of the banks, capturing the link between liquidity and solvency. It is assumed that financial conditions tighten or ease depending on creditors' view of the expected real GDP growth. That is, if the growth is expected be above trend (a strong economy), there will be a tendency to ease lending

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[13] We follow theoretical (see for example Darracq and others, 2011) and empirical literature (see for example, Berrospide and Edge, 2010, Kida, 2008) to include the capital buffer instead of the capital requirement in the credit equation. This approach is similar to Hancock and Wilcox (1993) who show that it is the difference between a bank actual capital and target capital that is important for determining loan growth.

[14] The stress test assesses the level of individual banks' common equity Tier 1 ratios against the regulatory threshold consistent with the Basel III transition schedule, but also accounts for a capital conservation buffer and a domestic systemically important bank (D-SIB) capital surcharge as minimia.

[15] The regulatory requirement is modeled as a random walk to examine shocks to the capital requirement. Also note that the estimated model treats the requirement as being observable over history and the projection horizon.

conditions, while if it is expected to be below trend (a weak economy), there will be a tendency to tighten lending conditions:

$$f_t = \chi_1 f_{t-1} - \chi_2(y_{t+2} - y_{t-1}) + \epsilon_t^f \tag{7}$$

where f_t is the financial conditions index (FCI) and ϵ_t^f is an AR(1) shock to financial conditions:

$$\epsilon_t^f = \chi_3 \epsilon_{t-1}^f + \omega_t^f \tag{8}$$

To establish the links between credit, the financial conditions, and demand it is assumed that shocks to credit and financial conditions ($\epsilon_t^{c^{pb}}$, $\epsilon_t^{c^{pr}}$ and ϵ_t^f) reflect changes in the lending practices of banks and/or financing conditions that can directly affect output. For example, if financial conditions are easier than anticipated on the basis of expectations for output growth or if credit supply is higher than anticipated on the basis of past demand and past credit adjustments, the effect will be a larger output gap and a stronger economy.

The credit shocks in the demand function allow us to model the feedback effects between the output gap and other macroeconomic variables due to the credit crunch assumption. The output gap is assumed to be related to a lead and lag of itself, the real interest rate gap, r_t, a foreign activity gap, y_t^* , and the real effective exchange rate gap, z_t, in addition to 'autonomous' FCI and credit shocks, i.e.,:

$$y_t = \rho_1 y_{t-1} + \rho_2 y_{t+1} - \rho_3 r_t + \rho_4 z_t + \rho_5 y_t^* + \rho_6\left(\sum_{i=1}^{I} w_i^{pb} \epsilon_{it}^{c^{pb}} + \sum_{j=1}^{J} w_j^{pr} \epsilon_{jt}^{c^{pr}}\right) - \rho_7 \epsilon_t^f + \varepsilon_t^y \tag{9}$$

where ε_t^y is an idiosyncratic demand shock, and the weights w_i^{pb} and w_j^{pr} reflect the shares of the public and private banks in total real credit, respectively. The first five terms in equation (9) are elements of a fairly standard new Keynesian IS cure, with output being positively related to lags and leads of itself, negatively related to the real interest rate, and positively related to a depreciated real exchange rate and the level of foreign demand. An expansion in public or private credit that is unrelated to past demand and past credit is assumed to increase demand, while an autonomous tightening of the FCI is assumed to reduce demand.

The other behavioral equations that characterize endogenous behavior of inflation (including regulated prices), interest rates, unemployment, real effective exchange rate, foreign demand and definitions, identities and stochastic processes that complete the model are provided in Appendix I.

B. Banks: Stress-Testing Module

The stress-testing module, which is a part of the overall framework, projects the capital ratios of the individual banks that are used to model the feedback effects on the real economy via the credit and the demand equations. Projected capital in the stress-testing module are determined by projections of net income and accumulated other comprehensive income (AOCI) over the 5-year testing horizon together with Basel III capital deductions (Chart).[16] In other words, for each bank i, capital ratio accumulates according to the following equation:

$$CAPITAL_{it} = CAPITAL_{it-1} + NI_{it} + AOCI_{it} - DED_{it} \tag{10}$$

where $CAPITAL_{it}$ is common equity tier 1 capital ratio, NI_{it} is net income, $AOCI_{it}$ is accumulated other comprehensive income (AOCI), and DED_{it} is Basel III deductions.

Net income is one of the main drivers of capital. For each bank, net income, NI_{it}, is determined as:

$$NI_{it} = IR_{it} - IE_{it} + NIR_{it} - NIE_{it} + OI_{it} - TAX_{it} - DIV_{it} - PROV_{it} \tag{11}$$

where there are three streams of revenue (interest revenue, IR_{it}, non-interest revenue, NIR_{it}, and net other income, OI_{it}) and five types of expenses (interest expenses, IE_{it}, non-interest expenses, NIE_{it}, taxes, TAX_{it}, dividend payments, DIV_{it}, and provisions, $PROV_{it}$). For the purposes of estimation and to make all variables in the banking sector stationary, capital and all income-statement items are expressed as ratios to risk-weighted assets.[17]

A set of simple panel models was used to model the main components of each bank's income statement. The panel models are intended to capture how the net income of each bank is affected by lagged macroeconomic variables and financial conditions (as independent variables) determined in the macro module in period *t-1*. Endogenous reaction of banks to shock to capital were also considered. For each income statement item *X*, the general model is:

$$X_{it} = (1 - a_i)X_{it-1} + a_i X_i^* + b_i \Delta y_{t-1} + c_i \Delta\big(R_{t-1} - (\overline{rr}_{t-1} + \pi_{t-1}^*)\big) + d_i \Delta f_{t-1} + e_i K_{it-1} + \varepsilon_{it}^X \tag{12}$$

where Δy_t is the quarterly change in the output gap, $\Delta(R_t - (\overline{rr}_t + \pi_t^*))$ is the change in the nominal interest rate gap (the nominal interest rate less its trend—the trend real interest rate plus the inflation target), Δf_t is the change in the FCI, K_{it} is the capital buffer, and X_i^* is the steady state of each income statement variable for each bank (taken as the historical average

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[16] In Brazil, Basel III deductions follow the Basel III transition schedule. Consistent with Brazilian regulation, we incorporated 100 percent of accumulated other comprehensive income (AOCI) into CET1 capital in 2016 and onwards.

[17] While scaling all the variables by risk-weighted assets simplifies the analysis, it leads to an approximation error in the capital accumulation equation and possible circularity problems because risk-weighted assets can change due to changes to endogenous variables outside the income statement, including credit. To ensure that all accounting identities hold over history, this approximation error is assumed to be part of deductions. Separately modeling risk-weighted assets, capital, and items in the income statement introduces a non-linearity into the model when computing endogenous capital ratios. Analysis of this more complicated model is outside the scope of this paper and is left for future work.

of each variable), ε_{it}^{X} is an idiosyncratic shock to each variable. The parameters a_i, b_i, c_i, d_i, and e_i are constant across banks for each balance sheet item.

For estimation purposes, the restrictions displayed in table 1 are imposed. A more favorable economic environment should boost banks' profits—higher output gap should increase all income statement items except provisions for loan losses. Higher interest rates and tighter financial conditions should both increase interest income and interest expense as higher policy rates would increase funding costs and possibly lending rates. Higher lending rates would in turn lower borrowers' debt repayment capacity and increase provisions for loan losses. They would also increase non-interest income as banks substitute lower yielding loans with riskier trading activities or higher fees. Moreover, higher interest rates would increase losses on fixed income portfolio. Basel III deductions are fixed and do not depend on macro and financial variables.

Two specifications of the panel regression models are also analyzed: with and without the endogenous reaction of banks' income statement items to shocks to past levels of capital. The parameter e_i describes this endogenous reaction. The reaction is intended to capture banks' efforts to increase their net income in response to negative shocks to capital. For example, if capital is falling, banks are expected to cut dividends and salaries (affecting non-interest expense), move into riskier and/or non-lending activities (affecting non-interest income) and increase spreads (affecting net interest income).

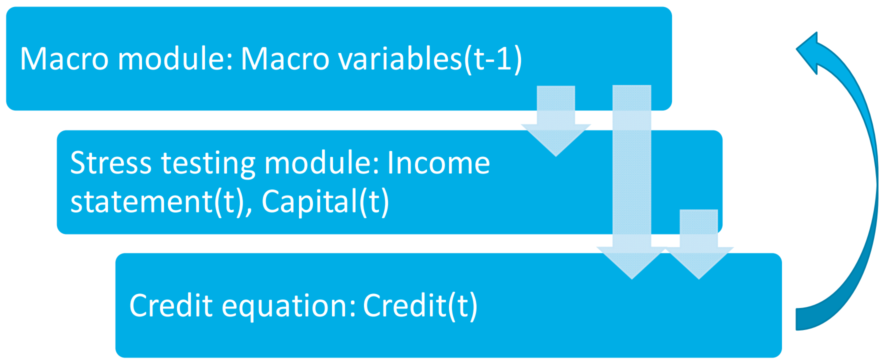
Table 1. Restrictions on the Banking Parameters

	a_i	b_i	c_i	d_i	e_i
Revenues					
IR_{it}	[0,1]	$[0,\infty]$	$[0,\infty]$	$[0,\infty]$	$[-\infty,0]$
NIR_{it}	[0,1]	$[0,\infty]$	$[-\infty,0]$	$[-\infty,0]$	$[-\infty,0]$
OI_{it}	[0,1]	$[0,\infty]$	$[-\infty,\infty]$	$[-\infty,0]$	0
$AOCI_{it}$	[0,1]	$[0,\infty]$	$[-\infty,0]$	$[-\infty,0]$	0
Expenses					
IE_{it}	[0,1]	$[0,\infty]$	$[0,\infty]$	$[0,\infty]$	$[0,\infty]$
NIE_{it}	[0,1]	$[0,\infty]$	0	0	$[0,\infty]$
TAX_{it}	[0,1]	$[0,\infty]$	0	0	$[0,\infty]$
DIV_{it}	[0,1]	$[0,\infty]$	0	0	$[0,\infty]$
$PROV_{it}$	[0,1]	$[-\infty,0]$	$[0,\infty]$	$[0,\infty]$	0
DED_{it}	[0,1]	0	0	0	0

C. Mechanics of the Model

Figure 3 presents a stylized illustration of the model. In the first period, *t*, banks' income statements are projected as function of the values of three macro variables (GDP growth, interest rate, the FCI) from the previous period, *t-1*. Net income in period *t* determines capital and the capital adequacy ratio in period *t*, which has a contemporaneous effect on credit. Together with output and credit in period *t-1*, the capital ratio determines the credit shock in period *t,* which will have an impact on output in period *t* together with the other endogenous variables that enter the demand function in the macro module. The values of the three macro variables in *t* enter the stress testing module to generate capital adequacy ratios in *t +1* and the sequence of events in Figure 3 is repeated.

Figure 3. Mechanics of the Model



IV. Applications

The framework described in the previous section can be used to strengthen stress testing, including in FSAPs, and macro financial analysis, including in bilateral surveillance and the recent efforts of the IMF to integrate macro-financial surveillance into Article IV surveillance.

- *Strengthening stress testing.* The framework can be used to capture and analyze the importance of feedback effects for the health of the banking sector. It can generate endogenous scenarios that ensure the links between all variables are taken into account in a consistent way.

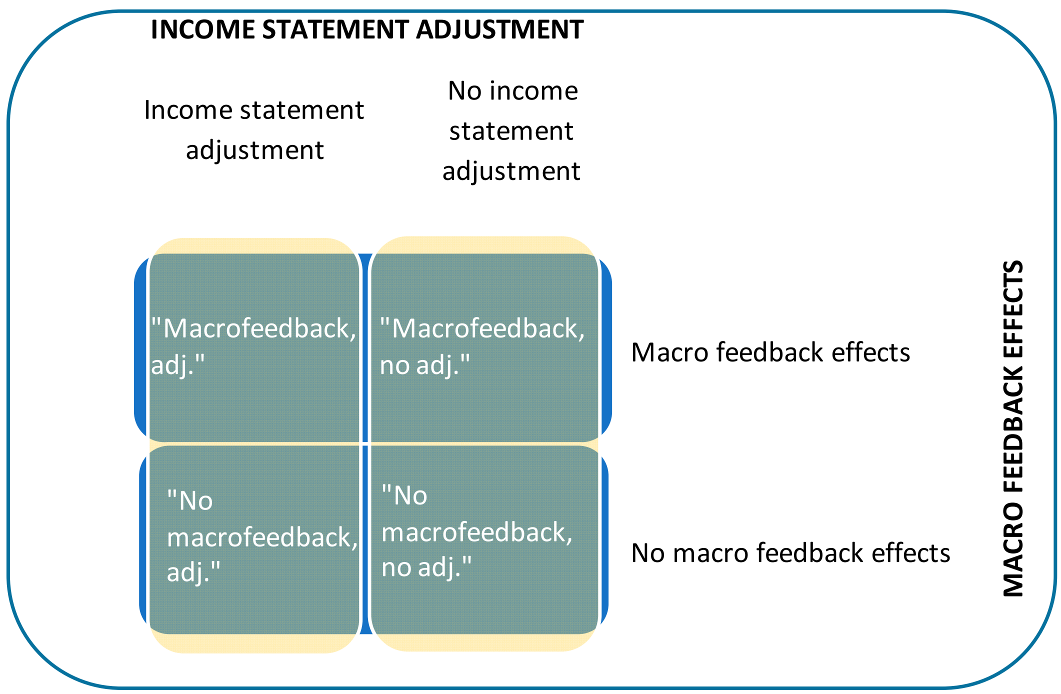
- *Strengthening macro-financial analysis.* The framework can generate medium-term projections, build scenarios, extract business and credit cycles, analyze linkages between individual banks and the real economy and the effects of monetary and macro-prudential policy.

As mentioned above, the framework is applied to the case of Brazil, for purposes of illustration.

A. Strengthening Stress Testing

To analyze the importance of macro-feedback effects for stress testing and the real economy, projections from four different model specifications can be examined: models with and without macro feedback effects and models with and without endogenous income statement adjustments (Figure 4). In the models with macro-feedback effects, credit depends on output, lagged credit, and the capital buffer; without macro-feedback effects, credit depends on output and lagged credit only (i.e., $\nu_3 = \tau_3 = 0$ in equations (3) and (4)). For each of these specifications, two different assumptions are made regarding how banks adjust their business activities (income statements) in response to their capital positions. The models with income statement reaction allow banks to adjust their business activities to affect their income statements in the face of capital shocks, while the models without the income reaction do not accommodate this effect (i.e., $e_i = 0$ in equation (12) for all income statement items). The model with no macro-feedback effects and no income statement reaction represents a standard stress testing framework that is typically used in FSAPs. The models with no macro-feedback effects, with or without banks adjusting their net incomes, delivers the same projections for the macroeconomic variables, including credit, since there is no link between capital and credit.

Figure 4. Four Specifications of the Model



The projections from the models highlight the importance of assumptions related to feedback effects for stress testing. Figure 5 compares projections of aggregate capital ratio, output, credit, inflation, and the policy interest rate under the baseline scenario across the different specifications of the model discussed above.

- *Models with no income statement adjustment.* The model with no macro-feedback effects and no income statement adjustments by banks (orange line) suggests that the capital ratio would fall by 50 bps over the next two years mostly due to lower output gap. However, once the macro-feedback effects are considered (red line) the capital ratio falls by an additional 90 bps as lower capital buffers impact credit supply and lower output (by about 100 bps). The impact on public credit is larger than for private credit since the capital buffers of public banks are generally smaller.[18] Inflation is projected to drop as demand falls, prompting an easing in monetary policy. Macro-feedback effects have important policy implications. For example, interest rates are projected to drop by almost 200 bps more in the model with macro-feedback effects due to the larger falls in output and inflation.

- *Models with income statement adjustment.* Aggregate capital ratio would be much higher if banks are assumed to adjust their business practices to affect streams of income and expenses in response to their capital buffers. The capital ratio is projected to reach 16 percent by the end of the stress-testing horizon, mainly as banks try to increase net income as a response to higher Basel III deductions that increase supervisory threshold. The feedback effects are still important, but less so since the capital ratio in the first year does not fall as much as in the case where banks do not adjust their net incomes.[19] This is also why credit and output decrease by less than in the case where banks are not assumed to adjust their net incomes. It is important to note that despite the relatively large increase in capital ratio, credit and output are still projected to fall. This is because credit depends on the difference between capital ratio and regulatory threshold. This difference will shrink due to negative shocks to capital, including from higher Basel III deductions and capital conservation buffer and therefore higher regulatory capital requirements resulting from the Basel III transition schedule.

B. Strengthening Macro Financial Analysis

The framework can strengthen macro financial analysis along a number of dimensions. The model can enhance understanding of the linkages between the real economy and the banking sector and improve medium-term macroeconomic projections. Business and credit cycles extracted using the model can be used to inform the risk analysis. The framework can also be utilized to build stress scenarios used for comprehensive and consistent risk analysis. Policy recommendations in IMF's bilateral surveillance could benefit from simulating the effects of micro-prudential and macro-prudential capital tools in addition to understanding their interaction with monetary policy.

Building Scenarios/Projections

The framework ensures consistency of macroeconomic and banking sector projections that can be used in AIV teams' baseline scenario forecasts and risk analysis. Due to macro-feedback loops, the macro scenarios and associated projections are necessary endogenous. Therefore, macroeconomic scenario building is inseparable from the analysis of the solvency

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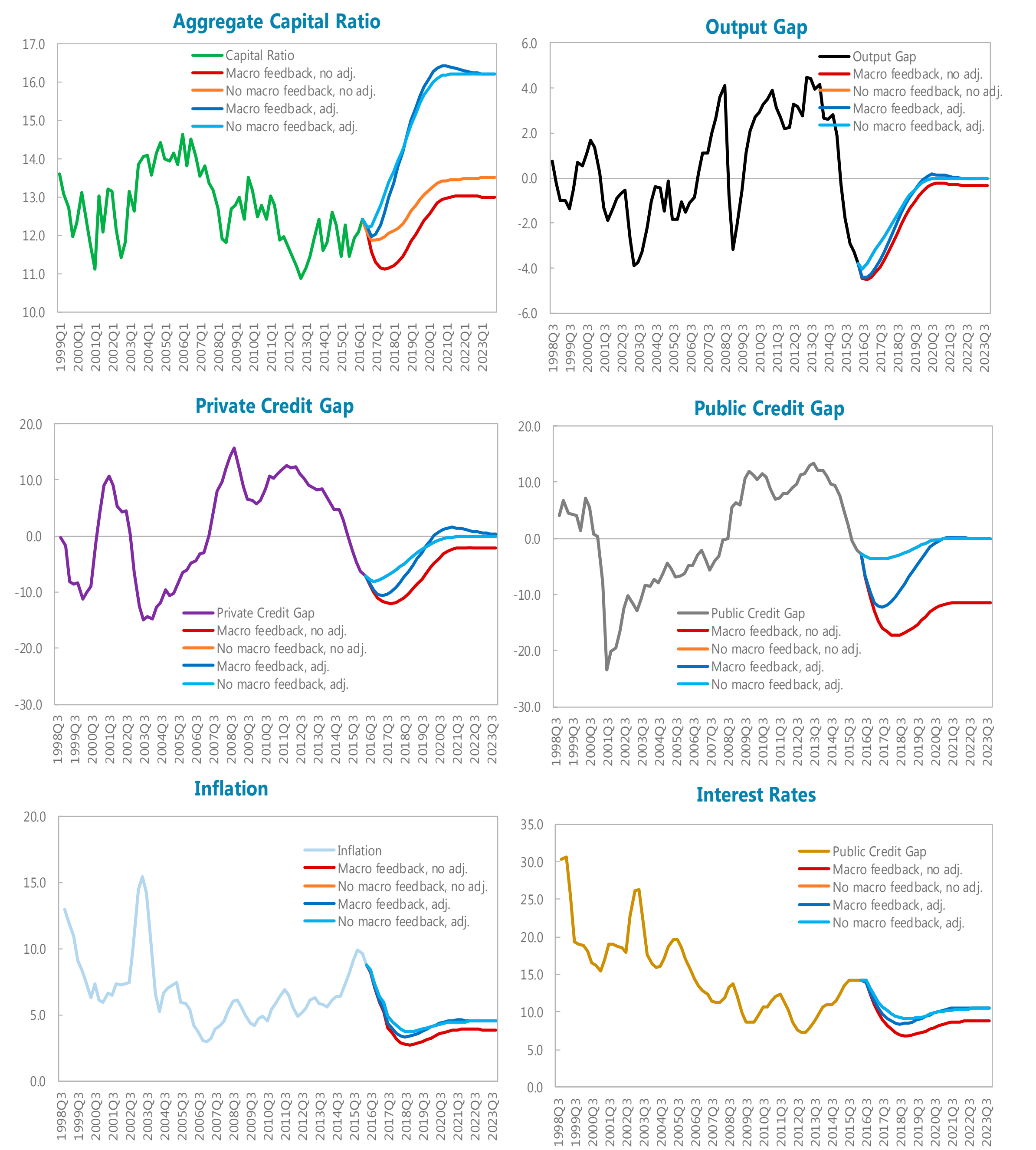
[18] While reactions of capital and credit are large, responses of output are relatively small because of small coefficient of credit shock in the IS curve. However, this is consistent magnitudes of output response to credit shocks in a VAR model (see Krznar and Matheson, 2017).

[19] Note that the smaller feedback effects are due to the assumptions of the model. In reality, feedback effects could be larger if banks adjust their balance sheets or income statements to increase their net income and capital. For example, banks can increase interest rates to earn more interest income or pay lower dividends. These endogenous reactions, which are not modeled here, would affect demand and result in larger macro feedback effects.

position of the banking sector and its reactions to stress. For example, all baseline projections in Figure 5 are endogenously determined by the structure of the model. Figure 5 also highlights the importance of feedback effects for macroeconomic projections.

Figure 5. Projections of Capital Ratio, Output, Credit Gaps



By providing a richer description of the data, the framework might also help to improve forecasting accuracy. Overall, the root-mean squared forecast errors, shown in Table 2, suggest that the models with income-statement adjustment have better forecast accuracy than models with no adjustment, regardless of whether or not the macro-feedback effects are included. However, it seems that including macro-feedback effects does not significantly improve the accuracy of projections. This might be due to the links between credit, capital and output in Brazil being more complicated than assumed in the model.

Table 2. Root-Mean-Squared Forecast Errors for the Four Specifications of the Model

		Income Statement Adjustement		No Income Statement Adjustement	
	Horizon	Macro feedback	No Macro feedback	Macro feedback	No Macro feedback
Growth	1 year	2.3	2.2	2.3	2.2
(percent yoy)	2 year	2.9	2.8	2.9	2.8
	3 year	3.7	3.6	3.7	3.6
Inflation	1 year	2.7	2.7	2.8	2.7
(percent yoy)	2 year	3.1	3.0	3.3	3.0
	3 year	3.3	3.1	3.6	3.1
Policy Rate	1 year	3.2	3.2	3.2	3.2
(percentage points)	2 year	3.6	3.3	4.0	3.3
	3 year	3.9	3.6	4.9	3.6
Aggregate Capital	1 year	1.5	1.3	2.0	1.7
(percent RWA)	2 year	1.4	1.2	2.6	2.1
	3 year	1.0	1.1	2.9	2.4

Understanding linkages between the banking sector and the real economy

The model allows a formal examination of linkages between the banking sector, including at the individual bank's level, and the real economy using impulse response functions and historical shock decompositions. In addition to a "standard" analyses of macroeconomic shocks on aggregate variables, the framework can be used to measure the impact of macroeconomic shocks on the specific activities of the banking sector and the impact of banking sector shocks on the real economy. This is similar to sensitivity analysis in FSAP stress-testing exercises. However, the framework also traces the impact of a given shock on other variables that might also affect the banking sector. For example, in the framework, net interest income is affected by interest rate shocks directly and indirectly via its impact on demand and financial conditions. Historical decompositions allow for the analysis of the contributions of particular shocks such as credit and capital shocks for the dynamics of macroeconomic variables such as output.

Impulse responses underscore the importance of demand shocks and capital shocks for credit and financial conditions, and capital shocks for output (Figure 6).[20] The impulse responses

[20] To calculate impulse responses or shocks, we construct the aggregate response or shock for J public banks and L private banks:

$$X_t^{pb} = \sum_{j=1}^{J} w_j X_j$$

following 1 percent shocks to output, credit, financial conditions and capital suggest the following:

- *Credit responds more to output than output responds to credit.* Moreover, both private and public credit responses to a demand shock double once the macro-feedback effects are taken into account due to the impact of an increase in capital buffers. The peak impact of output and credit shocks occurs around one year after the shock. While the peak impacts on output and credit following shocks occur relatively quickly, the effects of the shocks are persistent; a 1 percent shock to output boosts credit for 2 years. The macro-feedback effects make the effects more persistent as credit shocks have positive impacts on credit, output and capital.

- *Private credit is more responsive to output shocks than public credit.* Private credit increases by 2 percent following a positive output shock, while public credit only increases by around 1.5 percent. This result is not surprising—in Brazil's case, the extension of credit by private banks is likely more driven by macroeconomic developments than that extended by public banks, which have adopted countercyclical policy measures in the past.

- *Output responds strongly to shocks to financial conditions.* While financial conditions loosen following a positive demand shock, the response is relatively small and short-lived. On the other hand, there is a significant reaction of output to shocks to financial conditions. Macro-feedback effects contribute to the drop of output since the FCI shock lowers net income and capital, affecting credit and output.

- *The impact of capital ratio shock on output and credit is significant.* Credit responds to capital only if macro-feedback effects are taken into account. Credit drops by 6 percent following a 1 percent shock to capital across all banks, prompting a 0.6 percent fall in output.[21]

A detailed analysis of macroeconomic shocks on different activities of the banking sector suggests that shocks to demand, interest rates, and the FCI are important drivers of banks' profits and capitalization. Figure 7 illustrates the impacts of 1 percent shocks to demand, the FCI, and the interest rate on the income statement items of the banking sector, and the

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$$X_t^{pr} = \sum_{j=1}^{L} w_j X_j$$

where X_t^{pb} and X_t^{pr} are impulse responses or shocks for public and private banks in aggregate, respectively, and w_j and w_l are the shares of bank *j* in total public credit and bank *l* in total private credit, respectively.

[21] Note that, if it is not assumed that banks actively manage their activities and income statement to preserve capital buffers, income statement shocks have permanent effects on capital levels (i.e., capital is non-stationary) and macro variables.

aggregate capital ratio.[22] While the interest rate shock can be thought of as a shock to the risk-free rate, the FCI shock is assumed to proxy for a funding spread shock.

- *A positive demand shock increases profits and capital ratios.* A positive demand shock increases net interest income, non-interest revenue, non-interest expense and unrealized gains on portfolios, and reduces provisions for credit losses. This results in higher net income and capital. The signs of impulse responses are as expected; during a period of positive economic growth, banks extend more credit, resulting in higher interest income. Realized and unrealized gains on trading assets increase with a rise in asset prices and the incidence of default decreases. At the same time, expenses increase as banks expand their activities to satisfy increased demand.

- *A positive interest rate shock results in lower profits and aggregate capital, mainly due to higher funding costs, credit losses and unrealized losses.* Higher risk-free interest rates lower net interest income due to maturity transformation, and realized and unrealized gains due to repricing effects. Higher interest rates also affect borrowers' repayment capacity and quality of assets, dampen economic activity, and reduce non-interest expenses.[23]

- *The effects of the FCI shock are very similar to the effects of interest rate shock.* This is mostly due to similar impact of both shocks on funding and interest expenses. Moreover, the interest income is affected as the result of a negative impact of the FCI shock on economic activity.

The framework can be also used to analyze the effects on the real economy of shocks to any or all of the individual banks' income statement items. For example, the impulse responses following an asset-quality shock resulting in higher provisions in the income statement are displayed in Figure 8. This shock would lower net income, the aggregate capital ratio, credit supply, and output and inflation. The subsequent easing of monetary policy would help to strengthen demand and inflation and support banks' balance sheets (via higher credit, net interest income, trading income and lower provision). Macro-feedback effects prolong the negative impact on net income and capital ratios through a larger negative impact on output and the FCI.

A historical decomposition of the output gap suggests that financial conditions shocks, credit shocks, and capital shocks are important in explaining fluctuations in economic activity in Brazil. [24] The impacts of the financial shocks on output since 1999 are displayed in Figure 9:

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[22] Here, the model with macro-feedback effects and net income adjustments to capital shocks is used.

[23] Note that interest income does not increase with interest rate shock. There a couple of explanations for this. First, historically banks might have not been able to pass on higher funding costs onto borrowers. Second, higher interest rates reduce demand and increase the FCI, which in turn reduce interest income.

[24] The capital shocks are the sum of all the contributions from income statement items shocks in equation 12.

- *Private credit shocks boosted output in the lead up to the global financial crisis and public credit shocks boosted output following the crisis.* Strong growth in private credit in over 2005 to 2008 acted to support output. When the crisis hit in late 2008, private credit growth began to slow as private banks acted to bolster their balance sheets. At the same time, public credit was expanded in an effort to support demand after the crisis, providing a boost to output over 2009-10. The impact of the slowdown in private credit is reflected in the drop in importance of private credit shocks towards the end of 2008. Likewise, public credit went from being broadly neutral for growth in the lead up the crisis to being strongly expansionary.

- *While both public and private capital shocks weakened output and credit during the 2008/2009, only private capital shocks supported output and credit following the crisis.* Both public and private banks took a solvency hit during the crisis resulting in slower credit and output dynamics. Following the crisis, private banks issued new equity and scaled back lending in order to strengthen their balance sheets, thereby raising capital ratios. This provided the foundation for new credit and stronger output growth in the following years. On the other hand, public banks' expansion during and after the crisis was behind the negative impact of public capital ratio shocks on credit and output.

- *Financial conditions shocks played an important role both during the 2008/2009 and during the recovery period.* Looser financial conditions were a key driver in the 2009 recovery of output. The positive impact of financial conditions lasted until 2013 when financial conditions tightened drastically following sharp increase in foreign funding costs.

- *More recently, public and private credit and financial conditions shocks have begun to be a drag on output.* In response to slowing demand, private credit began slowing before public credit. Estimates suggest both public and private credit have been a drag on output since early 2015 when a policy was adopted to limit the expansion of credit by public banks, largely due to fiscal considerations. Financial conditions also tightened in 2015, largely due to a rise in uncertainty related to the outlook for growth, inflation, and public finances. The negative impact of FCI shocks has become smaller since the change of the government in May 2016.

- *On the other hand, both private and public capital shocks contributed positively to credit and output dynamics.* Positive shocks to capital ratios are likely due to higher issuance of new shares since mid-2015, especially for private banks, and dividend cut backs by public banks that are not captured by our model (Figure 10). Moreover, the recent slowdown in risk-weighted assets (which are not model explicitly) could have boosted capital ratios by more than our model allows; this could result in a positive shock to capital ratios and a positive contribution to credit and output dynamics. Nevertheless, these positive effects on credit and output are more than outweighed by the adverse impact of other shocks (e.g., demand shocks, cost-push shocks, and monetary policy shocks).

Figure 6. Macrofinancial Linkages: Selected Impulse Responses

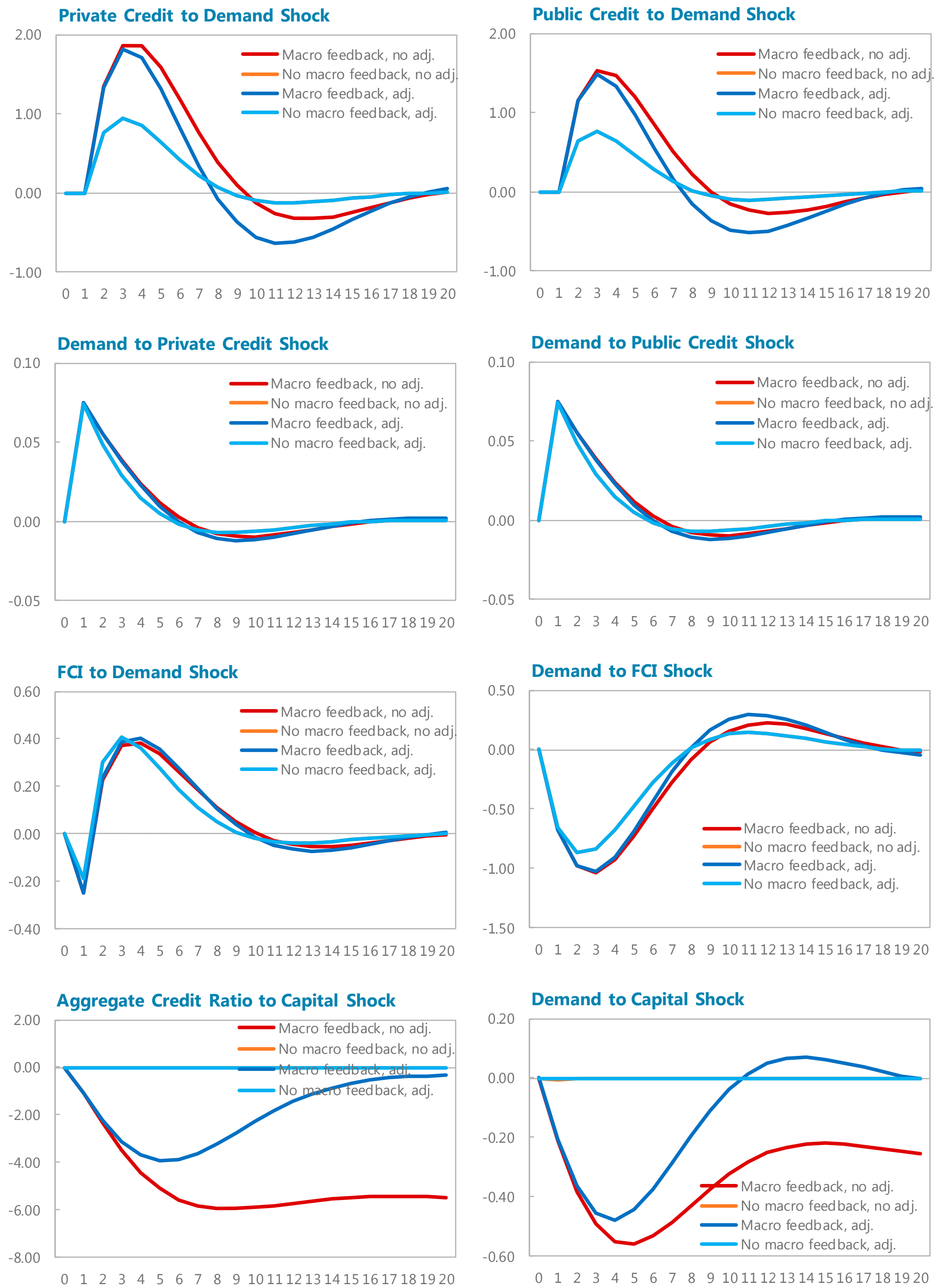


Figure 7. Banking Sector Impulse Responses

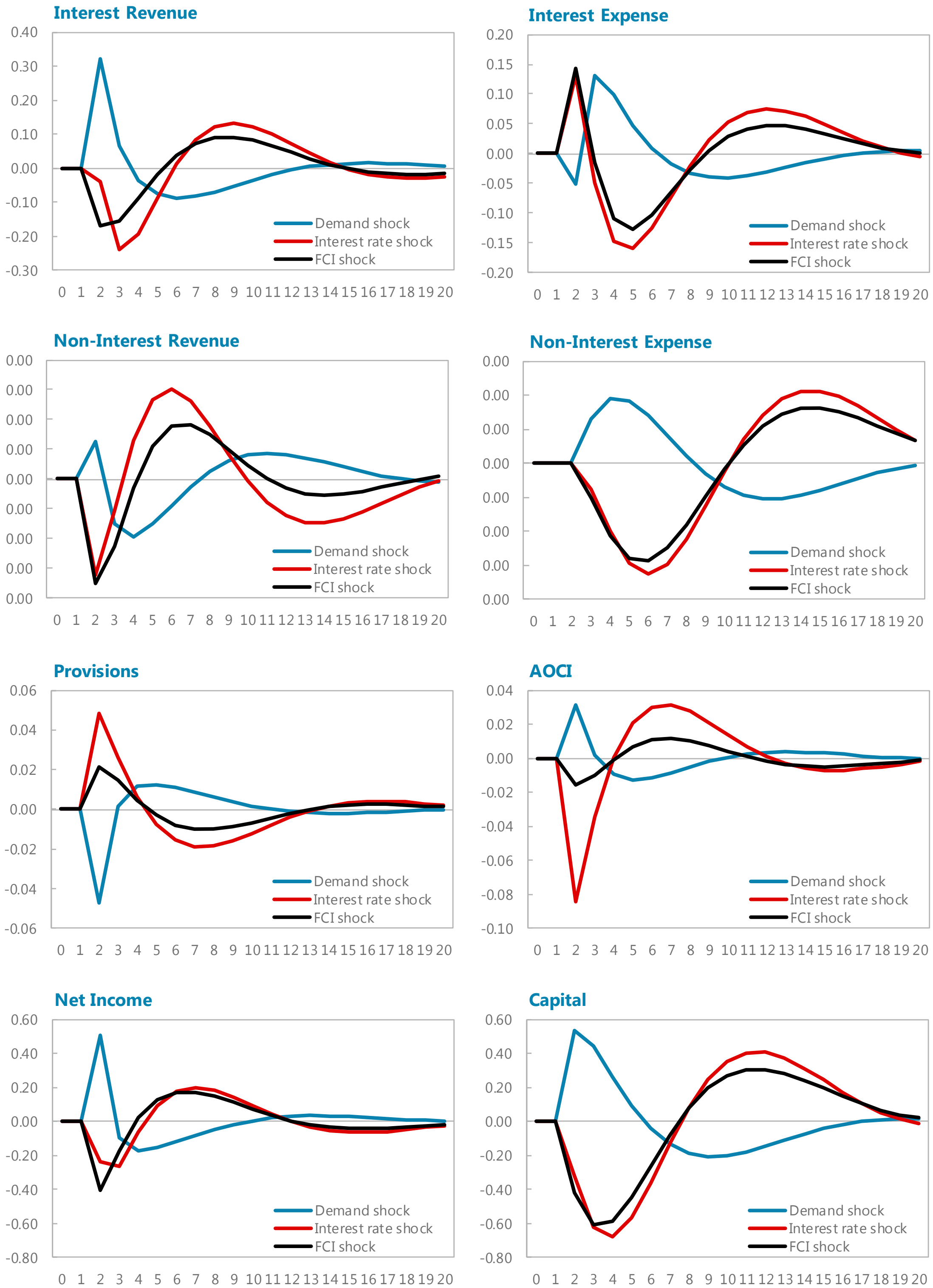


Figure 8. Macrofinancial Linkages: Selected Impulse Responses to Provisions Shock

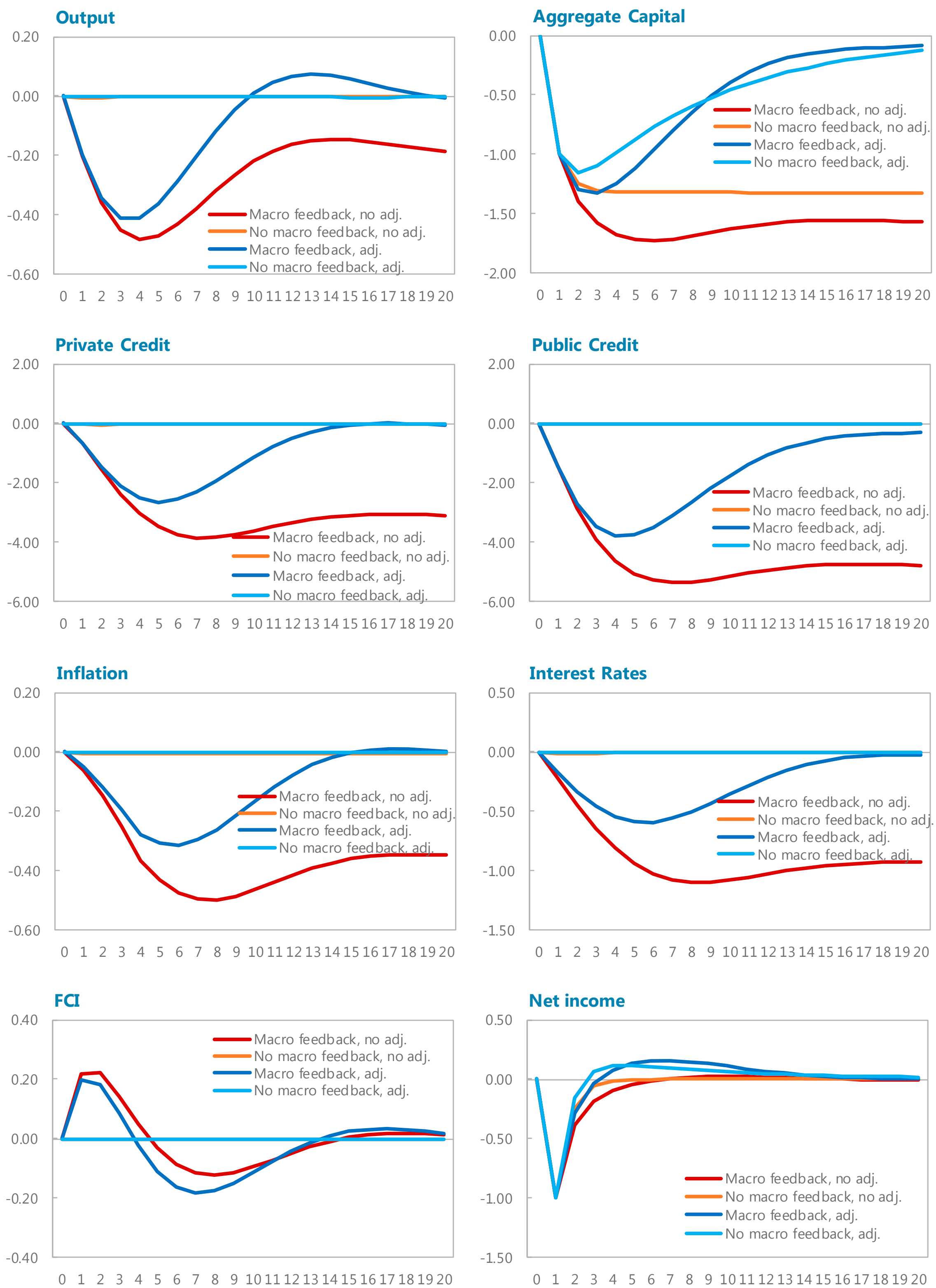


Figure 9. Historical Decomposition of Output and Credit Gaps

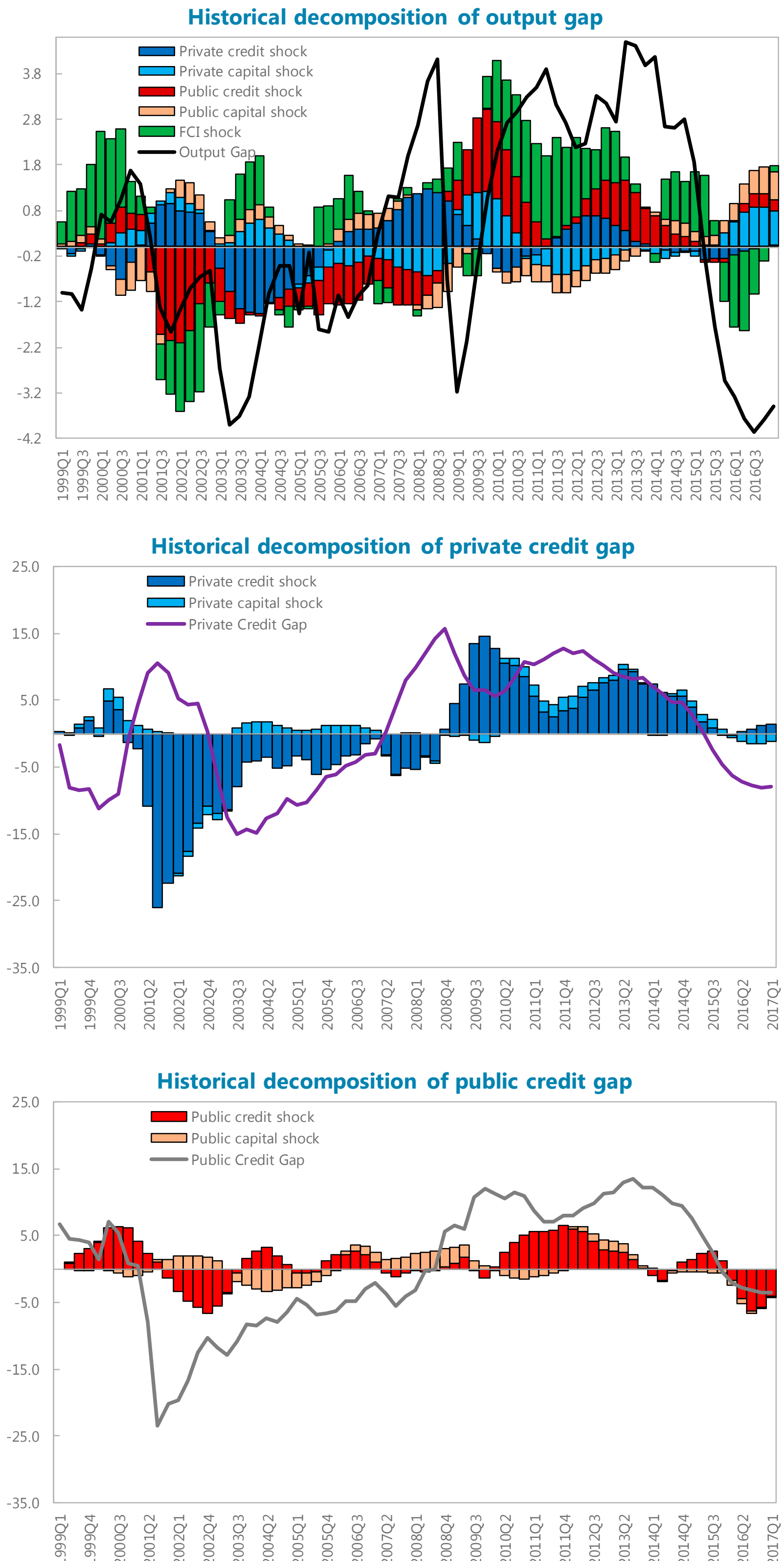
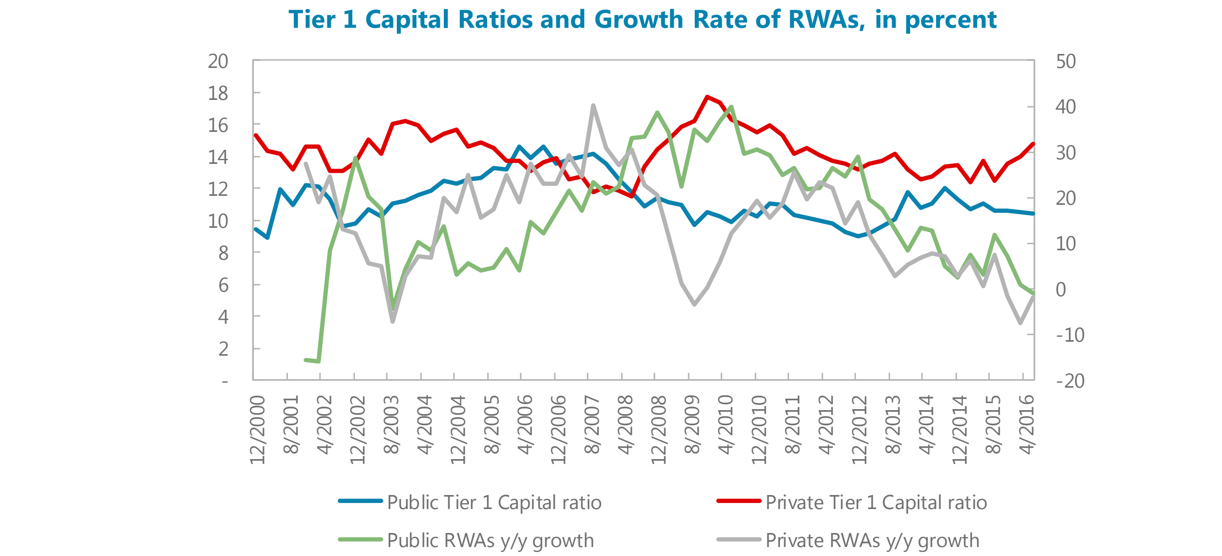


Figure 10. Capital Ratios and RWAs



Extracting cycles

The framework is a "gap model". As such, financial and business cycles can be jointly estimated by specifying relationships between the cycles based on economic theory and empirical evidence, where the trend of each variable is endogenously determined. In general, identifying credit booms and whether they are likely to continue is pivotal to improving macroeconomic projections. Excessive credit growth and sizeable financial cycle upswings frequently portend financial or economic crises that result from deleveraging. The model estimates suggest that, in mid-2016, Brazil was in a downturn phase of the credit cycle and this coincided with the downturn phase of the business cycle. With cross-country evidence suggesting that periods of strong credit growth are typically followed by periods of sluggish growth, this result points to potential vulnerabilities for Brazil going forward.

Simulating policy responses

The framework can be used to assess the macro-financial impacts of micro- and macro-prudential changes to capital. For example, the macroeconomic implications can be traced out:

- if a higher capital buffer is imposed on an individual bank (for example, if it is determined that the bank's loss absorbency level is not appropriate);
- if a countercyclical capital buffer is imposed on the banking sector based on developments in the real economy, allowing for an endogenous macroprudential policy reaction.

Figure 11 shows that a higher capital requirement for all banks would reduce output. The higher requirement lowers the difference between capital held by the bank and the regulatory threshold, inducing a drop in credit supply and aggregate demand. The estimated effects in Brazil are in line with the empirical literature measuring the impact of higher capital on credit and output.[25] The impact of higher capital on output and inflation would induce monetary policy loosening. As mentioned above, the models with macro-feedback generate more volatile impulse responses. The model with macro feedback and no adjustment of net incomes to capital levels suggests that banks would have lower capital ratios after the increase in the capital requirement. On the other hand, assuming endogenous adjustments to net income to satisfy the capital requirement, suggests that banks would quickly change their business model to increase net income and capital.[26]

V. Future Work: Possible Extensions

The model is flexible enough to incorporate additional elements that would improve both micro- and macro-prudential aspects of the framework. However, it should be noted that any extension of the framework comes at the cost of additional analytical and computational complexity. Nevertheless, understanding the most important feedback channels between banks, such as interactions between solvency, liquidity and contagion risks, are crucial to quantify the likely impact of adverse conditions on the banking sector and the real economy. Further developing these channels would strengthen the macro-prudential aspect of the stress-testing framework. The microprudential aspect of the framework can also be improved by enhancing the stress testing module.

A. Strengthening Macro-Prudential Aspects of the Stress-testing Module: Incorporating Non-linearities Between Capital and Credit, Liquidity, Network Risk

The global financial crisis showed that banks can be affected by two sources of risk during periods of stress that are usually not embedded in the solvency stress testing: liquidity risk and spillover effects that arise as a results of solvency problems. These second-round effects can give rise to important non-linearities that are at the heart of periods of financial crisis and should therefore be captured by stress tests (Borio and others, 2011).

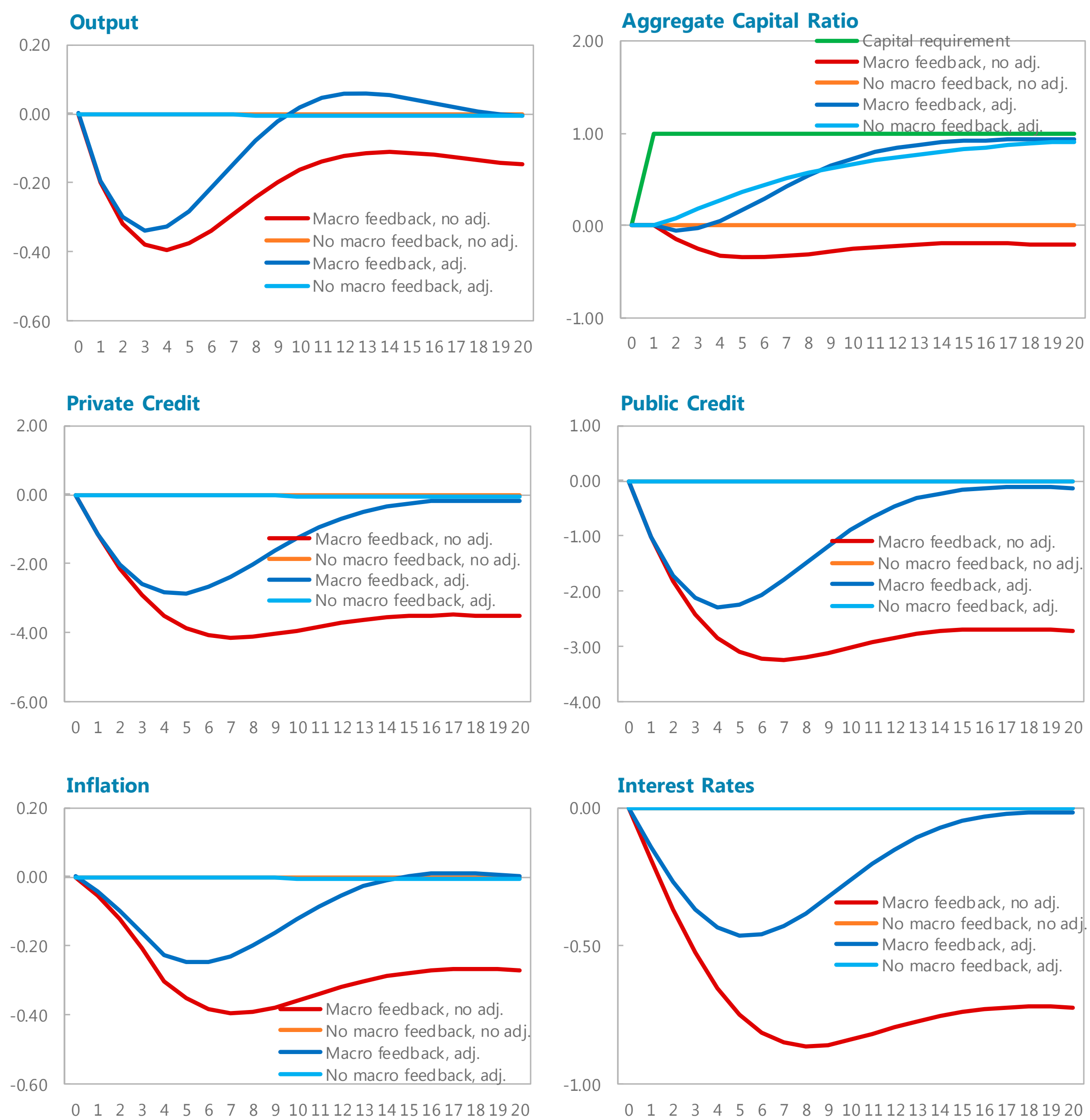
For example, a bank that has solvency problems might not be able to roll over existing funding or to obtain new funding (funding liquidity risk) and easily sell assets in financial markets to meet funding needs (market liquidity risk). These liquidity risks might lead to additional losses and magnify solvency problems. Network spillover effects occur when an insolvent bank is unable to fulfill its obligations to other banks, creating counterparty credit losses for those banks. The interactions between solvency, liquidity, and contagion risks can give rise to non-linearities between capital and credit that can amplify the impact of solvency

[25] See for example, De Nicolo (2015), Bridges and others (2014), Aiyar, Calomiris and Wieladek (2014) and references therein.

[26] Note: the framework does not take into fully account for the benefits of higher capital. A comprehensive analysis of the effectiveness of macro-prudential capital buffers should weigh the effects of stricter capital requirements on economic activity against the benefits resulting from greater financial stability and lower probability of a crisis.

shocks on the real economy.[27] Another source of the nonlinearity between capital and credit comes from the fact that banks' decisions to cut credit likely depend on how close capital is to regulatory threshold.

Figure 11. Output and Credit Impulse Responses to Capital Requirement Shock



[27] See BIS (2015) for various stress-testing frameworks that consider solvency, liquidity, and contagion interactions.

Incorporating liquidity risks

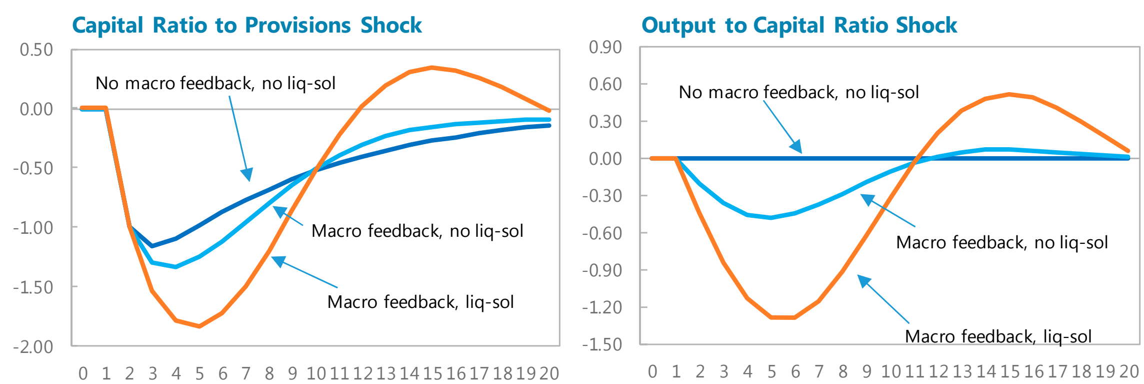
The framework in this paper captures some aspects of liquidity risks. Higher funding costs affect interest expenses, provisions for credit losses, and realized and unrealized losses on available for sale securities portfolio. Funding costs are modeled using the financial conditions index, which depends on the expectation of future output growth (relative to trend). Ideally, funding costs should be modeled at the level of the individual bank, as a function of each bank's fundamentals and aggregate variables. However, funding costs of individual banks are not publicly available. A simple way of capturing these effects is to extend the FCI equation to include the aggregate capital buffer to capture the effect of solvency problems on liquidity, which is turn has consequences for future solvency position of the banks:

$$f_t = \chi_1 f_{t-1} - \chi_2(y_{t+2} - y_{t-1}) + \tau_6 K_t + \epsilon_t^f \tag{13}$$

where K_t is a weighted average of capital buffer of the six banks examined.

Impulse responses from this model suggest that the impact of link between solvency and liquidity enlarges macro-feedback effects (Figure 12). Capital ratio would fall by 1.2 percent (trough) following a provisions shock of 1 percent in the model with no macro-feedback effects and no link between solvency and liquidity. There is no effect on output as there is no link between credit and capital. Once the macro-feedback effects are considered, the capital ratio goes down by an additional 20 bps and output falls by 0.4 percent. Finally, the impact of the interlinkages between solvency and liquidity on the aggregate capital ratio amounts to 60 bps. Lower capital lowers credit and output; the resulting changes to funding costs affect net income and capital, generating additional macro feedback effects. Output drops by 1.3 percent following a capital ratio shock—the impact of interaction between solvency and liquidity on output is three times as large as in the model without the link between solvency and liquidity. The impact of all other shocks on macroeconomic and banking sector variables are presented in Appendix III.

Figure 12. Incorporating Second Round Effects due to Macro Feedback Loops and the Liquidity-Solvency Link



Incorporating all aspects of liquidity risks in a fully endogenous manner would be challenging. Integration between liquidity and solvency risks is challenging because of difficulties in defining possible interaction channels (Cetina, 2015), and difficulties in modeling these interactions endogenously. In general, liquidity risks would emerge if capital becomes a binding constraint.[28] Declining capital ratios would lead to higher funding costs (as in the extension of the model described above), fire-sales and haircuts on assets, and lower funding rollover.[29] These effects could be explicitly defined based on ad-hoc behavioral reactions (e.g., RAMSI models access to funding as a function of bank solvency position, which affects funding costs); modeling them as a function of solvency shocks endogenously would be too difficult. The alternative would be to model the balance sheet structure of banks based on optimizing behavior and the interactions between asset prices and banks' portfolio adjustment.[30] Contagion due to a generalized loss of confidence could be incorporated as well. For example, RAMSI links funding liquidity risks of banks to the correlation of stock prices across banks.[31]

Incorporating contagion effects

Contagion effects could easily be embedded in the stress-testing framework by adding counterparty losses due to contagion in banks' income statements. In case that data on interbank, bilateral exposures are available, the contagion module based on the loss-cascading, iterative mechanism of Sole and Espinosa (2013) could calculate the counterparty credit losses for all banks that have exposure to a bank that fails the solvency stress test. This module could possibly take into account losses due to liquidity risks and additional fire-sale effects arising from banks trying to liquidate their assets in order to fulfil their obligations. If interbank data are missing, simulation techniques based on entropy maximization could be used (see for example, Anand and others, 2014).

Introducing non-linearities between capital and credit

The coefficient of capital buffer would be ideally time variant. When banks are adequately capitalized, and the capital ratios are far from the regulatory threshold, banks' decisions on loan supply are largely free from constraint. Banks' lending decisions are more constrained

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[28] See Kapan and Minoiu (2013), who found that banks' lending during the financial crisis was largely determined by their capital position. Pierret (2015) find that banks lose their access to short-term funding when markets expect they will be insolvent.

[29] This would also have consequences for loan supply. There is evidence that banks reduce loan supply when hit by a liquidity shock (Kashyap and Stein, 2000, Cingano and others, 2013). See Cetina (2015) for ideas on how to incorporate liquidity shocks in a solvency stress test.

[30] See Nadal De Simone and Stragiotti (2010) on how to model the interaction between assets prices and changes in banks' balance sheet structure.

[31] It the correlation between stock prices of particular banks is high, it is assumed that investors will pull funding from these banks being identified as similar when one fails the solvency test.

when the capital ratios are approaching the threshold and when they fall below it.[32] In other words, in cases where banks' capital ratios approach regulatory thresholds, banks may reduce the supply of loans more than when they are not capital constrained. This can be incorporated into credit supply by adding and additional credit buffer term (possibly quadratic) that affects credit supply if the capital buffer is close to zero or negative. This approach could also proxy for non-linearities that arise due to the interaction between solvency, liquidity and contagion. As banks capital ratios approach the regulatory threshold the second-round effects —due to this interaction—will gain more importance. The problem with this approach is that the non-linear effects will be difficult to estimate if banks have not experienced solvency problems in the past. Calibration of elasticities, based on cross-country experience, could be an imperfect solution in this case.

Modeling macroprudential policy response

The macro module can be easily extended to incorporate a countercyclical capital buffer. This would not only allow for a more detailed analysis of the effects of macro-prudential policy but also its interaction with monetary policy.[33] For example, a countercyclical capital buffer can be set to depend on credit gap or credit growth (Angelini et al. 2012, Ferreira and Nakane, 2015) such that capital requirements increase in good times (banks must hold more capital for a given amount of loans) and decrease in recessions. Following an adverse event, the reaction of macro-prudential policy (and monetary policy) would reduce the impact of the initial solvency shock on the real economy, mitigating the macro-feedback effects.

Modeling optimal banks reaction to adverse shocks

Ideally, a general equilibrium, structural framework could be built to properly account for all the feedback channels in a consistent and dynamic manner. However, structural stress-testing is in infancy and there are a variety of potentially fruitful avenues that have yet to be explored. Corbae and others (2016) build a structural framework for stress testing. They replace ad-hoc portfolio allocation and dividend policy by optimizing behavior derived from a structural model of banking. They show that structural predictions for capital shortfalls deviate from their static, ad-hoc counterparts. The ECB stress-testing framework embeds a dynamic balance sheet module to model the structure of banks' balance sheets based on their optimizing response to the economic environment (Halaj, 2013). While this type of model helps to project banks' balance sheet dynamics in an endogenous manner consistent with the scenario, they do not model macro-feedback loops.

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[32] For example, Carlson and others (2013) find that the impact of capital ratios on lending is higher when the capital ratio is low than when it is high. Albertazzi and Marchetti (2010) show that in Italy only banks with low levels of capital cut lending during the crisis. Labonne and Lame (2014) show that there is positive relationship between capital and credit for French banks, but the elasticity depends on the intensity of the supervisory capital constraint. Nier and Zicchino (2008) find that loan losses lead to a reduction in credit and that this effect is more pronounced when either initial bank capitalization is thin.

[33] Since macro-prudential policy has direct and indirect effects, it is likely to influence the transmission mechanism of monetary policy.

B. Improving Micro-Prudential Aspects of the Stress Testing Module

The stress testing module can be improved along various dimensions to improve the micro-prudential aspect of the framework. The stress-testing module is very simple due to data constraints. Rather than presenting full-blown solvency stress test, the objective of this paper is to show that a simple stress-testing framework can easily be embedded in a macroeconomic model to analyze macro-feedback effects. To make the framework operational, the stress-testing module and the macroeconomic model were designed to be very simple. Nevertheless, depending on data availability, the stress-testing module can easily be extended to resemble an FSAP stress test based on supervisory data. In an ideal case where supervisory data are available this would entail: (i) calculating net interest income using maturity gap analysis; (ii) modeling provisions for credit losses using PDs, LGDs for each asset class; (iii) calculating realized and unrealized gains/losses on available for sales securities using the duration approach; (iv) modeling credit risk RWAs for each asset class using the IRB formula and projected PDs, LGDs; and (v) imposing a dividend distribution rule.

C. Additional Caveats

Use flow of credit

As mentioned above, the framework uses the stock of credit since data on the flow of new credit is too short for modeling purposes. GDP growth tends to be more closely related to growth in the flow of new credit rather than to growth in the credit stock, which tends to lag output growth by more (Mayer, Biggs, and Pick, 2010).

Identification of credit demand vs credit supply

Uncovering the effect of capital on credit growth requires disentangling supply effects from demand effects on bank lending. Empirical assessment of a credit crunch is outside the scope of this paper. Theoretical and other empirical findings on credit crunches are used to motivate our modeling approach of macro-feedback effects. Nevertheless, assessing the impact of capital on credit requires isolating supply from demand determinants of credit growth.[34] While the credit equation in this paper controls for loan demand factors via aggregate demand and capital,[35] the framework still likely suffers from identification problems due to simultaneity, including in the stress testing module; banks' capital, income, expenses, and loan growth are likely to be endogenously determined. For example, if the real economy slows, households' and non-financial corporations' demand for loans would fall. At the same time, credit worthiness of non-financial sector would fall, giving rise to non-performing loans that hurt banks' capital, prompting a tightening in lending conditions and

[34] See Jimenez and others (2009). This would also have policy relevance.

[35] Lagging capital in the credit equation would not solve the problem as a positive correlation between credit growth and lagged capital ratio could be because banks increase capital ratios preemptively in anticipation of an increase in loan volumes (Berrospide and Edge, 2010).

lower loan supply. A solution would be to use different identification strategies found in the literature (see for example, Carlson and other, 2011 or Jimenez and others, 2012)

VI. Conclusion

This paper is the first to our knowledge to incorporate a solvency stress test into a macroeconomic model in a consistent way. The framework combines the granularity of a stress-testing exercise based on individual bank data with the general equilibrium nature of a macroeconomic model. The framework measures both the first-round direct effects of macroeconomic shocks on the solvency of individual banks and the feedback effects on the economy that are amplified by bank deleveraging. At the same time, the framework ensures consistency in relationships between macroeconomic and financial variables and individual banks' balance sheets.

While the framework can strengthen stress testing and macro financial analysis along various dimensions, other factors are needed for more comprehensive systemic risk analysis. Understanding the feedback channels between banks, such as interactions between solvency, liquidity and contagion risks, is crucial to quantify the likely impact of adverse conditions on the banking sector and the real economy. This paper shows how to incorporate these channels. To this end, the paper argues that the link between solvency and liquidity can create non-linear effects from negative shocks and can enlarge macro-feedback effects. Avenues to strengthen the microprudential aspect of the framework are also discussed. While the stress-testing module developed here is very simple due to data constraints and our objective to make the framework operational with publicly-available data, the stress-testing module can easily be extended to resemble an FSAP stress test based on supervisory data. All these extensions are left for future work.

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APPENDIX I: MODEL DETAILS[36]

A. Behavioral Equations

- ***IS Curve***

$$y_t = \rho_1 y_{t-1} + \rho_2 y_{t+1} - \rho_3 r_t + \rho_4 z_t + \rho_5 y_t^* + \rho_6 \left(\sum_{i=1}^{I} w_i^{pb} \epsilon_{it}^{c^{pb}} + \sum_{j=1}^{J} w_j^{pr} \epsilon_{jt}^{c^{pr}} \right) - \rho_7 \epsilon_t^f + \varepsilon_t^y$$

- ***Phillips Curve (Non-Regulated-Price inflation)***

$$\pi_t^N = \gamma_1 \pi_{t-1}^4 + (1-\gamma_1)\pi_{t+1}^N + \gamma_2 y_t + \gamma_3 \Delta z_t + \varepsilon_t^{\pi^N}$$

- ***Regulated-Price Inflation***

$$\pi_t^R = \omega \pi_t^* + (1-\omega)\pi_t^R + \varepsilon_t^R$$

- ***Policy Rule***

$$R_t = \xi_1 R_{t-1} + (1-\xi_1)(\overline{r_t} + \pi_{t+3}^4 + \xi_2(\pi_{t+3}^4 - \pi_{t+3}^*) + \xi_3 Y_t) + \varepsilon_t^R$$

- ***Real Interest Rate (Fisher Equation)***

$$rr_t = R_t - \pi_{t+1}$$

- ***Real Credit Gaps***

$$c_{it}^{pb} = \nu_1 c_{it-1}^{pb} + \nu_2 y_{t-1} + \epsilon_{it}^{c^{pb}}$$

$$c_{it}^{pr} = \tau_1 c_{it-1}^{pr} + \tau_2 y_{t-1} + \epsilon_{it}^{c^{pr}}$$

where:

$$\epsilon_{it}^{c^{pb}} = \nu_3 K_{it}^{pb} + E_{it}^{c^{pb}}$$

$$\epsilon_{it}^{c^{pb}} = \tau_3 K_{it}^{pr} + E_{it}^{c^{pr}}$$

- ***Financial Conditions***

[36] All shocks (denoted ε_t^x for variable x_t) are assumed to be independently and identically distributed white noise processes.

$$f_t = \chi_1 f_{t-1} - \chi_2(y_{t+2} - y_{t-1}) + \epsilon_t^f$$

where: $\epsilon_t^f = \chi_3 \epsilon_{t-1}^f + \varepsilon_t^f$

- ***Okun's Law***

$$u_t = \kappa_1 u_{t-1} + \kappa_2 y_t + \varepsilon_t^u$$

- ***Capacity Utilization Gap***

$$capu_t = \phi_1 capu_{t-1} + \phi_2 y_t + \varepsilon_t^{capu}$$

- ***Foreign Output Gap***

$$y_t^* = \lambda y_{t-1}^* + \varepsilon_t^{Y^*}$$

- ***Real Exchange Rate Gap***

$$z_t = \mu z_{t-1} + \varepsilon_t^z$$

B. Stochastic Processes and Definitions

- ***Output gap***

$$y_t = Y_t - \overline{Y_t}$$

where Y_t is the (log) level of real GDP and $\overline{Y_t}$ is potential output.

- ***Potential output***

$$\overline{Y_t} = \overline{Y}_{t-1} + \frac{1}{4} G_t + \varepsilon_t^{\overline{Y}}$$

- ***Potential output growth***

$$G_t = \delta\, g + (1-\delta) G_{t-1} + \varepsilon_t^G$$

where g is steady state annual real GDP growth.

- ***Real credit gap***

$$c_t^x = C_t^x - \overline{C_t}^x$$

where C_t^x is the (log) level of real credit and $\overline{C_t}^x$ is trend real credit and $x = [pb, pr]$. .

- ***Real credit trend***

$$\bar{C}_t^{\,x} = \bar{C}_{t-1}^{x} + \frac{1}{4} G_t^{C^x} + \varepsilon_t^{\bar{C}^x}$$

- ***Real credit trend growth***

$$G_t^{C^x} = \psi\, g^C + (1-\psi) G_{t-1}^{C^x} + \varepsilon_t^{G^{\,C^x}}$$

where g^C is steady state annual real credit growth of both public and private credit.

- ***Inflation target***

$$\pi_t^* = \pi_{t-1}^* + \varepsilon_t^{\pi^*}$$

- ***Headline Inflation***

$$\pi_t = \alpha \pi_t^N + (1-\alpha)\pi_t^R$$

where π_t^N is non-regulated-price inflation and π_t^R is regulated-price inflation.

- ***Annual headline inflation***

$$\pi_t^4 = \frac{1}{4}(\pi_t + \pi_{t-1} + \pi_{t-2} + \pi_{t-3})$$

- ***Real interest rate gap***

$$r_t = rr_t - \overline{rr}_t$$

where rr_t is the real interest rate and $\overline{rr}_t$ is the trend real interest rate.

- ***Trend real interest rate***

$$\overline{rr}_t = \overline{rr}_{t-1} + \varepsilon_t^{\overline{rr}}$$

- ***Unemployment gap***

$$u_t = \bar{U}_t - U_t$$

where U_t is the unemployment rate and $\bar{U}_t$ is the NAIRU.

- ***NAIRU***

$$\bar{U}_t = \bar{U}_{t-1} + \varepsilon_t^{\bar{U}}$$

- ***Capacity utilization gap***

$$capu_t = CAPU_t - \overline{CAPU}_t$$

where $CAPU_t$ is (log) capacity utilization and $\overline{CAPU}_t$ is its trend.

- ***Trend capacity utilization***

$$\overline{CAPU}_t = \overline{CAPU}_{t-1} + \varepsilon^{\overline{CAPU}}$$

- ***Real exchange rate gap***

$$z_t = Z_t - \bar{Z}_t$$

where Z_t is the (log) real effective exchange rate and $\bar{Z}_t$ is the trend real exchange rate.

- ***Trend real exchange rate***

$$\bar{Z}_t = \bar{Z}_{t-1} + \varepsilon^{\bar{Z}}$$

- ***Foreign output gap***

$$y_t^* = Y_t^* - \overline{Y}_t^*$$

where Y_t^* is the (log) level of U.S real GDP and $\overline{Y}_t^*$ is foreign potential output.

- ***Foreign potential output***

$$\overline{Y}_t^* - \overline{Y}_{t-1}^* = \overline{Y}_{t-1}^* - \overline{Y}_{t-2}^* + \varepsilon_t^{\overline{Y}^*}$$

C. Estimated Parameters

The model outlined in Appendix A is estimated using the Kalman Filter and Bayesian estimation. The tables below display the calibrated parameters and the estimated parameters, along with the prior distributions used in posterior maximization. For more details on Bayesian estimation, see Herbst and Schorfheide (2015).[37]

Table 3. Calibrated Parameters

g	2.00
g^c	5.00
δ	0.05
ψ	0.05
σ	0.05
α	0.75

Note: The shock standard deviations for the trends of all variables are calibrated based on trends extracted using a standard HP filter (i.e., with smoothing parameter of 1600).

[37] Herbst, Edward, and Frank Schorfheide (2015), "Bayesian Estimation of DSGE Models", Unpublished Manuscript. http://sites.sas.upenn.edu/schorf/files/herbst_and_schorfheide_v5.pdf

Table 4. Estimated Parameters

	Estimated Parameters	Prior Distribution F(mean,std)	Posterior	Std Dev.
Transitory	γ_1	$\beta(0.2,0.05)$	0.38	0.04
	γ_2	$\gamma(0.35,0.05)$	0.24	0.03
	γ_3	$\gamma(0.1,0.025)$	0.08	0.03
	ρ_1	$\beta(0.8,0.05)$	0.66	0.05
	ρ_2	$\beta(0.1,0.025)$	0.07	0.02
	ρ_3	$\gamma(0.35,0.05)$	0.31	0.04
	ρ_4	$\gamma(0.05,0.025)$	0.02	0.01
	ρ_5	$\gamma(0.5,0.2)$	0.28	0.07
	ρ_6	$\gamma(0.5,0.2)$	0.07	0.03
	ρ_7	$\gamma(1,0.2)$	1.07	0.06
	ξ_1	$\beta(0.8,0.025)$	0.76	0.03
	ξ_2	$\gamma(1.5,0.05)$	1.51	0.10
	ξ_3	$\gamma(0.2,0.025)$	0.20	0.05
	ν_1	$\beta(0.5,0.1)$	0.58	0.10
	ν_2	$\gamma(0.8,0.2)$	0.78	0.07
	ν_3	$\gamma(1.5,0.1)$	1.14	0.04
	τ_1	$\beta(0.5,0.1)$	0.52	0.14
	τ_2	$\gamma(0.8,0.2)$	0.65	0.29
	τ_3	$\gamma(1.5,0.1)$	1.01	0.09
	ϕ_1	$\beta(0.5,0.1)$	0.26	0.10
	ϕ_2	$\gamma(0.5,0.2)$	0.43	0.07
	κ_1	$\beta(0.5,0.1)$	0.54	0.09
	κ_2	$\gamma(0.5,0.2)$	0.25	0.03
	χ_1	$\beta(0.5,0.1)$	0.41	0.05
	ξ_2	$\gamma(0.8,0.2)$	0.48	0.07
	χ_3	$\gamma(0.8,0.05)$	0.74	0.06
	ω	$\beta(0.5,0.1)$	0.42	0.05
	μ	$\beta(0.5,0.1)$	0.60	0.08
	λ	$\beta(0.5,0.1)$	0.75	0.04
Shocks				
	σ_{ε^Y}	$\gamma^{-1}(1,\infty)$	0.36	0.04
	$\sigma_{\varepsilon^{\pi^R}}$	$\gamma^{-1}(1,\infty)$	1.60	0.14
	$\sigma_{\varepsilon^{\pi^N}}$	$\gamma^{-1}(1,\infty)$	0.90	0.04
	σ_{ε^R}	$\gamma^{-1}(1,\infty)$	0.44	0.04
	σ_{ε^z}	$\gamma^{-1}(1,\infty)$	1.40	0.25
	σ_{ε^u}	$\gamma^{-1}(1,\infty)$	0.14	0.02
	$\sigma_{\varepsilon^{capu}}$	$\gamma^{-1}(1,\infty)$	0.12	0.02
	$\sigma_{\varepsilon^{Y^*}}$	$\gamma^{-1}(1,\infty)$	0.19	0.02
	σ_{ε^f}	$\gamma^{-1}(1,\infty)$	0.17	0.02

Table 5. Estimated Banking Parameters

Estimated Parameters	Prior Distribution F(mean,std)	Posterior	Std Dev.
a_{IR}	$N(0.9{,}0.1)$	0.61	0.01
b_{IR}	$N(0.4{,}0.05)$	0.28	0.04
c_{IR}	$N(0.1{,}0.05)$	0.10	0.04
e_{IR}	$N(-0.1{,}0.05)$	0.00	0.00
a_{NIR}	$N(0.9{,}0.1)$	0.25	0.00
b_{NIR}	$N(0.4{,}0.05)$	0.00	0.00
c_{NIR}	$N(0.1{,}0.05)$	0.00	0.00
d_{NIR}	$N(-0.1{,}0.05)$	0.00	0.00
e_{NIR}	$N(-0.1{,}0.05)$	0.00	0.00
a_{AOCI}	$N(0.9{,}0.1)$	0.41	0.00
b_{AOCI}	$N(0.4{,}0.05)$	0.03	0.00
c_{AOCI}	$N(0.1{,}0.05)$	-0.02	0.00
d_{AOCI}	$N(-0.1{,}0.05)$	-0.01	0.00
a_{OI}	$N(0.9{,}0.1)$	0.92	0.00
b_{OI}	$N(0.4{,}0.05)$	0.08	0.00
c_{OI}	$N(0.1{,}0.05)$	0.03	0.00
d_{OI}	$N(-0.1{,}0.05)$	-0.04	0.00
a_{IE}	$N(0.9{,}0.1)$	0.77	0.03
d_{IE}	$N(0.3{,}0.05)$	0.20	0.04
e_{IE}	$N(0.1{,}0.05)$	0.08	0.00
a_{NIE}	$N(0.9{,}0.1)$	0.35	0.00
b_{NIE}	$N(0.2{,}0.05)$	0.00	0.00
e_{NIE}	$N(0.1{,}0.05)$	0.00	0.00
a_{TAX}	$N(0.9{,}0.1)$	0.94	0.03
b_{TAX}	$N(0.2{,}0.05)$	0.02	0.00
e_{TAX}	$N(0.1{,}0.05)$	0.00	0.00
a_{DIV}	$N(0.9{,}0.1)$	0.91	0.04
b_{DIV}	$N(0.2{,}0.05)$	0.00	0.00
e_{DIV}	$N(0.1{,}0.05)$	0.00	0.00
a_{PROV}	$N(0.9{,}0.1)$	0.76	0.00
b_{PROV}	$N(-0.2{,}0.05)$	-0.04	0.00
c_{PROV}	$N(0.1{,}0.05)$	0.00	0.00
d_{PROV}	$N(0.1{,}0.05)$	0.00	0.00
a_{DEDUCT}	$N(0.9{,}0.1)$	0.86	0.03

Note: All prior distributions of the error standard deviations for the banking model are drawn from $\gamma^{-1}(1,\infty)$. These posterior estimates are available on request.

APPENDIX II: IMPULSE RESPONSES OF THE MODEL THAT INCORPORATES MACRO FEEDBACK EFFECTS AND THE LINK BETWEEN LIQUIDITY AND SOLVENCY

Figure 13. Demand Shock

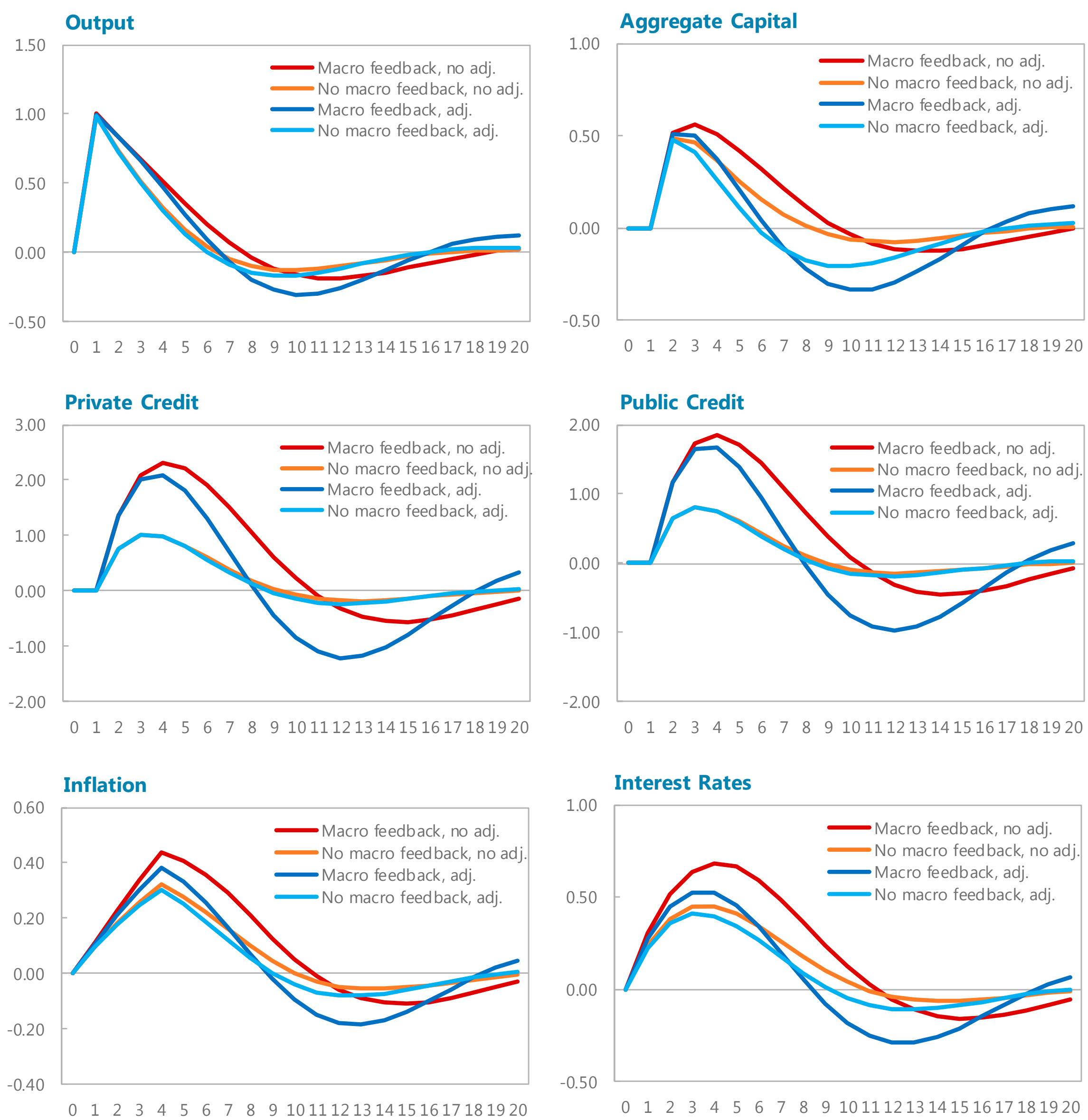

Figure 14. Capital Requirement Shock

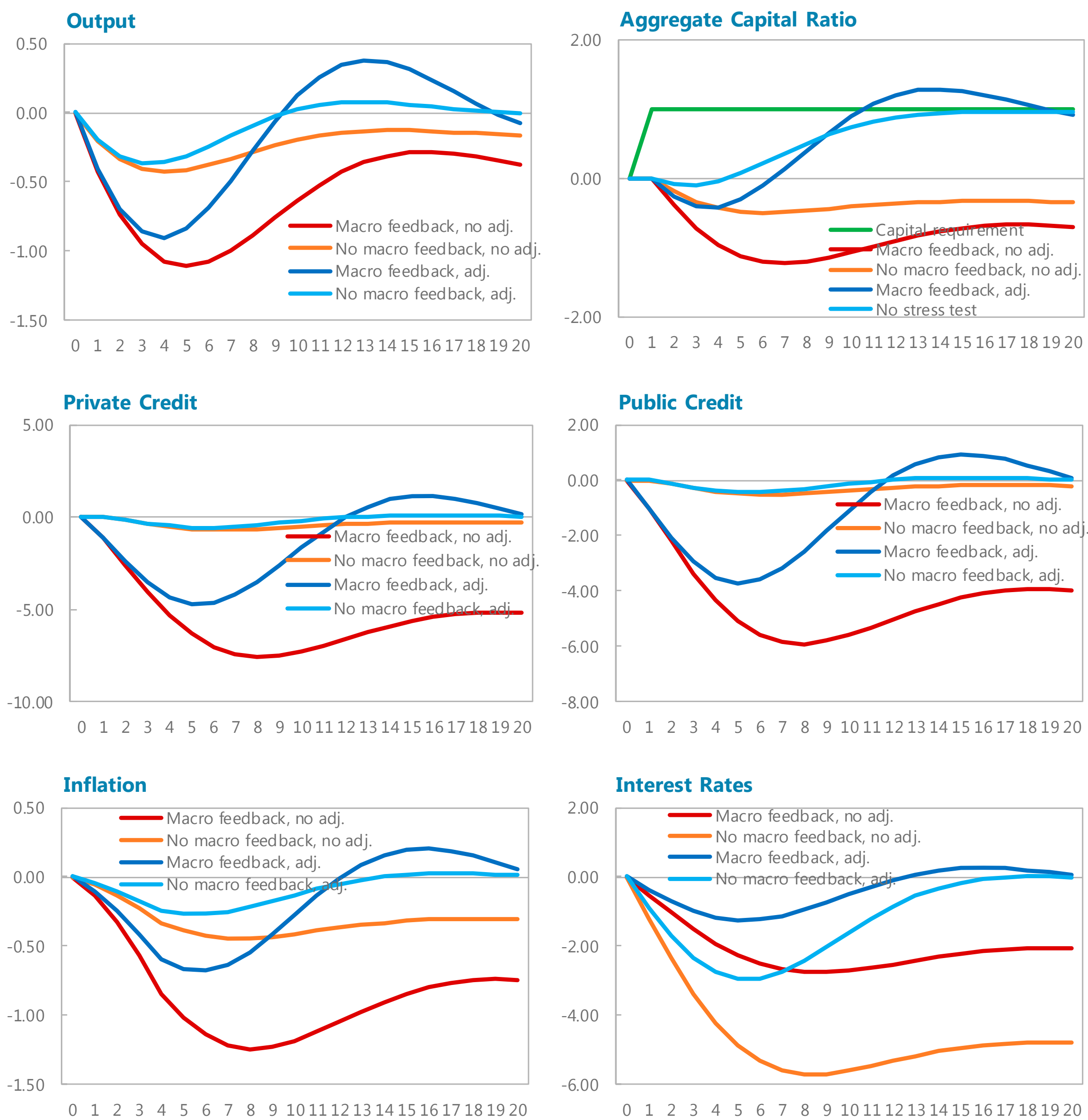

Figure 15. Provisions Shock

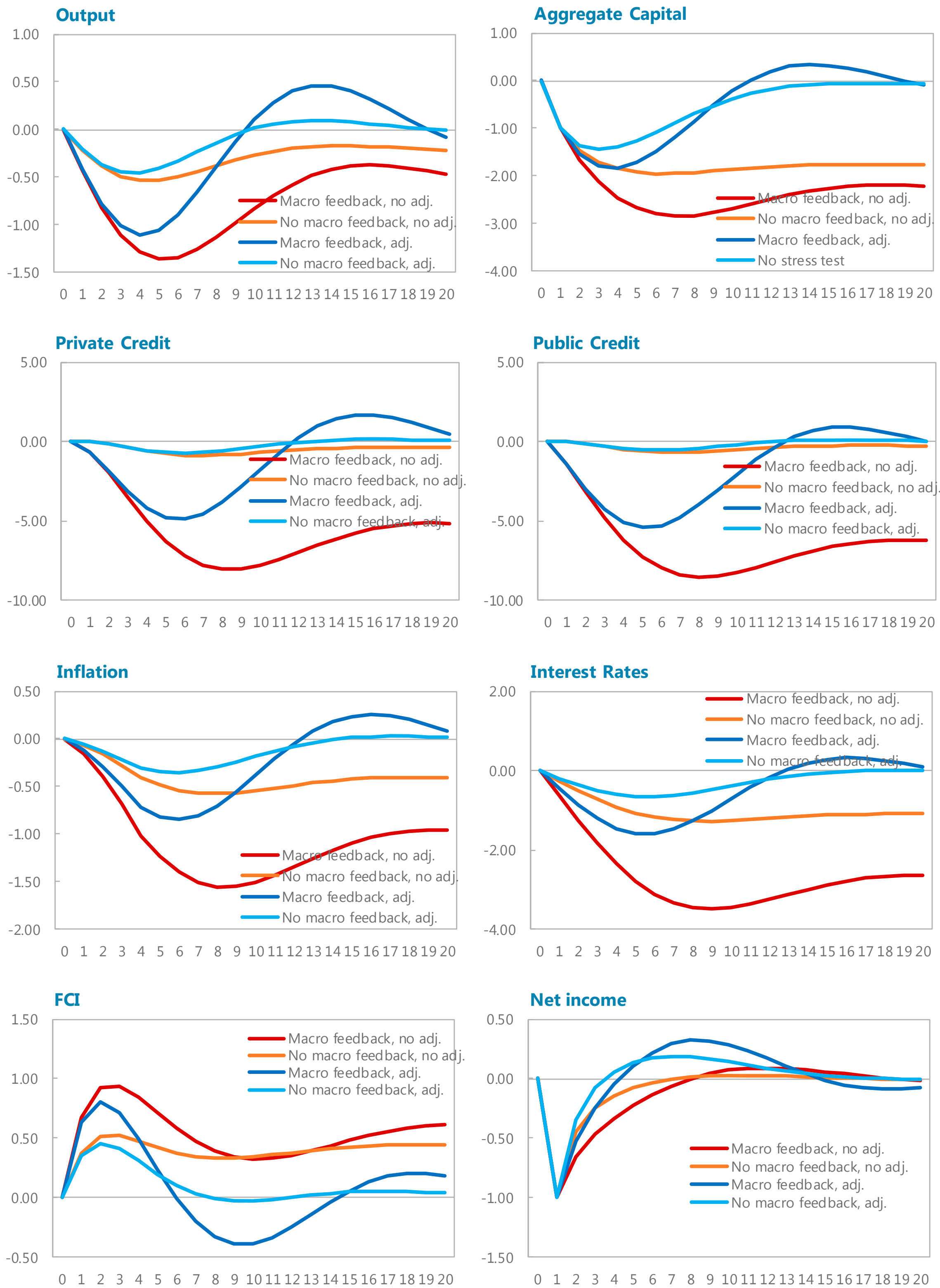

Figure 16. Selected Impulse Responses

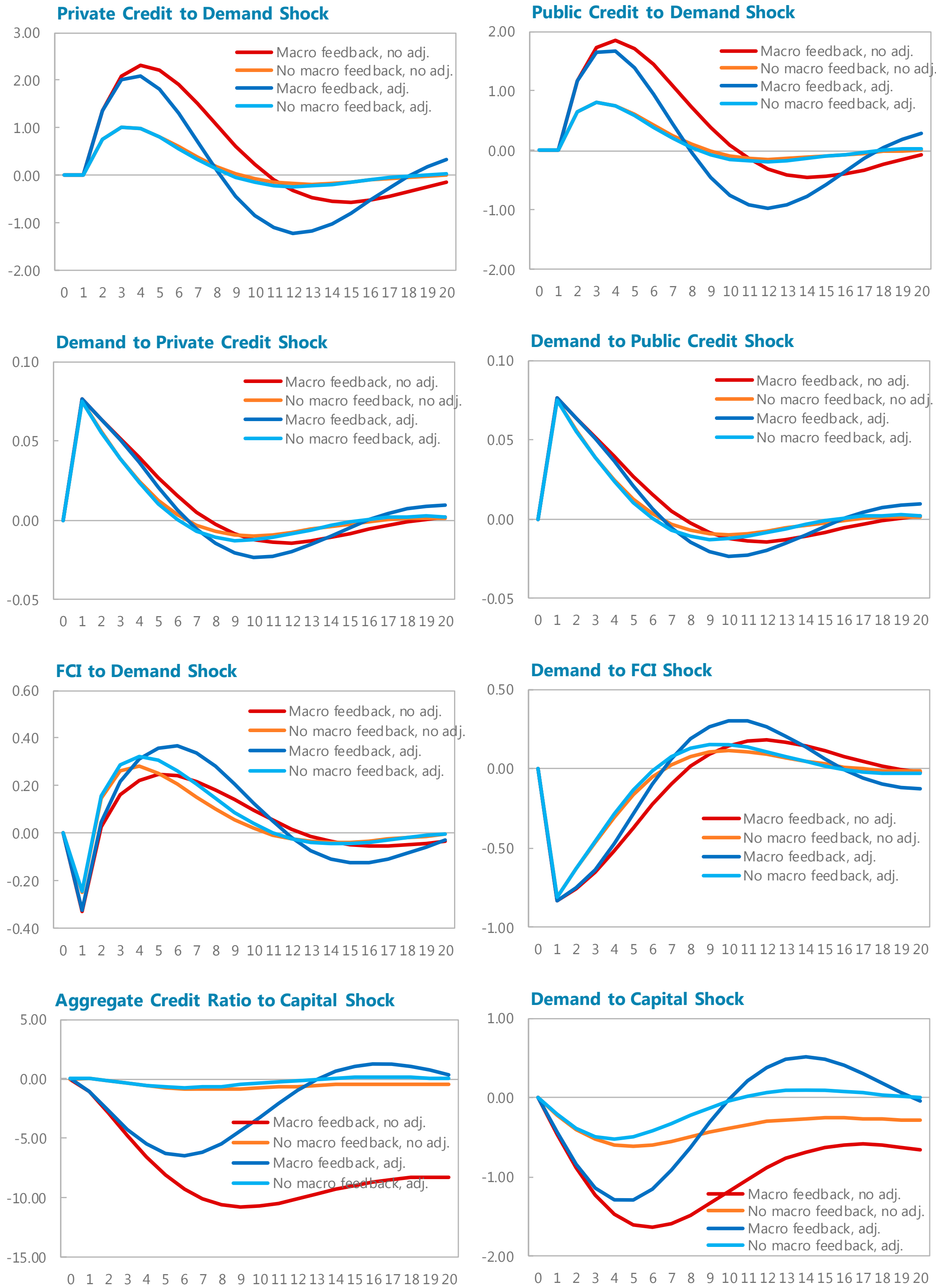

Figure 17. Projections