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Huixin Bi, Wenyi Shen, and Shu-Chun S. Yang

FEDERAL RESERVE BANK *of* KANSAS CITY

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Abstract

This paper studies fiscal implications of interest rate normalization from the zero lower bound (ZLB) in the United States. At the ZLB, the decline in the tax revenue and the real bond price drives up government debt. During normalization, the interest payment continues to stay higher than the path without the ZLB. Despite the recovery of output and tax revenue, government debt can grow further. Against the yardstick of ability to pay, interest rate normalization is unlikely to pose an immediate threat to debt sustainability at the current net federal debt level of 90%-100% of GDP. If the net federal debt reaches 150% of GDP, however, sovereign default risk can rise more quickly. Also, a more active monetary policy during normalization can better anchor inflation expectations and generate a faster recovery in investment and output, helping slow debt accumulation relative to the path with a less active one.

Keywords: interest rate normalization, monetary and fiscal policy interaction, debt sustainability, non-linear DSGE model, New Keynesian model

JEL Codes: E43, E52, E62, E63, H30

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1   Introduction

After the longest expansion in history since the Great Recession, the U.S. economy is once again trapped at the zero lower bound (ZLB) by the health and economic crisis from the COVID-19 pandemic. With a sharp revenue decline and a series of legislation in response to the pandemic, federal deficits are projected to rise to $3.7 trillion and $2.1 trillion in fiscal years 2020 and 2021 (Congressional Budget Office (2020b)), roughly 17.2% and 9.5% of 2020Q1 annualized GDP.[1] The 2020 deficit will register the highest level for the federal government since 1945, and the federal debt is projected to grow sharply to 108% by the end of fiscal year 2021, up from 79% in 2019 (Congressional Budget Office (2020b); Office of Management and Budget (2020)).[2] Although the interest rates of U.S. Treasury securities are extremely low at the ZLB, it is concerning whether the debt servicing cost will surge and debt sustainability can be at risk when interest rates normalize as the economy recovers.

This paper focuses on the implications of interest rate normalization against a backdrop of elevated government debt.[3] A higher policy rate, propagating through financial markets, raises interest rates on government bonds and therefore government interest payments. Figure 1 highlights that federal government's interest payments are highly correlated with the federal funds rate. It is notable that since the Great Recession, the federal funds rate plays a more important role in determining government interest payments than government debt levels. Despite a rapidly rising net debt from 35% of GDP in 2008 to 79% in 2019, the federal government's net interest payments as a share of GDP were largely unchanged: 1.7% of GDP in 2008 versus 1.8% in 2019. Moving forward, Congressional Budget Office (2020a) estimates that the average annual interest payments as a share of GDP in 2041-2050 would

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[1]The legislation includes the Coronavirus Preparedness and Response Supplemental Appropriation Act ($8 billion), the Families First Coronavirus Response Act ($192 billion), the Coronavirus Aid, Relief and Economic Security Act ($1,721 billion), and the Paycheck Protection Program and Health Care Enhancement Act ($483 billion).

[2]Throughout the paper, we refer to the federal debt held by the public as the net federal debt.

[3]Interest normalization is part of monetary policy normalization. Another part involves reducing the Federal Reserve's holding of longer term securities. An emerging literature focuses on fiscal implications of changing the size or portfolio composition of a central bank's balance sheet. In particular, several papers study remittance transfers from a central bank to the Treasury from the income risk perspective, e.g., Carpenter et al. (2015), Christensen et al. (2015), Del Negro and Sims (2015) (reverse transfers—or fiscal support—from fiscal authorities to a central bank), and Hall and Reis (2015). See Cavallo et al. (2019) for a literature survey.

be more than three times as much as the 2019 level.[4]

U.S. Treasury debt has been perceived as risk free, reflected in persistent low yields. Bohn (2008) concludes that historically U.S. debt satisfies a sufficient sustainability condition, as the primary surplus responds positively to government debt fluctuations. Even combining expected rising interest rates with existing high debt and low growth, Blanchard and Zettelmeyer (2017) argue that fiscal crises are unlikely, unless risky macroeconomic policies are pursued. Elmendorf and Sheiner (2017) recognize that the federal budget is on an unsustainable path. In a low interest rate environment, however, they argue that policy retrenchment aiming at reducing federal budget deficits is not necessary in the short run. Blanchard (2019) also argues that with persistently low interest rates and negative interest-growth differentials, the fiscal and welfare costs of debt issuance are low, and government debt need not be urgently reduced. While the sharp rise of federal government debt in 2020-2021 is likely to be one-off, alternative views highlight that increasing government liabilities associated with Social Security, Medicare, and Medicaid are a systematic factor threatening debt sustainability (Hagist and Kotlikoff (2008), Davig et al. (2010), Kotlikoff (2015), Cao et al. (2018), and Government Accountability Office (2020)).

To study the fiscal implications of interest rate normalization amid mixed views on federal debt sustainability, we take a theoretical approach using a New Keynesian (NK) model with sovereign default risk. Debt sustainability is assessed based on a government's ability to pay. We follow Bi's (2012) approach to simulating fiscal limits (a collection of possible values for the maximum sustainable debt) for the U.S. federal government.[5] Fiscal limits, which account for the underlying economic fundamentals and future fiscal policy paths, are represented by a distribution that incorporates economic and policy uncertainty. Sovereign default risk premia arise endogenously as government debt approaches its fiscal limits, because agents take into account rising default risk. In this framework, debt sustainability is

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[4]This projection, published in January 2020, does not account for the additional debt from the pandemic related legislation and is based the slowest growth path of the federal government debt among the scenarios simulated.

[5]The concept of debt sustainability we use here differs from the classic strategic sovereign default approach, which focuses on a government's willingness to pay (e.g., Eaton and Gersovitz (1981), Aguiar and Gopinath (2006), and Arellano (2008)). Instead it is similar to the empirical approach based on primary balance (Ghosh et al. (2013), Tanner (2013), and Collard et al. (2015)). In addition, we do not consider the possibility that debt can be stabilized through monetization.

based on the probability that the current debt level exceeds a randomly drawn fiscal limit from a simulated distribution: a higher debt level implies a higher default probability and hence a higher risk premium of government debt.

The model specification captures the U.S. economy along several dimensions. It features a regime-switching process for government transfers to capture the most important factor underpinning the long-run federal debt sustainability: an upward trend in the transfers-to-GDP ratio (the solid line in Figure 2) and uncertainty associated with transfers policy reform. Our baseline fiscal limit simulation indicates that the sovereign default risk is virtually zero for the federal government if the net federal debt is below 100% of GDP. The mean and the distribution of the fiscal limits, however, are subject to great uncertainties from a range of factors, including the maximum implementable tax rates and the future transfers policy.

We focus on the interest normalization process when the economy exits from the ZLB. Following Smets and Wouters (2007), we introduce a sequence of financial shocks that increase the return of a risk-free asset to generate a liquidity trap.[6] The financial shocks induce households to substitute away from investment, pushing the economy into the ZLB and generating a severe recession. The sharp decline in output lowers tax revenues and drives up the debt-to-output ratio. In the baseline analysis, we consider a scenario with government debt at 90-100% of GDP, roughly the current net federal debt level. As the large financial shocks abate, the economy exits from the ZLB with inflation rebounding and the real interest rate dropping. As a result, government's payments on debt interest decline sharply relative to the ZLB period. Despite the recovery in tax revenues and the real bond price, the debt level remains elevated for a sustained period, as well as the default probability, albeit at a low level. To account for economic uncertainty during normalization, the economy continues to be hit by periodic financial shocks drawn from its distribution.

To check robustness of our results, we consider a range of alternative scenarios. First, we show a more pessimistic case with a higher level of government debt around 150–160% of GDP against an alternative fiscal limit distribution with a lower mean. This alternative

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[6]The financial shock has been shown to be important in explaining the Great Recession (Christiano et al. (2015) and Gust et al. (2017)). In the sensitivity analysis, we use the investment efficiency shock as the macroeconomic shock.

distribution would arise if federal transfers as a share of GDP is expected to rise relentlessly for several decades as projected by Congressional Budget Office (2020a) under current law. In this situation, interest rate normalization raises the default probability by about 3-4 percentage points and increases the risk premium. A higher risk premium translates into a higher real interest rate, leading to a slower recovery. Second, we find that the central bank's stronger commitment to raise the inflation expectations during normalization through a more active monetary policy can lower the real interest rate and facilitate the economic rebound. With a faster recovery in tax revenues, government debt increases less than the baseline analysis with a less active monetary policy. Third, the longer the average debt maturity, the higher the fiscal costs associated with the ZLB, because the real return of debt also depends on its resale value, which is higher with longer-term debt.

Our paper is closely related to Battistini et al. (2019), which also studies monetary and fiscal policy interactions in an NK model with sovereign default risk. Their paper relies on the peak of the Laffer curve when simulating the fiscal limits following Bi (2012). Instead, we use historical income tax rates to gauge a reasonable range of maximum implementable tax rates for the U.S. federal government. Another important distinction is that their paper investigates how monetary policy, joint with the ZLB, shapes the distribution of fiscal limits, while ours focuses on the macroeconomic dynamics in an interest rate normalization process conditional on a fiscal limit distribution. Finally, their model abstracts from capital, and we show that capital can significantly amplify macroeconomic responses both at the ZLB and during normalization.

2 The Model Setup

We lay out an NK model with a regime-switching process for government transfers. Our model includes capital and, therefore, allows interest rates to affect saving decisions between investment and government bonds. Capital is often absent in existing papers that model sovereign default risk with fiscal limits (e.g., Corsetti et al. (2013), Bi et al. (2013), and Battistini et al. (2019)). Our baseline model features a typical one-period bond as in most

DSGE models. Later in sensitivity analysis, we modify the model to allow for a longer debt maturity.

A representative household chooses consumption (c_t), labor (n_t), investment (i_t), and one-period nominal bonds (B_t, B_t^f) to maximize life-time discounted utility:

$$\max E_t \sum_{t=0}^{\infty} \beta^t \left(\frac{c_t^{1-\sigma}}{1-\sigma} - \chi \frac{n_t^{1+\varphi}}{1+\varphi} \right). \tag{1}$$

subject to the budget constraint:

$$P_t c_t + P_t i_t + \frac{B_t}{R_t} + \frac{B_t^f}{\eta_t R_t^f} = (1-\Delta_t) B_{t-1} + P_t \left[\left(1 - \tau_t^l\right) w_t n_t + \left(1 - \tau_t^k\right) r_t^k k_{t-1} \right] + P_t z_t + \Upsilon_t + P_t \omega. \tag{2}$$

P_t is the price level of the final goods, w_t is the real wage rate, r_t^k is the real return to capital, and Υ_t is the real profits of the monopolistic competitive intermediate goods firms. z_t is real government transfers, τ_t^l and τ_t^k are the tax rates on labor and capital income, and ω is a real lump-sum tax to capture all other taxes and fees paid to the government.

Following Bi et al. (2018), we distinguish the nominal return of a risky government bond (R_t) from the return of a risk-free bond (R_t^f). At time $t-1$, the government sells B_{t-1} units of a risky nominal bond at a price of $\frac{1}{R_{t-1}}$. At time t, if the government does not default ($\Delta_t = 0$), it pays B_{t-1} dollars; if the government defaults ($\Delta_t = \Delta > 0$), it only pays $(1 - \Delta) B_{t-1}$ of liabilities. Households can also trade a risk-free bond, which, for simplicity, is assumed to be in zero net supply.

To introduce a macroeconomic shock that can drive the economy to the ZLB, the baseline model follows Smets and Wouters (2007) and includes a financial disturbance, η_t, that creates a wedge between the return to risk-free bonds and the policy rate set by the central bank

(R_t^f).[7] The financial disturbance follows an exogenous process,

$$\ln \frac{\eta_t}{\eta} = \rho_\eta \ln \frac{\eta_{t-1}}{\eta} + \varepsilon_t^\eta, \tag{3}$$

where a variable without a time subscript indicates its steady-state value, and $\varepsilon_t^\eta \sim N(0, \sigma_\eta^2)$ is the financial shock.

When making decisions on purchasing risky government debt, households account for default risk, and the optimality condition is

$$\frac{1}{R_t} = \beta E_t \frac{\lambda_{t+1}}{\lambda_t} \frac{(1 - \Delta_{t+1})}{\pi_{t+1}}, \tag{4}$$

compared to the optimality condition for risk-free debt:

$$\frac{1}{\eta_t R_t^f} = \beta E_t \frac{\lambda_{t+1}}{\lambda_t} \frac{1}{\pi_{t+1}}. \tag{5}$$

Equation (4) implies that, when default probabilities rise, households demand a higher return to hold government debt.

The law of motion for capital is

$$k_t = (1 - \delta)k_{t-1} + i_t - \frac{\kappa}{2} \left(\frac{i_t}{k_{t-1}} - \delta \right)^2 k_{t-1}, \tag{6}$$

where δ is the capital depreciation rate and κ is the capital adjustment cost parameter.

The representative competitive final goods producer produces y_t, using $y_t(i)$ units of each intermediate goods i with the technology:

$$y_t = \left[\int_0^1 y_t(i)^{\frac{\theta-1}{\theta}} di \right]^{\frac{\theta}{\theta-1}}. \tag{7}$$

The final goods producer's profit maximization yields the demand function for each inter-

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[7]In reality, business cycle fluctuations are caused by various structural and policy shocks. To minimize the number of state variables in solving the nonlinear model, we rely on a single macroeconomic shock to generate a severe recession that constrains the economy at the ZLB. We do not perform the analysis using other common macroeconomics shocks in the DSGE literature, as we want to capture two data patterns observed during the recent two severe recessions: 1) a positive co-movement in output, consumption, and investment, and 2) falling, rather than rising, inflation. A preference or discount factor shock produces negative consumption but a positive investment response, and a negative technology shock reduces output but leads to prices to increase, moving the economy away from the ZLB.

mediate good i:

$$y_t(i) = \left[\frac{P_t(i)}{P_t}\right]^{-\theta} y_t, \tag{8}$$

where $P_t(i)$ is the price for $y_t(i)$.

Intermediate goods are produced by monopolistically competitive firms. Following Rotemberg (1982), each intermediate goods-producing firm i ($\in [0,1]$) faces a quadratic cost to change its nominal price. At each period, the intermediate goods firm i chooses $n_t(i)$, $k_t(i)$, and $P_t(i)$ to maximize its discounted total profit in units of current marginal utility for consumption, λ_t:

$$\max_{n_t(i),k_t(i),P_t(i)} E \sum_{t=0}^{\infty} \beta^t \lambda_t \left[\left(\frac{P_t(i)}{P_t}\right)^{1-\theta} y_t - w_t n_t(i) - r_t^k k_{t-1}(i) - \frac{\psi}{2}\left(\frac{P_t(i)}{\pi P_{t-1}(i)} - 1\right)^2 y_t \right], \tag{9}$$

subject to the demand function, (8), and the production function

$$y_t(i) = a_t \left[k_{t-1}(i)\right]^{\alpha} n_t(i)^{1-\alpha}. \tag{10}$$

The government collects taxes and sells bonds each period to pay for its purchase (g_t), transfers, and liabilities. The government's flow budget constraint is

$$\frac{B_t}{R_t} + P_t \left[\tau_t^l w_t n_t + \tau_t^k r_t^k k_{t-1} + \omega\right] = (1 - \Delta_t) B_{t-1} + P_t g_t + P_t z_t. \tag{11}$$

Following Bi (2012), a realized effective fiscal limit, $b_t^{\max}$, is drawn from a fiscal limit distribution each period. If the government's real debt liabilities at the end of $t-1$ ($b_{t-1} = \frac{B_{t-1}}{P_{t-1}}$) are less than $b_t^{\max}$, it fully repays its debt; otherwise, it defaults a fixed fraction of its liabilities. Specifically,

$$\Delta_t = \begin{cases} 0 & \text{if } b_{t-1} < b_t^{\max}; \\ \Delta & \text{if } b_{t-1} \geq b_t^{\max}. \end{cases} \tag{12}$$

The distribution of fiscal limits is derived under the assumption that the government faces a limit in raising tax revenues for economic or political reasons (see Section 4 for details). In this framework, the uncertainty associated with the debt threshold reflects factors influ-

encing sovereign default decisions in reality, such as institutional and policy making quality, which is omitted in the model.[8] Although sovereign default in the model is stochastic, default probabilities are linked to economic fundamentals, which increase nonlinearly when government debt burden escalates as observed in reality.

The model features a regime-switching process for government transfers between a stable and an unstable regime, as in Davig et al. (2010):

$$
z_t(i_t^z) = \begin{cases} (1 - \rho_z)z + \rho_z z_{t-1}, & \text{if } i_t^z = 1, \qquad \rho_z < 1, \\ \mu z_{t-1}, & \text{if } i_t^z = 2, \qquad \mu > 1, \end{cases}
\tag{13}
$$

where the regime index i_t^z evolves according to the transition matrix

$$
\begin{pmatrix} p_1^z & 1 - p_1^z \\ 1 - p_2^z & p_2^z \end{pmatrix}.
\tag{14}
$$

p_1^z (p_2^z) is the probability of continuing to stay in the stable (unstable) regime each period, calibrated to be highly persistent. The solid line in Figure 2 plots the mandatory spending of the federal government, which maps to government transfers in our model. Congressional Budget Office's projection (2019) shows that federal mandatory spending under the current law will continue to rise as a share of GDP. This modeling approach intends to capture the uncertainty in the timing of transfers policy reform.[9]

We keep the government consumption, g_t, fixed at its steady state for simplicity. As shown in Figure 2 (the dashed line), federal government purchases, which map to g_t in our model, have a downward trend since 1960 and is projected to stabilize at about 5.5% of GDP. Thus, g_t is less likely to be used as a main fiscal adjustment instrument for the federal government. We assume $g_t = g \ \forall \ t$. The income tax rates, on the other hand, have room to

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[8]Kraay and Nehru (2006) find that policy and institution quality is important for sovereign debt stress, aside from debt burden and economic growth shocks.

[9]Social Security reform is an on-going policy agenda in the U.S. Without any reform, only 76% of the scheduled benefits can be paid with the continuing tax contribution after 2034 (Federal OASDI Trust Funds (2020)).

increase and are assumed to be the fiscal adjustment instruments to stabilize debt:

$$\tau_t^l = \tau^l + \gamma^l(b_{t-1} - b) + \phi^l(y_t - y); \qquad \tau_t^k = \tau^k + \gamma^k(b_{t-1} - b) + \phi^k(y_t - y), \qquad (15)$$

where $\phi^l, \phi^k > 0$ capture a progressive income tax system, fluctuating with macroeconomic conditions to reflect the automatic stabilization role of the federal income tax policy.

The central bank adjusts its policy interest rate to stabilize inflation. Monetary policy follows the Taylor-type rule:

$$R_t^f = \max\left[R^f\left(\frac{\pi_t}{\pi}\right)^{\alpha_\pi}, 1\right], \qquad (16)$$

where $\pi_t = \frac{P_t}{P_{t-1}}$ is the inflation rate of final goods, and $\alpha_\pi > 1$ signals an active monetary policy to stabilize inflation, following Leeper (1991). As α_π increases, the central bank puts more weight on inflation stabilization and is more willing to adjust the policy rate when inflation deviates from its target. Household optimization conditions, equations (4) and (5), highlight that as the monetary authority raises the policy rate, the return to government debt also increases through the no-arbitrage conditions, inducing households to hold risky government debt.

Lastly, the aggregate resource constraint is

$$y_t = c_t + g_t + i_t + \frac{\psi}{2}\left(\frac{\pi_t}{\pi} - 1\right)^2 y_t. \qquad (17)$$

3 Calibration and Solution

Table 1 summarizes the parameter calibration and the steady-state values of fiscal variables. The model is calibrated at the quarterly frequency. The capital depreciation rate, δ, is 0.025, and the capital income share, α, is 0.36. Taking the mean estimates in Smets and Wouters (2007), we calibrate the inverse of the intertemporal substitution elasticity for consumption σ at 1.38, and the inverse of the Frisch labor elasticity ϕ at 1.83. The capital adjustment costs κ is set to 1.7, as in Gourio (2012). To calibrate the market power of intermediate goods

producing firms, we set $\theta = 7.67$, implying a markup of 15%, in line with the estimates for U.S. firms of 5–15% in Basu and Fernald (1995). Following Smets and Wouters (2007), the degree of price stickiness is assumed to be one year, implying $\psi = 78.2$.[10] The steady-state quarterly inflation rate π is set to 1.005, equivalent to an annualized net inflation rate of 2%. To determine the real interest rate, we use the average real long-term interest rate for the U.S. between 1970 and 2007 as constructed by Jordá et al. (2017): $\frac{R^f}{\pi} = 1.008$, which implies the quarterly discount factor $\beta = 0.992$. Without default risk in the steady state ($\Delta_t = 0$) and the steady-state financial disturbance $\eta = 1$, the annualized net policy rate is 5.2%, roughly matching average annual effective federal funds rate from 1970 to 2019. For the financial shock process, we set $\rho_\eta = 0.8$ and $\sigma_\eta = 0.001$.[11] For the Taylor rule, we choose the response of the interest rate to inflation, α_π, to be 1.8 in the baseline, following the estimate in Smets and Wouters (2007).[12] When studying the role of monetary policy, we explore a more active rule with $\alpha_\pi = 3$ for comparison.

To calibrate the steady-state fiscal variables, we use the average values from 1970 to 2019 in the Historical Tables published by Office of Management and Budget (2020). The discretionary outlay-to-output ratio ($\frac{g}{y}$) and the mandatory outlay-to-output ratio ($\frac{z}{y}$) are 0.083 and 0.12 respectively.[13] Given the importance of debt servicing costs in the model, we calibrate the government interest payments as a share of output to be 2%, which matches the 1970–2017 average of net interest outlays to GDP. The steady-state debt-to-annual output ratio is set to 0.55, matching the average of the net federal government debt-to-GDP ratio between 2000 and 2019. The lump-sum tax ω, the residual in the government budget constraint, equals 4% of output in the steady state.

We use NIPA data with Jones's (2002) method for constructing the average income tax rates. We set $\tau^l = 0.203$ and $\tau^k = 0.212$, the 1970–2019 average of the constructed series.[14]

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[10] Ascari and Rossi (2012) illustrate the equivalence of the Rotemberg and the Calvo price specifications in terms of the NK Phillips curve.

[11] We choose a relative small σ_η to ensure convergence when solving the model nonlinearly.

[12] Smets and Wouters (2007) fit an NK model to the U.S. data for 1966-2004 and obtain the 90-percent posterior range for α_π of 1.7–2.3.

[13] Federal discretionary outlays include national defense and non-defense outlays but exclude net interest payments. Federal mandatory outlays mainly include spending on Social Security, Medicare, and Medicaid.

[14] Jones (2002) computes the average capital and labor income tax rates for all government levels in the U.S. We apply the method to federal income taxes only. The main difference is that federal capital income taxes do not have property taxes. The data of National Income and Product Account (NIPA) used for the calculation include: compensation of employees (NIPA Table

For the response of the labor and capital income tax rates to output, we adopt the estimates in Leeper et al. (2010), setting the elasticity of the labor (capital) income tax rate with respect to output to be 0.36 (1.7).[15] For the response of the tax rates to debt, we set $\gamma^l = 0.012$ and $\gamma^k = 0.001$. Since an increase in the capital income tax rate is more distorting than in the labor income tax rate, we assume that the government chooses the labor income taxes to bear most adjustments. The adjustment magnitudes are kept small, sufficient to satisfy the transversality condition for government debt.

In calibrating the transfer process, we set $\rho_z = 0.96$, $\mu = 1.005$, $p_1^z = 0.9944$, and $p_2^z = 0.9875$, in line with those used in Bi et al. (2016). From a long-run perspective, federal mandatory spending as a share of GDP has been largely on an upward trend since the early 1960s. The trend, however, has experienced different growth periods, from 1965 to 1985, 2000 to 2009, and 2018 to 2038 (the solid line in Figure 2). The calibration of $p_2^z = 0.9875$ gives an average length of an unstable regime of 20 years, and a sufficiently high p_1^z is required to maintain the stationarity of the equilibrium system. Given the uncertainty of the average length staying in an unstable regime—important in affecting expected future surplus, we also simulate a fiscal limit distribution under a higher value of $p_2^z = 0.9917$, implying the average length of 30 years in the unstable regime.

Our default scheme assumes a constant haircut rate Δ. Without default experience for the U.S. federal government, we use the haircut rate estimated from the emerging market economies. Sturzenegger and Zettelmeyer (2008) collect the estimated haircut rates of sovereign debt restructures in emerging market economies. Relying on those data, Bi (2012) calculates that 90% of the annual haircut rates (as a share of existing sovereign debt) fall below 0.3 for the period between 1998 and 2005. Thus, we assume a constant annual haircut rate of 0.28, implying a quarterly rate of haircut $\Delta = 0.07$.

Appendix A lists equations that characterize the equilibrium system. We use the mono-

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1.12, line 2), wages and salaries (NIPA Table 1.12, line 3), proprietors' income with inventory valuation adjustment and capital consumption adjustment (NIPA 1.12, line 9), rental income of persons with capital consumption adjustment (NIPA Table 1.12, line 13), net interest and miscellaneous payments (NIPA Table 1.12, line 18), federal personal current taxes (NIPA Table 3.2, line 3), contributions for government social insurance (NIPA Table 3.2, line 10), and taxes on corporate income (NIPA Table 3.2, line 8).

[15] We convert Leeper at al.'s (2010) estimates to be consistent with our tax rule specification in level deviation so that $\phi^l = 0.0235$ and $\phi^k = 0.116$.

tone mapping method of Coleman (1990) and Davig (2004) to obtain a fully-nonlinear solution. Appendix B describes the numerical solution method.

4 Fiscal Limit Distributions

Fiscal limits are defined as the discounted expected sum of future maximum primary surplus over an infinite horizon. By iterating (11) forward, imposing the tranversality conditions for government debt, and assuming no default at t ($\Delta_t = 0$), we obtain the equilibrium debt valuation equation:

$$\frac{b_{t-1}}{\pi_t} = \sum_{i=0}^{\infty} \beta^i E_t \left[\frac{\lambda_{t+i}}{\lambda_t} \left(tax_{t+i} - g_{t+i} - z_{t+i} \right) \right], \tag{18}$$

where $\frac{b_{t-1}}{\pi_t} = \frac{B_{t-1}}{P_t}$ is the real value of government nominal liabilities at t. Fiscal limits are simulated based on (18), but all the variables are computed under $\tau_{t+i}^l = \tau_t^{l,\max}$ and $\tau_{t+i}^k = \tau_t^{k,\max}$, the maximum labor and capital income tax rates that the government is willing and able to impose in the future. We assume that $\tau_t^{l,\max}$ and $\tau_t^{k,\max}$ are drawn from two normal distributions to capture uncertainties surrounding the highest tax rates (see Section 4.1 for details). Let the superscript "max" denote a variable's value computed under $\tau_t^{l,\max}$ and $\tau_t^{k,\max}$. Specifically, conditional on an initial state, $\mathbf{S}_t = \{\eta_t, k_{t-1}, z_t, i_t^z\}$, a fiscal limit distribution is

$$\frac{\mathbf{b}(\mathbf{S}_t)}{\pi_t^{\max}(\mathbf{S}_t)} \sim \sum_{i=0}^{\infty} \beta^i E_t \left\{ \frac{\lambda_{t+i}^{\max}(\mathbf{S}_{t+i})}{\lambda_t^{\max}(\mathbf{S}_t)} \left[tax_{t+i}^{\max}(\mathbf{S}_{t+i}) - g_{t+i}(\mathbf{S}_{t+i}) - z_{t+i}(\mathbf{S}_{t+i}) \right] \right\}. \tag{19}$$

Equation (19) makes explicit the factors important for the fiscal limits at the beginning of t, which include inflation, the stochastic discount factor ($\beta^i E_t \frac{\lambda_{t+i}}{\lambda_t}$), and expected primary surplus at the maximum tax rates. Ceteris paribus, fiscal limits would be higher with 1) higher inflation, which enhances the debt devaluation effect on existing nominal liabilities, 2) higher expected stochastic discount factors, which lower expected real interest rates, or 3) higher future primary surplus, which signals stronger debt repayment capacity.

4.1 The Baseline Distribution

We rely on the historical income tax rates at the federal level to infer the maximum tax rates, which are not observable for a country that has not defaulted. Specifically, the implementable labor income tax rates, $\tau_t^{l,\max}$, are drawn from an assumed normal distribution, which is calibrated based on the data series of the average marginal federal income tax rate on individuals from 1921 to 2006 constructed by Barro and Redlick (2011). The distribution centers at 0.34, the 75th percentile of the data series on the average marginal income tax rate, with a standard deviation of 0.05. It implies that 95% of maximum labor tax rates in our simulation falls in the range of $[0.24, 0.44]$, substantially higher than the average federal labor income tax rate of around 0.2 since 2001.[16]

On the capital income tax rates, the historical rate has been on a clear downward trend, gradually falling from the post-WWII peak of 0.38 in 1951 to the trough of 0.15 in 2019 (Figure 3). This trend can be partly explained by competition among countries to attract investment and profit allocation of international firms. Therefore, it is less likely that the federal capital income tax rates would return to the high levels observed before 1980. We set the distribution of the maximum capital income tax rate to center at 0.24, the peak during the post-1980 period, with the same standard deviation as the distribution for labor income tax rates.

Instead of relying on historical tax rates, the original approach proposed in Bi (2012) is to impose the peak of Laffer curve. Bi (2017) simulates fiscal limits for a group of advanced economies and emerging market economies with the peak of model-implied Laffer curve ranging from 0.5 to 0.7. Given the relatively low levels of federal income tax rates in the U.S., 0.2 for labor income tax and 0.15 for capital tax in 2019, policymakers would encounter a daunting task, should they attempt to double or triple the current tax rates. Our approach has a similar idea as Collard et al. (2015), who use the maximum historical primary surplus to compute a country's maximum sustainable debt.

As Figure 2 (the dashed line) shows that future government purchases are expected to be

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[16]See footnote 14 for the calculation of the average federal labor income tax rate.

stable, we assume $g_{t+i} = g \ \forall \ i$. Transfers as a share of GDP, however, appear to be on an unstable path. We capture the rising trend and the uncertain timing of a potential reform by the regime switching process, (13) and (14), between stable and unstable regimes.

The solid line in Figure 4 plots the cumulative density function of the baseline fiscal limit distribution (assuming the expected duration of an unstable regime is 20 years; $p_2^z = 0.9875$). It shows that default probabilities are essentially zero for net federal debt below 100% of annual output. Although the probability rises along with the debt level, it does not increase significantly until the debt ratio exceeds about 200% of annual output. The net federal debt level is projected to be around 100% of GDP in 2020 (Congressional Budget Office (2020b)). Although this level of federal government debt is approaching the post-WWII peak of 106% of GDP in 1946, the federal debt remains essentially risk free judged by the baseline fiscal limit distribution as the default probability is close to zero. When the expected duration is assumed to be 30 years ($p_2^z = 0.9917$), the red dotted-dashed line (Figure 4) shows that the fiscal limit distribution is flattened somewhat relative to the baseline. An expected longer duration of transfers policy staying in an unstable regime means that expected future primary surplus is lower, implying a higher default probability for a given debt ratio.

The fiscal limit distributions simulated are conditional on an initial state, $\mathbf{S}_t$, at the steady state. After period t, the financial shock and transfers follow the stochastic processes specified in (3), (13), and (14). The framework allows for the possibility to condition the fiscal limit simulation on an initial major financial shock that drives the economy to the ZLB. We conduct such a simulation but find that its impact on the fiscal limit distribution—in terms of changes in the level and the shape of the distribution—is quite small. Thus, we pursue the analysis with a distribution starting from the steady state.[17]

4.2 Alternative Distribution: Uncertain Future Fiscal Policies

The yardstick we use to assess a government's debt sustainability emphasizes on a government's debt repayment capacity. Given the significant uncertainties surrounding the

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[17]Battistini et al. (2019) also find that the impact of a macroeconomic shock on the fiscal limit distribution is relatively small at the ZLB.

timing of Social Security and health spending reform in the U.S., we simulate an alternative distribution assuming that federal transfers as a share of output follow the projection by Congressional Budget Office (2019), in which federal mandatory spending rises from 12.8% of GDP in 2020 to 17.5% in 2049, as shown by the solid line in Figure 2. After 2049, transfers are assumed to revert to the regime-switching process as assumed in the baseline simulation. The alternative distribution represents a more pessimistic view about the future fiscal policy relative to the baseline, as the federal government can encounter resistance in reforming social security or health care programs. In this case, the default probability is 5% with the net debt ratio at 100% of annual output, and the default probability would rise quickly after the debt ratio reaches 150% of annual output.

The comparison of the baseline and the alternative fiscal limit distributions leads to two observations. First, sovereign default risk and government debt levels have a non-linear relationship: once the risk starts rising, it tends to rise quickly. By then, it may be too late to enact fiscal reforms to change expectations about future primary surplus and to shift the fiscal limit distribution in a meaningful way. Second, conditional on a debt level, the assessment about the debt sustainability can be different. At 200% of output, the risk of sovereign default remains relatively low under the baseline distribution but can reach 40% when the government's debt repayment capacity is perceived to be lower, as shown in the alternative distribution.

5   The Effects of Interest Rate Normalization

Prior to studying the fiscal implication of interest rate normalization, we first simulate a scenario in which the economy has a high level of government debt and is constrained at the ZLB. We proceed in two steps. Firstly, at $t = -160$ the economy starts at the steady state with a debt-to-annual output ratio of 0.55. Between $t = -160$ and $t = 0$, the economy is subject to the stochastic process of government transfers, as specified in (13) with 5,000 simulations being performed. This step generates government debt significantly higher than the steady-state level. Secondly, the economy is injected with a series of major negative

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macroeconomic disturbances in the form of financial shocks from $t = 1$ to 5.[18] Out of the 5,000 simulations, we retain 310 that satisfy two conditions: 1) government debt is in the range of 90–100% of annual output at $t = 5$, and 2) the economy is constrained at the ZLB from $t = 1$ to 5.

Next, we explore the dynamics during the interest rate normalization stage based on the 310 retained paths. Starting from $t = 6$, most simulation exit the ZLB, and all retained simulations are subject to periodic financial shocks drawn from its distribution. The continuous macroeconomic disturbances allow us to characterize the stochastic nature of interest rate normalization. At $t = 6$, 12% of retained simulations remain at the ZLB, and we characterize the dynamics of the interest rate normalization with a median response and the 90-percent confidence bands as shown in Figure 5.

5.1 The Economy at the ZLB

The black solid lines in Figure 5 are the median responses of 310 retained simulations and the median value of government debt-to-annual output is 95% of annual output at $t = 5$. The responses are the differences between the paths with and without the financial shocks. The bands in dashed lines are the 90-percent confidence intervals.

Financial shocks that increase the return to risk-free assets push the economy into a deep recession. The shocks raise η_t persistently starting from $t = 1$, which drive up households' demand for risk-free assets and channel savings away from investment. Investment declines by about 20% for the median response in the trough, shrinking the aggregate goods demand, as well as firms' labor demand. The median labor response declines by 4.6% in the trough. Lower labor demand, joint with declined capital, reduces the marginal product of labor and hence the real wage, despite a substantial decline in the price level. With reduced wage income, households cut consumption, further reducing private demand. The median reduction in output is 3.3% at the quarterly rate in the trough.

The deep contraction in demand significantly lowers inflation, driving the economy to the

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[18]Ideally, the economy should also be subject to financial shocks before $t = 1$. Since the simulation before t=1 is solely aimed at generating a high level of government debt, we simplify the simulation by shutting down the financial shocks before $t = 1$.

ZLB. Inflation stays in the deflationary territory from $t = 1$ to 5 and reaches -5% at the annualized rate in the trough.[19] Monetary policy responds by cutting the policy rate, R_t^f, all the way to its ZLB. The inflation decline, joint with the bounded nominal interest rate, raises the real interest rate and decreases the real government bond price.

Higher debt servicing costs increase government indebtedness. This channel is particularly pronounced when the economy is trapped at the ZLB. With the ZLB binding from $t = 1$ to 5, the government's real interest payments—computed as $\frac{B_{t-1}}{P_t} - \frac{B_{t-1}}{R_{t-1}P_{t-1}}$—increase by more than 200 percent, compared to the case without the major financial shocks. Our baseline model features a one-period government bond, and therefore the government has to roll over all the existing debt in one quarter. In Section 6, we extend the maturity of government debt to five years and find that a longer debt maturity can further amplify the impact.

In addition, income tax revenues contract as a result of a smaller tax base and lower average income tax rates, the latter of which is due to a progressive tax system. A higher real interest rate also decreases the real bond price, which is the inverse of the real interest rate. The lower real bond price, together with declined tax revenues, increases the financing needs and hence a rapid debt accumulation at the ZLB. The labor income tax rate falls much less than the capital income tax rate, because it is assumed to bear most of the fiscal adjustment burden.

5.2   The Process of Interest Rate Normalization

As the financial shocks die down, the financial disturbance, η_t, gradually returns to the steady-state level. The economy exits the ZLB for most simulations, and only 12% of retained simulations remain at the ZLB at $t = 6$. As private demand rebounds and the price level rises, the central bank starts to normalize the policy rate toward its steady-state level. In our simulation, the normalization process takes about 4 years, with the length crucially depending on the persistence of the financial shock. Compared to output and investment,

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[19]Deflation can be shallower and shorter in duration if we adopt a more general Taylor rule, in which the policy rate also responds to output deviation from the steady state. The macroeconomic and fiscal dynamics under a more general Taylor rule remain qualitatively the same as the baseline simulation. Hence, we maintain a simpler monetary policy rule in the baseline specification.

consumption recovers more slowly. This is because households expect most fiscal adjustment to be borne by an increase in future labor income taxes. The negative wealth effect leads households to cut current consumption, slowing the pace of consumption recovery from the ZLB.

A rising policy rate (from the ZLB) increases the interest rate on government debt through the no-arbitrage conditions of (4) and (5).[20] Relative to the ZLB period, the real interest payment falls substantially, mainly driven by the recovery in the price level. Although the accumulation of government debt slows after exiting from the ZLB, the debt stock continues to be elevated despite the recovery of income tax revenues. The median level of government debt remains at 94% of annual output at $t = 20$, but the 90-percent upper bound reaches 103% of annual output. During normalization, the elevated debt level keeps the interest payment-to-output ratio 0.5 percentage points higher than the path without the ZLB. This is mainly driven by the legacy of a high level of government debt from the severe recession. Overall, the result suggests that without aggressive fiscal adjustments, government debt burden is difficult to retreat through economic growth alone during the interest normalization stage.

In the baseline analysis, the sovereign default risk is trivial. The baseline fiscal limit distribution (the solid line in Figure 4) shows that the default probability is negligible at the level of government debt round 100% of annual output. During normalization, the increase in the default probability—when comparing the path with and without experiencing the ZLB—is only 0.4% for the median path, with the 90-percent interval of 0.2–0.6 percentage points (the (4,3) panel of Figure 5). This level of default risk is empirically unimportant. The assessment of debt sustainability, to a large extent, is based on the current debt level and government's ability in generating future primary surplus. Since fiscal limits are highly uncertain and the federal government debt is likely to rise further, the next simulation explores a high-debt scenario against a more pessimistic view on the fiscal limits of the federal government.

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[20]While the nominal interest rate (R_t) is not plotted in Figure 5, it follows closely the dynamics of the policy rate, R_t^f.

5.3 Normalization with a High-Debt Level and Lower Fiscal Limits

In this high-debt simulation, we assume that the initial debt level is 150–160% of steady-state annual output prior to the interest rate normalization, and the fiscal outlook is more pessimistic relative to the baseline fiscal limit distribution. To this end, we consider the alternative fiscal limit distribution—the dashed line in Figure 4. The distribution is derived under the assumption that the federal government's transfer spending will follow the projection under current law from 2020 to 2049. Figure 6 plots the median responses of the retained simulations—110 out of the total 5,000 simulations—that have the government debt ratio in the range of 150–160% of output at $t = 5$, while the solid lines are the median responses in the baseline simulation as in Figure 5.

In this alternative simulation, the government faces nontrivial default risk. The median response indicates that the debt ratio would increase to 160% of GDP during normalization. It corresponds to a default probability of around 11% (the dashed line in Figure 4), compared to the default probability of only 2% in the baseline. The marginal increase in default probability due to the financial shocks is also more visible, at about 3 percentage points during normalization as shown in the bottom right panel of Figure 6.

The higher default probability raises government financing costs, leading to a slower recovery. The default risk premium, defined as $R_t - \eta_t R_t^f$, increases by close to 100 basis points during normalization in this alternative simulation, compared to only 9 basis points in the baseline. The significant increase in risk premia, together with the higher existing debt level, translates into much higher interest payments. In order to maintain debt sustainability, the labor income tax rate has to increase more, about 0.8 percentage points more during normalization, suppressing private consumption more. Compared to the baseline with lower debt burden, output and consumption in the alternative high-debt scenario decline more during the ZLB period and also recover more slowly afterwards. Although the channel of sovereign default risk may seem irrelevant for the analysis at the current net federal debt level as shown in the baseline analysis, it is increasingly important as the government becomes more indebted.

5.4 Normalization with a More Active Interest Rate Policy

During the normalization stage, one question concerning the central bank is how fast it should allow the policy rate to rise. We approach this question by conducting a simulation with a more aggressive response to inflation—$\alpha_\pi = 3$, compared to $\alpha_\pi = 1.8$ in the baseline. Since our focus is on the normalization process, we compare the two cases from $t = 5$ onward.[21] Figure 7 plots the impulse responses, which are the differences between the path with and without financial shocks.

If the monetary authority makes a stronger commitment to its inflation target by increasing α_π, households expect inflation to return to its targeted level more quickly. Higher expected inflation lowers the real interest rate more, prompting a stronger rebound in investment and consumption. An increase in private demand reinforces the increase in the price level, leading to a higher policy rate in the case with a bigger α_π. On the one hand, higher interest rates increase government debt servicing costs and thus the financing needs. A faster recovery in output, on the other hand, generates more income tax revenues. Government debt as a share of output instead is lower during normalization under a more active interest rate rule. The median debt ratio is about 0.8 percentage points lower with $\alpha_\pi = 3$ than in the baseline analysis. As a result, real interest payments are about the same between the two interest rate rules. The major discrepancy occurs at $t = 6$, driven by the unanticipated pickup in inflation as the response to inflation switches, deflating the real value of interest payments.

Our simulation result suggests that a more active monetary policy is preferred as it leads to a faster recovery in the economy. The concern that a faster pace of interest rate normalization could lead to a bigger debt accumulation is alleviated by a stronger rebound in income tax revenues and hence a bigger decline in government debt burden.

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[21]Starting from $t = 6$, the economy with a more active interest rate rule switches to $\alpha_\pi = 3$, compared to 1.8 in the baseline. The switch is unanticipated, so the two simulations have the same economic conditions prior to $t = 6$.

6 Sensitivity Analysis

Given the challenge in solving a fully nonlinear model with rational expectations, the baseline specification has been simplified in many aspects. In this section, we conduct sensitivity analysis on the following aspects: 1) a different macroeconomic shock that drives the economy to the ZLB, 2) a longer debt maturity, 3) a model without sovereign default risk, and 4) a model without capital.

6.1 Investment Efficiency Shock

The two recent recessions that drove the U.S. economy to the ZLB—the Global Financial Crisis and the Global Health Crisis—were triggered by very different causes. Our baseline model relies on the frequently used financial shock in the literature to generate the ZLB. To see whether the source of negative macroeconomic shocks matters for the fiscal implications, we also simulate the model with an investment efficiency shock.

We follow the setup in Greenwood et al. (1988) and modify the law of motion for capital, (6), to introduce an investment efficiency shock as follows.

$$k_t = (1 - \delta)k_{t-1} + \nu_t \left[i_t - \frac{\kappa}{2} \left(\frac{i_t}{k_{t-1}} - \delta \right)^2 k_{t-1} \right], \tag{20}$$

where ν_t is the investment efficiency shock that follows an AR(1) process:

$$\ln \frac{\nu_t}{\nu} = \rho_\nu \ln \frac{\nu_{t-1}}{\nu} + \varepsilon_t^\nu, \qquad \varepsilon_t^\nu \sim N(0, \sigma_\nu^2). \tag{21}$$

This type of shock has been shown to be important for business cycle fluctuations (Greenwood et al. (2000) and Justiniano et al. (2010)). We calibrate $\rho_\nu = 0.8$, following Justiniano's (2008) estimate. A relatively small $\sigma_\nu = 0.001$ is chosen to ensure determinacy.

Figure 8 compares responses under the investment efficiency shocks (solid lines) to those in the baseline under the financial shocks (dashed lines). Both lines are the median responses of the retained simulations with the government debt ratio in the range of 90–100% of annual

output at $t = 5$. Like the financial shocks in the baseline analysis, the negative investment efficiency shocks are injected from $t = 1$ to 5 to keep the economy at the ZLB, after which the economy continues to experience investment efficiency shocks drawn from the assumed distribution.

While the responses of the key macroeconomic variables are similar, the two types of shocks have different impact on the real interest rate and government bond prices. Negative shocks on investment efficiency lower investment directly, reducing aggregate demand. Output and inflation fall, driving the economy to the ZLB, similar to the baseline analysis. The real interest rate and the bond price, however, move in the opposite directions for the two macroeconomic shocks. Specifically, the financial shock can be seen as a risk premium shock that also increases the interest rate of holding the risky asset (government debt) and, therefore, lowers the real bond price. The investment efficiency shock, on the other hand, discourages investment in physical assets. As a result, the demand for government bond increases and therefore decreases the real interest rate, raising bond prices at the ZLB.

Although government debt builds up as well with the investment efficiency shock, the pace is slower than with the financial shock, as the higher bond price eases the pressure on government financing.[22] When exiting from the ZLB, the higher bond price also helps lower the debt ratio. A lower real interest rate, combined with a lower government debt level, reduces interest payments and further ease debt sustainability concern during normalization. Hence, our basic conclusion that the debt sustainability of the federal government at the current debt level is unlikely to be threatened when the interest rates normalize continues to hold with the investment efficiency shock.

6.2 A Longer Debt Maturity

The baseline model features a one-period government bond, which is at variance with the reality. To see how government debt maturity can matter for our baseline result, we conduct simulations under a longer average debt maturity of five years. Following Woodford (2001),

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[22]Given the different natures of the shocks, it is difficult to construct a scenario with the exact same declines in output under the two shocks during the ZLB period. Instead, we let investment efficiency shocks be sufficiently negative to keep the economy at the ZLB from $t = 1$ to 5.

the specification with long debt assumes that households have access to a government bond portfolio, B_t, which sells at a price of Q_t at t and pays Ω^t dollars $t+1$ periods later for each $t \geq 0$. The average bond maturity is $(1-\beta\Omega)^{-1}$ quarters. With the long-term debt, the household's budget constraint is revised as

$$P_t c_t + P_t i_t + \frac{B_t^f}{\eta_t R_t^f} + Q_t \left[B_t - \Omega \left(1 - \Delta_t \right) B_{t-1} \right]$$

$$= (1 - \Delta_t) B_{t-1} + P_t \left[\left(1 - \tau_t^l \right) w_t n_t + \left(1 - \tau_t^k \right) r_t^k k_{t-1} \right] + P_t z_t + \Upsilon_t + \omega. \qquad (22)$$

With $\Omega = 0$, it is collapsed to the baseline specification of a one-quarter bond. We set $\Omega = 0.95$, matching the average maturity of U.S. Treasury marketable debt from 2000 to 2018 to be five years (Office of Debt Management (2018)).

The responses with a long-term bond are very close to those with a short-term bond, as shown in Figure 9.[23] The main difference shows up in the ex-post real interest rate, which can be derived as

$$r_t^{ex-post} = \frac{1 + \Omega Q_t}{\pi_t Q_{t-1}}. \qquad (23)$$

The initial spike in the ex-post real interest rate can be explained from the rising nominal price at t. In the case of short-term debt, the ex-post real interest rate, or the real return to government debt purchased at $t-1$, is not affected by the current nominal bond price. With a long-term bond, the real return at t also depends on the resale value of debt that has not matured at t. The longer the average debt maturity is, the more important role the resale price Q_t plays in the ex-post real rate at t. Since the financial disturbance is expected to last for a prolonged period in a deep recession, the expected low nominal interest rate implies that the nominal bond price would rise, increasing the ex-post real rate as shown in (23). With a higher real rate, interest payments and hence debt rise more with a long-term bond. At an initial debt at 90-100% of annual output, the assessment on the federal debt sustainability is, however, similar to that in the baseline analysis.

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[23]In this analysis, we drop the regime-switching transfer process, as it is very challenging to solve the nonlinear model with sovereign default risks, long-term debt, and a regime-switching transfer process. We assume the initial government debt starts from a high level set exogenously, rather than simulating it by drawing from the regime-switching transfers. The condition of the economy at time 0 is close to the baseline analysis.

6.3 The Role of Sovereign Default Risk

One important feature of the model is that it uses fiscal limits to assess debt sustainability. Sovereign default risk is highly nonlinear, as it is relatively invariant when debt increases at low levels but can rise rapidly at high levels. The baseline analysis shows little sovereign default risk associated with interest rate normalization but becomes more important with high debt. To see the role of sovereign default risk, Figure 10 compares the median responses with an initial high debt at 150-160% of annual output at $t = 5$ (solid lines) to those with same level of debt but without facing sovereign default risk (dashed lines). In other words, $\Delta = 0 \ \forall \ t$ in (12) for the case without default risks.

The most conspicuous difference between the responses with and without sovereign default risk is the risk premium, which is the difference between the risk free rate $(\eta_t R_t^f)$ and the interest rate on government bonds (R_t). The model with sovereign default risk implies an increase in the premium close to 100 basis points relative to the path without the financial shocks, compared to no change in the risk premia for the model without default risk. When there is no sovereign default risk, a smaller increase in interest payments leads to a more rapid decline in debt, shrinking the increase in the income tax rate by 0.4 percentage points and thus contributing to a slightly faster recovery in the economy. By construction, the default probability in the model without sovereign default risk remains at zero throughout the horizon regardless of the debt level. As government debt climbs higher, the analysis using a model without sovereign default risk would overlook the warning from default risk and its impact on risk premia when assessing debt sustainability, both at the ZLB and during normalization.

6.4 The Role of Capital

Lastly, we contrast our baseline model, which captures the investment channel during the interest rate normalization, to an alternative setup that abstracts from capital. On the topic of fiscal limits, most NK models in the literature do not include capital, including Bi (2012) and Battistini et al. (2019). In this section, we show how capital can amplify the

macroeconomic responses during the normalization process.

To pursue, we modify the baseline model, so that the household's budget constraint is[24]

$$P_t c_t + \frac{B_t}{R_t} + \frac{B_t^f}{\eta_t R_t^f} = (1 - \Delta_t)B_{t-1} + P_t \left[\left(1 - \tau_t^l \right) w_t n_t + P_t z_t \right] + \omega. \tag{24}$$

The production of intermediate goods firms, (10), is revised as

$$y_t(i) = a_t n_t(i). \tag{25}$$

Also, the goods market clearing condition is revised as

$$y_t = c_t + g_t. \tag{26}$$

As shown in Figure 11, capital can significantly amplify the recession. Financial shocks that are required to push the economy to the ZLB are slightly bigger in the model without capital. However, the contraction in the model with capital is much more severe than the one without. This is due to the pronounced decline in investment in the model with capital, significantly lowering labor demand and output. The severe contraction in demand has a larger deflationary impact, leading to a higher ex-post real interest rate. As a result, lower ex-post real bond prices induce higher interest payments and thus higher debt accumulation both at the ZLB and during normalization. Conditional on given macroeconomic shocks, the model without capital is likely to understate the fiscal and macroeconomic implications at the ZLB and during normalization, especially when the government debt level is high.

7   Conclusion

We study the macroeconomic and fiscal implications of interest rate normalization from the ZLB in the United States, using a fully nonlinear NK model. The analysis focuses on a policy regime that the monetary authority is expected to resume its role in controlling inflation once

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[24]In this section, we abstract from the regime-switching transfer process for both models with and without capital. The detail of the model specification and simulation is available upon request.

the economy recovers. At the ZLB, the decline of the price level implies that the real interest rate increases, driving up the real interest payment of the government. Moreover, the sharp decline in tax revenues from the negative macroeconomic shocks and a lower real bond price contribute to the growing financing needs and hence the rapid accumulation of government debt. As the economy recovers, the much higher stock of government debt implies higher debt servicing costs. Although the real interest rate declines substantially relative to the level at the ZLB, it remains higher than the path without the macroeconomic shocks. Also, a lower real bond price increases the cost of rolling over existing debt. When fiscal adjustments are insufficient, government debt is likely to remain elevated during the interest normalization stage.

At the current federal government debt level of 90–100% of GDP, interest rate normalization is unlikely to pose an immediate threat to debt sustainability of the U.S. federal government, assessed by the government's ability to pay. If, however, federal debt continues to rise (such as to 150–160% of GDP) and federal transfers are not expected to revert to a stable regime within a reasonable time frame, interest normalization can increase sovereign default risk more noticeably. Also, a more active monetary policy has inflation return to the steady-state level of 2% sooner. Expecting higher future prices helps facilitate investment recovery and hence the output recovery. Despite higher nominal policy rates, a more active monetary policy leads to a smaller increase in debt accumulation during normalization and hence a smaller increase in sovereign default risk.

Given the simple structure of our baseline model, sensitivity analysis considers alternative model specifications, including 1) a different macroeconomic shock—the investment efficiency shock—in driving the economy to the ZLB, 2) a longer debt maturity, 3) a model without sovereign default risk, and 4) a model without capital. The first two show that our assessment on debt sustainability of the federal government remains valid in the baseline analysis, while the last two demonstrate the importance of accounting for sovereign default risk and capital in the model specification for studying the fiscal implications at the ZLB, as well as during the interest rate normalization process.

Appendix A   The Equilibrium System

Equations (A.1)-(A.19) below plus (12) and (13) in Section 2 characterize the equilibrium system. When simulating the fiscal limit distributions, the labor tax rate rule, (A.15), and capital tax rate rule, (A.16), are replaced by $\tau_t^l = \tau_t^{l,\max}$, $\tau_t^k = \tau_t^{k,\max}$, and $\Delta_t = 0$.

$$\lambda_t = (c_t)^{-\sigma} \tag{A.1}$$

$$\chi n_t^\varphi = \lambda_t(1 - \tau_t^l)w_t \tag{A.2}$$

$$\frac{1}{R_t} = \beta E_t \frac{\lambda_{t+1}}{\lambda_t} \frac{1 - \Delta_{t+1}}{\pi_{t+1}} \tag{A.3}$$

$$\frac{1}{R_t^f \eta_t} = \beta E_t \frac{\lambda_{t+1}}{\lambda_t} \frac{1}{\pi_{t+1}} \tag{A.4}$$

$$q_t = \left(1 - \kappa\left(\frac{i_t}{k_{t-1}} - \delta\right)\right)^{-1} \tag{A.5}$$

where q_t is the Tobin's q.

$$q_t = \beta E_t \frac{\lambda_{t+1}}{\lambda_t}\left[(1 - \tau_{t+1}^k)r_{t+1}^k + q_{t+1}\left((1 - \delta) - \frac{\kappa}{2}\left(\frac{i_{t+1}}{k_t} - \delta\right)^2 + \kappa\left(\frac{i_{t+1}}{k_t} - \delta\right)\left(\frac{i_{t+1}}{k_t}\right)\right)\right] \tag{A.6}$$

$$\psi\left(\frac{\pi_t}{\pi} - 1\right)\frac{\pi_t}{\pi} = 1 - \theta + \theta mc_t + \beta\psi E_t\left(\frac{\lambda_{t+1}}{\lambda_t}\left[\frac{\pi_{t+1}}{\pi} - 1\right]\left[\frac{y_{t+1}\pi_{t+1}}{y_t\pi}\right]\right) \tag{A.7}$$

$$w_t = (1 - \alpha)mc_t a_t(k_{t-1})^\alpha n_t^{-\alpha} = (1 - \alpha)mc_t\frac{y_t}{n_t} \tag{A.8}$$

$$r_t^k = \alpha mc_t a_t(k_{t-1})^{\alpha-1}n_t^{1-\alpha} = \alpha mc_t\frac{y_t}{k_{t-1}} \tag{A.9}$$

$$y_t = a_t k_{t-1}^\alpha n_t^{1-\alpha} \tag{A.10}$$

$$k_t = (1 - \delta)k_{t-1} + i_t - \frac{\kappa}{2}\left(\frac{i_t}{k_{t-1}} - \delta\right)^2 k_{t-1} \tag{A.11}$$

$$tax_t = \tau_t^l w_t n_t + \tau_t^k r_t^k k_{t-1} + \omega \tag{A.12}$$

$$\frac{b_t}{R_t} + tax_t = \frac{(1 - \Delta_t)b_{t-1}}{\pi_t} + g_t + z_t(i_t^z) \tag{A.13}$$

$$
z_t(i_t^z) = \begin{cases} (1 - \rho_z)z + \rho_z z_{t-1}, & \text{if } i_t^z = 1, \qquad \rho_z < 1 \\[2ex] \mu z_{t-1}, & \text{if } i_t^z = 2. \qquad \mu > 1 \end{cases} \tag{A.14}
$$

$$
\tau_t^l = \tau^l + \gamma^l(b_{t-1} - b) + \phi^l(y_t - y) \tag{A.15}
$$

$$
\tau_t^k = \tau^k + \gamma^k(b_{t-1} - b) + \phi^k(y_t - y) \tag{A.16}
$$

$$
R_t^f = \max\left(R^f \left(\frac{\pi_t}{\pi}\right)^{\alpha_\pi}, 1 \right) \tag{A.17}
$$

$$
y_t = c_t + g_t + i_t + \frac{\psi}{2}\left(\frac{\pi_t}{\pi} - 1\right)^2 y_t \tag{A.18}
$$

$$
\ln\frac{\eta_t}{\eta} = \rho_\eta \ln\frac{\eta_{t-1}}{\eta} + \varepsilon_t^\eta \tag{A.19}
$$

Appendix B   The Numerical Solution Method

The method discretizes the state space and finds a fixed point in decision rules for each point in the state space. The solutions converge to functions that map the minimum set of state variables into values for the endogenous variables.

Appendix B.1   Simulating Fiscal Limit Distributions

Since the fiscal limits are the maximum level of government debt that can be supported without default, when simulating fiscal limits, we set $\Delta_t = 0 \ \forall \ t$. For simulating fiscal limit distributions, the minimum set of state variables is $\mathbf{S}_t = \left\{ \eta_t, k_{t-1}, \tau_t^{l,\max}, \tau_t^{k,\max}, z_t, i_t^z \right\}$. Define the decision rules for hours as $n_t = f^n(\mathbf{S}_t)$, inflation as $\pi_t = f^\pi(\mathbf{S}_t)$, and consumption as $c_t = f^c(\mathbf{S}_t)$.

1. Define the grid points by discretizing the state space. Make initial guesses for f_0^n, f_0^π, and f_0^c over the state space.

2. At each grid point, solve the nonlinear model using the given rules f_{j-1}^n, f_{j-1}^π, and f_{j-1}^c, and obtain the updated rules f_j^n, f_j^π, and f_j^c. Specifically:

    (a) Derive λ_t and w_t in terms of c_t, n_t, and $\tau_t^{l,\max}$ using (A.1) and (A.2).

(b) Derive y_t in terms of a_t, k_{t-1}, and n_t using (A.10). Compute mc_t and r_t^k from (A.8) and (A.9).

(c) From (A.5), (A.11), and (A.18), derive i_t, q_t, and k_t.

(d) Given π_t, obtain the policy rate, R_t^f, from equation (A.17). If $R_t^f < 1$, set $R_t^f = 1$.

(e) Use linear interpolation to obtain $f_{i-1}^n(\mathbf{S}_{t+1})$, $f_{i-1}^\pi(\mathbf{S}_{t+1})$, and $f_{i-1}^c(\mathbf{S}_{t+1})$. Then follow the above steps to solve λ_{t+1}, y_{t+1}, r_{t+1}^k, q_{t+1}, and i_{t+1}.

(f) Update the decision rules f_i^n, f_i^π, and f_i^c, using (A.4), (A.6), and (A.7). The integral in expectation terms is evaluated using numerical quadrature.

3. Check convergence of the decision rules. If $|f_j^n - f_{j-1}^n|$, $|f_j^\pi - f_{j-1}^\pi|$, or $|f_j^c - f_{j-1}^c|$ is above the desired tolerance (set to $1e-6$), go back to step 2. Otherwise, f_j^n, f_j^π, and f_j^c are the decision rules. Use the converged rules—f_j^n, f_j^π, and f_j^c—to compute the decision rules for f_j^T and f_j^λ, where f_j^T is the rule for maximum tax revenue.

After we obtain the decisions rules, f_j^T, f_j^λ, and f_j^π, a fiscal limit distribution is simulated using Markov Chain Monte Carlo methods, described below.

1. For each simulation $l = \{1, 2, ..., 10000\}$, we randomly draw a sequence of financial shocks (ε_{t+i}^η), maximum labor tax rate ($\tau_{t+i}^{l,\max}$), maximum capital tax rate ($\tau_{t+i}^{k,\max}$), and the transfer regime (i_{t+i}^z) for 1000 periods ($i = \{1, 2, ..., 1000\}$), conditional on the starting state $\mathbf{S}_t = \left\{ \eta_t, k_{t-1}, \tau_t^{l,\max}, \tau_t^{k,\max}, z_t, i_t^z \right\}$. As labor and capital income tax rates are set to the maximum rates ($\tau_{t+i}^{l,\max}$ and $\tau_{t+i}^{k,\max}$) and transfers follow the regime switching process in (A.14), we obtain $T_{t+i}^{\max}$, $\lambda_{t+i}^{\max}$, and $z_{t+i}^{\max}$, for $i = \{1, 2, ..., 1000\}$. Then, the expected discounted maximum fiscal surplus for period $t + i$ is computed as

$$\pi_t^{\max}(\mathbf{S}_t) \, \beta^i E_t \left\{ \frac{\lambda_{t+i}^{\max}(\mathbf{S}_{t+i})}{\lambda_t^{\max}(\mathbf{S}_t)} \left(tax_{t+i}^{\max}(\mathbf{S}_{t+i}) - g - z_{t+i}(\mathbf{S}_{t+i}) \right) \right\}, \qquad \text{(B.1)}$$

30

for $i = \{1, 2, ..., 1000\}$. The maximum sustainable debt is

$$\mathbf{b}^{\max}(\mathbf{S}_t) = \pi_t^{\max}(\mathbf{S}_t) E_t \sum_{i=0}^{1000} \beta^i E_t \left\{ \frac{\lambda_{t+i}^{\max}(\mathbf{S}_{t+i})}{\lambda_t^{\max}(\mathbf{S}_t)} \left(tax_{t+i}^{\max}(\mathbf{S}_{t+i}) - g - z_{t+i}(\mathbf{S}_{t+i}) \right) \right\}.$$

(B.2)

2. Repeat the simulation for 10000 times to generate $\left\{ \mathbf{b}^{\max,l} \right\}_{l=1}^{10000}$, which forms the distribution of $\mathbf{b}(\mathbf{S}_t)$ in (19).

Appendix B.2   Solving the Nonlinear Model

When solving the nonlinear model, the minimum set of state variables is denoted by $\mathbb{S}_t = \{\eta_t, b_{t-1}^d, k_{t-1}, z_t, i_t^z\}$. Define the decision rules for hours as $n_t = f^n(\mathbb{S}_t)$, inflation as $\pi_t = f^\pi(\mathbb{S}_t)$, consumption as $c_t = f^c(\mathbb{S}_t)$, and debt as $b_t = f^b(\mathbb{S}_t)$. The decision rules are solved as follows.

1. Define the grid points by discretizing the state space. Make initial guesses for f_0^n, f_0^π, f_0^c, and f_0^b over the state space.

2. At each grid point, solve the nonlinear model and obtain the updated rules f_i^n, f_i^π, f_i^c, and f_i^b using the given rules f_{i-1}^n, f_{i-1}^π, f_{i-1}^c, and f_{i-1}^b. Specifically:

   (a) Derive y_t in terms of a_t, k_{t-1}, and n_t using (A.10).

   (b) Derive τ_t^l and τ_t^k using (A.15) and (A.16).

   (c) Derive λ_t and w_t in terms of c_t, n_t, and τ_t^l using (A.1) and (A.2).

   (d) Compute mc_t and r_t^k from (A.8) and (A.9).

   (e) From (A.5), (A.11), and (A.18), we can derive i_t, q_t, and k_t.

   (f) Given π_t, obtain the risk free nominal interest rate, R_t^f, from equation (A.17). If $R_t^f < 1$, set $R_t^f = 1$ as the nominal interest rate.

   (g) Given b_t, solve the risky rate R_t using (A.13).

   (h) Use linear interpolation to obtain $f_{i-1}^n(\mathbb{S}_{t+1})$, $f_{i-1}^\pi(\mathbb{S}_{t+1})$, and $f_{i-1}^c(\mathbb{S}_{t+1})$, where the state vector is $\mathbb{S}_{t+1} = \{\eta_{t+1}, b_t^d, k_t, z_{t+1}, i_{t+1}^z\}$. Then follow the above steps to solve

y_{t+1}, λ_{t+1}, r^k_{t+1}, q_{t+1}, and i_{t+1}.

(i) Update the decision rules f^n_i, f^π_i, f^c_i, and f^b_i, using (A.3), (A.4), (A.6), and (A.7). The integral in expectation terms is evaluated using numerical quadrature.

3. Check convergence of the decision rules. If $|f^n_i - f^n_{i-1}|$, $|f^\pi_i - f^\pi_{i-1}|$, $|f^c_i - f^c_{i-1}|$, or $|f^b_i - f^b_{i-1}|$ is above the desired tolerance (set to $1e - 6$), go back to step 2. Otherwise, f^n_i, f^π_i, f^c_i, and f^b_i are the decision rules.

| parameters or steady-state variables		values
β	discount factor	0.992
σ	inverse of intertemporal elasticity for consumption	1.38
ϕ	inverse of Frisch labor elasticity	1.83
δ	capital depreciation rate for capital	0.025
α	capital income share	0.36
κ	investment adjustment cost parameter	1.7
a	normalized TFP in the steady state	1
n	steady-state labor	1
θ	price markup parameter	7.67
ψ	price adjustment cost parameter	78.2
π	steady-state inflation	1.005
$R,\ R^f$	steady-state risky and risk-free nominal rate	1.013
$r = \frac{R}{\pi}$	steady-state real interest rate	1.013
Δ	the haircut rate if defaulting	0.07
α_π	nominal rate response to inflation deviation	1.8
τ^l	labor income tax rate	0.203
τ^k	capital income tax rate	0.212
$\frac{b}{4y}$	debt-to-annual output ratio	0.55
γ^l	response of the labor tax rate to debt	0.012
γ^k	response of the capital tax rate to debt	0.001
ϕ^l	response of the labor tax rate to output	0.0235
ϕ^k	response of the capital tax rate to output	0.116
$\frac{g}{y}$	government purchase-output ratio	0.083
$\frac{z}{y}$	government transfers-output ratio	0.12
p_1^z	regime-switching parameter for the stable regime	0.9944
p_2^z	regime-switching parameter for the unstable regime	0.9875
ρ_z	AR(1) coefficient for z_t in the stable regime	0.96
μ	coefficient for z_t in the unstable regime	1.005
η	financial disturbance in the steady state	1
ρ_η	AR(1) coefficient for η_t	0.8
σ_η	standard deviation of ε^ν	0.001

Table 1: **Baseline calibration**.
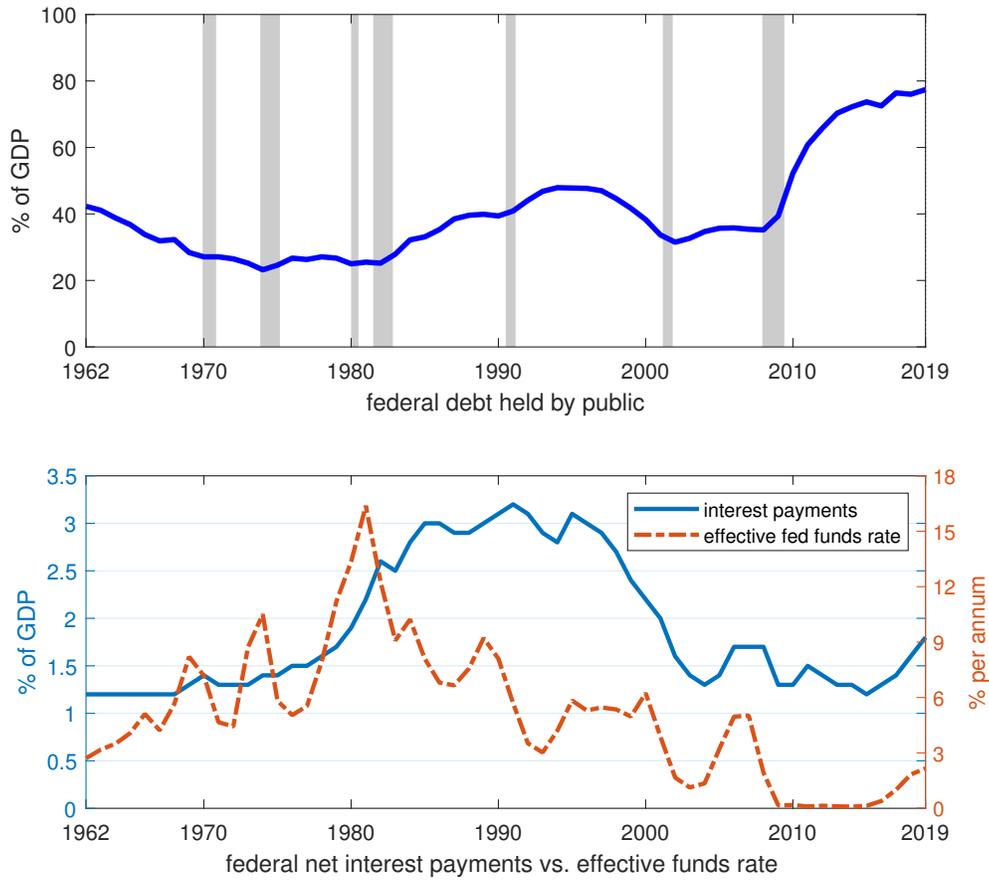
Figure 1: **Federal government debt, interest payments, and the federal funds rate.** All three series are plotted in the annual frequency. The federal funds rate is the average of the monthly effective rate (Board of Governors of the Federal Reserve System (2020)). The data of federal debt held by the public and interest payments are in fiscal years (Historical Tables 7.1 and 8.4 of Office of Management and Budget (2020)).
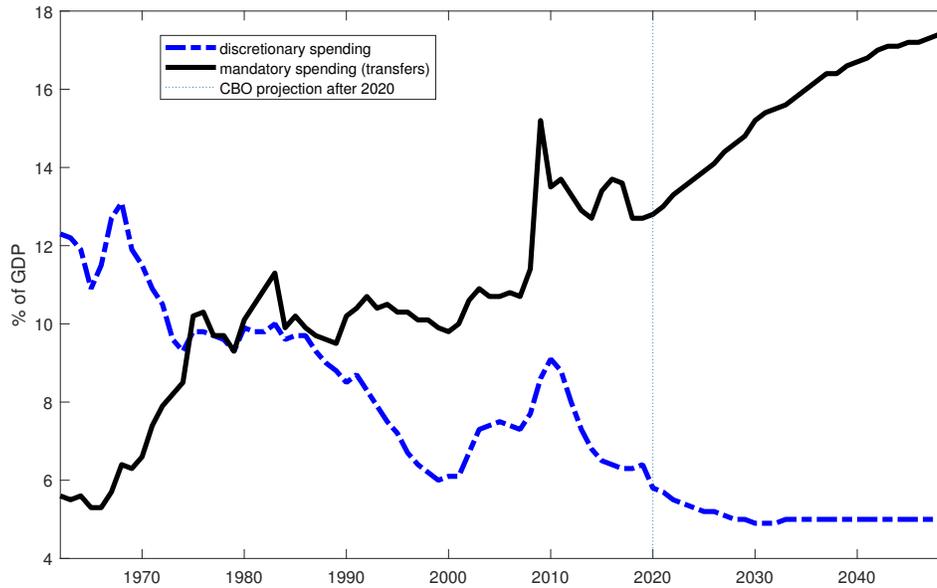
Figure 2: **Mandatory and discretionary spending of the federal government.** Mandatory spending includes spending on Social Security, health care programs (such as Medicare and Medicaid), income security, veterans' programs, etc. Historical spending data are the taken from Table 8.4 of the Historical Tables in Office of Management and Budget (2020). Projection from 2020 is the CBO's projection (2019) under the extended baseline scenario. Note that this projection does not account for the budgetary effect of the pandemic related legislation.
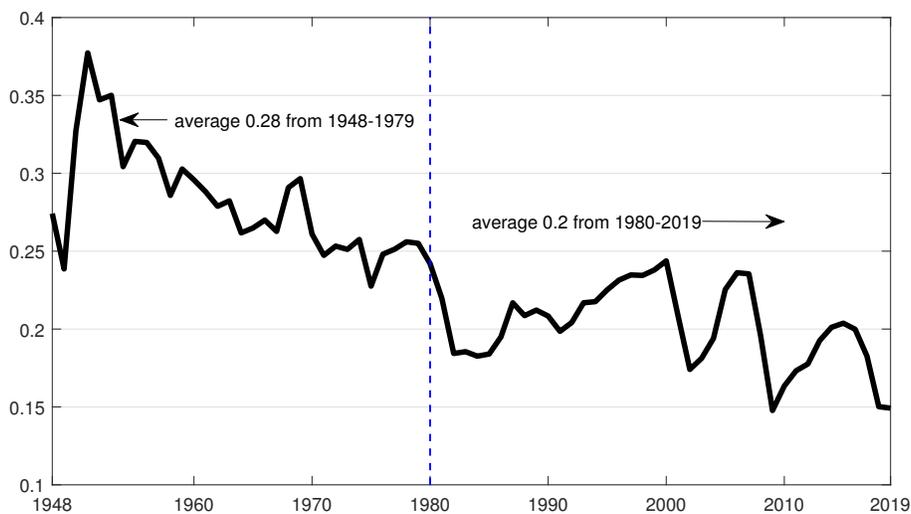
Figure 3: **Federal average capital income tax rates.** The annual average capital income tax rates are calculated based on Jones's (2002) method; see footnote 14.
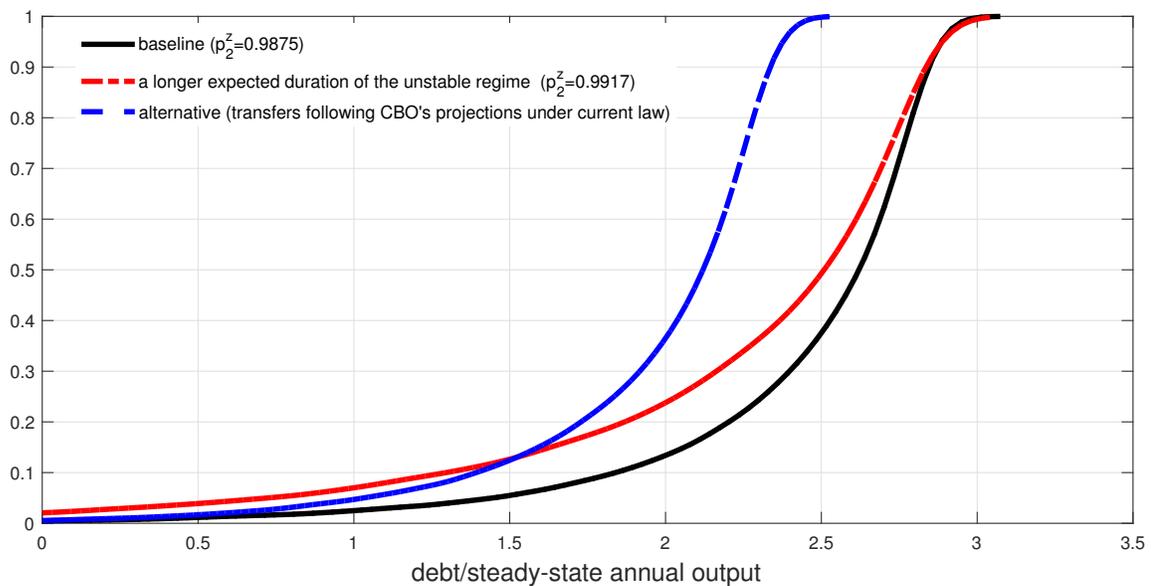
Figure 4: **Fiscal limit distributions (the cumulative density function) of the U.S. federal government.** The baseline distribution assumes that federal government transfers follow a regime-switching process between a stable and an unstable regime, expected to last for 20 years ($p_2^z = 0.9875$); the red dotted-dashed line also has the the regime-switching transfers process but the unstable stable regime is expected to last for 30 years ($p_2^z = 0.9917$); and the alternative distribution assumes that federal government transfers follow the projection of Congressional Budget Office (2019) for federal mandatory spending under current law.
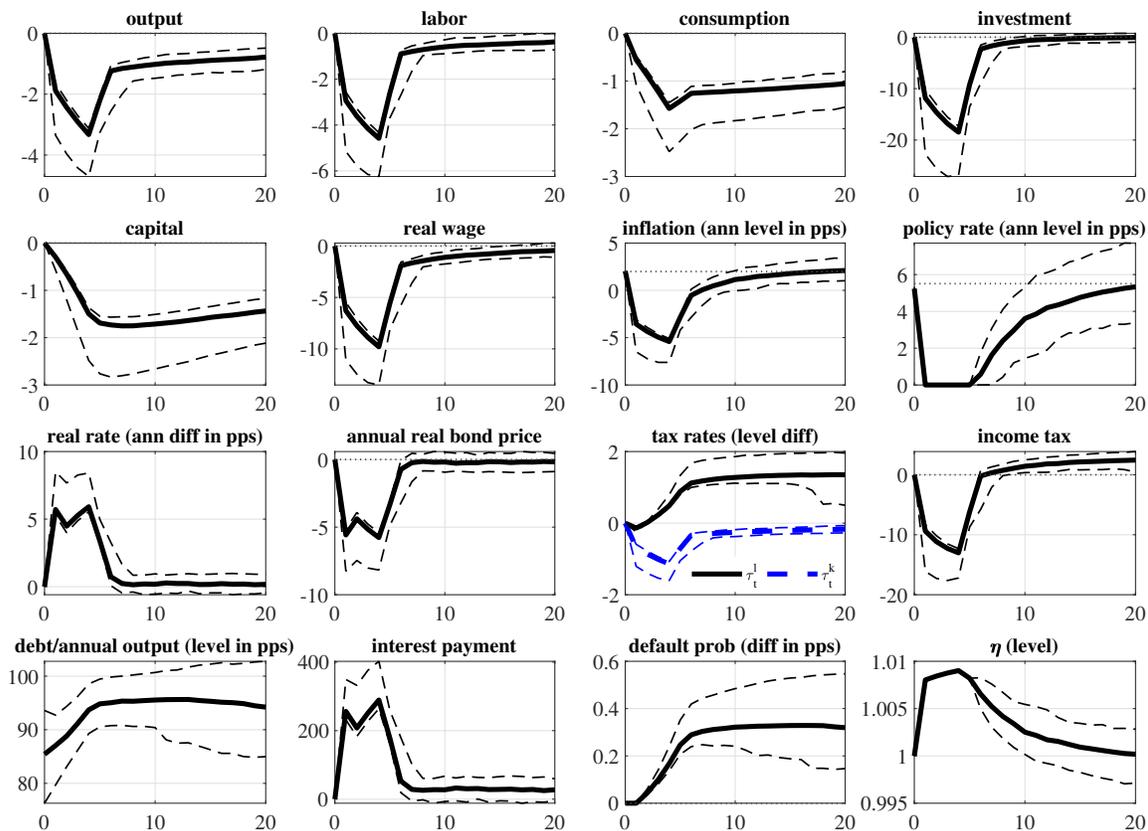
Figure 5: **Dynamics of interest rate normalization from the ZLB: the baseline analysis.** The responses (for those without a parenthesis) are plotted as the differences in percent of stochastic steady-state levels between the paths with and without financial shocks. The units of x-axes are in quarters. In parentheses for y-axis units, "ann" standards for annualized, "diff" for difference, and "pps" for percent points. The solid lines are the median responses of the 310 simulations that have government debt-to-annual output ratio at 90-100% at $t = 5$. The dashed lines are the 90-percent confidence intervals.
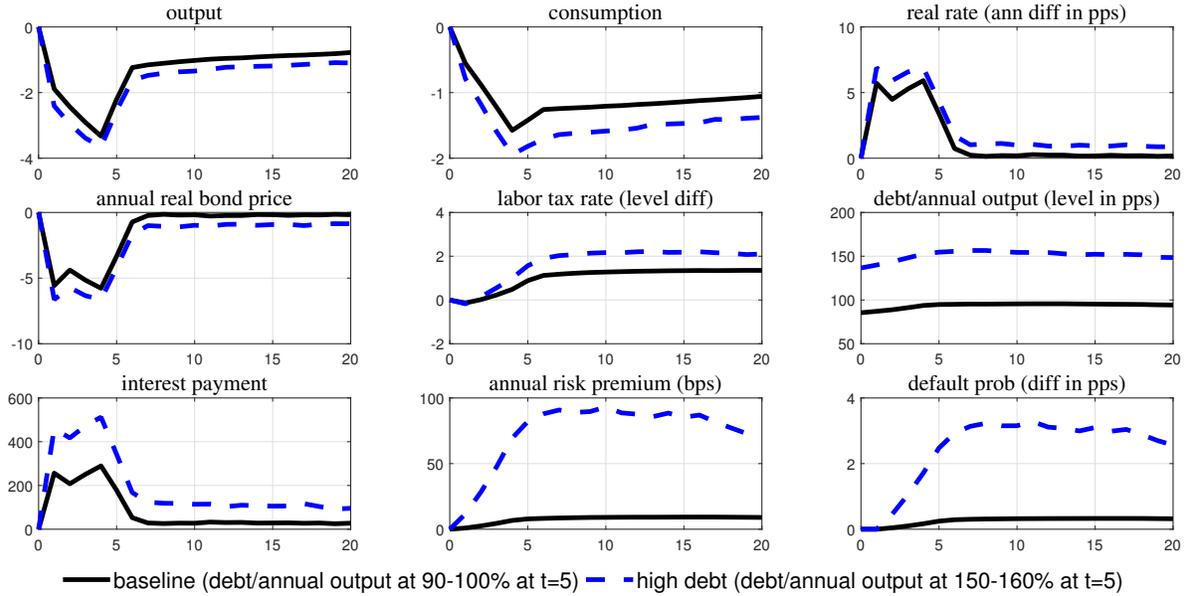
Figure 6: **Dynamics of interest rate normalization from the zero lower bound: different initial debt levels.** The solid lines are the same as the baseline responses in Figure 5. The dashed lines are the median responses of 110 simulations (among the 5000 simulations) that have government debt-to-annual output ratio at 150-160% at $t = 5$. See Figure 5 for axis unit description.
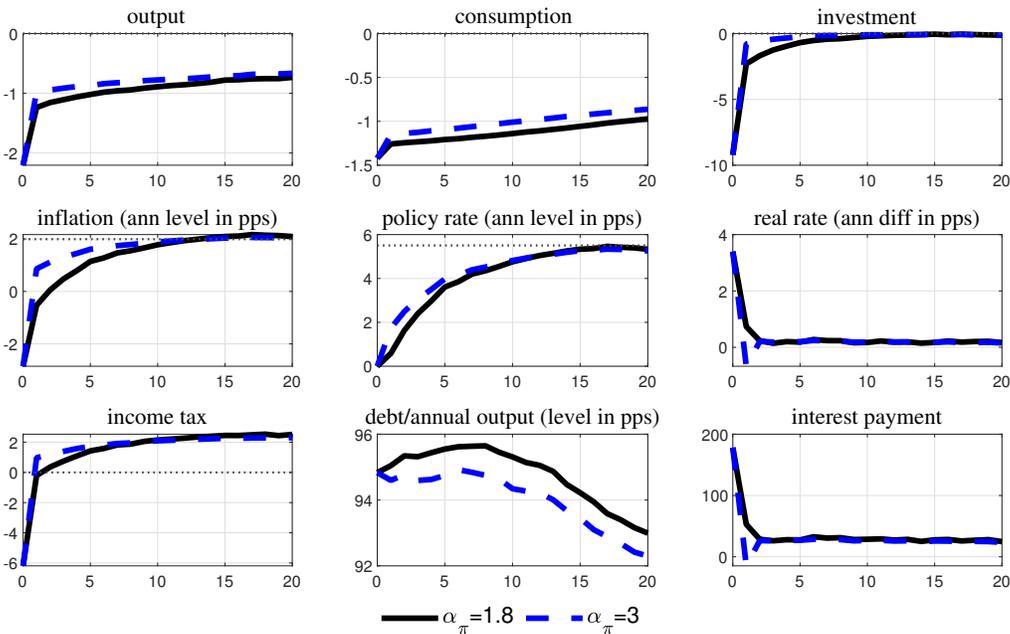

Figure 7: **Dynamics of interest rate normalization from the ZLB: activeness of monetary policy to inflation.** See Figure 5 for axis unit description.
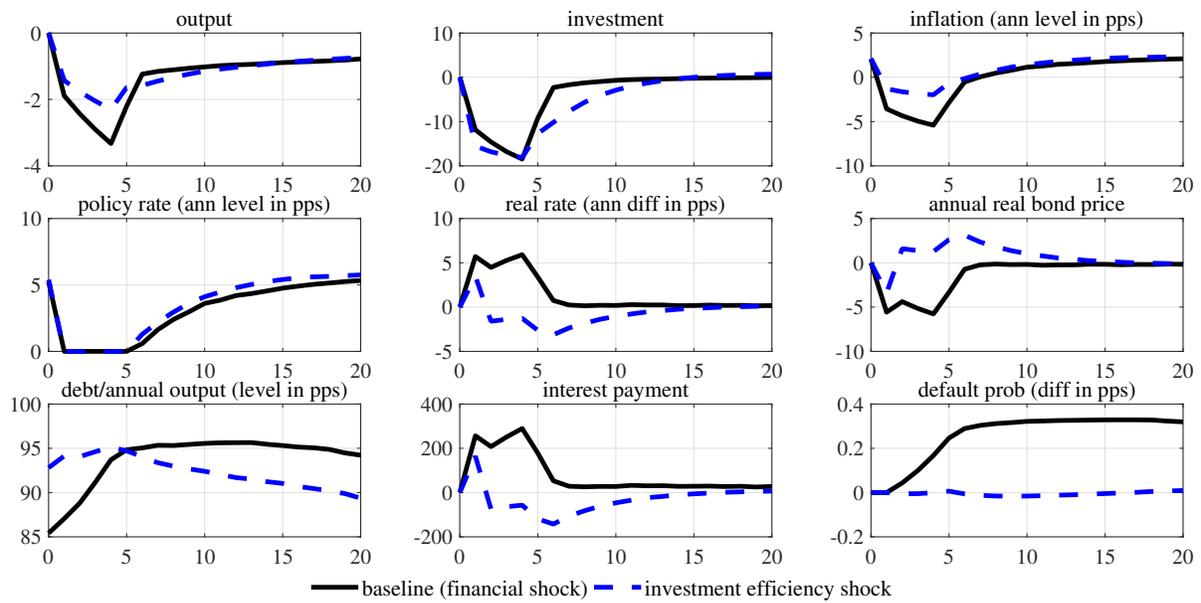
Figure 8: **Sensitivity analysis: the ZLB driven by the investment efficiency shock.** The responses are the median responses of simulations that have the debt ratio fall in 90-100% of annual output at $t = 5$. See Figure 5 for axis unit description.
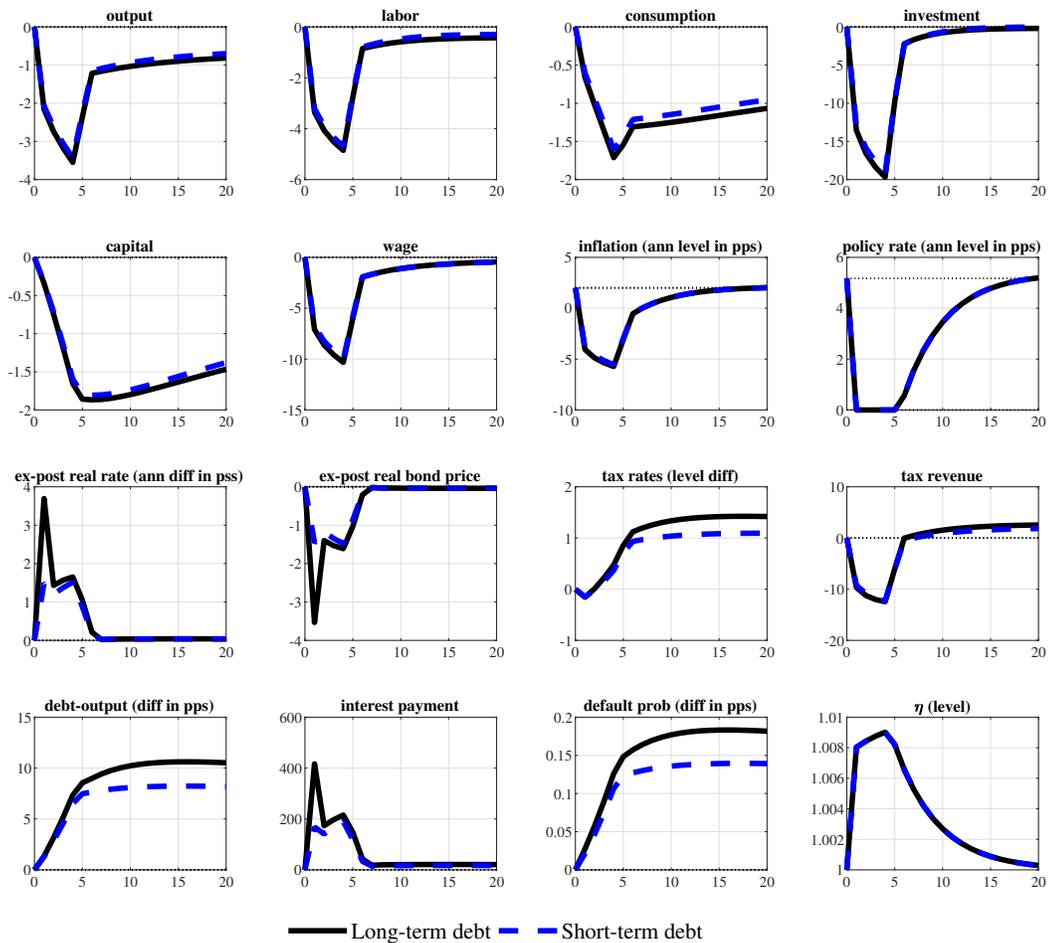
Figure 9: **Sensitivity analysis: a longer debt maturity.** The solid lines are the responses in the model with an average debt maturity of five years, and the dashed lines are responses to the model with a one-quarter short debt. See Figure 5 for axis unit description.
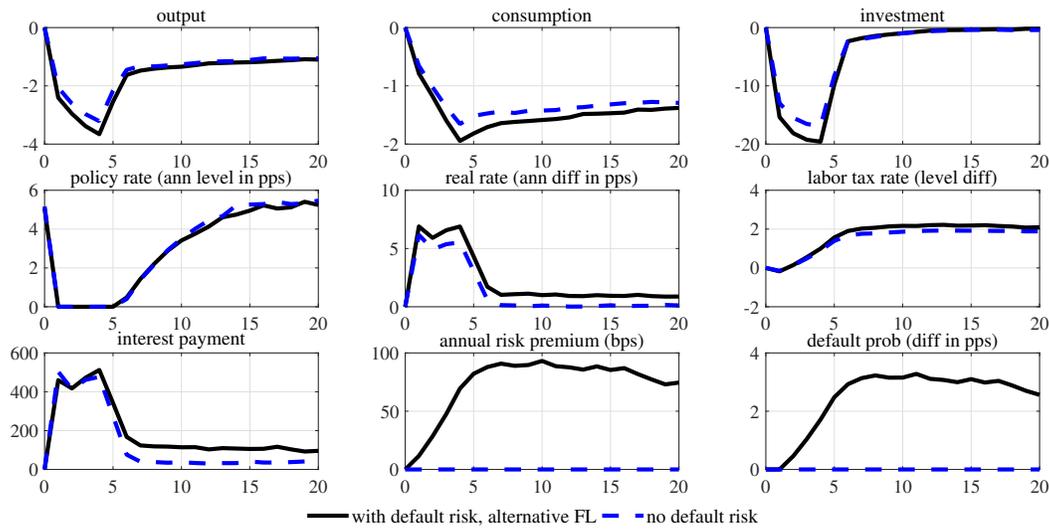
Figure 10: **Sensitivity analysis: the role of sovereign default risk in the high-debt state.** The responses are the median responses of simulations that have debt ratio fall in 90-100% of annual output at $t = 5$. See Figure 5 for axis unit description.
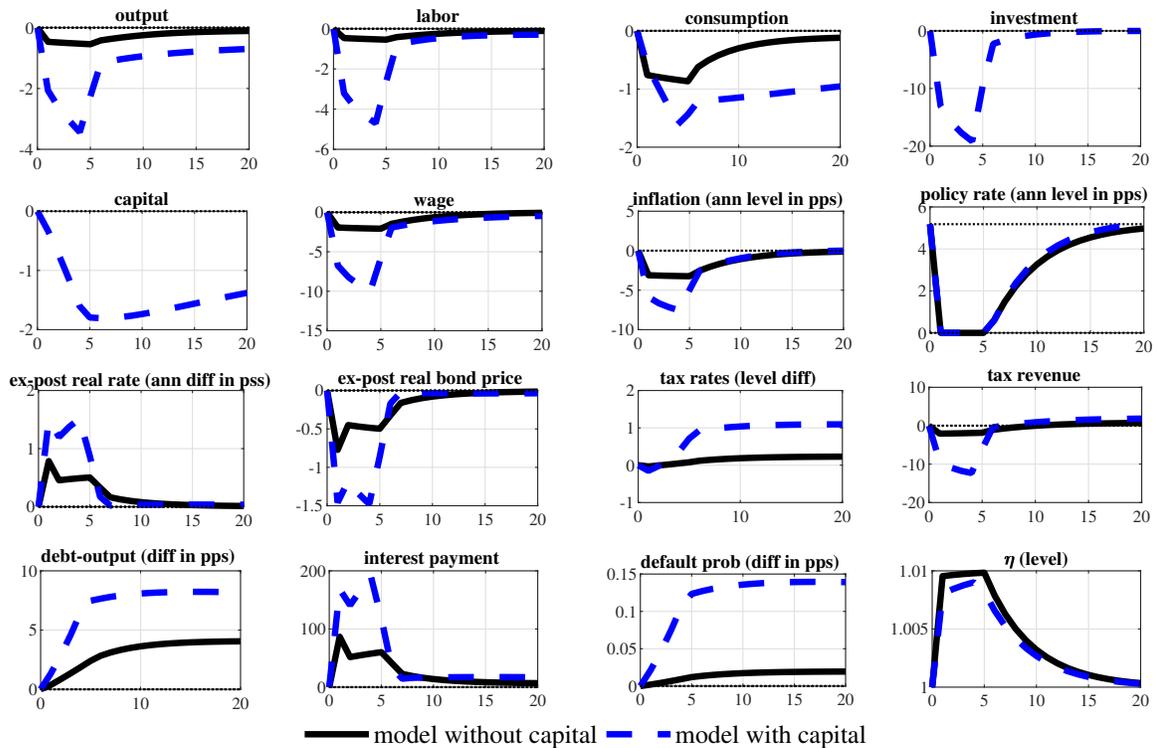

Figure 11: **Sensitivity analysis: a model without capitl.** The solid lines are the responses to the model without capital and the dashed lines are those to one with capital. See Figure 5 for axis unit description.

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