Unwinding Quantitative Easing: State Dependency and Household Heterogeneity*

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Abstract

This paper studies the asymmetry in the macroeconomic effects of central bank asset market operations induced by state dependency and the associated role of household heterogeneity. We build a New Keynesian model with borrowers and savers in which quantitative easing and tightening operate through portfolio rebalancing between short-term and long-term government bonds. We highlight the significance of an occasionally binding zero lower bound in explaining a weaker aggregate impact of asset sales relative to asset purchases. In this context, when close to the lower bound, raising the nominal interest rate prior to unwinding quantitative easing mitigates the economic costs of monetary policy normalization. Furthermore, our results imply that household heterogeneity in combination with state dependency amplifies the revealed asymmetry, while household heterogeneity alone does not enhance the aggregate effects of asset market operations.

JEL Classification: E21, E32, E52, E58

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1 Introduction

In recent years, large-scale asset purchases have considerably increased the size of central banks' balance sheets. Future crises might once more call for similar unconventional policy tools to stabilize the economy should interest rates fall back to low levels. Central banks therefore started to reduce their long-term bond holdings to preserve flexibility for future monetary stimulus. However, while various studies have investigated the macroeconomic implications of quantitative easing (QE)[1], the aggregate impact of unwinding QE remains largely unknown.

It seems reasonable to assume that balance sheet reductions do not necessarily result in macroeconomic effects that are equal but opposite to expansions. The economic environment is very different now that major central banks have started to reduce their balance sheets compared to when they were expanding them. For example, the Federal Reserve's unwind experience in 2017-2019 revealed strong asymmetries (Smith & Valcarcel, 2023). Bailey, Bridges, Harrison, Jones, and Mankodi (2020) and Haldane et al. (2016) argue that the effectiveness of unwinding can indeed be closely linked to the state of the economy and financial markets. Additionally, past asset purchases are expected to be unwound more gradually and the impact will depend on the interaction with policy rates (Vlieghe, 2018, 2021).

Understanding the implications of reducing the central bank balance sheet is key for the planning of monetary policy normalization. Due to the lack of empirical evidence on the subject, this issue has to be studied theoretically.

In this paper, we present a two-agent New Keynesian model with borrowers and savers (TANK-BS) that we use to study: i) the asymmetry between the macroeconomic effects of QE and quantitative tightening (QT) that is induced by state dependency in the form of a zero lower bound (ZLB) on the short-term nominal interest rate; and ii) how household heterogeneity influences this asymmetry. We define QT as the reduction of a central bank balance sheet through sales of assets back to the secondary market, aimed at decreasing the amount of liquidity within the economy. Our focus is on long-term bonds from the government only and we calibrate the model to the U.S. economy.

Similar to QE, tightening operates through different transmission mechanisms. This paper focuses on the portfolio balance channel. Asset purchases or sales by the central bank change the supply of assets held by the private sector, implying movements in relative asset prices and yields.[2] In our model, households can borrow and save in short-term and long-term government bonds. The imperfect substitutability between these securities allows the portfolio balance channel to be at work as investors value bonds differently along the yield curve.[3] Following Harrison (2017),

[1] See, e.g., Baumeister and Benati (2013), Haldane, Roberts-Sklar, Wieladek, and Young (2016), Joyce, Miles, Scott, and Vayanos (2012), Kapetanios, Mumtaz, Stevens, and Theodoridis (2012), and Weale and Wieladek (2016).

[2] Existing evidence shows that QE programs have indeed raised financial asset prices and lowered longer-term interest rates, often substantially. See, e.g., Christensen and Rudebusch (2012), Gagnon, Raskin, Remache, and Sack (2011), Greenwood and Vayanos (2014), Hamilton and Wu (2012), Joyce, Lasaosa, Stevens, and Tong (2011), and Krishnamurthy and Vissing-Jorgensen (2011).

[3] Several papers have highlighted the significance of portfolio rebalancing for the impact of QE (e.g., Christensen & Rudebusch, 2012; D'Amico & King, 2013; Froemel, Joyce, & Kaminska, 2022; Joyce et al., 2011). We deem this channel as equally important for large-scale asset sales as they also change the relative supply of assets in the

we use portfolio adjustment costs to capture this idea. The shifts in relative prices after an asset market operation incentivize investors to rebalance their portfolios. The associated costs affect average returns, which ultimately changes demand.

Consequently, large-scale asset sales affect bond returns, raising long-term interest rates and lowering short-term real rates. These changes impact the real economy through both household portfolio allocation shifts and general-equilibrium effects on real wages, leading to a drop in consumption. The *direct* effects of QT via the bond market have thereby a more persistent impact on consumption than the *indirect* effects through net labor income changes. A key difference between household types is countercyclical profit income, which positively affects savers' income, resulting in a smaller consumption drop compared to borrowers.

We examine the impact of QE and its unwind on aggregate variables such as consumption and real output, taking into account the state dependency induced by an occasionally binding ZLB. The purpose is to capture, in the simplest possible way, the markedly different state of the world when a central bank shrinks its balance sheet compared to when it expands it. Analogous to the fiscal policy literature, we find that a binding ZLB amplifies the macroeconomic effects of central bank asset market operations, which creates an asymmetry.[4] The short-term real interest rate response is larger and changes direction when the economy is in or near a liquidity trap. Specifically, a QT shock results in a short-term real rate decrease away from the ZLB, while the rate increases at the lower bound, further intensifying the initial decline in aggregate demand.

Two important implications arise from this result. First, when facing the risk of hitting the ZLB, raising the policy rate prior to initiating asset sales mitigates the economic costs associated with monetary policy normalization. We thus address the question of when central banks might ideally unwind QE. The likelihood of a liquidity trap increases if QT starts too early or if the tightening is executed too rapidly relative to the short-term rate normalization. Second, imposing that large-scale asset purchases have been predominantly executed at the ZLB in the past, our model suggests that QT has a smaller impact on the macroeconomy than QE. This asymmetry is entirely driven by the two distinct states of the economy and the (non-)availability of the short-term nominal interest rate as a policy tool.

The second aim of the paper is to study the interaction between the state dependency of QE/QT and household heterogeneity. The empirical literature provides some evidence of the heterogeneous effects of QE on households across the income distribution (Montecino & Epstein, 2015; Mumtaz & Theophilopoulou, 2017; Saiki & Frost, 2014). On the other hand, theoretical research yields mixed findinds. Cui and Sterk (2021) and Wu and Xie (2022) show sizable distributional

economy and the portfolio composition of households, thus implying potentially considerable real effects. Relatedly, see Andrés, López-Salido, and Nelson (2004) and Vayanos and Vila (2009, 2021) for the theoretical foundation of imperfect substitutability between assets along the yield curve and preferred-habitat theory, respectively.

[4] Away from the ZLB, the TANK-BS model is symmetric up to a first-order approximation. However, when considering higher-order solutions, additional non-linearities would emerge even off the ZLB, primarily driven by the presence of the borrowing constraint and the resulting wedge in borrowers' Euler equation. Importantly, such non-linearities would not be exclusive to QE or QT but apply to any shock affecting the income of borrowers and go in the same direction as the state dependency coming from the ZLB. We therefore abstract from them and indicate that the respective results presented in this paper should be considered as a lower bound of the possible asymmetry between the impact of QE and QT.

implications, while Sims, Wu, and Zhang (2022) report no amplification of QE via heterogeneity.

Our results indicate that household heterogeneity alone does not amplify the aggregate effects of asset market operations when the economy is off the ZLB. This lack of amplification arises from a composition effect of changes in the balance sheets of the two household types, and these changes largely cancel out when transitioning from a standard representative-agent New Keynesian (RANK) to the TANK-BS model. In TANK-BS, borrowers replace part of the savers in the population, diminishing savers' relative contribution to total spending. Following a QT shock, the attenuated drop in aggregate demand is offset by a reduction in the labor income of borrowers, who have a larger marginal propensity to consume (MPC). The net effect is nearly neutral. Profit income remains essential as a greater proportion of savers reduces the benefit each agent receives from increased countercyclical firm earnings. In contrast, household heterogeneity combined with state dependency amplifies the aggregate impact of asset market operations. When asset sales occur at the ZLB, the direct and indirect effects on borrowers lead to a more pronounced decline in the labor income of these high-MPC agents compared to the decrease in spending contributed by savers.

Related literature. This paper aligns with the literature that merges earlier work on QE in RANK frameworks with the more established strand on the effects of conventional monetary policy in heterogeneous-agent models (Cui & Sterk, 2021; Nisticò & Seccareccia, 2022; Sims et al., 2022; Sims, Wu, & Zhang, 2023; Wu & Xie, 2022).[5] Unlike most of these papers, we do not consider leverage constraints on financial intermediaries engaging in bond maturity transformation. We emphasize instead the effects of asset market operations on household balance sheets and the portfolio balance channel. In Cui and Sterk (2021), the impact of QE on the macroeconomy also emerges from the household side. They employ a heterogeneous-agent model with liquid and illiquid wealth, focusing on the different MPCs out of the two wealth types. We use a simpler setup, with only two agent types as in Eggertsson and Krugman (2012) or Bilbiie, Monacelli, and Perotti (2013), and abstract from illiquid assets, while examining the impact of QE on household bond positions at various maturities. Nonetheless, our model is able to quantitatively replicate the impact of QE on economic aggregates reported in Cui and Sterk (2021). The two-agent setup is also found in Nisticò and Seccareccia (2022), Sims et al. (2023), and Wu and Xie (2022), but with notable differences. In contrast to them, we allow both agents to have direct access to short-term and long-term bonds. Additionally, while the constrained household in Sims et al. (2023) and Wu and Xie (2022) receives no labor income, we stress the importance of the indirect, general-equilibrium effect of asset purchases on borrowers' labor earnings.[6] This effect is central to our finding that QE lacks amplification through household heterogeneity. Crucially, while the result on amplification is consistent with Sims et al. (2022), the explanation differs. In their framework, it arises because

[5]From a theoretical standpoint, QE has primarily been explored in RANK setups (e.g., Chen, Cúrdia, & Ferrero, 2012; Falagiarda, 2014; Gertler & Karadi, 2013; Harrison, 2012, 2017; Harrison, Seneca, & Waldron, 2021; Sims & Wu, 2021). Meanwhile, much of the literature on household heterogeneity and monetary policy has largely focused on conventional monetary policy (e.g., Auclert, 2019; Bilbiie, 2008, 2020; Kaplan, Moll, & Violante, 2018).

[6]This channel is also present in Nisticò and Seccareccia (2022), but their primary focus is on highlighting the cyclical-inequality and idiosyncratic-inequality channels, which are both absent in our setup.

only a few households at the bottom of the wealth distribution behave differently from the average household, by increasing their consumption significantly in response to a QE shock. Since these agents represent a very small share of the population in the economy, their impact on aggregate consumption remains marginal. Lastly, unlike Cui and Sterk (2021), Sims et al. (2022), and Wu and Xie (2022), we are interested not only in the role of heterogeneity for QE and QT, but also in the state dependency induced by the ZLB, a factor abstracted from in these studies.[7] Although both Nisticò and Seccareccia (2022) and Sims et al. (2023) study the implications of the ZLB for QE, they do not focus on the asymmetry relative to QT.

Turning specifically to QT, we also relate to recent theoretical work by Airaudo (2023), Benigno and Benigno (2022), Cui and Sterk (2021), Karadi and Nakov (2021), and Wei (2022). Cui and Sterk (2021) analyze the speed of QE exit, captured by the policy's persistence in the model. They demonstrate that a faster exit results in a lower real impact as agents anticipate the associated dampening effects. However, by keeping the nominal interest rate pegged, they do not examine the interaction between conventional and unconventional monetary policy. Karadi and Nakov (2021) investigate the optimal conditions for exiting QE in a model in which bank balance sheet constraints bind only occasionally, making asset purchases not always effective. Unlike them, we do not conduct a normative analysis and highlight the implications of asset market operations through household portfolio rebalancing. Wei (2022) employs the preferred-habitat model of Vayanos and Vila (2021) to quantify how many interest rate hikes QT is equivalent to. Our focus, however, is on the macroeconomic consequences, exploring the interaction of balance sheet operations with conventional monetary policy instead of treating the two as substitutes. A similar idea is proposed by Benigno and Benigno (2022) who explore optimal monetary policy normalization strategies when exiting a liquidity trap. While they consider reserves as an additional tool apart from the policy rate to influence macroeconomic aggregates, we simplify the central bank balance sheet by disregarding liquidity and emphasize the transmission through portfolio rebalancing. In contrast to our finding, their analysis suggests that efforts to reduce the balance sheet should ideally begin prior to raising the policy rate. This conclusion follows from the impact of active reserves management on the liquidity premium in their model, which mitigates output losses from QT. However, it is important to note that their exercise differs substantially from ours. We compare different states of the world in which QE or QT might occur, whereas they study initial asset purchases and their subsequent unwind in an optimal policy framework, making a direct comparison difficult. Airaudo (2023) studies the role of fiscal-monetary policy interactions for the macroeconomic effects of QT. While that paper allows for regime changes in the policy rules of fiscal and monetary authorities, we assume a passive role for fiscal policy and restrict the analysis to two states determined by the presence of the ZLB.

Finally, this work is related and motivated by the policy debate regarding state-dependent QE or QT and possible asymmetries between their effects. Policymakers have extensively discussed the potential causes and implications of state dependency, primarily focusing on different finan-

[7] Cui and Sterk (2021) assume in their model simulations for QE that the interest rate is pegged at zero. However, they do not compare simulations with and without the peg.

cial market conditions (Bailey et al., 2020; Haldane et al., 2016; Vlieghe, 2021). To maintain tractability and due to our focus on household portfolio composition, we abstract in this paper from financial markets and instead highlight the state dependency induced by the ZLB.[8]

In summary, this paper contributes to the existing literature along three lines. First, to the best of our knowledge, we are the first to study the asymmetry of QT relative to QE effects induced by state dependency, addressing a gap in theoretical exploration of this aspect. Second, our approach to analyzing state dependency is relatively simple but allows us to isolate the unequal consequences of the ZLB, starting from a scenario where QE and QT have symmetric effects. The model also includes access to the same assets for both household types, whereas comparable studies assume segmented bond markets. Third, we do this within the simplest possible framework that still accounts for heterogeneity, emphasizing the dynamics of household balance sheets and their implications for asset market operations through portfolio rebalancing. We thereby particularly stress the significance of indirect, general-equilibrium effects via labor income when constrained agents are considered.

Outline. The remainder of the paper is organized as follows. Section 2 presents the TANK-BS model economy and describes the calibration and the solution method. Section 3 discusses the simulation results and their robustness. Finally, Section 4 concludes.

2 Asset market operations in a borrower-saver model

This section presents the main elements of the model used for our analysis. Further details on the derivation, a description of the steady state, and an overview of all model equations can be found in Appendix A.

The model economy consists of four sectors: households, firms, a government, and a central bank. The household sector is populated by two agent types, savers and borrowers, who differ in their degree of patience, modeled as in Bilbiie et al. (2013) and Eggertsson and Krugman (2012). Firms are modeled as in standard New Keynesian models, with nominal frictions that generate sticky prices. The government finances public spending by issuing bonds and levying lump-sum taxes, while also implementing redistributive policies by taxing firm profits. Finally, the monetary authority sets the nominal interest rate according to a Taylor rule and participates in the long-term bond market, with asset market operations designed as in Harrison (2017). The discussion below mainly focuses on describing the household sector and the policy block, which deviate somewhat from conventional models.

[8]Concerning asymmetries, our analysis is also related to the idea held by policymakers that QT is likely to impact the economy less than QE. Potential explanations for this view include a milder reaction of bond markets, as observed during the Federal Reserve's 2017-2019 unwind (Neely, 2019), the disappearance of the signaling effects of asset market operations once policy rates are well above zero (Bullard, 2019), or differences in the nature and scope of QE/QT episodes and the prevailing economic and financial conditions (Smith & Valcarcel, 2023; Vlieghe, 2018, 2021).

2.1 Households

There is a continuum of households with a share λ being borrowers (B) who are constrained in terms of how much they can borrow. The remaining $1-\lambda$ are savers (S) with unconstrained access to asset markets. Borrowers are assumed to be less patient than savers, such that $\beta^S > \beta^B$. As will become clear later, this difference in the discount factors will induce lending from S to B in equilibrium.

The period utility function of household type $j = \{B, S\}$ is given by

$$U\left(c_t^j, N_t^j\right) = \theta_t \left(\frac{(c_t^j)^{1-\frac{1}{\sigma}}}{1-\frac{1}{\sigma}} - \zeta^j \frac{(N_t^j)^{1+\varphi}}{1+\varphi} \right),$$

where c_t is real consumption, N_t are hours worked, θ_t is a preference shock that follows an AR(1) process, σ is the elasticity of intertemporal substitution, $1/\varphi$ is the Frisch elasticity of labor supply, and ζ indicates how leisure is valued relative to consumption.

Households have access to bonds issued by the government. Following Harrison (2017), we differentiate between short-term and long-term nominal bonds. The former are one-period assets: a bond with real value b_{t-1}^j purchased in period $t-1$ pays a real return $r_{t-1} = R_{t-1}/\Pi_t$ at time t, where R is the gross nominal interest rate and $\Pi_t = P_t/P_{t-1}$ is the gross inflation rate. On the other hand, we assume that long-term government debt is captured by perpetuities with coupon payments that decay exponentially over time, as in Woodford (2001). Denoting by $\widetilde{B}_t^{j,L}$ the long-term nominal bond holdings of household j and by V_t the nominal price of each of these bonds, we can write the value of long-term bond holdings as $B_t^{j,L} = V_t \widetilde{B}_t^{j,L}$. A bond issued today pays the sequence of nominal coupons $1, \chi, \chi^2, \ldots$ from tomorrow, where $\chi \in [0,1]$ is the coupon decay rate. Using this, we can define the nominal one-period return on long-term bonds as $R_t^L = (1 + \chi V_t)/V_{t-1}$. This formulation allows us to express the long-term asset in the budget constraint of households in terms of a single stock variable and a single bond return rather than having to keep track of issued bonds and their prices over time. In real terms, a long-term bond $b_{t-1}^{j,L}$ pays $r_t^L = R_t^L/\Pi_t$ in interest one period later.

Households face portfolio adjustment costs whenever they change the allocation of their assets between short-term and long-term bonds. In the style of Chen et al. (2012) and Harrison (2017), this adjustment cost is specified as

$$\Psi_t^j = \frac{\nu}{2} \left(\delta^j \frac{b_t^j}{b_t^{j,L}} - 1 \right)^2,$$

where $\delta^j = b^{j,L}/b^j$ is the steady-state ratio of long-term bonds to short-term bonds and $\nu > 0$ captures how costly deviations from a household's preferred steady-state portfolio mix are.[9]

Introducing adjustment costs implies a direct role for asset market operations to stimulate the

[9]The proposed adjustment cost function only captures the impact of changes in the relative supply of an asset and thus deviations from a household's desired portfolio composition (stock effects), which is the focus of much of the literature. Harrison (2017) or Harrison et al. (2021) also address the impact of fundamental changes in the portfolio mix (flow effects).

economy, namely through the portfolio balance channel. If the central bank purchases bonds of a specific maturity, it thereby lowers the relative supply of those assets and so increases their price. Investors will rebalance their portfolios, which is costly due to the presence of Ψ and affects their average portfolio returns, thus implying a real impact through changes in individual and aggregate demand.[10] The adjustment cost captures in a parsimonious way the preferred-habitat theory which assumes that investors have preferences for specific maturities (Vayanos & Vila, 2009, 2021). In other words, these agents view different assets along the yield curve as imperfect substitutes (Andrés et al., 2004).

Before turning to the detailed description of each household type, it is important to highlight two key assumptions regarding their access to bond and labor markets. First, other two-agent models in the literature typically assume a distinct bond market access for each type of household, with constrained households trading in only one asset without transaction costs (Chen et al., 2012; Nisticò & Seccareccia, 2022; Sims et al., 2023; Wu & Xie, 2022). In our setup, both types can save in short-term and long-term bonds alike, which ensures as much symmetry as possible within the household sector and thus rules out any distortionary forces other than a borrowing limit. Second, contrary to Sims et al. (2023) and Wu and Xie (2022) but similar to Nisticò and Seccareccia (2022), borrowing-constrained agents participate in the labor market and earn labor income. This assumption proves crucial for the propagation of monetary policy shocks in our model, implying general-equilibrium effects via the labor market, as discussed in Section 3.1.

2.1.1 Savers

Unconstrained agents can save and borrow in both short-term and long-term bonds and receive dividends from their shareholdings in monopolistically competitive firms. Apart from these asset returns, savers also earn labor income and pay taxes. They each maximize their lifetime utility from consumption and leisure subject to their budget constraint in real terms, taking prices and wages as given:

$$\max_{c_t^S, N_t^S, b_t^S, b_t^{S,L}} \mathbb{E}_t \sum_{t=0}^{\infty} \left(\beta^S\right)^t \theta_t \left(\frac{(c_t^S)^{1-\frac{1}{\sigma}}}{1-\frac{1}{\sigma}} - \zeta^S \frac{(N_t^S)^{1+\varphi}}{1+\varphi} \right) \quad \text{subject to}$$

$$c_t^S + b_t^S + b_t^{S,L} = r_{t-1} b_{t-1}^S + r_t^L b_{t-1}^{S,L} + w_t N_t^S + \frac{1-\tau^D}{1-\lambda} d_t - t_t - \Psi_t^S - \frac{tr}{1-\lambda} ,$$

where b_t^S and $b_t^{S,L}$ are the real values of short-term and long-term nominal government bonds held by a saver, respectively, with corresponding interest rates r and r^L. Furthermore, w_t is the real wage, d_t are real dividends from firm profits equally distributed to savers, t_t are real lump-sum taxes levied by the government, Ψ_t^S are portfolio adjustment costs described above, and tr are steady-state transfers from savers to hand-to-mouth agents that ensure consumption equality

[10] Asset market operations prove to be ineffective in baseline New Keynesian models. Changes in the portfolio allocation of households have no impact on real economic variables as shown, among others, by Eggertsson and Woodford (2003).

between the two household types in steady state.[11] The profits of intermediate firms that are owned by savers are taxed at a rate of τ^D. The government redistributes the tax revenues as a direct transfer to constrained households.

Solving the decision problem results in the following consumption-leisure choice condition and Euler equations for short-term and long-term bonds, respectively:

$$
\begin{aligned}
w_t &= \zeta^S\,(N_t^S)^{\varphi}\,(c_t^S)^{\frac{1}{\sigma}}\,,\\
1 &= \beta^S R_t\,\mathbb{E}_t\left[\frac{\theta_{t+1}}{\theta_t}\left(\frac{c_{t+1}^S}{c_t^S}\right)^{-\frac{1}{\sigma}}\frac{1}{\Pi_{t+1}}\right]-\frac{\nu\,\delta^S}{b_t^{S,L}}\left(\delta^S\,\frac{b_t^S}{b_t^{S,L}}-1\right)\,,\\
1 &= \beta^S\,\mathbb{E}_t\left[\frac{\theta_{t+1}}{\theta_t}\left(\frac{c_{t+1}^S}{c_t^S}\right)^{-\frac{1}{\sigma}}\frac{R_{t+1}^L}{\Pi_{t+1}}\right]+\frac{\nu\,\delta^S\,b_t^S}{\left(b_t^{S,L}\right)^2}\left(\delta^S\,\frac{b_t^S}{b_t^{S,L}}-1\right)\,.
\end{aligned}
$$

2.1.2 Borrowers

Constrained households have access to both types of government bonds as well and consume their disposable income together with transfers (net of taxes) from the government. Different from savers, they face a borrowing constraint such that the total value of bonds borrowed in each period cannot exceed a given limit. Each borrower therefore solves the following problem:

$$
\max_{c_t^B,N_t^B,b_t^B,b_t^{B,L}}\ \mathbb{E}_t\sum_{t=0}^{\infty}\left(\beta^B\right)^t\,\theta_t\left(\frac{(c_t^B)^{1-\frac{1}{\sigma}}}{1-\frac{1}{\sigma}}-\zeta^B\,\frac{(N_t^B)^{1+\varphi}}{1+\varphi}\right)\quad\text{subject to}
$$

$$
\begin{aligned}
&c_t^B+b_t^B+b_t^{B,L}\le r_{t-1}\,b_{t-1}^B+r_t^L\,b_{t-1}^{B,L}+w_t\,N_t^B+\frac{\tau^D}{\lambda}d_t-t_t-\Psi_t^B+\frac{tr}{\lambda}\,,\\
&-b_t^B-b_t^{B,L}\le\overline{D}\,,
\end{aligned}
$$

where $\overline{D}\ge 0$ is the exogenous borrowing limit. We assume that this constraint binds for all periods and borrowers thus have a high MPC out of a transitory income shock.

Apart from the debt constraint, the optimality conditions are very similar to those of the savers, namely

$$
\begin{aligned}
w_t &= \zeta^B\,(N_t^B)^{\varphi}\,(c_t^B)^{\frac{1}{\sigma}}\,,\\
1 &= \beta^B R_t\,\mathbb{E}_t\left[\frac{\theta_{t+1}}{\theta_t}\left(\frac{c_{t+1}^B}{c_t^B}\right)^{-\frac{1}{\sigma}}\frac{1}{\Pi_{t+1}}\right]-\frac{\nu\,\delta^B}{b_t^{B,L}}\left(\delta^B\,\frac{b_t^B}{b_t^{B,L}}-1\right)+\psi_t^B\,\theta_t^{-1}\,(c_t^B)^{\frac{1}{\sigma}}\,,\\
1 &= \beta^B\,\mathbb{E}_t\left[\frac{\theta_{t+1}}{\theta_t}\left(\frac{c_{t+1}^B}{c_t^B}\right)^{-\frac{1}{\sigma}}\frac{R_{t+1}^L}{\Pi_{t+1}}\right]+\frac{\nu\,\delta^B\,b_t^B}{\left(b_t^{B,L}\right)^2}\left(\delta^B\,\frac{b_t^B}{b_t^{B,L}}-1\right)+\psi_t^B\,\theta_t^{-1}\,(c_t^B)^{\frac{1}{\sigma}}\,,
\end{aligned}
$$

where $\psi_t^B\ge 0$ is the Lagrangian multiplier on the borrowing constraint, with complementary

[11] We use a symmetric steady state with $c^B=c^S=c$ as a benchmark, modeled similar to Bilbiie, Känzig, and Surico (2022).

slackness condition $\psi_t^B \left(b_t^B + b_t^{B,L} + \bar{D} \right) = 0$. If the constraint is binding, $\psi_t^B > 0$ so that the marginal utility of consuming today is larger than the expected marginal utility of saving in any of the two bonds. As a result, the presence of the borrowing constraint creates a divergence in the Euler equation of borrowers, thereby influencing their decision rule as the constraint either slackens or tightens.

2.2 Firms

The firm sector is standard and features two different types of agents: monopolistically competitive intermediate goods producers and perfectly competitive final goods firms.

Final goods producers. The final goods sector aggregates differentiated intermediate goods according to a CES production function:

$$y_t = \left(\int_0^1 y_t(i)^{\frac{\varepsilon-1}{\varepsilon}} \, di \right)^{\frac{\varepsilon}{\varepsilon-1}} ,$$

where ε is the elasticity of substitution. Final goods producers maximize their profits, resulting in a demand for each intermediate input of

$$y_t(i) = \left(\frac{P_t(i)}{P_t} \right)^{-\varepsilon} y_t \, ,$$

where $P_t(i)$ is the price of intermediate good i and $P_t^{1-\varepsilon} = \int_0^1 P_t(i)^{1-\varepsilon} \, di$ the aggregate price index.

Intermediate goods producers. Varieties of intermediate goods i are produced by a continuum of monopolistically competitive firms with production function $y_t(i) = z_t N_t(i)$, where technology z_t follows an AR(1) process. Cost minimization implies real marginal costs $mc_t = w_t / z_t$.

Intermediate goods firms set prices subject to a quadratic adjustment cost à la Rotemberg (1982) with the degree of nominal price rigidity governed by ϕ_p:

$$\Psi_t^p = \frac{\phi_p}{2} \left(\frac{P_t(i)}{P_{t-1}(i)} - 1 \right)^2 y_t \, .$$

Following Bilbiie (2020), we also assume that the government imposes an optimal subsidy on sales, τ^S, to induce marginal cost pricing in steady state. This subsidy is financed by a lump-sum tax on firms such that $t_t^F = \tau^S y_t$. Thus, the real profits of each intermediate goods producer i are given by

$$d_t(i) = \left(1 + \tau^S \right) \frac{P_t(i)}{P_t} y_t(i) - w_t N_t(i) - \Psi_t^p - t_t^F \, .$$

The solution to the price-setting problem leads to the standard Phillips curve:

$$\left(1 + \tau^S \right) (1 - \varepsilon) + \varepsilon \, mc_t - \phi_p \left(\Pi_t - 1 \right) \Pi_t + \beta^S \mathbb{E}_t \left[\frac{\theta_{t+1}}{\theta_t} \left(\frac{c_{t+1}^S}{c_t^S} \right)^{-\frac{1}{\sigma}} \phi_p \left(\Pi_{t+1} - 1 \right) \Pi_{t+1} \frac{y_{t+1}}{y_t} \right] = 0 \, .$$

Abstracting from price adjustment costs, the optimal subsidy that induces marginal cost pricing turns out to be $\tau^S = (\varepsilon - 1)^{-1}$. Finally, using the expression for the lump-sum tax and aggregating over firms yields total real profits:

$$d_t = \left[1 - mc_t - \frac{\phi_p}{2}(\Pi_t - 1)^2\right] y_t \ .$$

2.3 Government and Monetary Policy

Monetary and fiscal policy are combined in one entity. The government budget constraint is given by

$$b_t + b_t^L = r_{t-1}\, b_{t-1} + r_t^L\, b_{t-1}^L + \Omega_t + g_t - t_t \ ,$$

where b_t and b_t^L are the real values of short-term and long-term nominal bonds issued by the government, respectively, Ω_t are net purchases of long-term bonds by the central bank, and g_t is real government spending which follows an AR(1) process. Subsidy expenses and tax revenues from firm profits are balanced in every period and thus do not appear in the budget constraint above.

We assume that lump-sum taxes are set by the following rule:

$$\frac{t_t}{t} = \left(\frac{t_{t-1}}{t}\right)^{\rho^{\tau,t}} \left(\frac{b_t + b_t^L}{b + b^L}\right)^{\rho^{\tau,b}} \left(\frac{g_t}{g}\right)^{\rho^{\tau,g}} \ .$$

Moreover, the total supply of long-term bonds follows an AR(1) process:

$$\log\left(\frac{b_t^L}{b^L}\right) = \rho_{bL} \log\left(\frac{b_{t-1}^L}{b^L}\right) + \varepsilon_t^{b^L} \ .$$

Turning to the central bank, net asset purchases of long-term bonds are defined as

$$\Omega_t = b_t^{CB,L} - r_t^L\, b_{t-1}^{CB,L} \ ,$$

where $b_t^{CB,L}$ denotes the real value of long-term nominal bonds purchased by the central bank. Incorporating central bank asset purchases into the consolidated budget constraint, following Harrison (2017), implies that asset market operations are financed by the central government, which can pay for them through either tax revenues from households or the issuance of new short-term debt. This assumption has crucial implications for the interplay of monetary and fiscal policies in our model.

Importantly, the central bank has two policy tools. First, it conducts QE or QT by deciding on which fraction q_t of the total market value of long-term bonds to buy or sell, respectively:

$$b_t^{CB,L} = q_t\, b_t^L \ ,$$

where we model q_t as a AR(1) process:

$$\log\left(\frac{q_t}{q}\right) = \rho_q \log\left(\frac{q_{t-1}}{q}\right) + \varepsilon_t^q \ .$$

Apart from asset market operations, the monetary authority can implement conventional monetary policy by setting the short-term nominal interest rate, R, according to a standard Taylor rule:

$$\log\left(\frac{R_t}{R}\right) = \rho_r \log\left(\frac{R_{t-1}}{R}\right) + (1-\rho_r)\left[\phi_\pi \log\left(\frac{\Pi_t}{\Pi}\right)\right] + \varepsilon_t^m \ ,$$

where ε_t^m is an i.i.d. policy shock. Having both conventional and unconventional monetary policy tools simultaneously available in the central bank's toolkit allows us to study their interaction, which will prove crucial for understanding the asymmetry in the macroeconomic effects of asset market operations.

2.4 Aggregation and market clearing

Aggregate consumption and aggregate hours are given by

$$c_t = \lambda c_t^B + (1-\lambda) c_t^S \ ,$$
$$N_t = \lambda N_t^B + (1-\lambda) N_t^S \ .$$

Market clearing for short-term and long-term bonds, respectively, requires

$$b_t = b_t^H \ ,$$
$$b_t^L = b_t^{H,L} + b_t^{CB,L} \ ,$$

with households' total demand for short-term bonds $b_t^H = \lambda b_t^B + (1-\lambda) b_t^S$ and for long-term bonds $b_t^{H,L} = \lambda b_t^{B,L} + (1-\lambda) b_t^{S,L}$. By using the equation for asset market operations, we can write $b_t^{H,L} = (1-q_t) b_t^L$. This condition shows the direct impact of asset purchases and sales on long-term bond holdings and hence the portfolio mix of households.[12]

Finally, the aggregate resource constraint is given by

$$y_t = c_t + g_t + \frac{\phi_p}{2}(\Pi_t - 1)^2 y_t \ .$$

2.5 Steady state

We approximate our model around a deterministic steady state with zero net inflation and output normalized to one. Our assumption $\beta^S > \beta^B$ implies that the borrowing constraint will always

[12]In Appendix A.1, we derive a no-arbitrage condition between short-term and long-term bonds. It shows that changes in households' portfolio composition caused by central bank asset market operations directly affect the long-term bond return, namely due to the presence of the portfolio adjustment cost.

bind in steady state:

$$\psi^B = \left(c^B\right)^{-\frac{1}{\sigma}} \left[1 - \frac{\beta^B}{\beta^S}\right] > 0\,.$$

As a result, patient (impatient) agents will be net lenders (borrowers) in steady state.

The Euler equations of the saver yield for the nominal rates that $R = R^L = \left(\beta^S\right)^{-1}$ and we have $r = R$ and $r^L = R^L$. The presence of the optimal subsidy to firms implies zero profits ($d = 0$). Furthermore, we assume that labor supply is equalized across households ($N^B = N^S = N$) such that they will consume the same in steady state ($c^B = c^S = c$).

Regarding the steady-state ratio of bond holdings, δ^j, we impose the simplifying assumption that they are equal across household types such that individual demand variables can be replaced by their household-level counterparts:

$$\delta^S = \delta^B = \delta = \frac{b^{H,L}}{b^H}\,.$$

We further define $\tilde{\delta} = b^L/b$ as the steady-state ratio between total long-term and short-term bonds. Finally, portfolio and price adjustment costs will be zero at steady state.

2.6 Calibration and simulation setup

Our calibration is summarized in Table 1. We target the case of the U.S. economy.

The parameters for the household sector are mostly taken from Bilbiie et al. (2013) who build a borrower-saver model similar to ours. In particular, we target a steady-state real interest rate of 4% annually. The baseline value for the savers' discount factor is therefore set to 0.99. Regarding the production side, it is worth mentioning that we set taxes on profits to zero in order to rule out any impact from redistribution on the income of borrowers.

For the bond-related parameters, we choose $\chi = 0.975$ to match a duration of long-term bonds of slightly more than seven years in the non-stochastic steady state, following Harrison (2017) and Harrison et al. (2021). This value matches the average duration of ten-year U.S. Treasury bonds as in D'Amico and King (2013) and is also used by Sims et al. (2022). We thus consider the long-term asset as a ten-year bond, but χ can also be increased to study longer maturities or durations. The adjustment cost parameter ν is chosen such that the model matches the empirical evidence by Weale and Wieladek (2016) on the impact of a QE shock on real output, as discussed hereafter. Finally, the value of the central bank's long-term bond holdings in steady state implies that households hold a share of 0.75, namely three-quarters of the stock of long-term debt, which is equivalent to the calibration in Gertler and Karadi (2013) and Karadi and Nakov (2021).

Output is normalized to one in steady state, while the target for net inflation is 0%, in line with Cui and Sterk (2021). Moreover, the persistence of the preference shock is set to 0.8, a high value as is common in the literature (see, e.g., Bianchi, Melosi, & Rottner, 2021). This allows us to achieve a lasting ZLB spell of several quarters in our simulations. Finally, the chosen QE smoothing reflects the high persistence of asset market operations and resembles the value of 0.8 in Sims and Wu (2021) or Sims et al. (2023).

Table 1: Parameter values

Parameter	Description	Value	Source / Target
λ	Proportion of borrowers	0.35	Bilbiie et al. (2013)
σ	Intertemporal elasticity of substitution	1	Conventional
$1/\varphi$	Frisch elasticity of labor supply	1	Conventional
β^S	Discount factor, saver	0.99	Annual steady-state interest rate of 4%; Bilbiie et al. (2013)
β^B	Discount factor, borrower	0.95	Bilbiie et al. (2013)
$\bar{D}$	Borrowing limit	0.5	Bilbiie et al. (2013)
ε	Elasticity of substitution between goods	6	Price markup of 20%
τ^D	Tax on profits	0	No redistribution
ϕ_p	Rotemberg price adjustment cost	42.68	3.5-quarters price duration
ϕ_π	Taylor rule coefficient on inflation	1.5	Conventional
χ	Long-term bond coupon decay rate	0.975	Average bond duration of 7-8 years
ν	Portfolio share adjustment cost	0.05	Empirical evidence on output response by Weale and Wieladek (2016)
$\tilde{\delta} = b^L/b$	Steady-state ratio of long-term to short-term bonds	0.3	Harrison (2017), Harrison et al. (2021)
$q = b^{CB,L}/b^L$	Steady-state CB long-term bond holdings	0.25	Households' long-term bond holdings
g/y	Steady-state government-spending-to-GDP ratio	0.2	Galí et al. (2007)
$(b+b^L)/y$	Steady-state total-debt-to-GDP ratio	0.8	U.S. average since 2009
Π	Steady-state gross inflation rate	1	Inflation target
Y	Steady-state output	1	Normalized
τ^S	Production subsidy	$(\varepsilon-1)^{-1}$	Marginal cost pricing
ρ_θ	Persistence of preference shock	0.8	Sustained ZLB phase
$\rho^{\tau,t}$	Tax smoothing in fiscal rule	0.7	Tax inertia
$\rho^{\tau,b}$	Tax response to total debt	0.33	Galí et al. (2007)
$\rho^{\tau,g}$	Tax response to government spending	0.1	Galí et al. (2007)
ρ_r	Interest rate smoothing	0.8	Sims et al. (2023)
ρ_q	QE smoothing	0.9	Cui and Sterk (2021)

In each simulation we run in Section 3, the shock size is such that the central bank buys or sells long-term bonds worth 1% of annualized nominal GDP. We then match the output response to empirical evidence from the United States. The simulation results used for the matching are the impulse responses of the net effect of a QE shock that happens when the economy is in a liquidity trap; a situation brought about by a negative preference shock. See Section 3.2 for more details. All the other simulations build on the parameterization from this exercise.

Weale and Wieladek (2016) show that the peak impact on U.S. real GDP of an asset purchase in the size of 1% of annualized nominal GDP has been around 0.58% between March 2009 and May 2014.[13] We take this number as our target for the average output response during the first

[13] This number reflects the average of median peak effects of four different identification schemes in Weale and Wieladek (2016) that all leave the reaction of real GDP unrestricted. The chosen sample period reflects the time when asset purchases were an active tool of U.S. monetary policy.

four quarters after a QE shock at the ZLB, following the approach used in Cui and Sterk (2021). More specifically, we set the adjustment cost parameter ν accordingly to approximate this target.

To solve our model with the occasionally binding lower bound constraint, we use the dynare-OBC toolbox developed by Tom Holden.[14] Given that we approximate the model at first order, our simulation results will be perfect foresight transition paths in response to a QE or QT shock.

3 Results

In this section, we discuss the model simulations by proceeding in four steps. First, we study the impact of asset market operations when the economy is either close to or well above the ZLB and analyze the shock transmission to the real economy. Second, we examine the asymmetric macroeconomic effects of QE and QT induced by state dependency. Third, we compare our TANK-BS model to its representative-agent counterpart to isolate the implications of household heterogeneity. Finally, we provide robustness and stability results.

3.1 Asset market operations and unwinding QE close to the ZLB

We start by illustrating what the TANK-BS model implies about the potential impact on macroeconomic aggregates of doing QE or QT and of unwinding QE, taking into account state dependency in the form of a lower bound on the short-term nominal interest rate. Figure 1 shows selected impulse responses to a QE and QT shock occurring when the economy is sufficiently far away from the ZLB and to a QT shock that hits an economy that is already close to the ZLB. Appendix B.1 contains the entire set of impulse responses.

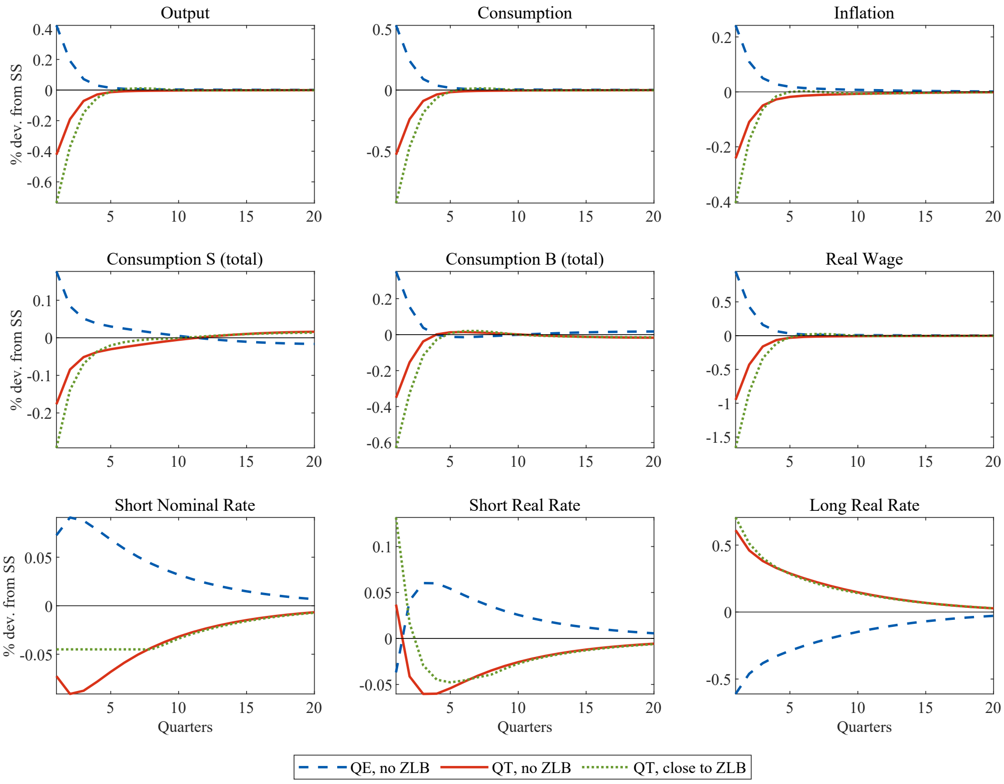
To explain how the model works, we begin by analyzing a standard QT shock, captured by the solid red line in the figure. When the central bank sells long-term bonds, the amount of assets available to other agents in the economy increases. The return of those bonds goes up and their price decreases. Given the lower short-term interest rate, constrained agents borrow now more in the short-term asset because it has become cheaper, while savers purchase the long-term asset sold by the central bank. Overall, the lower demand for long-term bonds from the central bank is exactly offset by the higher demand from households so that the supply of long-term bonds remains fixed.[15]

To understand the transmission of the shock to the real economy, it is useful to study the responses of the components of each agent's budget constraint to an asset market operation. Figure 2 shows that the individual consumption of both household types decreases in response to a QT shock far enough off the ZLB, but that the underlying driving forces differ. We distinguish between

[14] See Holden (2016, 2022) for theory and computational details.

[15] The magnitude of the effects of QT will depend on the maturity structure of household portfolios. For instance, holding more short-term debt exposes borrowers to higher rollover risk and makes them more sensitive to changes in short-term interest rates. On the other hand, borrowing at the long-term rate includes valuation effects, as remarked by Auclert (2019). If a larger portion of assets in borrowers' portfolios consists of long-term bonds, central bank asset market operations influence these agents more. Bond price changes induced by QE or QT directly affect their debt burden, wealth, and thus consumption behavior. Ferrante and Paustian (2019) refer to this mechanism in the context of forward guidance as the debt revaluation channel.

Figure 1: Impulse responses to a QE/QT shock and a QT shock near the ZLB



Notes: This figure depicts the impulse responses to a QE (dashed blue line) and a QT (solid red line) shock occurring far enough above the ZLB, and a QT shock happening close to the ZLB (dotted green line). The shock for each simulation is an asset purchase/sale of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

the direct effects of asset sales (changes in bond demand and returns) and the indirect, general-equilibrium effects (changes in the real wage and profits).[16]

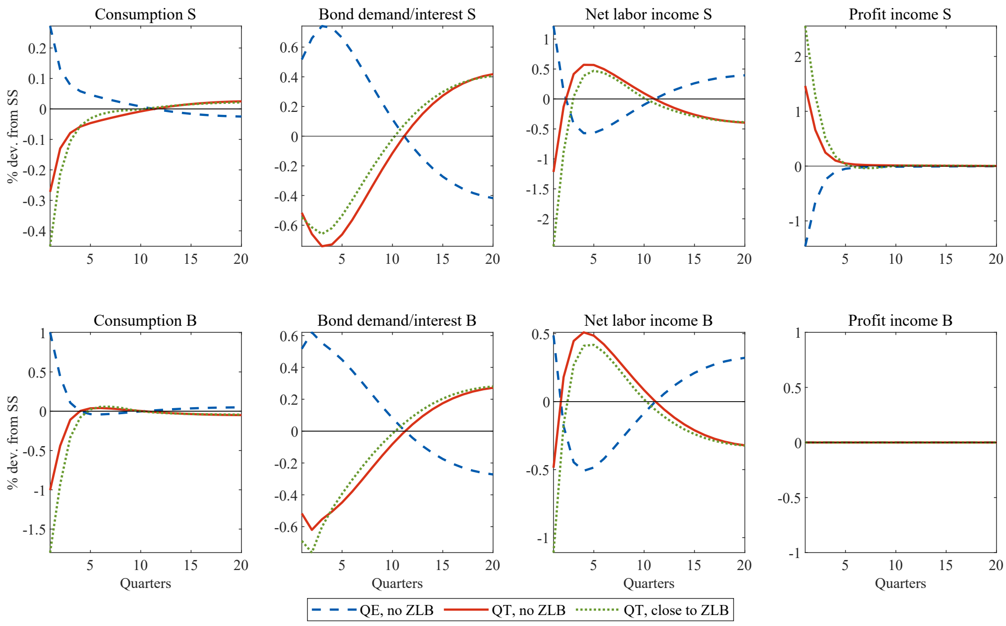
The first panel reveals that the change in savers' labor income through general equilibrium harms consumption, but only on impact of the shock. After that, the cut in lump-sum taxes and, in particular, the strong increase in countercyclical profits push the income of savers up and leads to a quick recovery. Instead, the medium-term negative consumption response is mainly driven by developments in their portfolio allocation. By buying long-term bonds from the central bank, savers give up some of their income because changes in the bond portfolio are costly. This drop in income is larger than the gains from selling short-term bonds together with the increase in interest income from the more long-term bonds in their portfolio and the higher real rate on these assets.[17] This effect depresses the consumption of savers and thus aggregate demand.

The bottom panel of Figure 2 shows some commonalities for borrowers. Their bond demand

[16]The partition in Figure 2 can be captured by the budget constraints of the two household types: $c_t^j = \left[-b_t^j - b_t^{j,L} + r_{t-1} b_{t-1}^j + r_t^L b_{t-1}^{j,L} - \Psi_t^j\right] + \left[w_t N_t^j - t_t\right] + \left[d_t^j\right] + tr^j$, for $j = \{B,S\}$ and with $d_t^B = \tau^D d_t/\lambda$ and $d_t^S = \left(1-\tau^D\right)/(1-\lambda)\, d_t$. The square brackets represent the bond demand and interest, the net labor income, and the profit income component, respectively.

[17]Strictly speaking, the rise in savers' long-term bond holdings is larger than the decrease in short-term bonds. Similarly, their interest income from long-term bonds increases by more than the income from short-term bonds falls. Combined, the former effect is larger and leads to a negative net impact out of the bond-related variables in the saver's budget constraint, as illustrated in Figure 2.

Figure 2: Household budget components after a QE/QT shock and a QT shock near the ZLB



Notes: This figure shows grouped components of the budget constraints of savers (top) and borrowers (bottom) in response to a QE (dashed blue line) and a QT (solid red line) shock occurring far enough above the ZLB, and a QT shock happening close to the ZLB (dotted green line). The shock for each simulation is an asset purchase/sale of size 1% of annualized GDP. Each panel consists of four columns, containing the responses of individual consumption, bond-related variables (bond demand, interest payments/income, net of adjustment cost), labor income net of taxes, and income from profits. All responses are shown in per-capita terms.

and interest payments respond similarly to those of savers. The other negative income effect comes from net labor income. Although borrowers do not substantially change their labor supply because they cannot afford to work much less, the lower spending from savers negatively impacts them through the drop in the real wage.[18] This influence on labor income is again short-lived due to the cut in taxes that causes a fast rebound.

Overall, the direct effects of QT and the ensuing changes in returns are considerable for all households and the indirect effect through the labor market is counterbalanced by a cut in taxes. The major difference that leads to a weaker response of savers, however, is the behavior of profits. Those constitute a strong boost for savers such that their consumption drops by much less in relative terms.

A key point to mention here is that QT is modeled as the exact opposite of QE. Due to the linearity of the model, both policies have therefore the same impact in absolute terms, as long as the economy is far enough away from the ZLB such that the QT shock cannot bring about a liquidity trap. As visible in Figure 1, QE decreases the long-term rate and increases the short-term rate. These effects then propagate to the real economy via households demanding more short-term and less long-term bonds, which translates into higher aggregate demand and leads to a rise in all main aggregate variables.

Starting from a scenario with symmetric effects of QE and QT allows us to isolate the asymmetry emerging from the presence of a ZLB. A binding lower bound on the short-term nominal

[18]The weak reaction of borrowers' labor supply is also visible in the full set of impulse responses in Appendix B.1.

interest rate creates different states of the world that can lead to asymmetric effects of asset market operations, similar to the literature about fiscal policy and the government-spending multiplier (see, e.g., Christiano, Eichenbaum, & Rebelo, 2011). This idea is also motivated by previous research that confirmed a stronger impact of asset purchases if the ZLB was binding (see Gertler & Karadi, 2013).

Assuming now that the economy is currently in a situation where the log interest rate is close to (but not at) zero, even a mild QT shock can push it into a liquidity trap.[19] We illustrate this case by a simulation applying our baseline calibration except that we set $\beta^S = 0.99955$. The implied lower steady-state real rate ensures that the ZLB will bind right on impact of the QT shock and for a total of eight quarters in the baseline model, given the same shock size used so far.

This case is captured by the dotted green impulse responses in Figure 1. If the policy rate were unconstrained, it would drop on impact of the shock and show a hump-shaped course, mitigating the contractionary implications of the asset sales. However, with a binding ZLB, it can no longer fall as sharply, while long-term rates remain at a higher level. As a consequence, the short-term real rate increases and both household types decrease their consumption more than in the unconstrained case, leading to larger drops in all aggregate variables and a deeper recession. We can deduce from Figure 2 that the stronger decrease in the consumption of savers right after the shock is substantially triggered by a magnified fall in labor income, which is again partly absorbed by positive profits. Borrowers are particularly hurt by the higher borrowing costs and the larger drop in the real wage.[20]

These findings have significant implications regarding when central banks might ideally unwind QE. It is crucial to ensure that any tightening will not push the policy rate back to zero as this could imply strong adverse effects for the aggregate economy. Therefore, when dealing with the risk of hitting the ZLB, our model indicates that the central bank can mitigate the economic costs of normalizing monetary policy by raising the policy rate before starting with active asset sales. This approach decreases the likelihood of a liquidity trap and is thus less harmful to the overall economy compared to the reverse sequencing.[21] As outlined in the introduction, this result is opposite to that of Benigno and Benigno (2022), primarily due to the different nature of our exercise. Importantly, the stronger economic contraction after a QT shock that drives the economy into a liquidity trap emphasizes in our case the importance of initiating rate hikes before doing QT.

[19] We do not discuss here the case of QE implemented near the ZLB. Due to its expansionary influence, such an asset market operation would move the economy away from the lower bound. Asset purchases can therefore even be an effective policy tool when the policy rate is unconstrained.

[20] Overall, bond demand and supply variables respond similarly to QT, whether the economy is close to or away from the lower bound. See Appendix B.1 for the respective impulse responses.

[21] The likelihood of staying away from the ZLB depends on the optimal coordination between interest rate hikes and QT with respect to the order, timing, and pace of actions. Selling assets before normalizing the policy rate increases the probability of ending in a liquidity trap for an extended time. A similar outcome arises if QT starts when the short-term rate has not yet been raised enough or if the tightening is executed too rapidly relative to the policy rate increases.

3.2 State-dependent asset market operations and their asymmetric impact

We now run a counterfactual exercise to compare QE and QT programs of similar size across different states of the economy. Based on the idea of state-dependent asset market operations, we compare two types of shocks: a QE shock that happens when the economy is in a liquidity trap, and a QT shock off the ZLB. Central banks have extensively used large-scale asset purchase programs to counteract the detrimental consequences of historically low interest rates in the past, particularly during times when the economy has been constrained by the ZLB. In contrast, we showed in the previous section that unwinding QE before the policy rate has reached a certain level is not advisable from our model's point of view.[22]

Figure 3 shows selected results of these simulations. Additional impulse responses are in Appendix B.2. We model the net effect of the QE shock by first simulating an asset purchase together with a negative preference shock and then deducting the impact of a mere preference shock. The size of the latter shock is chosen such that the economy is brought to the ZLB on impact and remains constrained for eight quarters. Generating a liquidity trap by a preference shock is a simple and effective way for our purpose to isolate the implications emerging from state dependency (see, e.g., Christiano et al., 2011). Otherwise, the QT shock is equivalent to the shock in the previous section, where we discussed its effects on macroeconomic aggregates and the associated transmission mechanism.

In this exercise, as outlined in Section 2.6, we match the output response to empirical evidence from the initial QE programs in the U.S. (Weale & Wieladek, 2016). These simulations closely resemble those in Cui and Sterk (2021). Specifically, the responses of output, inflation, and real wages are almost identical on impact and for the first few quarters after the shock, differing only in their persistence.[23] The discrepancy arises from the interest rate peg in Cui and Sterk (2021), which leads to longer-lasting effects in their simulations than the occasionally binding ZLB in our model.

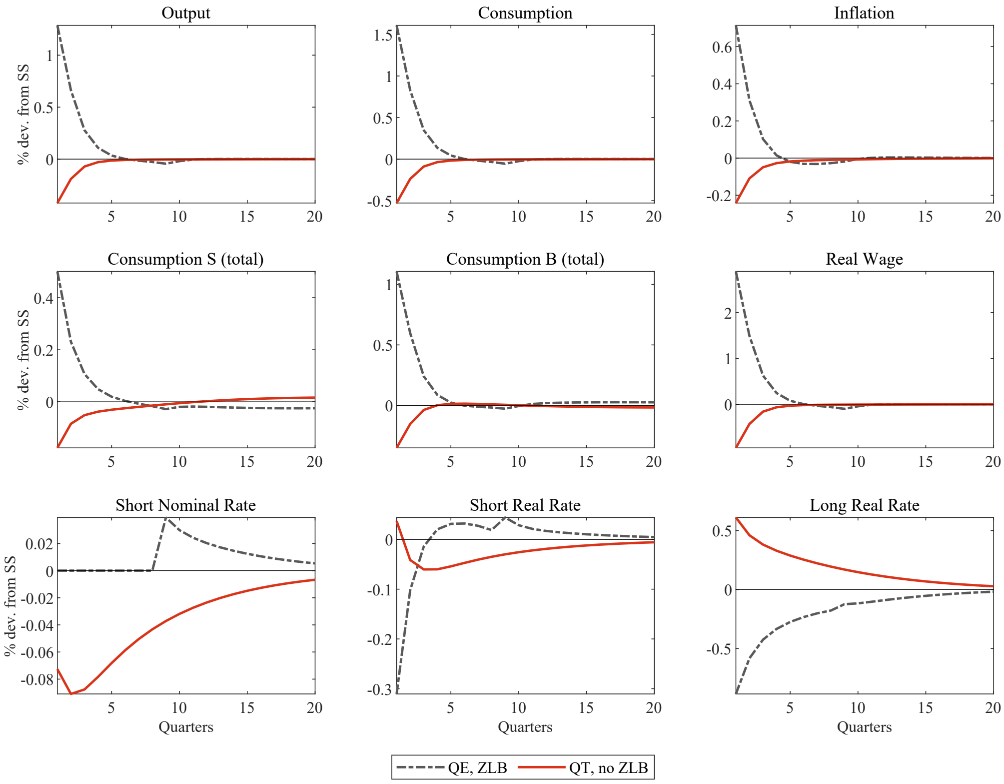
Figure 3 reveals clear differences in the macroeconomic implications of the two shocks. As seen above, QE has a positive effect on aggregate demand while QT affects the economy negatively. When QE is implemented at the ZLB, however, its positive impact is magnified compared to the findings without the lower bound from the previous section. The resulting uneven responses of aggregate variables emerge from the prevalent state dependency, best visible from the asymmetric behavior of interest rates. The long-term rate response shows only minor (absolute) differences across the two shocks. On the other hand, while the short-term real interest rate increases after a QE shock when the economy is away from the ZLB, its response changes direction when at the lower bound, falling considerably due to the inability of the policy rate to react.[24] In sum, imposing that asset purchases have been predominantly executed at the ZLB in reality, our model suggests that QT has a smaller impact on the macroeconomy than QE.

[22] There is an ongoing debate on whether a CB should raise the policy rate first or start with some tapering or active asset sales when exiting a liquidity trap. See Forbes (2021) for a recent consideration.

[23] The comparison is made with respect to the variables depicted in Figure 5 of Cui and Sterk (2021).

[24] This result resembles Gertler and Karadi (2013) who showed that central bank asset purchases lead to a larger drop in long-term rates the longer short-term rates are constrained.

Figure 3: Impulse responses to a QE shock at the ZLB and a QT shock off the ZLB



Notes: This figure depicts the impulse responses to a QE shock when the ZLB on the policy rate is binding (dash-dotted gray line, showing the impact of QE net of a negative preference shock), and a QT shock occurring far enough above the ZLB (solid red line). The shock for each simulation is an asset purchase/sale of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

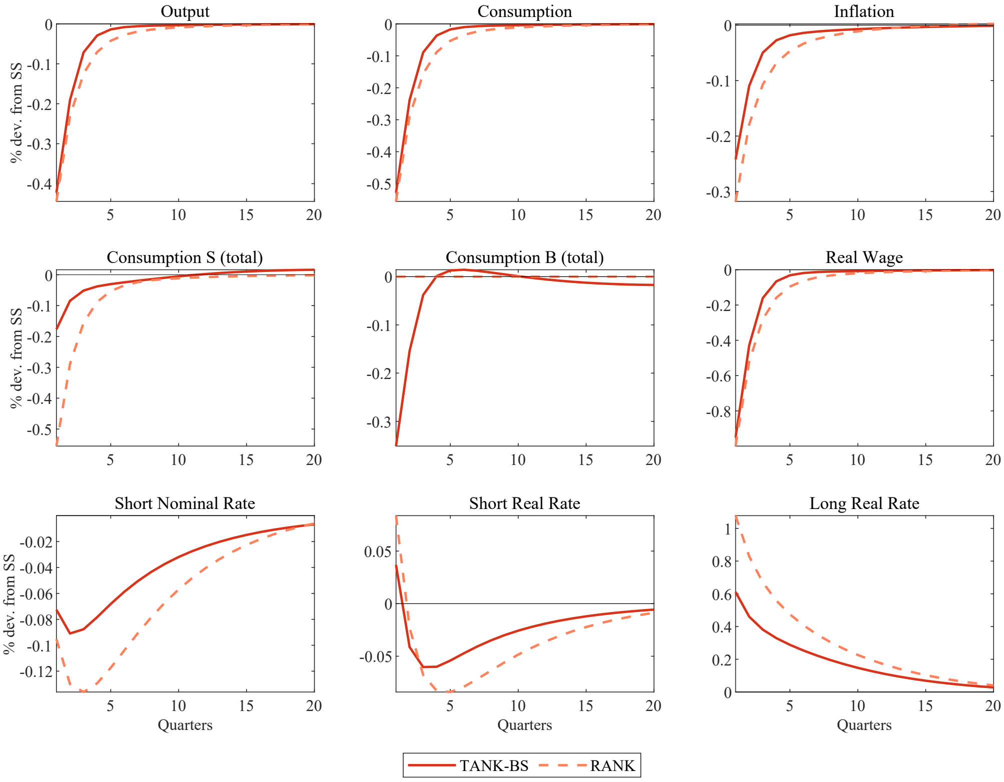
Our findings highlight the significance of the occasionally binding lower bound in explaining the asymmetric implications of QE and QT. If conventional monetary policy is constrained and the economy is stuck in a liquidity trap, QE helps to stimulate aggregate demand and will have a larger effect than in normal times. With the nominal interest rate being at the ZLB, the rise in output and prices following a QE shock decreases the real rate considerably and thus fosters spending by households and boosts real wages.[25] This, in turn, results in an even higher output and constitutes an expansionary spiral.

3.3 Household heterogeneity and state dependency in interaction

As a final exercise, we study how household heterogeneity influences the asymmetry between the macroeconomic impact of QE and QT. For this purpose, we compare the impulse responses resulting from our borrower-saver model (named TANK-BS) with those from a standard representative-agent framework (named RANK) without heterogeneity on the household side. See Appendices B.3 and B.4 for the entire set of impulse responses. The shocks we focus on are the same as in the previous section, namely an asset purchase at the ZLB and an asset sale away from it.

[25] The boost originating from the drop in the short-term real rate is so large that it generates an increase in real wages that induces borrowers to work less when QE is implemented at the ZLB. On the contrary, asset purchases away from the ZLB would induce them to increase their labor supply. See Appendix B.2 with the full set of impulse responses.

Figure 4: Impulse responses to a QT shock off the ZLB: RANK vs. TANK-BS



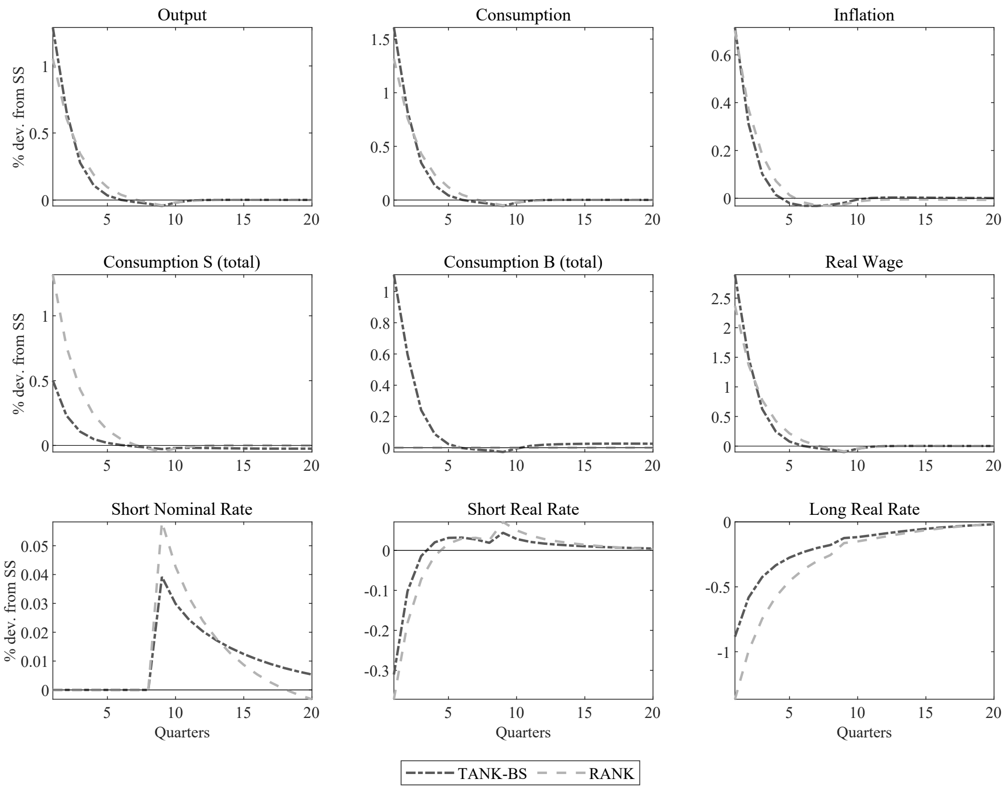
Notes: This figure depicts the impulse responses to a QT shock occurring far enough above the ZLB, for the borrower-saver model (TANK-BS, solid red line) and its representative-agent counterpart with $\lambda = 0$ (RANK, dashed light red line). The shock for each simulation is an asset sale of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

The motivation for such an exercise comes from the implications of heterogeneity in household income, wealth, or consumption and saving decisions found in the literature. Studies focusing on conventional monetary policy observe substantial amplification (e.g., Auclert, 2019; Bilbiie, 2018, 2020; Bilbiie et al., 2022; Debortoli & Galí, 2017), driven by heterogeneity in MPCs out of a transitory income shock. Sims et al. (2022) instead focus on QE and find no amplification coming from household heterogeneity. In our setup, borrowers have a higher MPC than savers. Any policy measure that relaxes their borrowing constraint frees up some individual income which is spent immediately and boosts aggregate demand and consumption. It appears therefore natural to study if amplification also arises after asset market operations.

Figure 4 shows the results for a QT shock when the economy is far enough off the ZLB such that the short-term nominal rate remains unconstrained. Adding household heterogeneity to a RANK model seems to have only a minor impact on the aggregate effects of QT (and due to the model linearity also of QE), which is in line with the finding in Sims et al. (2022).

The reason for this lack of amplification via heterogeneity lies in a composition effect of changes in the balance sheets of households that roughly cancel out when moving from RANK to TANK-BS. Without borrowers in the model, the propagation of the shock works entirely through the income of the saver. The representative agent purchases the bonds sold by the central bank, which drives down their income and thus aggregate demand. Compared to TANK-BS, we observe

Figure 5: Impulse responses to a QE shock at the ZLB: RANK vs. TANK-BS



Notes: This figure depicts the impulse responses to a QE shock net of a negative preference shock when the ZLB on the policy rate is binding, for the borrower-saver model (TANK-BS, dash-dotted gray line) and its representative-agent counterpart with $\lambda = 0$ (RANK, dashed light gray line). The shock for each simulation is an asset purchase of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

a higher effect on the demands of short-term and long-term bonds of the total responses across savers, as they are the only household type, and a larger impact on the long-term real rate.[26] Together with the lower increase in gains out of firm profits, this magnifies the income drop of savers from buying long-term bonds from the central bank, therefore decreasing their consumption more than in the TANK-BS case.

When moving to TANK-BS, savers behave like the representative agent in RANK. They affect, however, aggregate demand by relatively less due to their smaller share in the population and thus higher profit income per agent. The decreased contribution to the fall in spending is offset by a reduction in the labor income of borrowers who have a larger MPC.[27] The net effect of the lower drop in aggregate consumption coming from savers and the additional decrease through borrowers is almost neutral. Even though this finding is consistent with the complementary work of Sims et al. (2022), the story behind it is different. The lack of amplification in their model arises because only very few households at the bottom of the wealth distribution respond other than the representative agent to a QE shock and the impact of those households on aggregate consumption is therefore marginal.

[26] Bond demands of savers in the RANK model are only more sensitive in *total* terms. Once we look at *per-capita* bond demands, the effect of a shock will be lower in RANK compared to TANK-BS due to the higher share of savers.

[27] See Figure B.5 in Appendix B.3 for more details on each agent's budget constraint components.

Unlike a state of the world without a binding ZLB, household heterogeneity starts to matter more when combined with state dependency. Figure 5 shows that this case leads to amplified aggregate effects of asset purchases in the TANK-BS model. The reasoning combines what has been described so far. First, the presence of the ZLB generates an asymmetric behavior of the short-term real rate, pushing the consumption of both household types and thus aggregate demand upwards. Second, there is an extra boost from the presence of constrained households with a high MPC, such that an increase in their labor income through higher wages has a strong multiplier impact on aggregate demand. Together, these two elements lead to a larger increase in aggregate variables in TANK-BS.

Compared to the case of an asset market operation done off the ZLB, the direct and indirect effects of QE on borrowers together more than offset the reaction of savers in TANK-BS and the changes in their balance sheets no longer cancel out.[28] When an asset purchase occurs at the lower bound, the impact of the increased labor income of borrowers with their high MPC exceeds the diminished contribution from savers in terms of spending, with a strong reaction of profits per agent being crucial.[29]

In order to quantify the asymmetry induced by state dependency in this model, Table 2 lists the responses of the main aggregate variables to the two shocks we have analyzed in this section, both on impact and cumulated over four periods, and both for the RANK and the TANK-BS model.

The impact multipliers reveal two results. First, as seen in the previous section, the impact of QE on macroeconomic aggregates is larger than the absolute impact of QT. This holds for both models and constitutes a *within-model asymmetry*. Doing QE at the ZLB instead of unwinding it off the ZLB has a macroeconomic effect on impact that is more than two times stronger in RANK and about three times stronger in TANK-BS. Second, as described for Figure 5, household heterogeneity amplifies the aggregate effects of asset market operations only when it appears in combination with state dependency. This *across-model asymmetry* is therefore very weak in the case of our simulated QT shock, but sizable for QE simulated at the ZLB.[30] Moving from RANK to TANK-BS, the macroeconomic impact multiplier of QE is around 20% higher for output and consumption, but about the same for inflation. This latter result might arise because heterogeneity affects the slope of the aggregate demand curve but not that of the Phillips curve. OVerall and as a direct consequence, introducing household heterogeneity amplifies the within-model asymmetry.

3.4 Robustness and stability

We now conduct a series of sensitivity checks on the calibration, fiscal-monetary policy mix, and stability properties of the model. Appendix C presents all results.

[28]See Figure B.7 in Appendix B.4 for more details on each agent's budget constraint components.

[29]The degree of household heterogeneity may be assumed to change with the cycle and thus across different states of the world, or to be affected by the type of balance sheet policy. However, our main results are expected to hold also with an endogenous mass of borrowers, as the observed unequal effects persist even for extreme values of λ.

[30]Whether the macroeconomic effects of QT are slightly stronger or weaker depends on the calibrated parameter values. However, for a realistic calibration, QT has always around the same aggregate impact on output and total consumption in both models.

Table 2: Multipliers on impact and cumulated (in %)

	Output		**Inflation**		**Consumption**	
	QE	QT	QE	QT	QE	QT
RANK (impact)	1.05	-0.44	0.70	-0.32	1.32	-0.56
TANK-BS (impact)	1.29	-0.42	0.71	-0.24	1.61	-0.53
RANK (cumulative)	2.18	-0.86	1.32	-0.67	2.72	-1.08
TANK-BS (cumulative)	2.32	-0.71	1.14	-0.43	2.90	-0.89

Notes: This table summarizes the aggregate effects of a QE shock when the ZLB on the policy rate is binding and a QT shock occurring far enough above the ZLB, for the borrower-saver model (TANK-BS) and its representative-agent counterpart (RANK). The shock for each simulation is an asset purchase/sale of size 1% of annualized GDP. The table contains the multipliers both on impact of the shock and cumulated over the first four periods after the shock.

First, we test the robustness of the main findings concerning alternative values of key parameters in the baseline model. Table C.1 presents the impact multipliers and Appendix C.2 the impulse responses for each case. Variations in the parameters can influence the extent of the macroeconomic effects of asset market operations with respect to the baseline, both at or off the ZLB. A higher portfolio adjustment cost (ν) makes the long-term real interest rate more sensitive to changes in household portfolios, amplifying the aggregate impact. In contrast, a non-zero tax on profits ($\tau^D > 0$) reduces the indirect effect of asset market operations through wages on borrowers' consumption. However, varying the tax rule parameters for smoothing ($\rho^{\tau,t}$) and total debt ($\rho^{\tau,b}$) implies only minor changes in aggreate responses, even for extreme values.

Apart from these quantitative comparisons, the sensitivity checks indicate that the within-model asymmetry continues to hold for both TANK-BS and RANK models, with asset sales consistently having lower aggregate effects than asset purchases. Similarly, when contrasting the impact multipliers across models, we observe slightly stronger but still comparable implications after a QT shock in RANK compared to TANK-BS. However, the across-model asymmetry can reverse if state dependency is introduced. Specifically, the influence of a non-zero τ^D in dampening the general-equilibrium effect on the consumption of constrained agents appears particularly strong when QE is implemented at the ZLB. If borrowers bear a share of the resulting drop in total profits, they tend to work more due to the negative income effect on labor supply and consume less relative to the baseline. Consequently, the net effects of QE on the macroeconomy may become more pronounced in RANK than in TANK-BS for a sufficiently large τ^D.

Second, we explore the implications of alternative monetary-fiscal policies, which could be crucial in our setup with constrained households and balance sheet operations. Departing from the baseline model, we consider a fiscal rule for government spending, a rule for long-term assets that implies a non-constant government debt supply, and a Taylor rule responding to both output and inflation. Details on these rules are provided in Appendix C, while Table C.2 and Appendix C.2 present the impact multipliers and the impulse responses for each robustness check, respectively. Overall, although there are quantitative differences to the baseline, the results reaffirm the qualitative robustness of our main findings. The conclusions regarding the role of state dependency and the identified within- and across-model asymmetries persist, with one notable exception. When QE is implemented at the ZLB, a higher responsiveness of the central bank to output changes increases the likelihood of observing a lower aggregate effect in TANK-BS compared to RANK, which can reverse again our result on the across-model asymmetry. In general, however, our key results are only weakly dependent on the choice of the fiscal rule.

Third, to delve deeper into the monetary-fiscal policy interactions within our model, we can study its stability and determinacy properties under various policy rules. Figure C.29 displays the regions associated with a unique locally stable, indeterminate, or locally instable equilibrium, based on a simulation for an asset market operation off the ZLB. We investigate the equilibrium dynamics of the model for different combinations of the Taylor rule coefficient on inflation (ϕ_π) and the tax response to debt ($\rho^{\tau,b}$), while keeping the remaining parameters at their baseline unless mentioned otherwise. This allows us to speak to the relative policy activeness between monetary and fiscal policy, drawing on the distinction charaterized by Leeper (1991).

Panel (a) of Figure C.29 shows that the stability regions for our baseline calibration closely align with those of a more parsimonious model where all policy rule parameters except ϕ_π and $\rho^{\tau,b}$ are set to zero. We see that, as it is standard in the literature, a unique and stable equilibrium emerges whenever one authority is active and the other is passive. As a result, a passive monetary policy ($\phi_\pi < 1$) calls for active fiscal policy ($\rho^{\tau,b}$ smaller than a certain threshold), while an active monetary policy ($\phi_\pi > 1$) requires passive fiscal policy ($\rho^{\tau,b}$ larger than a certain threshold).[31] The remaining panels in the figure depict the stability regions corresponding to the different policy rules we considered above for robustness. They show thresholds that are either identical or close to the baseline. The only exception is the case of the government spending rule in panel (c), where fiscal policy can be more passive than in the baseline if monetary policy is active. This is because government spending is negatively related to changes in total debt, which helps to stabilize the latter and therefore requires a weaker tax response.

4 Conclusion

In this paper, we present a New Keynesian model with borrowers and savers that is used to study the state-dependency induced asymmetry in the macroeconomic effects of asset market operations and its interaction with household heterogeneity. Central bank asset purchases and sales operate via portfolio rebalancing between short-term and long-term government bonds held by the two types of households in the economy. These assets are imperfect substitutes due to the portfolio adjustment costs in place. State dependency arises through the presence of an occasionally binding ZLB on the short-term nominal interest rate.

We show that a binding ZLB enhances the macroeconomic effects of central bank asset market operations, due to the different behavior of the short-term real interest rate when the economy is

[31] These results also hold for $\rho^{\tau,b} > 0.2$ and our baseline calibration with $\rho^{\tau,b} = 0.33$ and $\phi_\pi = 1.5$ is thus well included in the unique and locally stable region.

in (or close to) a liquidity trap. Consequently, when dealing with the risk of hitting the ZLB, a central bank can mitigate the economic costs associated with monetary policy normalization by raising the nominal interest rate prior to unwinding quantitative easing. Additionally, in this context, QT has a smaller impact on the aggregate economy than QE implemented at the ZLB, implying asymmetry in their effects. Furthermore, we find that the role of household heterogeneity in propagating QE or QT shocks also considerably depends on the state of the economy, with heterogeneity leading to substantial amplification of aggregate output and consumption, but only for asset market operations conducted at the ZLB.

Our model aims to enhance the understanding of the potential implications of central bank balance sheet reductions. Considering the widespread belief that the effects of QE and QT are not exactly of equal but opposite size, further research on the consequences of monetary policy normalization is indispensable. First, from a modeling perspective, it would be essential to explore transmission channels other than portfolio rebalancing, to expand the heterogeneity dimension to a continuum of households, or to incorporate frictions on the firm side. Second, we assume a mass of borrowers that is not state-dependent. Future work could investigate the implications of endogenizing the share of constrained agents, which may be affected by the type of balance sheet policy or the state of the economy. Lastly, a closer examination of sources of non-linearities beyond the ZLB could be valuable, with a particular focus on the role of constrained households and the implications of higher-order solutions.

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Online Appendix

A Borrower-saver model derivations

This appendix provides details on the derivations of the model presented in Section 2.

A.1 Household problem

Each household of type $j = \{B, S\}$ faces the following optimization problem:

$$\max_{c_t^j, N_t^j, b_t^j, b_t^{j,L}} \mathbb{E}_t \sum_{t=0}^{\infty} \left(\beta^j\right)^t \theta_t \left(\frac{(c_t^j)^{1-\frac{1}{\sigma}}}{1-\frac{1}{\sigma}} - \zeta^j \frac{(N_t^j)^{1+\varphi}}{1+\varphi} \right) \quad \text{subject to}$$

$$c_t^j + b_t^j + b_t^{j,L} \leq r_{t-1} b_{t-1}^j + r_t^L b_{t-1}^{j,L} + w_t N_t^j + d_t^j - t_t - \frac{\nu}{2} \left(\delta^j \frac{b_t^j}{b_t^{j,L}} - 1 \right)^2 + tr^j ,$$

$$0 \leq \mathbb{I}^j \left(b_t^B + b_t^{B,L} + \overline{D} \right) ,$$

where $d_t^B = \tau^D d_t / \lambda$, $d_t^S = \left(1 - \tau^D\right)/(1-\lambda)\, d_t$, $tr^B = tr/\lambda$, and $tr^S = -tr/(1-\lambda)$. Moreover, $\mathbb{I}^j$ is an indicator function with values $\mathbb{I}^S = 0$ and $\mathbb{I}^B = 1$.

The resulting optimality conditions for each agent are:

$$U_{c,t}^j = \theta_t (c_t^j)^{-\frac{1}{\sigma}} ,$$

$$U_{N,t}^j = -\theta_t \zeta^j (N_t^j)^{\varphi} ,$$

$$w_t = -\frac{U_{N,t}^j}{U_{c,t}^j} ,$$

$$U_{c,t}^j + U_{c,t}^j \frac{\nu \delta^j}{b_t^{j,L}} \left(\delta^j \frac{b_t^j}{b_t^{j,L}} - 1 \right) = \beta^j R_t \mathbb{E}_t \left[U_{c,t+1}^j \frac{1}{\Pi_{t+1}} \right] + \mathbb{I}^j \psi_t^B ,$$

$$U_{c,t}^j - U_{c,t}^j \frac{\nu \delta^j b_t^j}{\left(b_t^{j,L}\right)^2} \left(\delta^j \frac{b_t^j}{b_t^{j,L}} - 1 \right) = \beta^j \mathbb{E}_t \left[U_{c,t+1}^j \frac{R_{t+1}^L}{\Pi_{t+1}} \right] + \mathbb{I}^j \psi_t^B ,$$

$$0 = \mathbb{I}^j \psi_t^B \left(b_t^B + b_t^{B,L} + \overline{D} \right) ,$$

where $\psi_t^B \geq 0$ is the Lagrangian multiplier on the borrowing constraint. It holds that $\psi_t^B > 0$ whenever the constraint is binding.

From the expressions above, we can derive the following Euler equations for short-term and long-term bonds, where we already imposed $\delta^S = \delta^B = \delta$ as specified in the description of the steady state:

$$1 = \beta^j R_t \mathbb{E}_t \left[\frac{\theta_{t+1}}{\theta_t} \left(\frac{c^j_{t+1}}{c^j_t} \right)^{-\frac{1}{\sigma}} \frac{1}{\Pi_{t+1}} \right] - \frac{\nu\,\delta}{b^{j,L}_t} \left(\delta \frac{b^j_t}{b^{j,L}_t} - 1 \right) + \mathbb{I}^j \,\psi^B_t\, \theta_t^{-1} \left(c^j_t \right)^{\frac{1}{\sigma}} ,$$

$$1 = \beta^j \mathbb{E}_t \left[\frac{\theta_{t+1}}{\theta_t} \left(\frac{c^j_{t+1}}{c^j_t} \right)^{-\frac{1}{\sigma}} \frac{R^L_{t+1}}{\Pi_{t+1}} \right] + \frac{\nu\,\delta\, b^j_t}{\left(b^{j,L}_t \right)^2} \left(\delta \frac{b^j_t}{b^{j,L}_t} - 1 \right) + \mathbb{I}^j \,\psi^B_t\, \theta_t^{-1} \left(c^j_t \right)^{\frac{1}{\sigma}} .$$

Combining the two equations leads to an expression for the nominal return on long-term bonds as a function of the nominal rate on short-term bonds and the bond holdings of households:

$$\mathbb{E}_t R^L_{t+1} = \frac{1 - \frac{\delta\, b^j_t}{\left(b^{j,L}_t\right)^2} \widetilde{\Psi}^j_t - \mathbb{I}^j \,\psi^B_t\, \theta_t^{-1} \left(c^j_t \right)^{\frac{1}{\sigma}}}{1 + \frac{\delta}{b^{j,L}_t} \widetilde{\Psi}^j_t - \mathbb{I}^j \,\psi^B_t\, \theta_t^{-1} \left(c^j_t \right)^{\frac{1}{\sigma}}} R_t ,$$

where $\widetilde{\Psi}^j_t = \nu \left(\delta \frac{b^j_t}{b^{j,L}_t} - 1 \right)$. This equation is a no-arbitrage condition between the two types of bonds and captures the key impact channel of asset market operations on bond returns. When the central bank buys or sells long-term bonds, it changes the quantity of assets available to the rest of the economy. Holding bond supply fixed, this implies that households' portfolio mix is not at the desired level and induces costly portfolio rebalancing. The impact of the adjustment cost and of changes in bond demands is directly visible from the equation above. It can be shown that the fraction is larger than one whenever $\delta < b^{j,L}_t / b^j_t$, and smaller than one otherwise.

A.2 Intermediate goods producer problem

The price-setting problem of an intermediate goods firm is

$$\max_{\{P_{t+k}(i)\}_{k=0}^{\infty}} \mathbb{E}_t \sum_{k=0}^{\infty} \Lambda_{t,t+k} \left[\left(1+\tau^S\right) \frac{P_{t+k}(i)}{P_{t+k}} y_{t+k}(i) - mc_{t+k}\, y_{t+k}(i) - \frac{\phi_p}{2} \left(\frac{P_{t+k}(i)}{P_{t-1+k}(i)} - 1 \right)^2 y_{t+k} - t^F_{t+k} \right]$$

$$\text{s.t.} \quad y_{t+k}(i) = \left(\frac{P_{t+k}(i)}{P_{t+k}} \right)^{-\varepsilon} y_{t+k} ,$$

where $\Lambda_{t,t+k} = \left(\beta^S\right)^k \left(\frac{U^S_{c,t+k}}{U^S_{c,t}} \right)$ is the stochastic discount factor for payoffs in period $t+k$. The optimality condition of this optimization problem is

$$\mathbb{E}_t \Bigg\{ \Lambda_{t,t} \left[\left(1+\tau^S\right) (1-\varepsilon)\, P_t(i)^{-\varepsilon} P_t^{\varepsilon-1} y_t + mc_t\, \varepsilon\, P_t(i)^{-\varepsilon-1} P_t^{\varepsilon} y_t - \phi_p \left(\frac{P_t(i)}{P_{t-1}(i)} - 1 \right) \frac{y_t}{P_{t-1}(i)} \right]$$
$$+ \Lambda_{t,t+1}\, \phi_p \left(\frac{P_{t+1}(i)}{P_t(i)} - 1 \right) \frac{P_{t+1}(i)}{P_t(i)^2} y_{t+1} \Bigg\} = 0 .$$

Since firms are identical and face the same demand from final goods producers, they will all set the same price. This yields the following optimal price-setting condition:

$$\phi_p (\Pi_t - 1) \Pi_t - \mathbb{E}_t \left[\Lambda_{t,t+1} \phi_p (\Pi_{t+1} - 1) \Pi_{t+1} \frac{y_{t+1}}{y_t} \right] = \left(1 + \tau^S\right)(1 - \varepsilon) + \varepsilon \, mc_t \, .$$

A.3 Steady state

For the approximation of the model around a deterministic steady state, we assume a long-run inflation rate of unity ($\Pi = 1$), normalize output to one (by setting $z = N = 1$), and set $\theta = 1$.

The Euler equations of the saver give $R = R^L = \left(\beta^S\right)^{-1}$. Using this in the Euler equations of the borrower implies that the borrowing constraint binds in steady state ($\psi^B > 0$) because we assumed $\beta^S > \beta^B$. We further impose for labor supply that $N^B = N^S = N$. Together with the steady-state transfer on the part of households, this results in $c^B = c^S = c$. Finally, the optimal subsidy to firms induces $mc = 1$ and thus zero profits ($d = 0$).

For the real returns, we get $r = R$ and $r^L = R^L$, which pins down the nominal bond price $V = 1/\left(R^L - \chi\right)$. The weights on hours are found through the labor supply equations, $\zeta^j = w\left(N^j\right)^{-\varphi}\left(c^j\right)^{\sigma}$ with $j = \{B, S\}$ and where $w = y$ from the expression for labor demand. Due to equalized levels of labor supply and consumption across household types, $\zeta^S = \zeta^B$. Lastly, as portfolio adjustment costs are zero in steady state ($\Psi^j = 0$), the aggregate resource constraint determines consumption through $c = (1 - g/y)\, y$.

With respect to the bond-related variables, we impose $\delta^S = \delta^B = \delta = b^{H,L}/b^H$. This expression can be rewritten by using bond market clearing as $b^L = \delta\, b/(1-q)$, where we define $\tilde{\delta} = b^L/b$. Moreover, we write the annual steady-state total government debt-to-GDP ratio (in quarterly terms) as $b_y^{tot} = \left(b + b^L\right)/(4y)$, where the denominator captures annualized output. In order to find an expression for short-term government debt, we rewrite the last equation as $b = 4 b_y^{tot} \left[(1-q)/(1-q+\delta)\right] y$, or $b = 4 b_y^{tot} \left[1/\left(1 + \tilde{\delta}\right)\right] y$. Market clearing then gives $b^H = b$.

Regarding the central bank, bond holdings are $b^{CB,L} = q b^L$. This pins down net asset purchases $\Omega = \left(1 - r^L\right) b^{CB,L}$ and households' total demand for long-term bonds $b^{H,L} = b^L - b^{CB,L}$. A borrower's bond holdings are then determined through the (binding) borrowing constraint, with $b^B = -\bar{D}/(1+\delta)$ and $b^{B,L} = -\bar{D} - b^B$. A saver's bond holdings are pinned down by market clearing, with $b^S = \left(b^H - \lambda b^B\right)/(1-\lambda)$ and $b^{S,L} = \left(b^{H,L} - \lambda b^{B,L}\right)/(1-\lambda)$. Finally, lump-sum taxes are given by $t = g + \Omega - b(1-r) - b^L(1-r^L)$ and the steady-state transfer by $tr = \lambda[c^B + (1-r)b^B + (1-r^L)b^{B,L} - wN^B - \tau^D d/\lambda + t]$.

A.4 Model summary

Table A.1 lists all equations of the TANK-BS model.

Table A.1: Model overview of the TANK-BS model with asset market operations

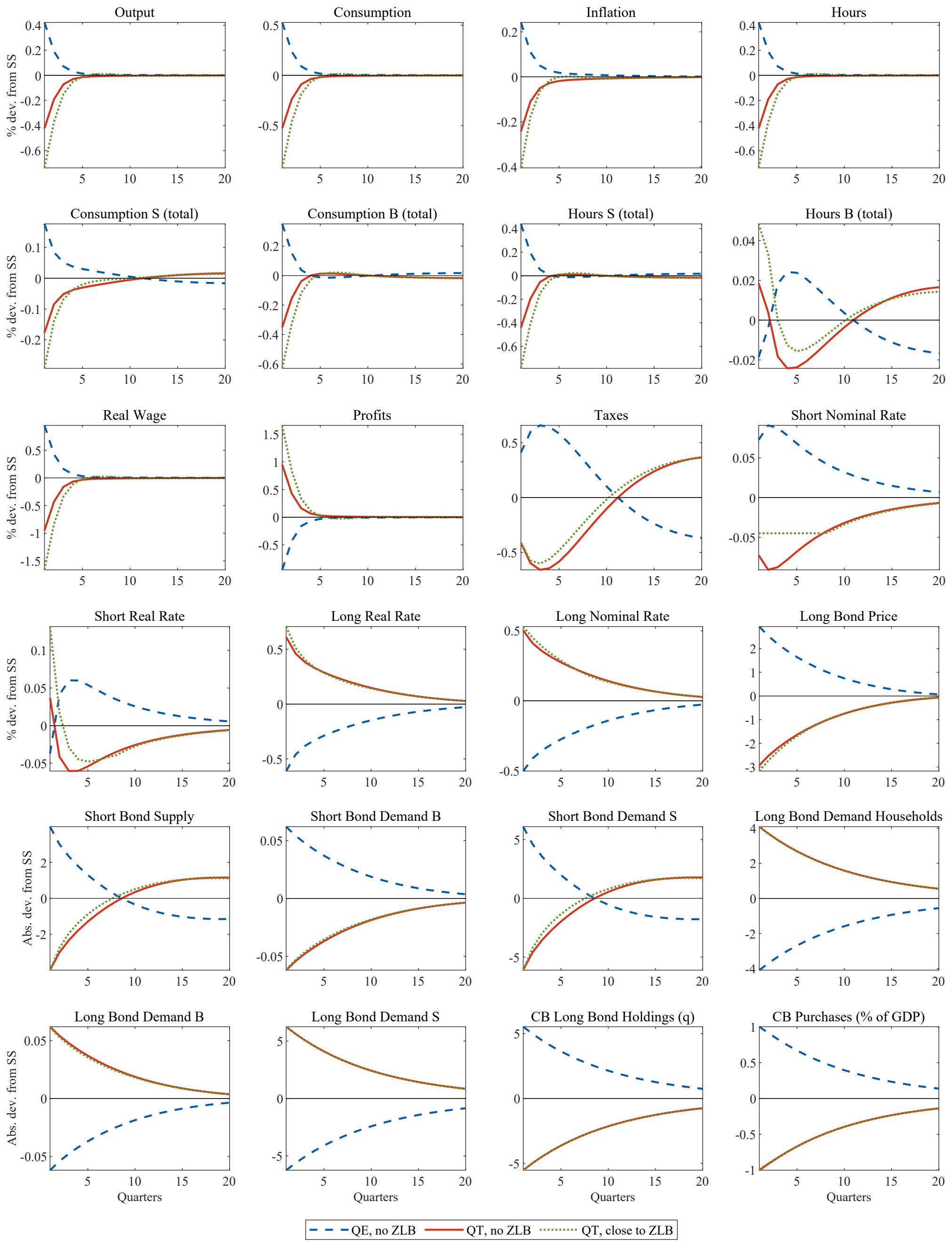
Labor supply	$w_t = \zeta^j \, (N_t^j)^{\varphi} (c_t^j)^{1/\sigma}, \;\; j = \{B, S\}$
Euler short-term bonds, S	$1 = \beta^S \, \mathbb{E}_t \left[\frac{\theta_{t+1}}{\theta_t} \left(\frac{c_{t+1}^S}{c_t^S} \right)^{-1/\sigma} \frac{R_t}{\Pi_{t+1}} \right] - \frac{\nu \, \delta^S}{b_t^{S,L}} \left(\delta^S \, \frac{b_t^S}{b_t^{S,L}} - 1 \right)$
Euler long-term bonds, S	$1 = \beta^S \, \mathbb{E}_t \left[\frac{\theta_{t+1}}{\theta_t} \left(\frac{c_{t+1}^S}{c_t^S} \right)^{-1/\sigma} \frac{R_{t+1}^L}{\Pi_{t+1}} \right] + \frac{\nu \, \delta^S \, b_t^S}{\left(b_t^{S,L}\right)^2} \left(\delta^S \, \frac{b_t^S}{b_t^{S,L}} - 1 \right)$
Budget constraint, S	$c_t^S + b_t^S + b_t^{S,L} = r_{t-1} \, b_{t-1}^S + r_t^L \, b_{t-1}^{S,L} + w_t \, N_t^S + \frac{1-\tau^D}{1-\lambda} d_t - t_t - \Psi_t^S - \frac{tr}{1-\lambda}$
Euler short-term bonds, B	$1 = \beta^B \, \mathbb{E}_t \left[\frac{\theta_{t+1}}{\theta_t} \left(\frac{c_{t+1}^B}{c_t^B} \right)^{-1/\sigma} \frac{R_t}{\Pi_{t+1}} \right] - \frac{\nu \, \delta^B}{b_t^{B,L}} \left(\delta^B \, \frac{b_t^B}{b_t^{B,L}} - 1 \right) + \frac{\psi_t^B}{\theta_t \left(c_t^B\right)^{-1/\sigma}}$
Euler long-term bonds, B	$1 = \beta^B \, \mathbb{E}_t \left[\frac{\theta_{t+1}}{\theta_t} \left(\frac{c_{t+1}^B}{c_t^B} \right)^{-1/\sigma} \frac{R_{t+1}^L}{\Pi_{t+1}} \right] + \frac{\nu \, \delta^B \, b_t^B}{\left(b_t^{B,L}\right)^2} \left(\delta^B \, \frac{b_t^B}{b_t^{B,L}} - 1 \right) + \frac{\psi_t^B}{\theta_t \left(c_t^B\right)^{-1/\sigma}}$
Budget constraint, B	$c_t^B + b_t^B + b_t^{B,L} = r_{t-1} \, b_{t-1}^B + r_t^L \, b_{t-1}^{B,L} + w_t \, N_t^B + \frac{\tau^D}{\lambda} d_t - t_t - \Psi_t^B + \frac{tr}{\lambda}$
Borrowing constraint	$-b_t^B - b_t^{B,L} \leq \bar{D}$
Portfolio adjustment cost	$\Psi_t^j = \frac{\nu}{2} \left(\delta^j \, \frac{b_t^j}{b_t^{j,L}} - 1 \right)^2, \;\; j = \{B, S\}$
Labor demand	$w_t = mc_t \, \frac{y_t}{N_t}$
Production function	$y_t = z_t \, N_t$
Profits, aggregate	$d_t = \left[1 - mc_t - \frac{\phi_p}{2} \, (\Pi_t - 1)^2 \right] y_t$
Phillips curve	$\phi_p \, (\Pi_t - 1) \, \Pi_t = \varepsilon \, mc_t + \left(1 + \tau^S\right) (1 - \varepsilon)$ $+ \beta^S \, \mathbb{E}_t \left[\frac{\theta_{t+1}}{\theta_t} \left(\frac{c_{t+1}^S}{c_t^S} \right)^{-\frac{1}{\sigma}} \phi_p \, (\Pi_{t+1} - 1) \, \Pi_{t+1} \frac{y_{t+1}}{y_t} \right]$
Government budget constraint	$b_t + b_t^L = r_{t-1} \, b_{t-1} + r_t^L \, b_{t-1}^L + \Omega_t + g_t - t_t$
Short-term real interest rate	$r_t = \frac{R_t}{\mathbb{E}_t \Pi_{t+1}}$
Nominal long-term bond return	$R_t^L = \frac{1 + \chi V_t}{V_{t-1}}$
Real long-term bond return	$r_t^L = \frac{R_t^L}{\Pi_t}$
Net bond purchases, CB	$\Omega_t = b_t^{CB,L} - r_t^L \, b_{t-1}^{CB,L}$
Value bond purchases, CB	$b_t^{CB,L} = q_t \, b_t^L$
Taylor rule	$\log\left(\frac{R_t}{R}\right) = \rho_r \, \log\left(\frac{R_{t-1}}{R}\right) + (1 - \rho_r) \left[\phi_\pi \, \log\left(\frac{\Pi_t}{\Pi}\right) \right] + \varepsilon_t^m$
QE shock rule	$\log\left(\frac{q_t}{q}\right) = \rho_q \, \log\left(\frac{q_{t-1}}{q}\right) + \varepsilon_t^q$
Fiscal rule	$\frac{t_t}{t} = \left(\frac{t_{t-1}}{t}\right)^{\rho^{\tau,t}} \left(\frac{b_t + b_t^L}{b + b^L}\right)^{\rho^{\tau,b}} \left(\frac{g_t}{g}\right)^{\rho^{\tau,g}}$
Aggregate consumption	$c_t = \lambda c_t^B + (1 - \lambda) c_t^S$
Aggregate labor	$N_t = \lambda N_t^B + (1 - \lambda) N_t^S$
Short-term bonds market clearing	$b_t = \lambda b_t^B + (1 - \lambda) b_t^S$
Long-term bonds market clearing	$b_t^L = \left(\lambda \, b_t^{B,L} + (1 - \lambda) \, b_t^{S,L} \right) + b_t^{CB,L}$
Resource constraint	$y_t = c_t + g_t + \frac{\phi_p}{2} \, (\Pi_t - 1)^2 \, y_t$
Other shock rules	$\log\left(\frac{x_t}{x}\right) = \rho_x \, \log\left(\frac{x_{t-1}}{x}\right) + \varepsilon_t^x, \;\; x = \{g, bL, z, \theta\}$

B Full sets of impulse responses

This appendix contains all impulse responses for the various QE or QT shocks studied in Section 3.

B.1 QE/QT and QT near the ZLB

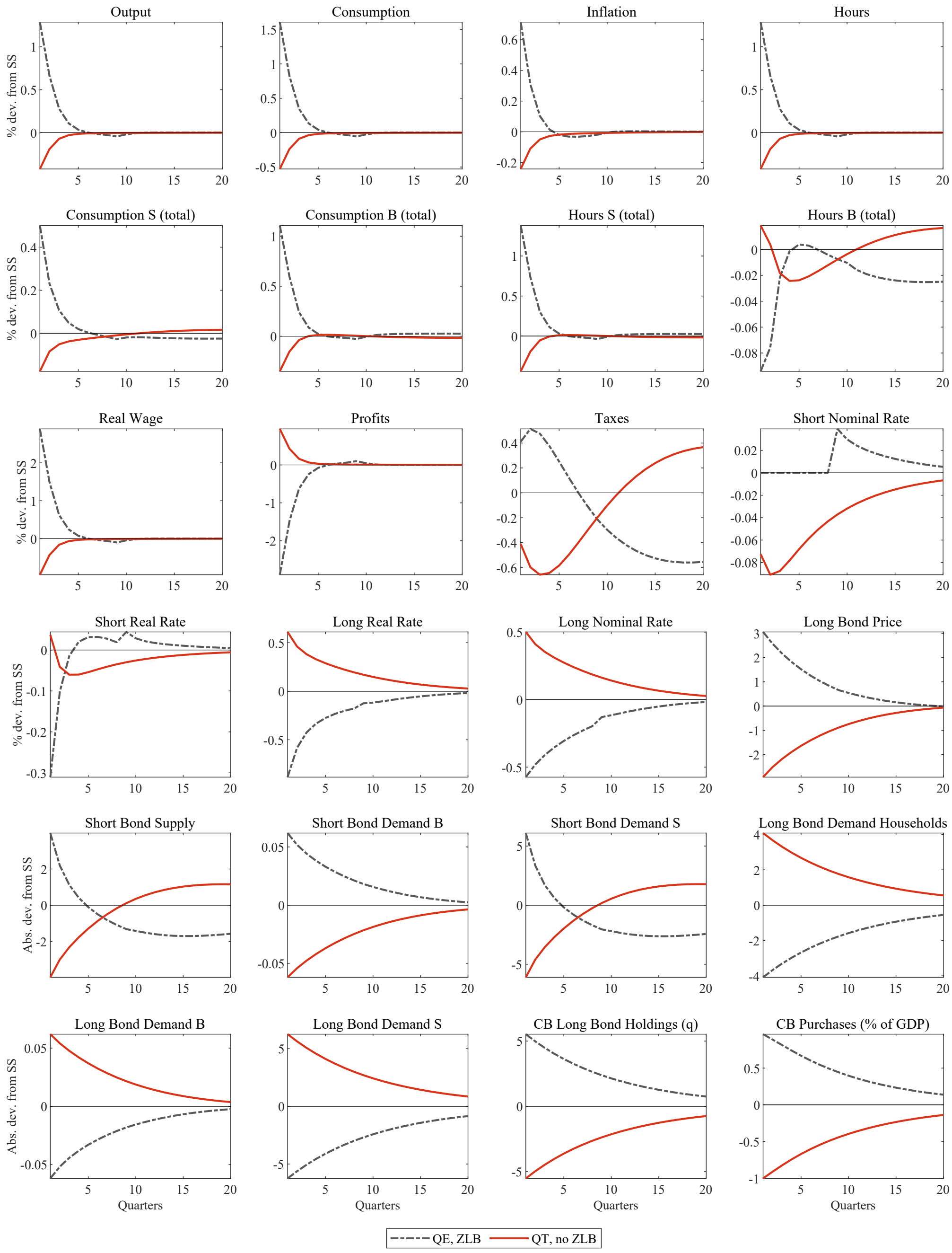
Figure B.1: Impulse responses to a QE/QT shock and a QT shock near the ZLB



Notes: This figure depicts the impulse responses to a QE (dashed blue line) and a QT (solid red line) shock occurring far enough above the ZLB, and a QT shock happening close to the ZLB (dotted green line). The shock for each simulation is an asset purchase/sale of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

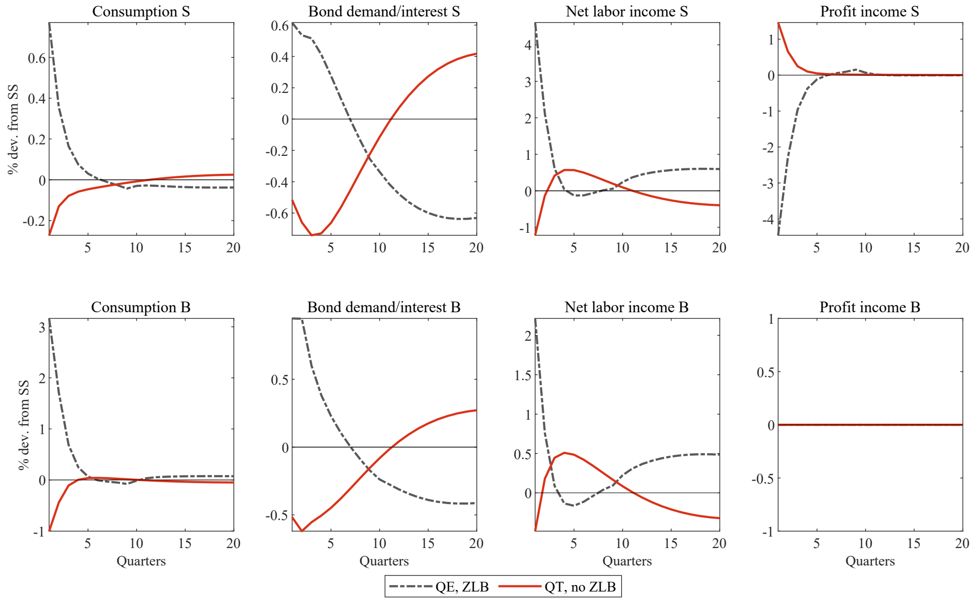
B.2 QE at the ZLB and QT off the ZLB

Figure B.2: Impulse responses to a QE shock at the ZLB and a QT shock off the ZLB



Notes: This figure depicts the impulse responses to a QE shock when the ZLB on the policy rate is binding (dash-dotted gray line, showing the impact of QE net of a preference shock), and a QT shock occurring far enough above the ZLB (solid red line). The shock for each simulation is an asset purchase/sale of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

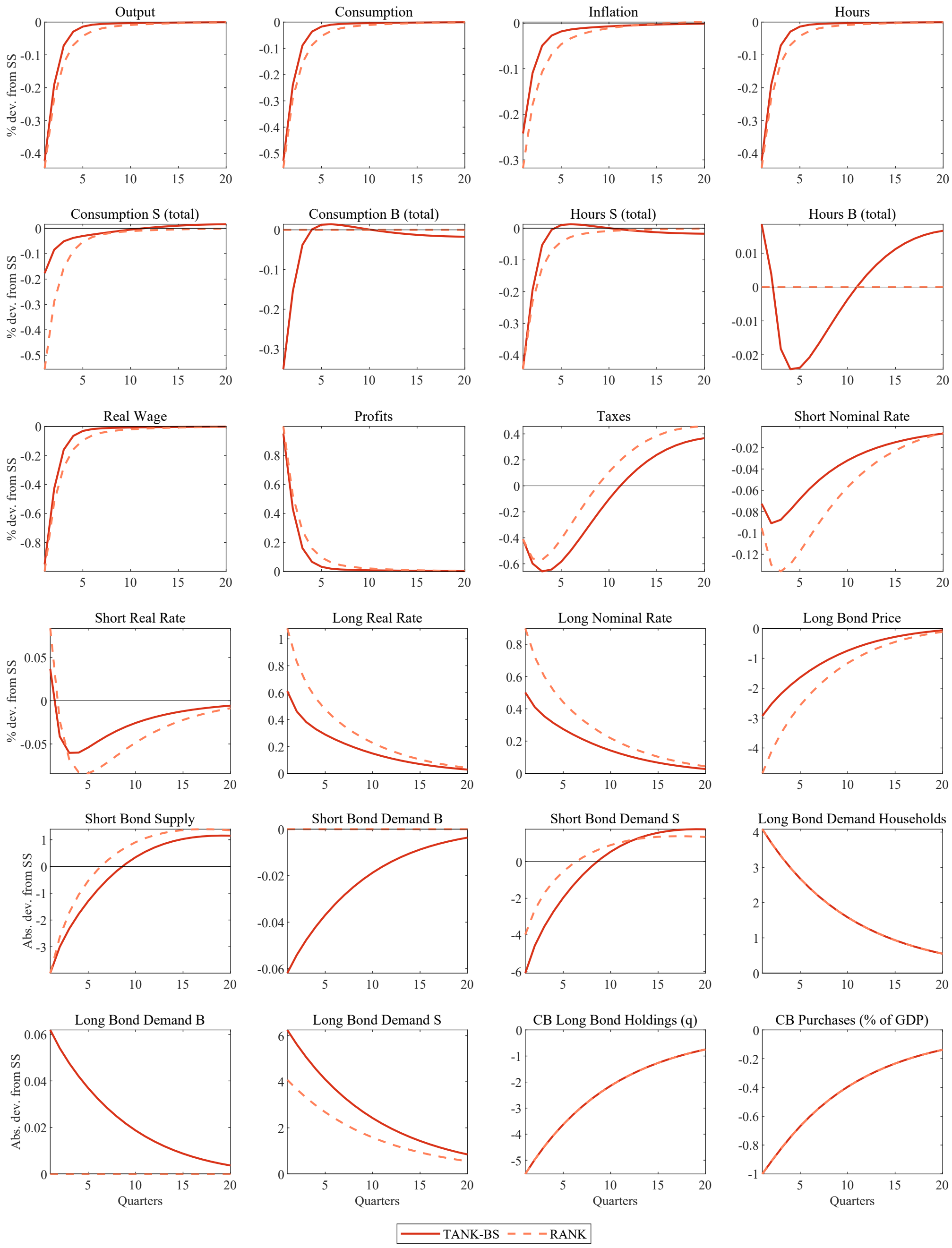
Figure B.3: Household budget components after a QE shock at the ZLB and a QT shock off the ZLB



Notes: This figure shows grouped components of the budget constraints of savers (top) and borrowers (bottom) in response to a QE shock when the ZLB on the policy rate is binding (dash-dotted gray line, showing the impact of QE net of a negative preference shock), and a QT shock occurring far enough above the ZLB (solid red line). The shock for each simulation is an asset purchase/sale of size 1% of annualized GDP. Each panel consists of four columns, containing the responses of individual consumption, bond-related variables (bond demand, interest payments/income, net of adjustment cost), labor income net of taxes, and income from profits. All responses are shown in per-capita terms.

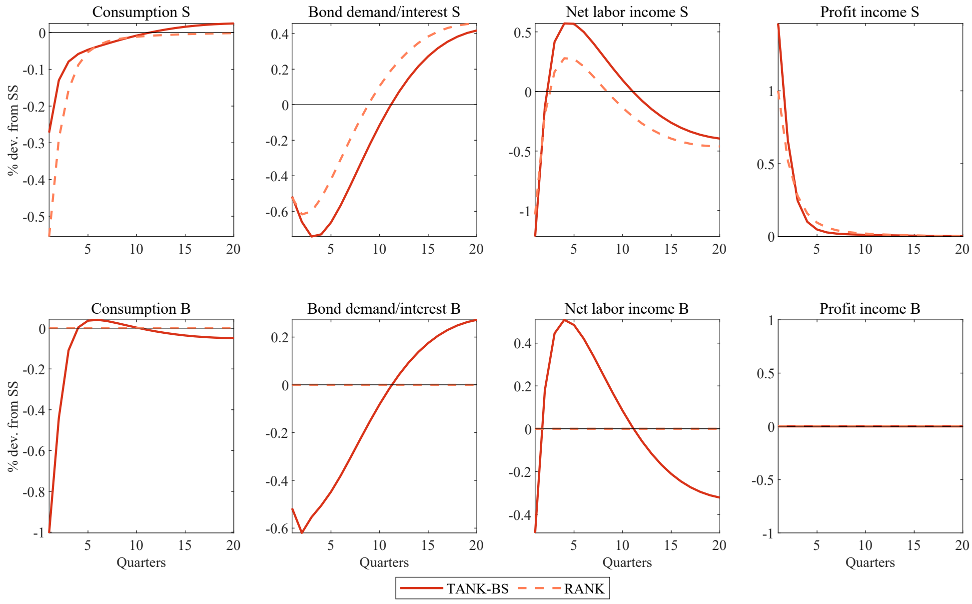
B.3 QT off the ZLB: RANK vs. TANK-BS

Figure B.4: Impulse responses to a QT shock off the ZLB: RANK vs. TANK-BS



Notes: This figure depicts the impulse responses to a QT shock occurring far enough above the ZLB, for the borrower-saver model (TANK-BS, solid red line) and its representative-agent counterpart with $\lambda = 0$ (RANK, dashed light red line). The shock for each simulation is an asset sale of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

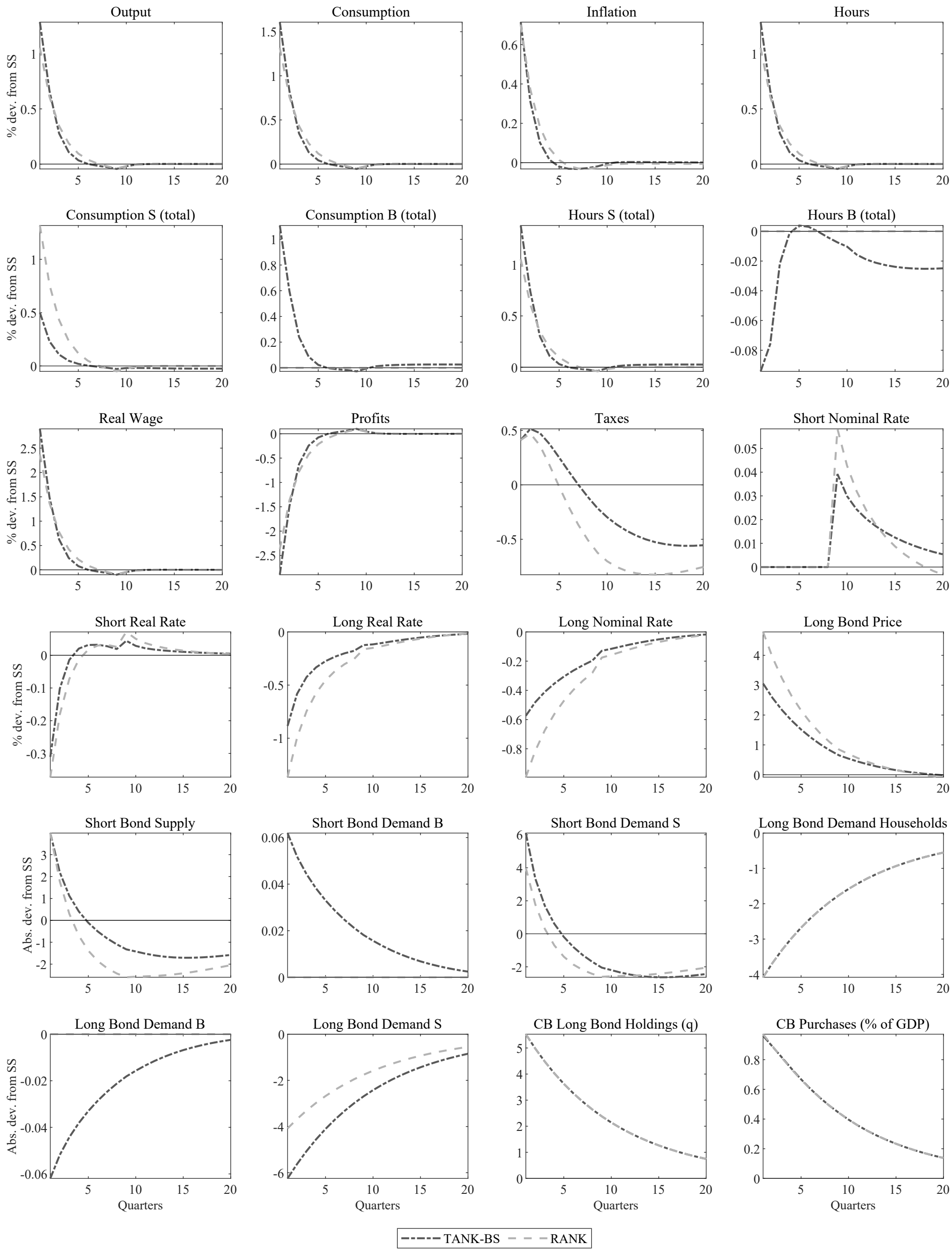
Figure B.5: Household budget components after a QT shock off the ZLB: RANK vs. TANK-BS



Notes: This figure shows grouped components of the budget constraints of savers (top) and borrowers (bottom) in response to a QT shock occurring far enough above the ZLB, for the borrower-saver model (TANK-BS, solid red line) and its representative-agent counterpart with $\lambda = 0$ (RANK, dashed light red line). The shock for each simulation is an asset sale of size 1% of annualized GDP. Each panel consists of four columns, containing the responses of individual consumption, bond-related variables (bond demand, interest payments/income, net of adjustment cost), labor income net of taxes, and income from profits. All responses are shown in per-capita terms.

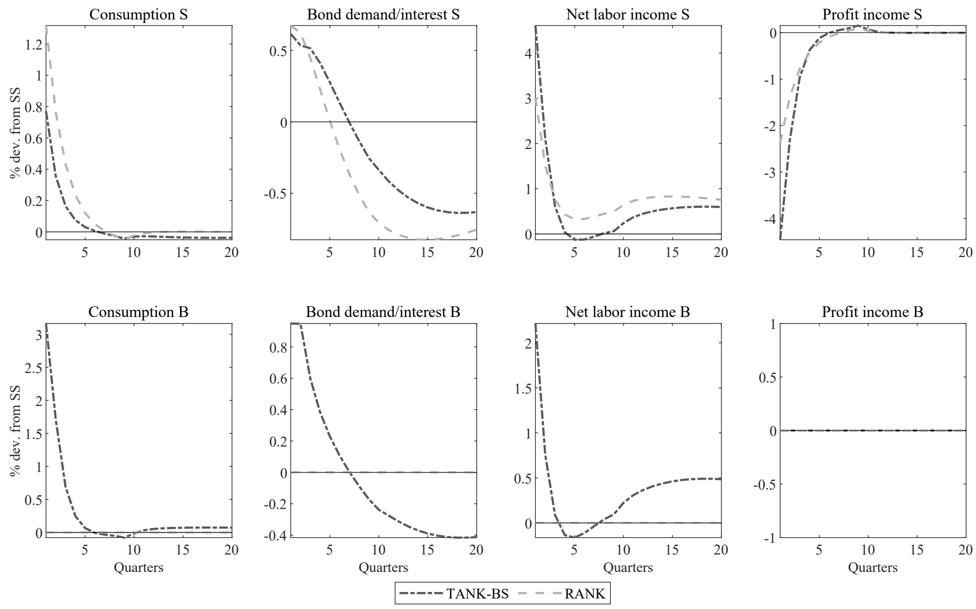
B.4 QE at the ZLB: RANK vs. TANK-BS

Figure B.6: Impulse responses to a QE shock at the ZLB: RANK vs. TANK-BS



Notes: This figure depicts the impulse responses to a QE shock net of a negative preference shock when the ZLB on the policy rate is binding, for the borrower-saver model (TANK-BS, dash-dotted gray line) and its representative-agent counterpart with $\lambda = 0$ (RANK, dashed light gray line). The shock for each simulation is an asset purchase of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

Figure B.7: Household budget components after a QE shock at the ZLB: RANK vs. TANK-BS



Notes: This figure shows grouped components of the budget constraints of savers (top) and borrowers (bottom) in response to a QE shock net of a negative preference shock when the ZLB on the policy rate is binding, for the borrower-saver model (TANK-BS, dash-dotted gray line) and its representative-agent counterpart with $\lambda = 0$ (RANK, dashed light gray line). The shock for each simulation is an asset purchase of size 1% of annualized GDP. Each panel consists of four columns, containing the responses of individual consumption, bond-related variables (bond demand, interest payments/income, net of adjustment cost), labor income net of taxes, and income from profits. All responses are shown in per-capita terms.

C Robustness checks

This appendix addresses the robustness of our baseline results. It provides the *impact multipliers* (Appendix C.1) and the *impulse responses* (Appendix C.2) both for alternative parameterization choices in the baseline model and for a number of different fiscal and monetary policy rules. Moreover, it contains sensitivity checks on the model's *stability and determinacy* properties under these specifications (Appendix C.3).

Below are the different robustness checks we considered, along with references to the corresponding impulse responses. The baseline calibration values are highlighted in bold. Tables C.1 and C.2 provide the impact multipliers for each specification.

- Alternative parameter values for the tax on profits, namely $\tau^D = \{\mathbf{0}, 0.2, 0.35\}$ (see Figures C.1 to C.4). Taxing dividends at rate $\tau^D = \lambda = 0.35$ corresponds to the case of full profit redistribution.

- Alternative parameter values for the portfolio adjustment cost, namely $\nu = \{0.04, \mathbf{0.05}, 0.06\}$ (see Figures C.5 to C.8).

- A fiscal rule as implemented in the baseline model, where taxes respond to past tax revenues, total debt, and government spending:

$$\frac{t_t}{t} = \left(\frac{t_{t-1}}{t}\right)^{\rho^{\tau,t}} \left(\frac{b_t + b_t^L}{b + b^L}\right)^{\rho^{\tau,b}} \left(\frac{g_t}{g}\right)^{\rho^{\tau,g}} .$$

  We run separate robustness checks for the tax smoothing parameter $\rho^{\tau,t} = \{0, 0.4, \mathbf{0.7}\}$ (see Figures C.9 to C.12)[32] and for the tax response to total debt $\rho^{\tau,b} = \{0.1, \mathbf{0.33}, 0.9\}$ (see Figures C.13 to C.16).[33]

- A different fiscal setup where government spending reacts to total debt and real output, while taxes only react to total debt:

$$\frac{g_t}{g} = \left(\frac{b_t + b_t^L}{b + b^L}\right)^{\rho^{g,b}} \left(\frac{y_t}{y}\right)^{\rho^{g,y}} \quad \text{and} \quad \frac{t_t}{t} = \left(\frac{b_t + b_t^L}{b + b^L}\right)^{\rho^{\tau,b}} .$$

  This setup mirrors the exercise in Cui (2016). Figures C.17 to C.20 present the sensitivity checks for each pair $\left(\rho^{g,b}, \rho^{g,y}\right) = \{\mathbf{(0,0)}, (-0.3, -0.2), (-0.9, -0.5)\}$. The selected values are either close to the optimal policy exercise parameters in Cui (2016) or chosen such that there is a larger spread between them.

- A different rule governing long-term debt based on its past value, taxes, and real output:

$$\frac{b_t^L}{b^L} = \left(\frac{b_{t-1}^L}{b^L}\right)^{\rho^{bL,b}} \left(\frac{t_t}{t}\right)^{\rho^{bL,t}} \left(\frac{y_t}{y}\right)^{\rho^{bL,y}} .$$

[32] The computational algorithm from the dynareOBC toolkit, used to implement the ZLB, was unable to find a solution for values of $\rho^{\tau,t}$ close to one for all simulations, which is why 0.7 is set as the upper bound for tax persistence.

[33] Since government spending follows an AR(1) process, we refrained from testing robustness regarding $\rho^{\tau,g}$.

This specification relaxes the constant-debt assumption for the long-term asset while short-term debt supply remains non-constant. Figures C.21 to C.24 show the robustness checks for each pair $\left(\rho^{bL,t}, \rho^{bL,y}\right) = \{(\mathbf{0,0}), (-0.2, -0.3), (-0.5, -0.9)\}$, whereby $\rho^{bL,b} = 0.9$. The selected values are mirror those of the previous specification, with an extreme parameterization included. Motivated by empirical evidence in Anzoategui (2022), we assign a larger weight to output.

- An extended Taylor rule where the nominal short-term interest rate not only reacts to inflation but also to output:

$$\log\left(\frac{R_t}{R}\right) = \rho_r \log\left(\frac{R_{t-1}}{R}\right) + (1-\rho_r)\left[\phi_\pi \log\left(\frac{\Pi_t}{\Pi}\right) + \phi_y \log\left(\frac{y_t}{y}\right)\right] + \varepsilon_t^m .$$

  Figures C.25 to C.28 depict the sensitivity checks for $\phi_y = \{\mathbf{0}, 0.4, 0.8\}$.

C.1 Multipliers on impact of a QE or QT shock: Sensitivity analysis

The following tables present the impact multipliers of the TANK-BS and RANK models for different robustness checks. Starting from the baseline calibration with $\tau^D = 0$, $\nu = 0.05$, $\rho^{\tau,t} = 0.7$, and $\rho^{\tau,b} = 0.33$, each row of Table C.1 changes one parameter value from the baseline model at a time. Table C.2 presents the impact multipliers under the various policy rules considered, where the baseline values are $\rho^{g,b} = \rho^{g,y} = \rho^{bL,t} = \rho^{bL,y} = \phi_y = 0$.

Table C.1: Impact multipliers (in %): Sensitivity in baseline TANK-BS model

	Output		Inflation		Consumption	
	QE	QT	QE	QT	QE	QT
TANK-BS						
Baseline	1.29	-0.42	0.71	-0.24	1.61	-0.53
(i) Tax on profits						
$\tau^D = 0.2$	0.81	-0.31	0.52	-0.20	1.02	-0.38
$\tau^D = 0.35$	0.63	-0.26	0.43	-0.18	0.79	-0.32
(ii) Portfolio adjustment cost						
$\nu = 0.04$	1.05	-0.34	0.58	-0.19	1.31	-0.43
$\nu = 0.06$	1.51	-0.50	0.84	-0.29	1.89	-0.63
(iii) Tax smoothing						
$\rho^{\tau,t} = 0$	1.32	-0.41	0.75	-0.26	1.65	-0.52
$\rho^{\tau,t} = 0.4$	1.32	-0.42	0.74	-0.25	1.64	-0.52
(iv) Tax response to debt						
$\rho^{\tau,b} = 0.1$	1.34	-0.44	0.75	-0.26	1.67	-0.55
$\rho^{\tau,b} = 0.9$	1.26	-0.39	0.70	-0.20	1.58	-0.48
RANK						
Baseline	1.05	-0.44	0.70	-0.32	1.32	-0.56
(i) Tax on profits						
$\tau^D = 0.2$	0.88	-0.39	0.62	-0.29	1.10	-0.49
$\tau^D = 0.35$	0.78	-0.36	0.57	-0.28	0.98	-0.45
(ii) Portfolio adjustment cost						
$\nu = 0.04$	0.90	-0.36	0.60	-0.26	1.12	-0.45
$\nu = 0.06$	1.20	-0.53	0.79	-0.37	1.50	-0.66
(iii) Tax smoothing						
$\rho^{\tau,t} = 0$	0.98	-0.45	0.64	-0.32	1.23	-0.56
$\rho^{\tau,t} = 0.4$	1.00	-0.45	0.66	-0.32	1.26	-0.56
(iv) Tax response to debt						
$\rho^{\tau,b} = 0.1$	0.98	-0.45	0.64	-0.32	1.22	-0.56
$\rho^{\tau,b} = 0.9$	1.18	-0.44	0.81	-0.31	1.48	-0.55

Notes: This table summarizes the aggregate effects for alternative parameter values in the baseline borrower-saver model (TANK-BS) and its representative-agent counterpart with $\lambda = 0$ (RANK), on impact of a QE shock when the ZLB on the policy rate is binding and on impact of a QT shock occurring far enough above the ZLB. The shock for each simulation is an asset purchase/sale of size 1% of annualized GDP.

Table C.2: **Table C.2:** Impact multipliers (in %): Sensitivity for alternative policy rules

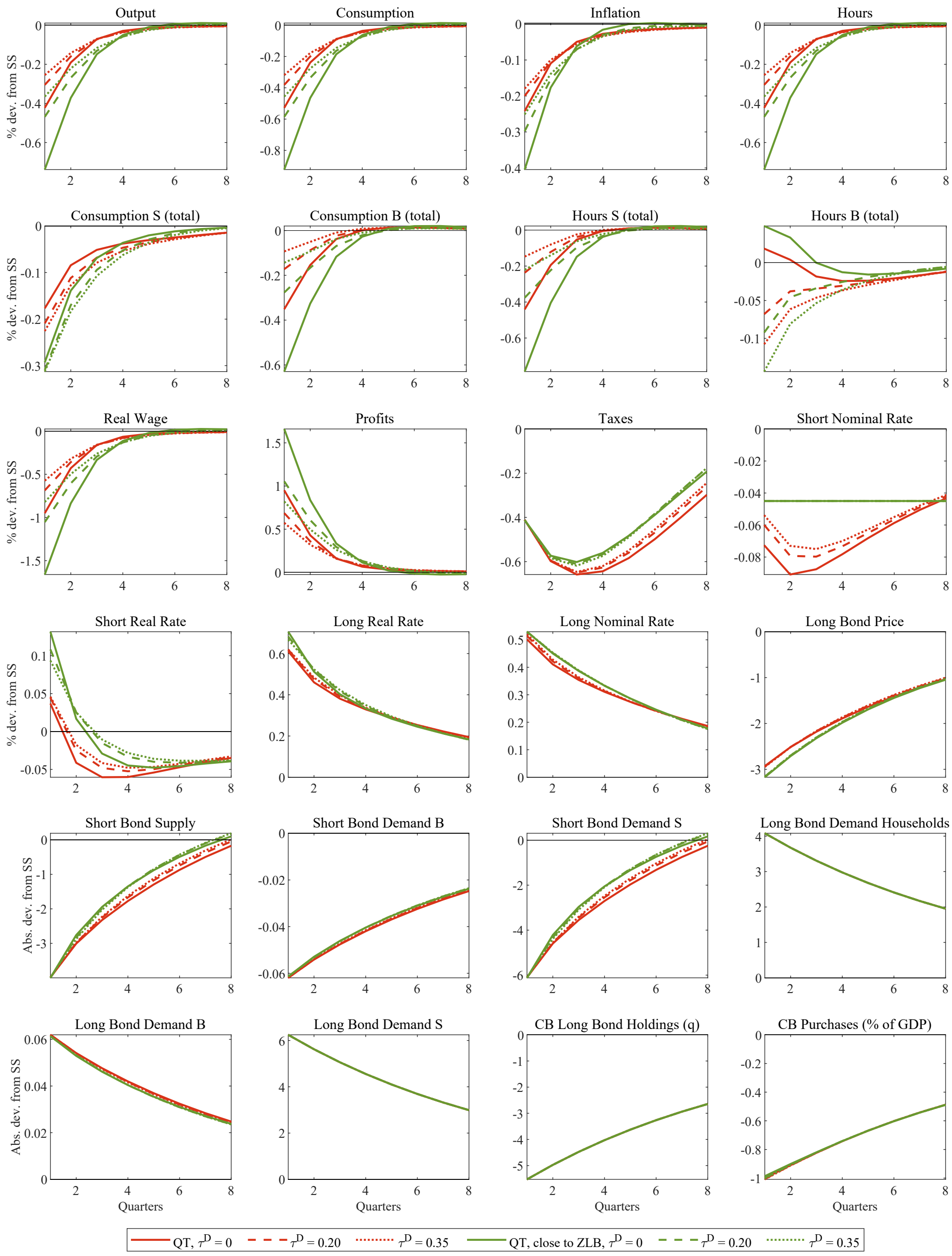
	Output		**Inflation**		**Consumption**	
	QE	QT	QE	QT	QE	QT
TANK-BS						
Baseline	1.29	-0.42	0.71	-0.24	1.61	-0.53
(v) Government spending response to debt and output						
$\rho^{g,b} = -0.3$, $\rho^{g,y} = -0.2$	1.06	-0.30	0.66	-0.22	1.47	-0.48
$\rho^{g,b} = -0.9$, $\rho^{g,y} = -0.5$	0.73	-0.10	0.56	-0.16	1.27	-0.41
(vi) Long-term debt response to taxes and output						
$\rho^{bL,t} = -0.2$, $\rho^{bL,y} = -0.3$	1.42	-0.46	0.79	-0.27	1.78	-0.57
$\rho^{bL,t} = -0.5$, $\rho^{bL,y} = -0.9$	1.49	-0.52	0.82	-0.32	1.87	-0.65
(vii) Taylor rule output coefficient						
$\phi_y = 0.4$	1.06	-0.31	0.57	-0.17	1.32	-0.38
$\phi_y = 0.8$	0.92	-0.24	0.48	-0.13	1.16	-0.31
RANK						
Baseline	1.05	-0.44	0.70	-0.32	1.32	-0.56
(v) Government spending response to debt and output						
$\rho^{g,b} = -0.3$, $\rho^{g,y} = -0.2$	0.88	-0.37	0.63	-0.30	1.23	-0.57
$\rho^{g,b} = -0.9$, $\rho^{g,y} = -0.5$	0.74	-0.23	0.63	-0.27	1.28	-0.58
(vi) Long-term debt response to taxes and output						
$\rho^{bL,t} = -0.2$, $\rho^{bL,y} = -0.3$	0.97	-0.48	0.62	-0.34	1.22	-0.60
$\rho^{bL,t} = -0.5$, $\rho^{bL,y} = -0.9$	0.85	-0.53	0.50	-0.38	1.06	-0.67
(vii) Taylor rule output coefficient						
$\phi_y = 0.4$	0.98	-0.35	0.64	-0.25	1.23	-0.44
$\phi_y = 0.8$	0.92	-0.29	0.59	-0.20	1.15	-0.36

Notes: This table summarizes the aggregate effects for different parameter values in the borrower-saver model under alternative policy rules (TANK-BS) and its representative-agent counterpart with $\lambda = 0$ (RANK), on impact of a QE shock when the ZLB on the policy rate is binding and on impact of a QT shock occurring far enough above the ZLB. The shock for each simulation is an asset purchase/sale of size 1% of annualized GDP.

C.2 Impulse responses: Sensitivity analysis

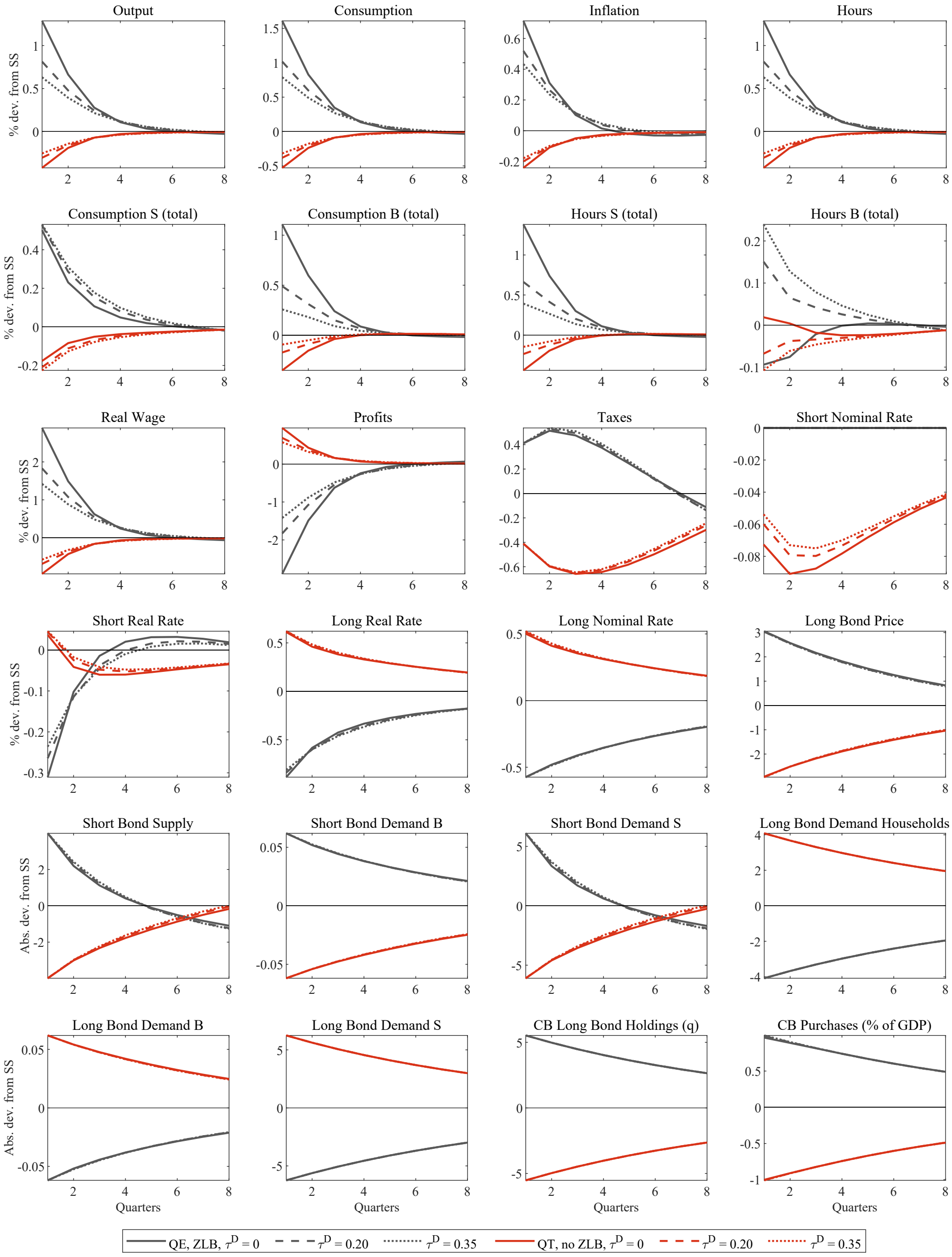
C.2.1 Tax on profits τ^D

Figure C.1: Impulse responses to a QT shock and a QT shock near the ZLB: Robustness for tax on profits τ^D



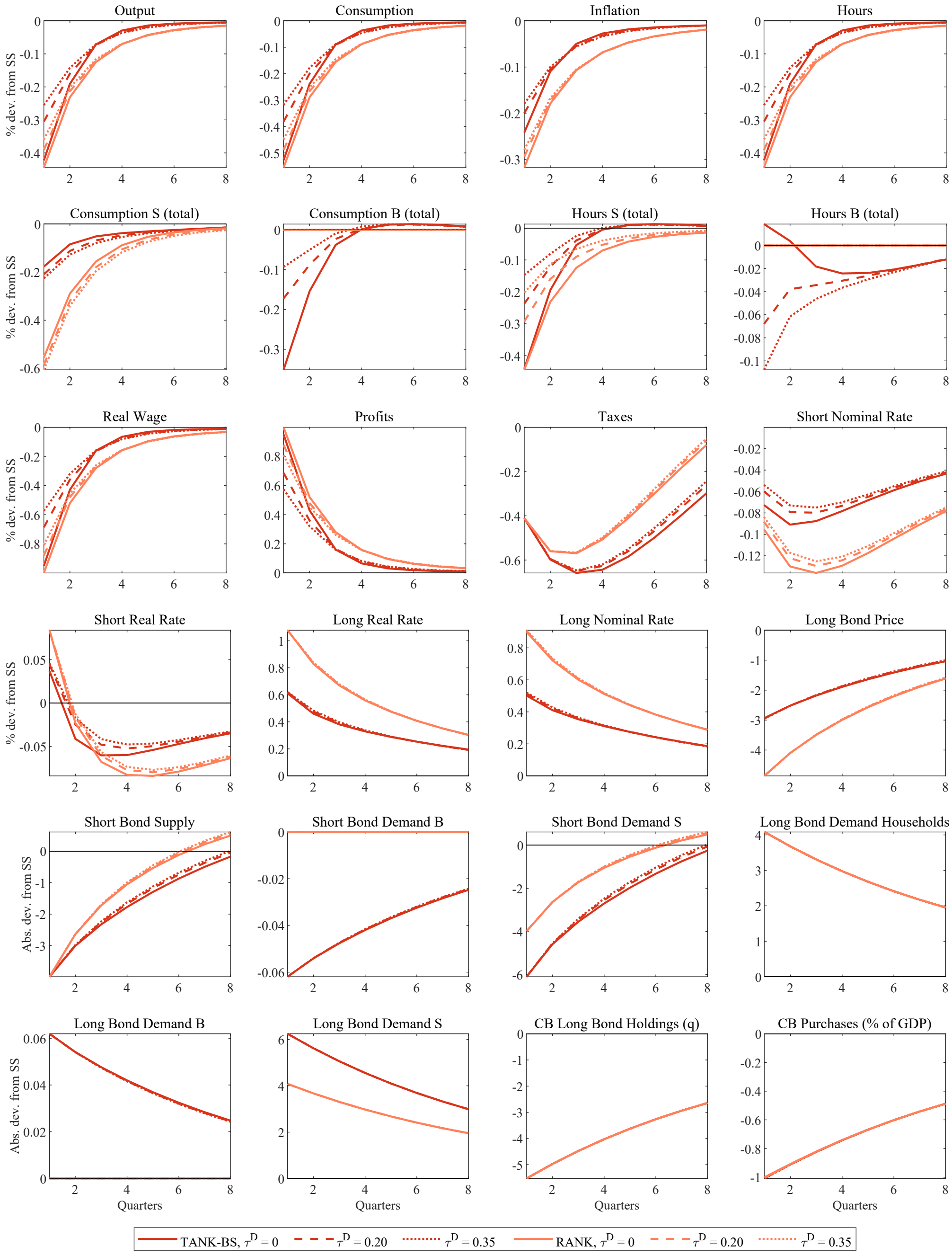
Notes: This figure depicts the impulse responses to a QT shock occurring far enough above the ZLB (red lines) and a QT shock happening close to the ZLB (green lines). The shock for each simulation is an asset purchase/sale of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

Figure C.2: Impulse responses to a QE shock at the ZLB and a QT shock off the ZLB: Robustness for tax on profits τ^D



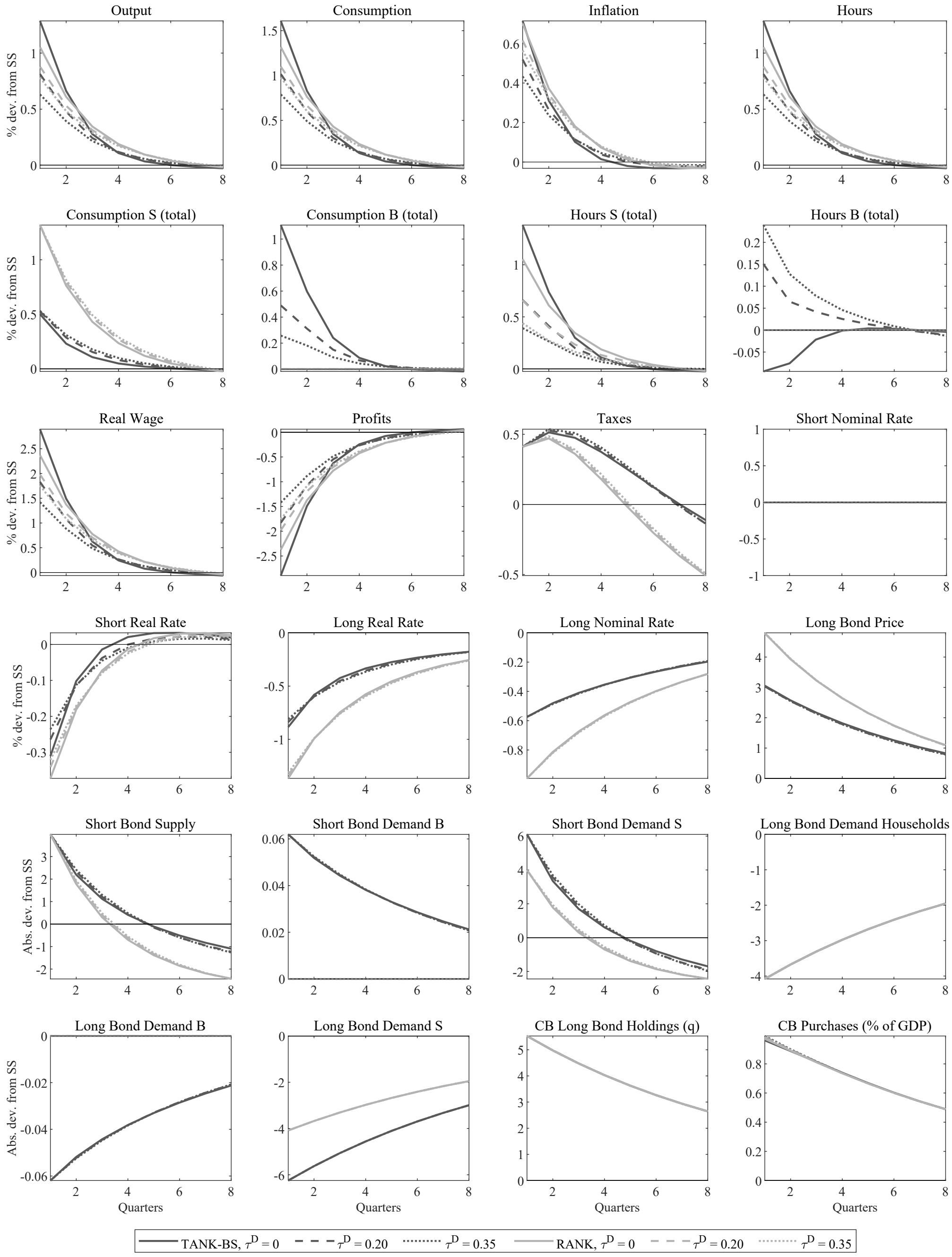
Notes: This figure depicts the impulse responses to a QE shock when the ZLB on the policy rate is binding (gray lines, showing the impact of QE net of a preference shock), and a QT shock occurring far enough above the ZLB (red lines). The shock for each simulation is an asset purchase/sale of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

Figure C.3: Impulse responses to a QT shock off the ZLB: RANK vs. TANK-BS: Robustness for tax on profits τ^D



Notes: This figure depicts the impulse responses to a QT shock occurring far enough above the ZLB, for the borrower-saver model (TANK-BS, red lines) and its representative-agent counterpart with $\lambda = 0$ (RANK, light red lines). The shock for each simulation is an asset sale of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

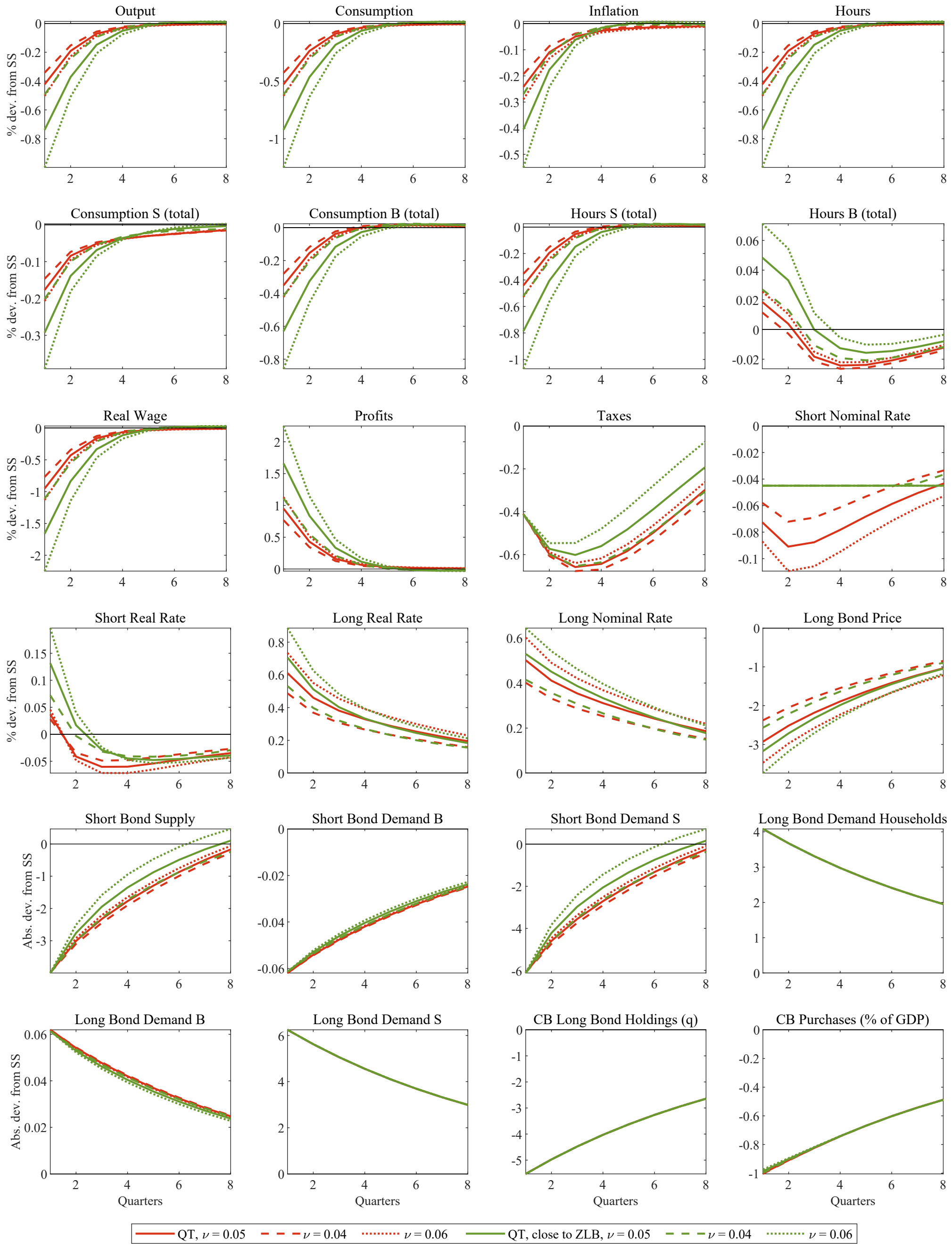
Figure C.4: Impulse responses to a QE shock at the ZLB: RANK vs. TANK-BS: Robustness for tax on profits τ^D



Notes: This figure depicts the impulse responses to a QE shock net of a negative preference shock when the ZLB on the policy rate is binding, for the borrower-saver model (TANK-BS, gray lines) and its representative-agent counterpart with $\lambda = 0$ (RANK, light gray lines). The shock for each simulation is an asset purchase of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

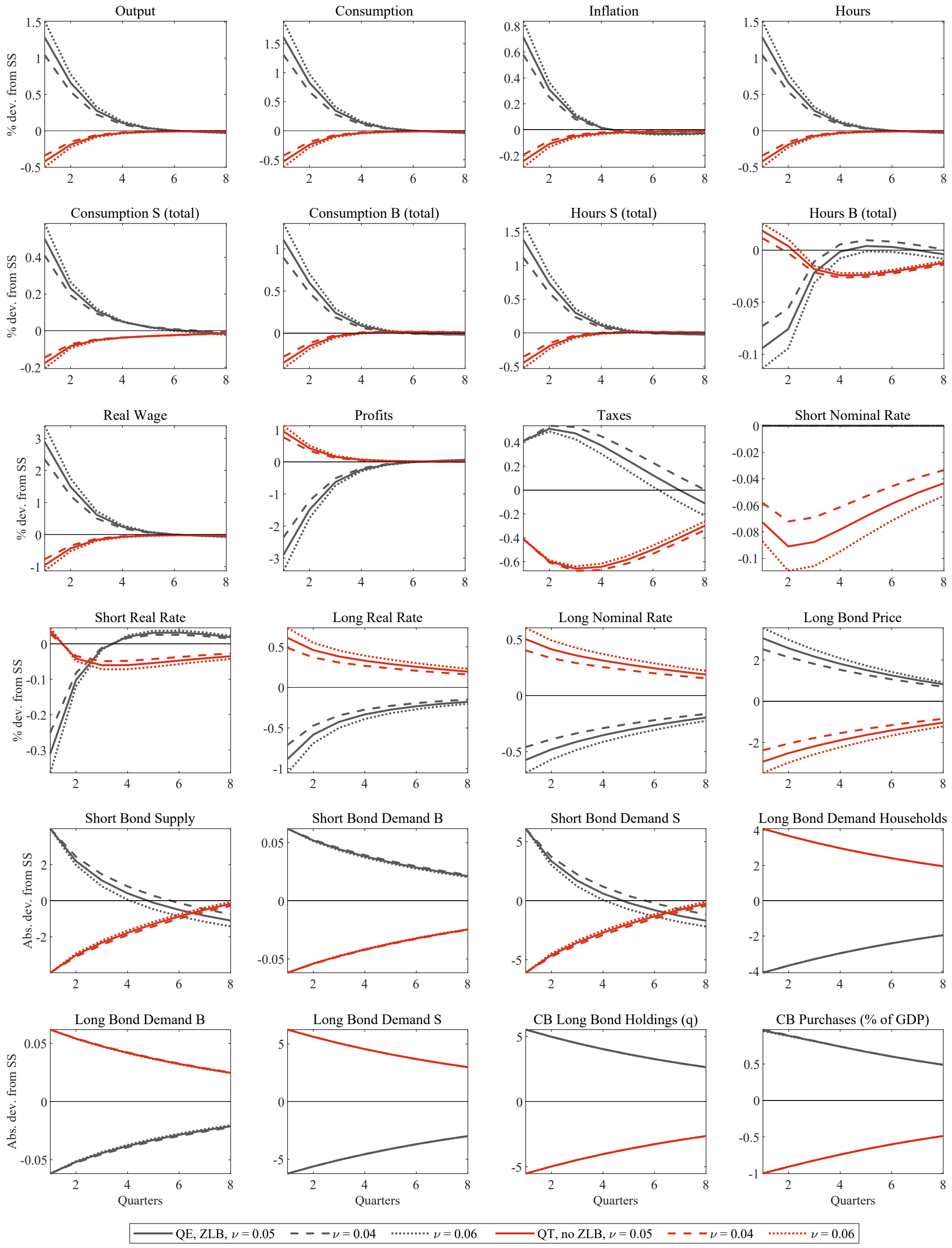
C.2.2 Portfolio adjustment cost ν

Figure C.5: Impulse responses to a QT shock and a QT shock near the ZLB: Robustness for portfolio adjustment cost ν



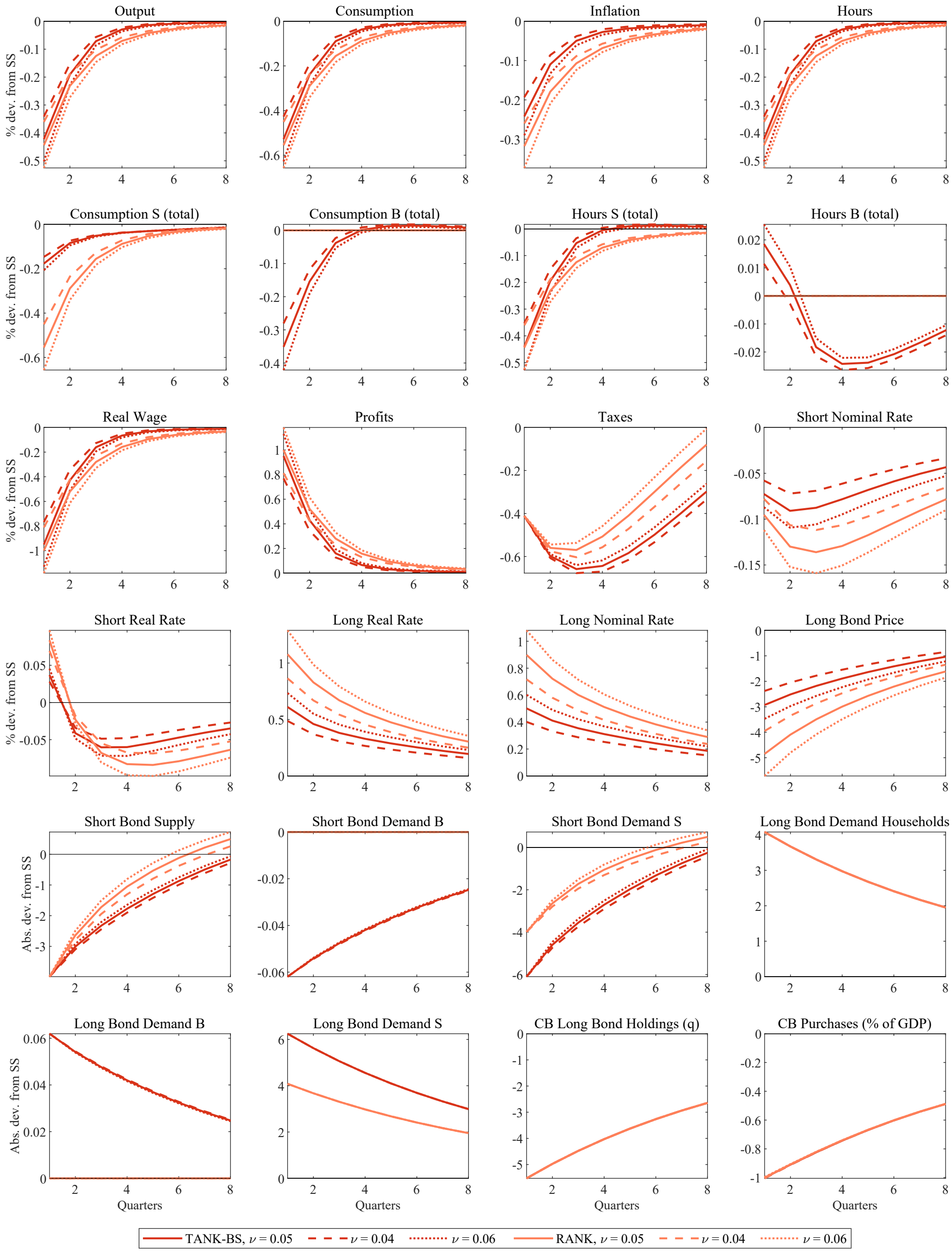
Notes: This figure depicts the impulse responses to a QT shock occurring far enough above the ZLB (red lines) and a QT shock happening close to the ZLB (green lines). The shock for each simulation is an asset purchase/sale of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

Figure C.6: Impulse responses to a QE shock at the ZLB and a QT shock off the ZLB: Robustness for portfolio adjustment cost ν



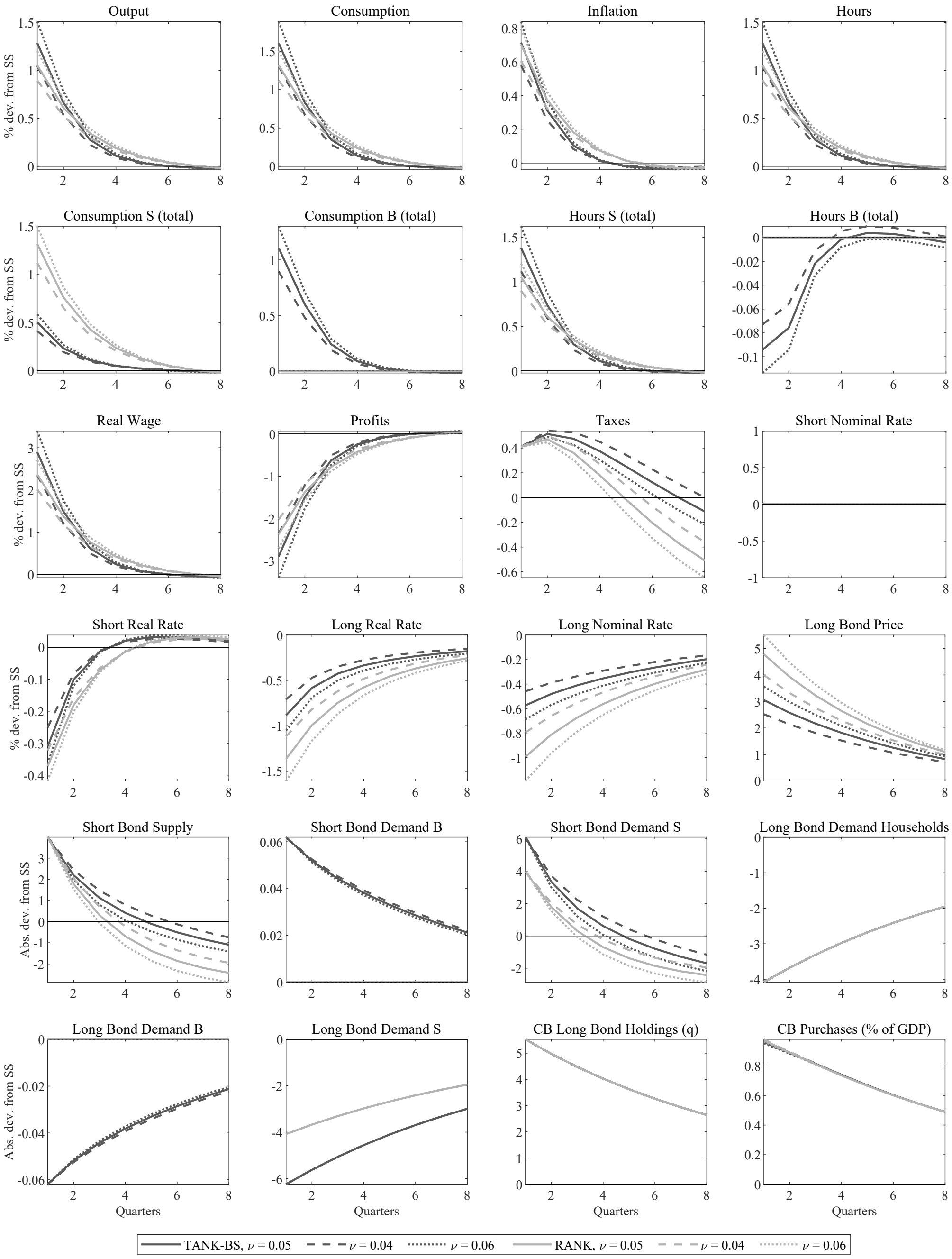
Notes: This figure depicts the impulse responses to a QE shock when the ZLB on the policy rate is binding (gray lines, showing the impact of QE net of a preference shock), and a QT shock occurring far enough above the ZLB (red lines). The shock for each simulation is an asset purchase/sale of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

Figure C.7: Impulse responses to a QT shock off the ZLB: RANK vs. TANK-BS: Robustness for portfolio adjustment cost ν



Notes: This figure depicts the impulse responses to a QT shock occurring far enough above the ZLB, for the borrower-saver model (TANK-BS, red lines) and its representative-agent counterpart with $\lambda = 0$ (RANK, light red lines). The shock for each simulation is an asset sale of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

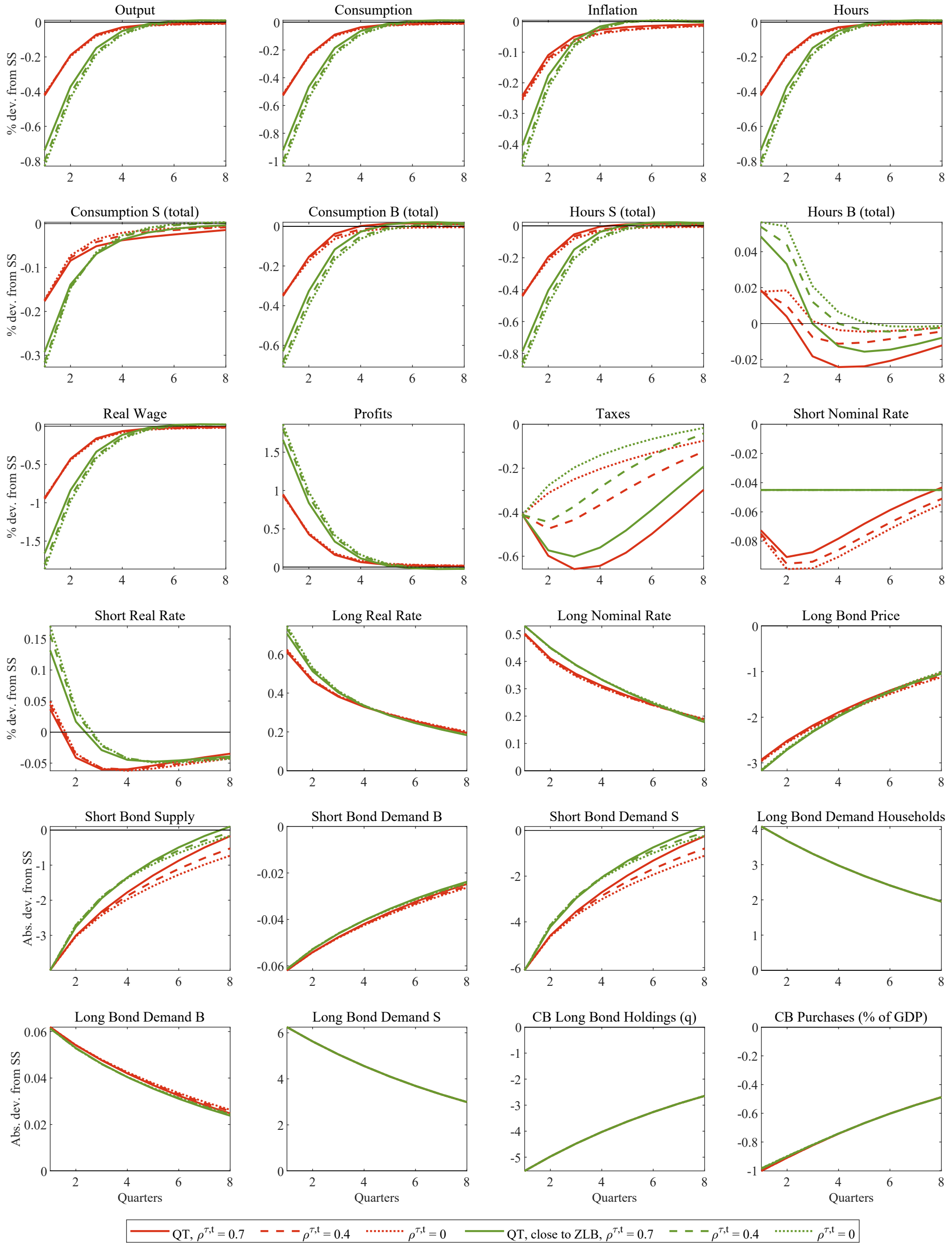
Figure C.8: Impulse responses to a QE shock at the ZLB: RANK vs. TANK-BS: Robustness for portfolio adjustment cost ν



Notes: This figure depicts the impulse responses to a QE shock net of a negative preference shock when the ZLB on the policy rate is binding, for the borrower-saver model (TANK-BS, gray lines) and its representative-agent counterpart with $\lambda = 0$ (RANK, light gray lines). The shock for each simulation is an asset purchase of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

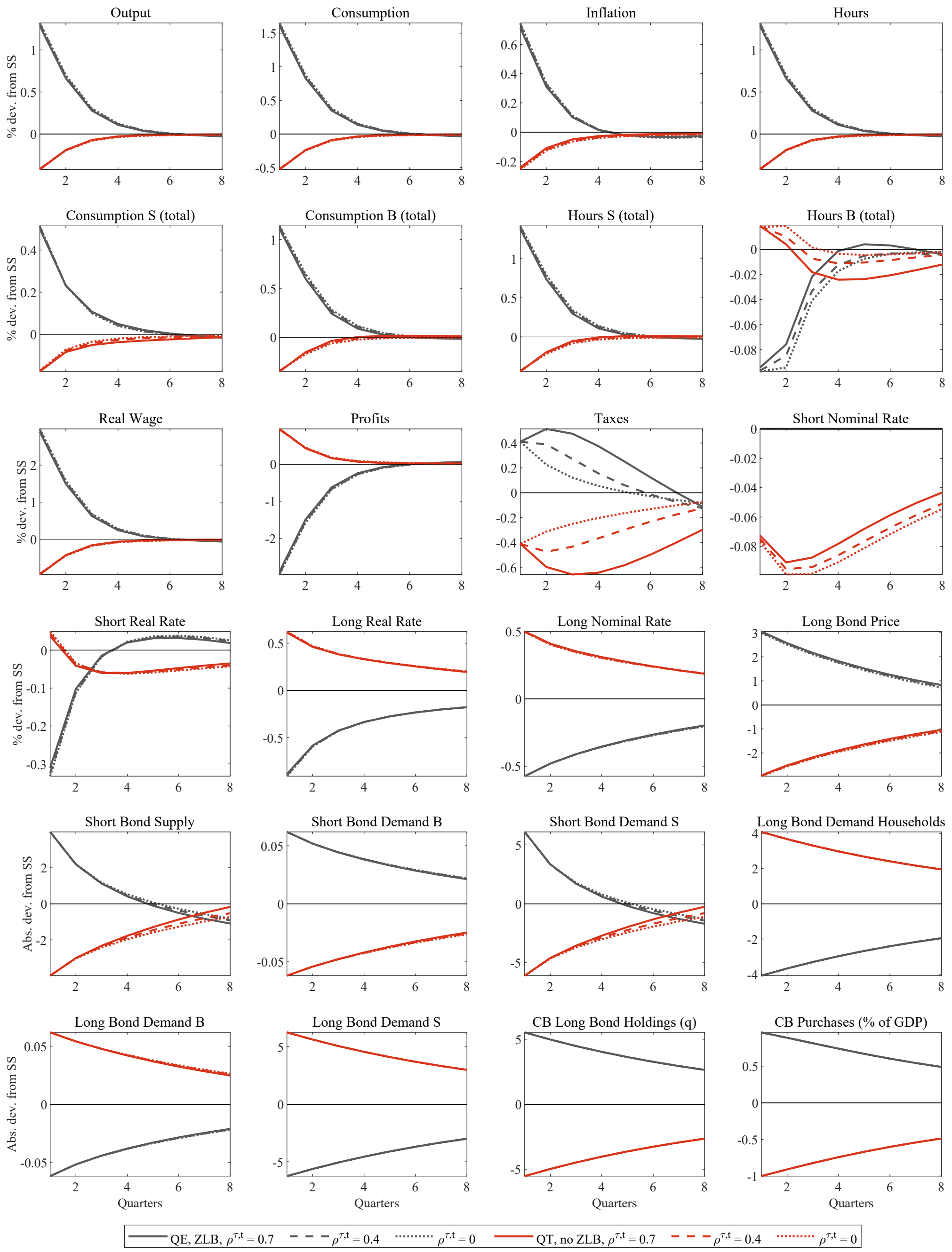
C.2.3 Tax smoothing in fiscal rule $\rho^{\tau,t}$

Figure C.9: Impulse responses to a QT shock off and a QT shock near the ZLB: Robustness for tax smoothing parameter $\rho^{\tau,t}$



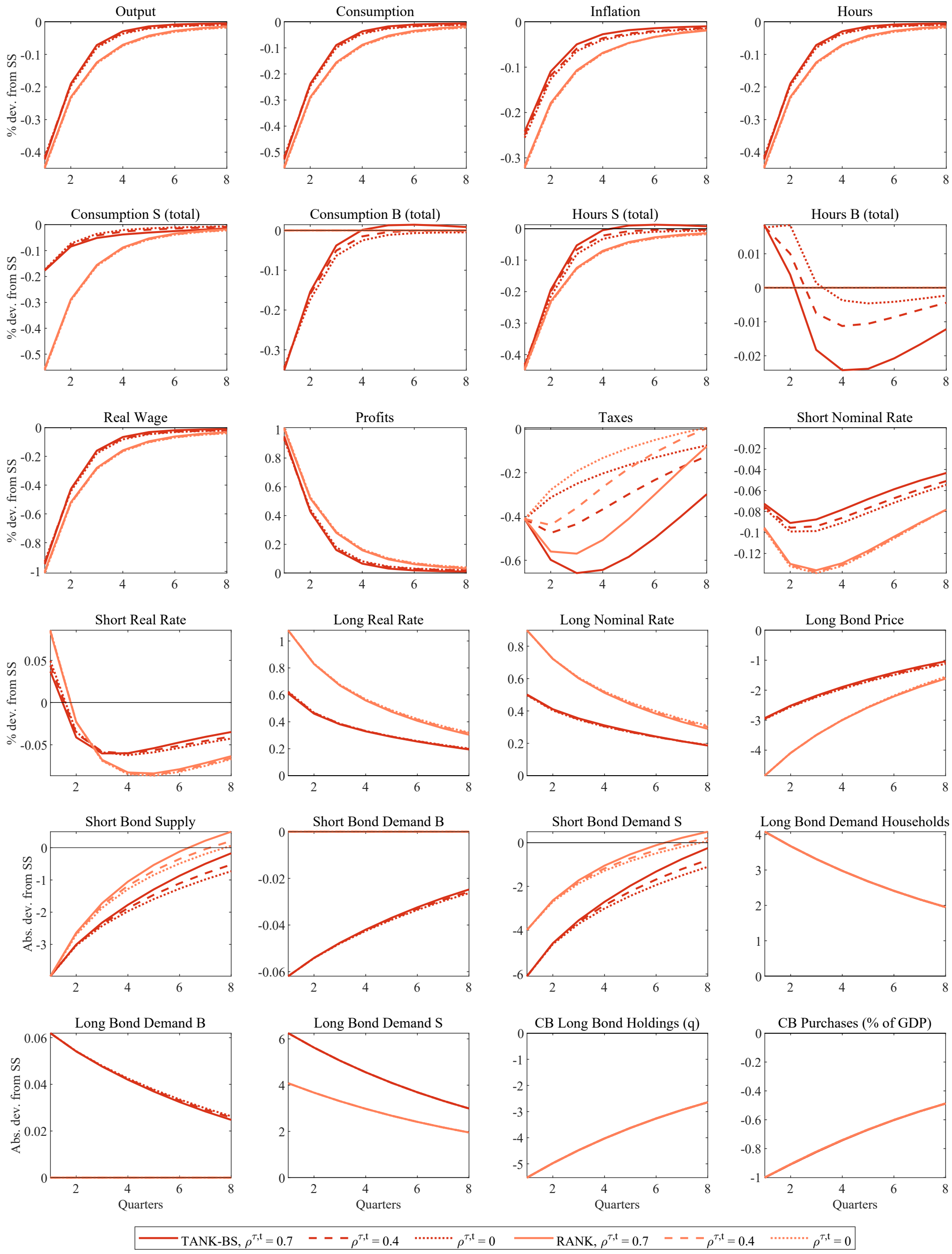
Notes: This figure depicts the impulse responses for the baseline borrower-saver model to a QT shock occurring far enough above the ZLB (red lines) and a QT shock happening close to the ZLB (green lines). The shock for each simulation is an asset purchase/sale of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

Figure C.10: Impulse responses to a QE shock at the ZLB and a QT shock off the ZLB: Robustness for tax smoothing parameter $\rho^{\tau,t}$



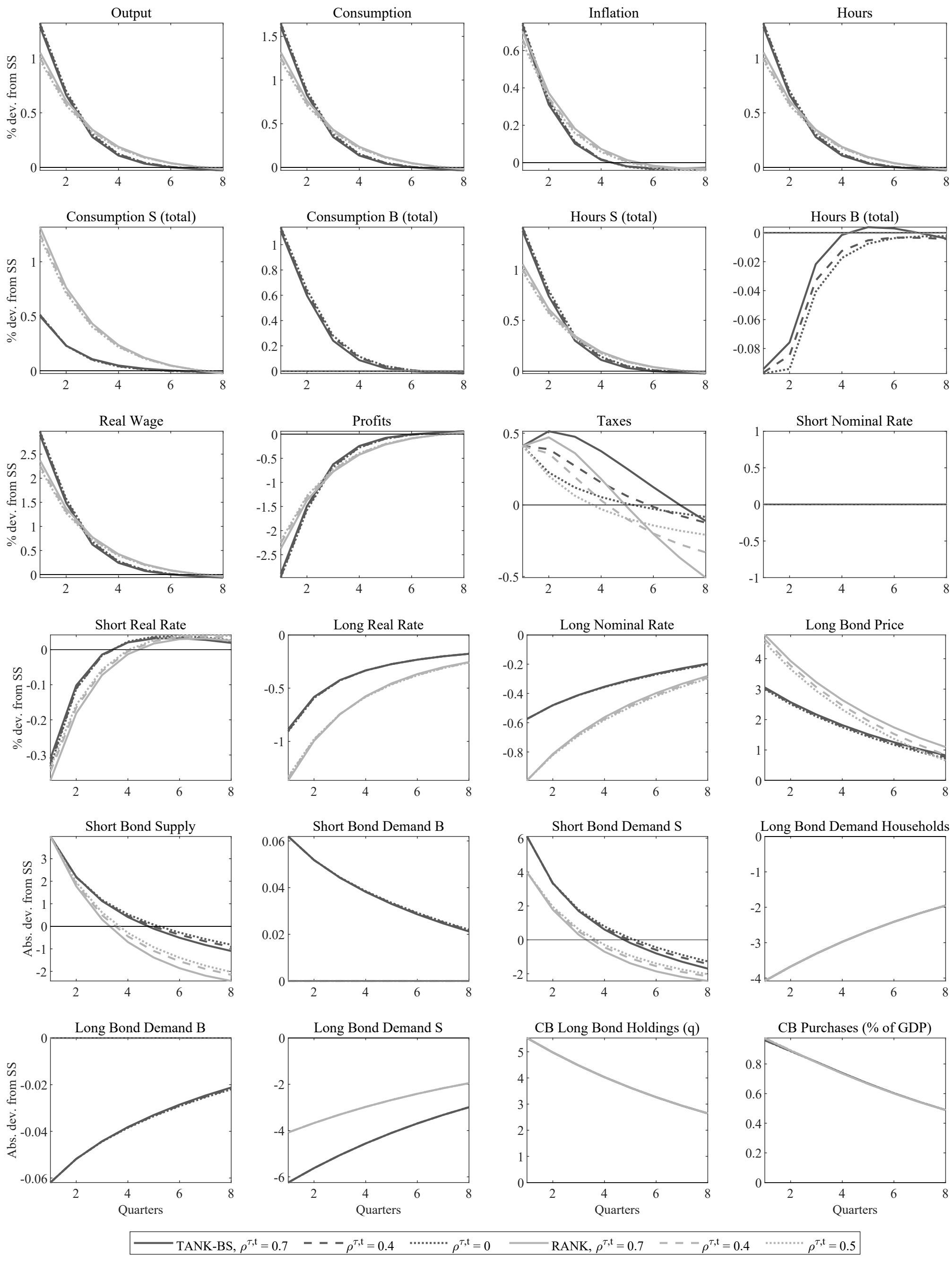
Notes: This figure depicts the impulse responses for the baseline borrower-saver model to a QE shock when the ZLB on the policy rate is binding (gray lines, showing the impact of QE net of a preference shock), and a QT shock occurring far enough above the ZLB (red lines). The shock for each simulation is an asset purchase/sale of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

Figure C.11: Impulse responses to a QT shock off the ZLB: Robustness for tax smoothing parameter $\rho^{\tau,t}$ in RANK vs. TANK-BS



Notes: This figure depicts the impulse responses to a QT shock occurring far enough above the ZLB, for the basline borrower-saver model (TANK-BS, red lines) and its representative-agent counterpart with $\lambda = 0$ (RANK, light red lines). The shock for each simulation is an asset sale of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

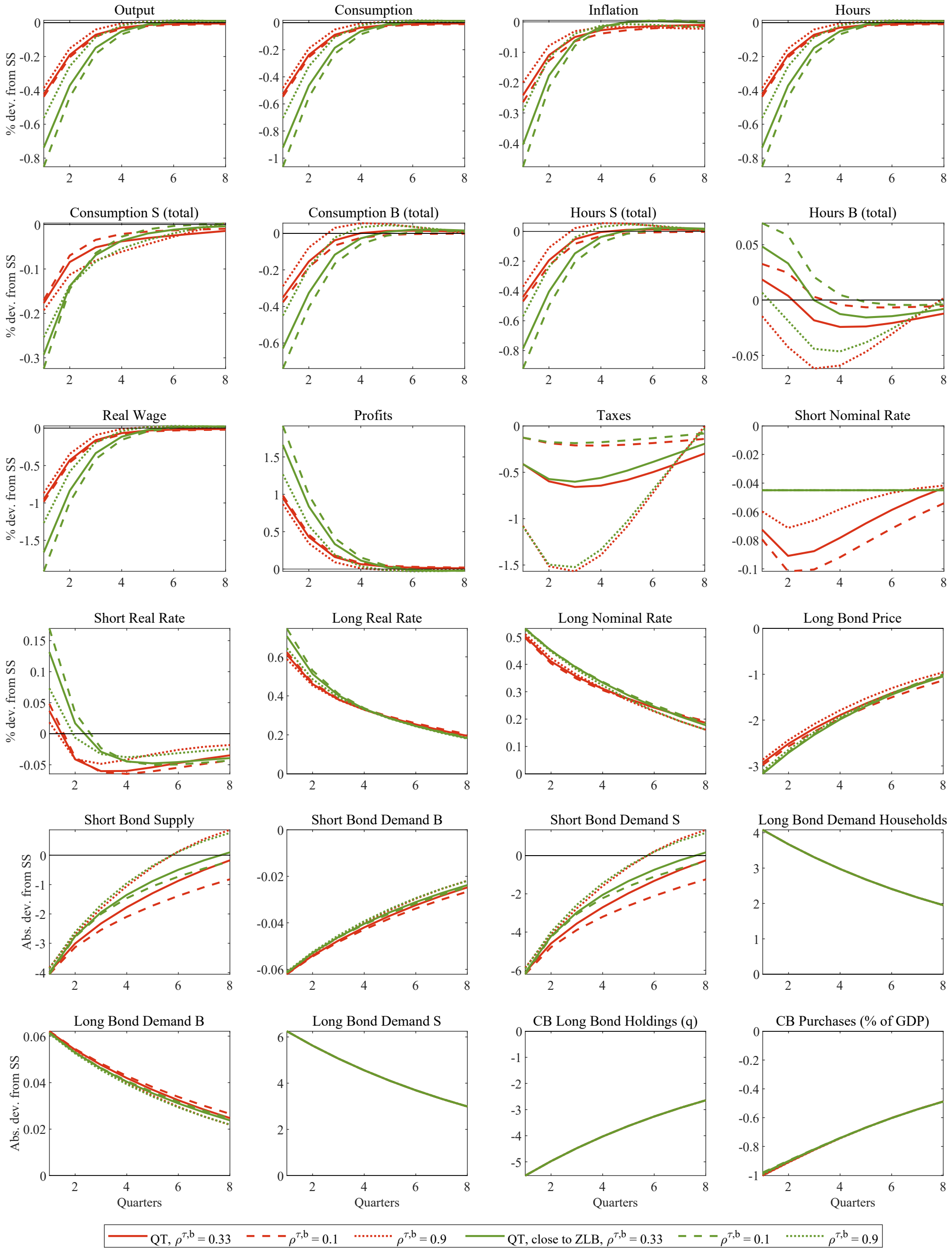
Figure C.12: Impulse responses to a QE shock at the ZLB: Robustness for tax smoothing parameter $\rho^{\tau,t}$ in RANK vs. TANK-BS



Notes: This figure depicts the impulse responses to a QE shock net of a negative preference shock when the ZLB on the policy rate is binding, for the baseline borrower-saver model (TANK-BS, gray lines) and its representative-agent counterpart with $\lambda = 0$ (RANK, light gray lines). The shock for each simulation is an asset purchase of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

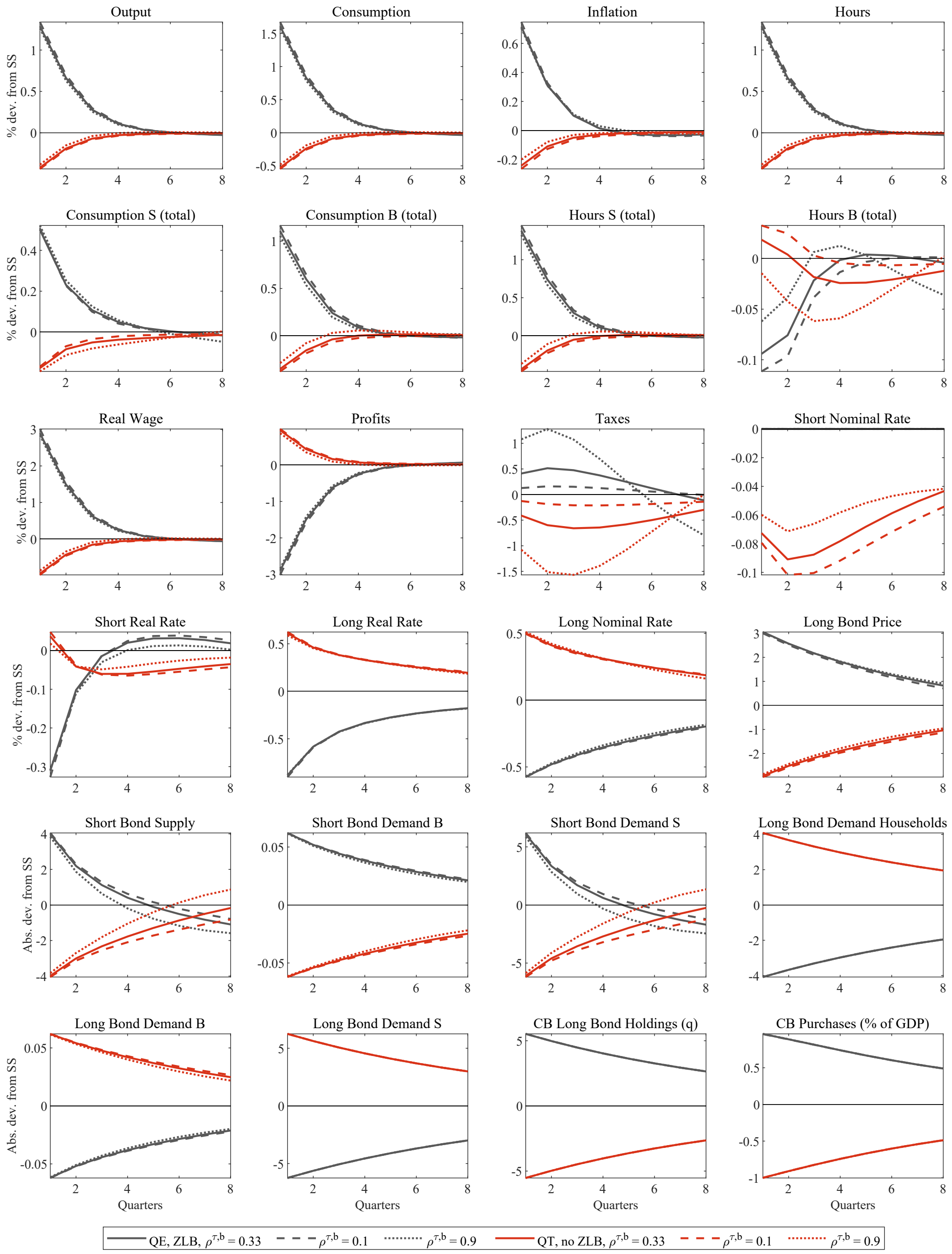
C.2.4 Tax response to total debt $\rho^{\tau,b}$

Figure C.13: Impulse responses to a QT shock off and a QT shock near the ZLB: Robustness for tax response to debt $\rho^{\tau,b}$



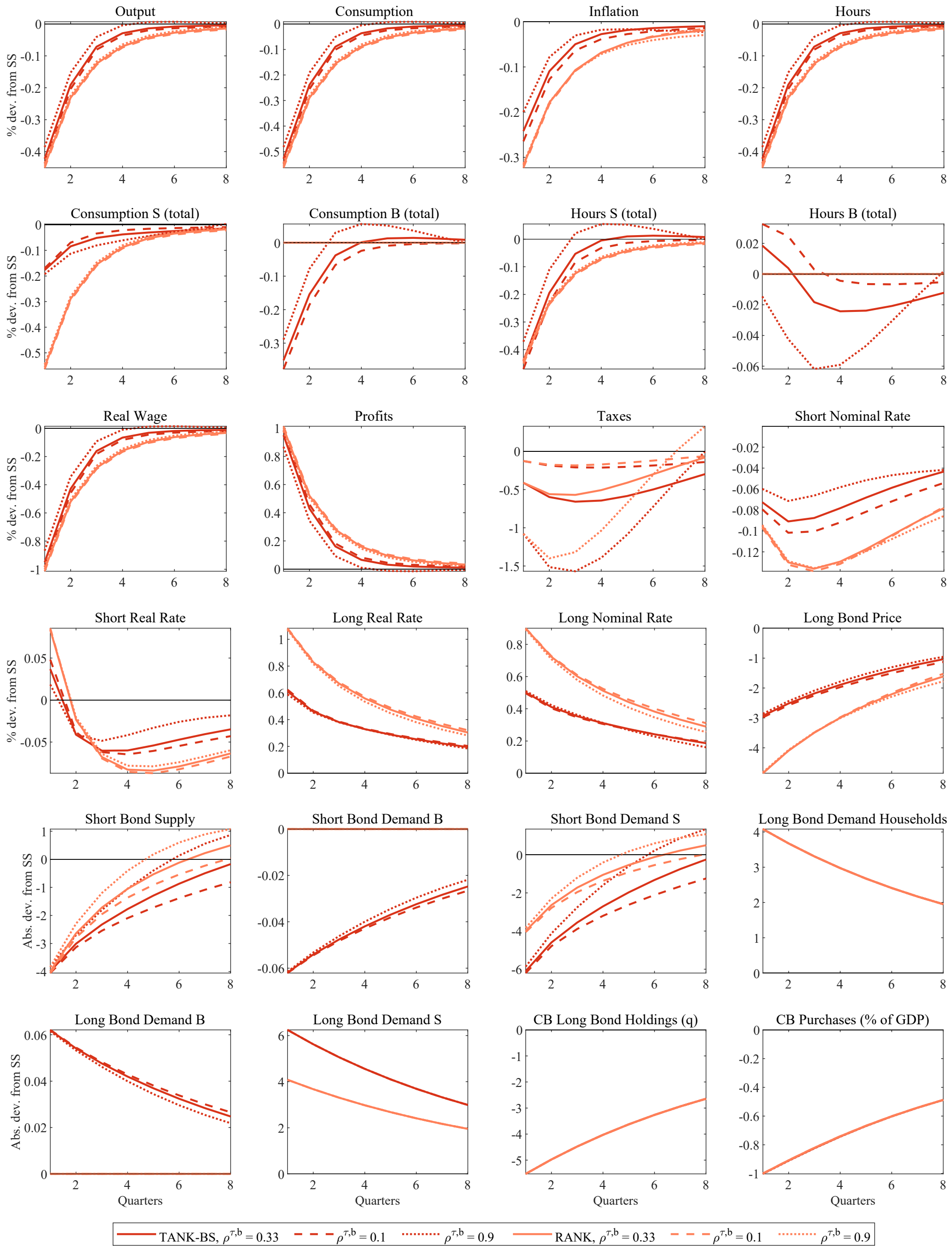
Notes: This figure depicts the impulse responses for the baseline borrower-saver model to a QT shock occurring far enough above the ZLB (red lines) and a QT shock happening close to the ZLB (green lines). The shock for each simulation is an asset purchase/sale of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

Figure C.14: Impulse responses to a QE shock at the ZLB and a QT shock off the ZLB: Robustness for tax response to debt $\rho^{\tau,b}$



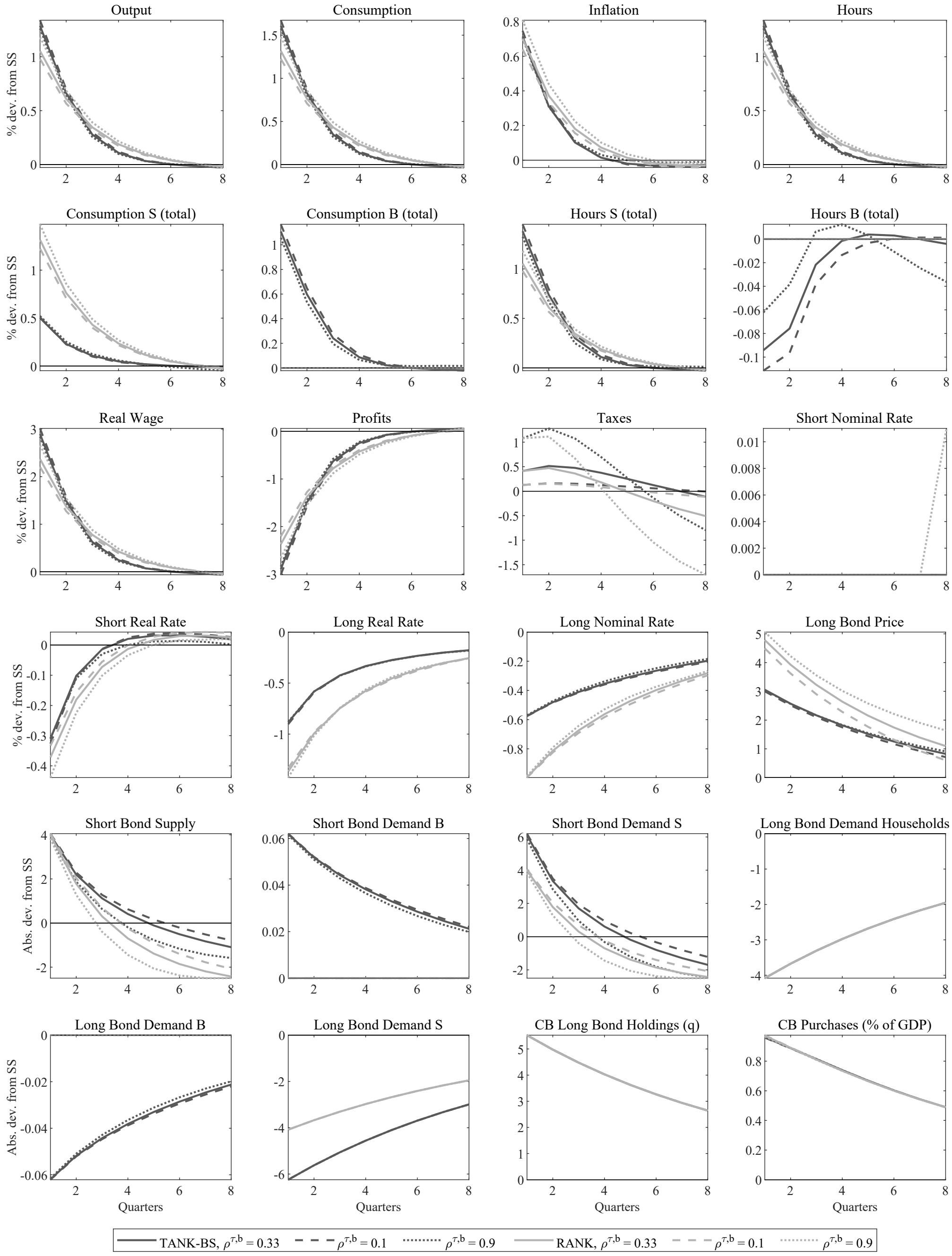
Notes: This figure depicts the impulse responses for the baseline borrower-saver model to a QE shock when the ZLB on the policy rate is binding (gray lines, showing the impact of QE net of a preference shock), and a QT shock occurring far enough above the ZLB (red lines). The shock for each simulation is an asset purchase/sale of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

Figure C.15: Impulse responses to a QT shock off the ZLB: Robustness for tax response to debt $\rho^{\tau,b}$ in RANK vs. TANK-BS



Notes: This figure depicts the impulse responses to a QT shock occurring far enough above the ZLB, for the baseline borrower-saver model (TANK-BS, red lines) and its representative-agent counterpart with $\lambda = 0$ (RANK, light red lines). The shock for each simulation is an asset sale of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

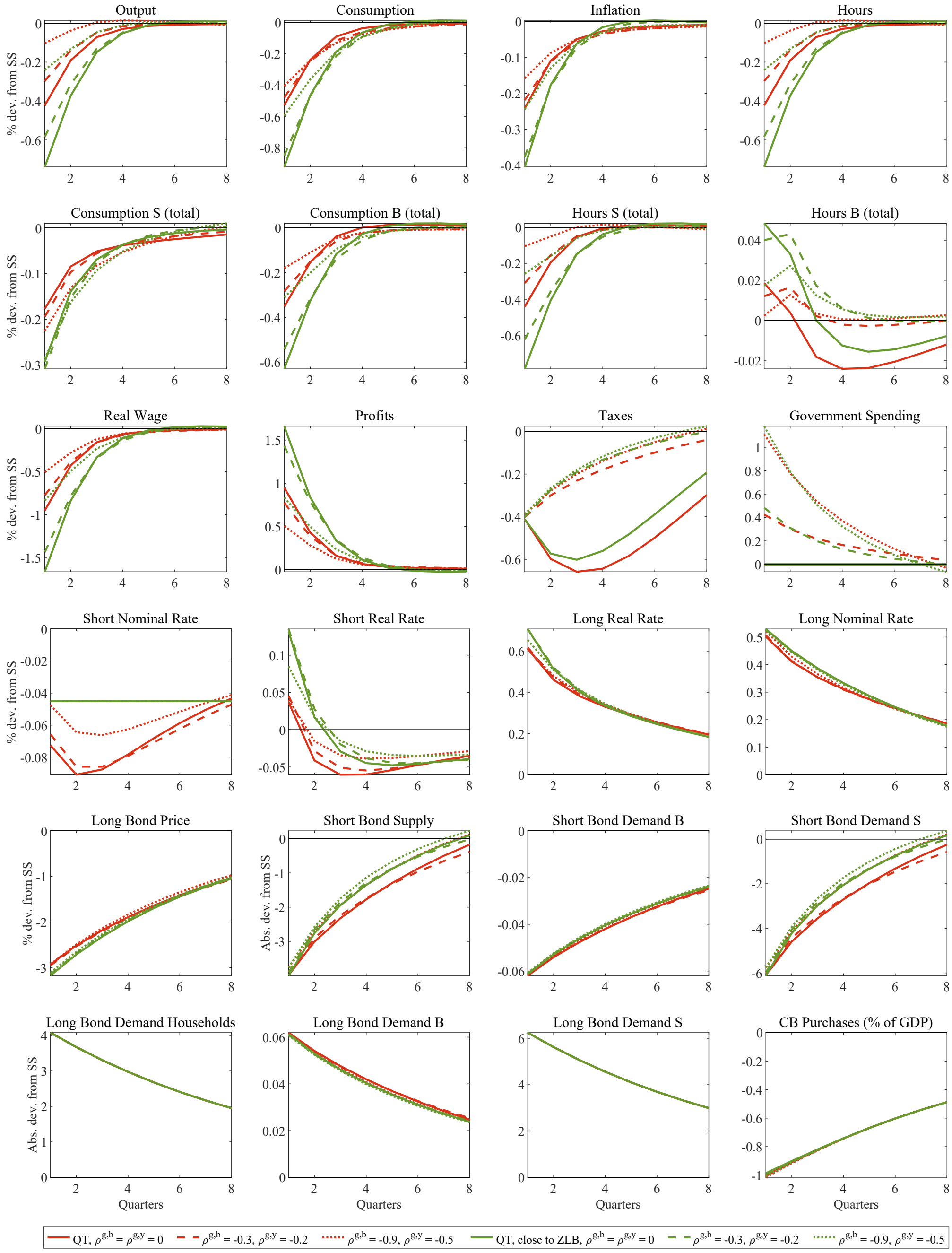
Figure C.16: Impulse responses to a QE shock at the ZLB: Robustness for tax response to debt $\rho^{\tau,b}$ in RANK vs. TANK-BS



Notes: This figure depicts the impulse responses to a QE shock net of a negative preference shock when the ZLB on the policy rate is binding, for the baseline borrower-saver model (TANK-BS, gray lines) and its representative-agent counterpart with $\lambda = 0$ (RANK, light gray lines). The shock for each simulation is an asset purchase of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

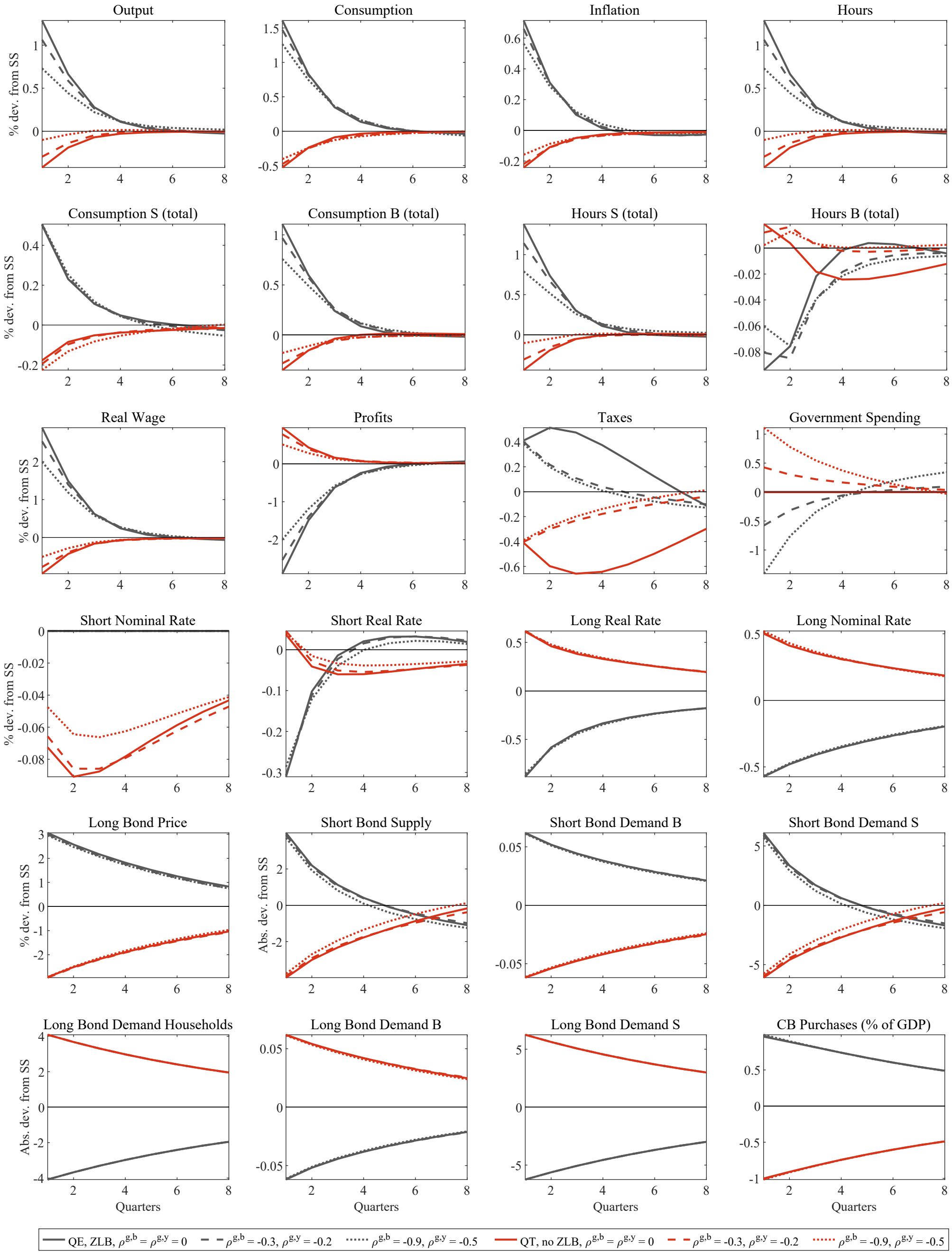
C.2.5 Fiscal rule for government spending: Response to total debt $\rho^{g,b}$ and output $\rho^{g,y}$

Figure C.17: Impulse responses to a QT shock off and a QT shock near the ZLB: Robustness for government spending rule coefficients $\rho^{g,b}$ and $\rho^{g,y}$



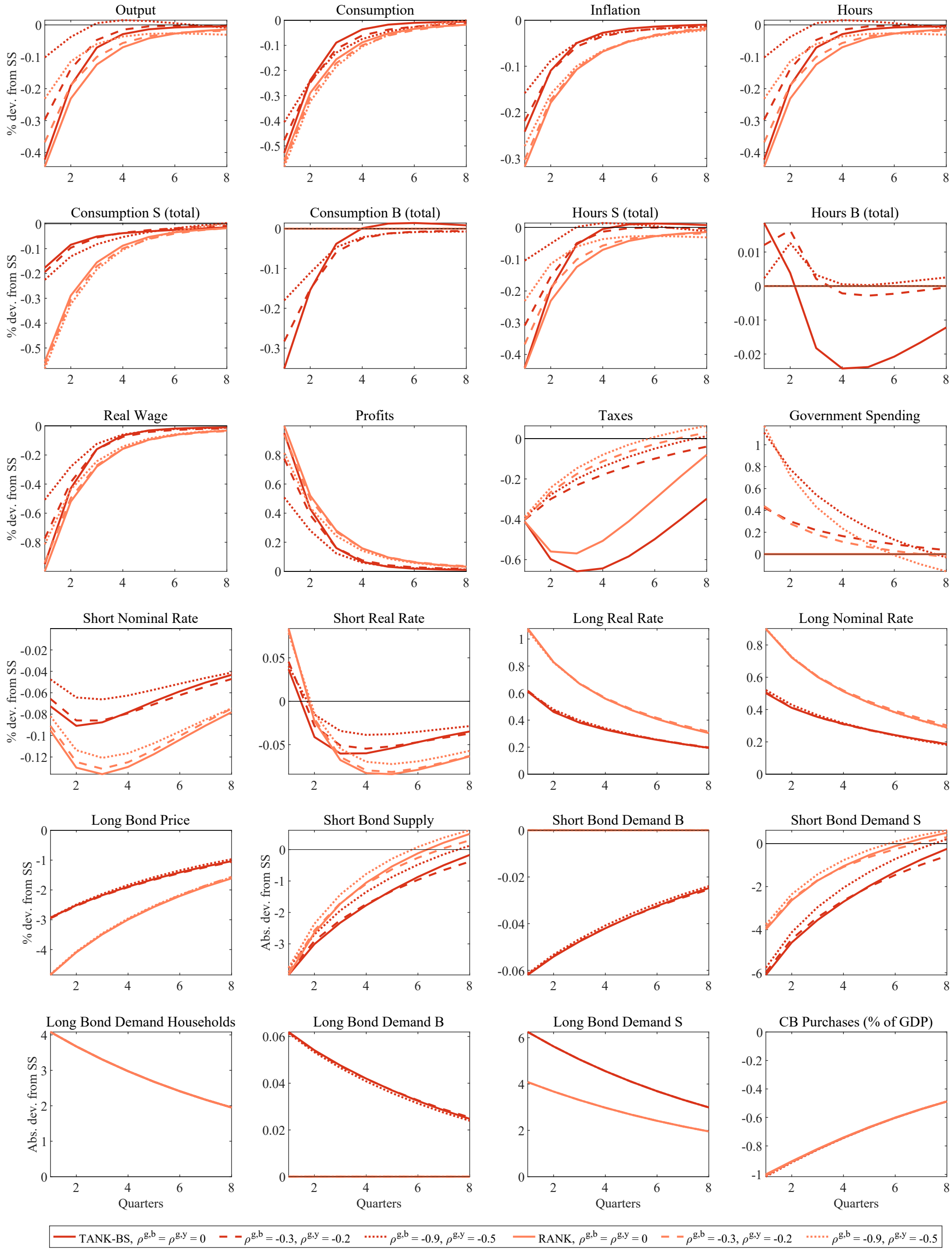
Notes: This figure depicts the impulse responses to a QT shock occurring far enough above the ZLB (red lines) and a QT shock happening close to the ZLB (green lines), for the borrower-saver model with a government spending rule. The shock for each simulation is an asset purchase/sale of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

Figure C.18: Impulse responses to a QE shock at the ZLB and a QT shock off the ZLB: Robustness for government spending rule coefficients $\rho^{g,b}$ and $\rho^{g,y}$



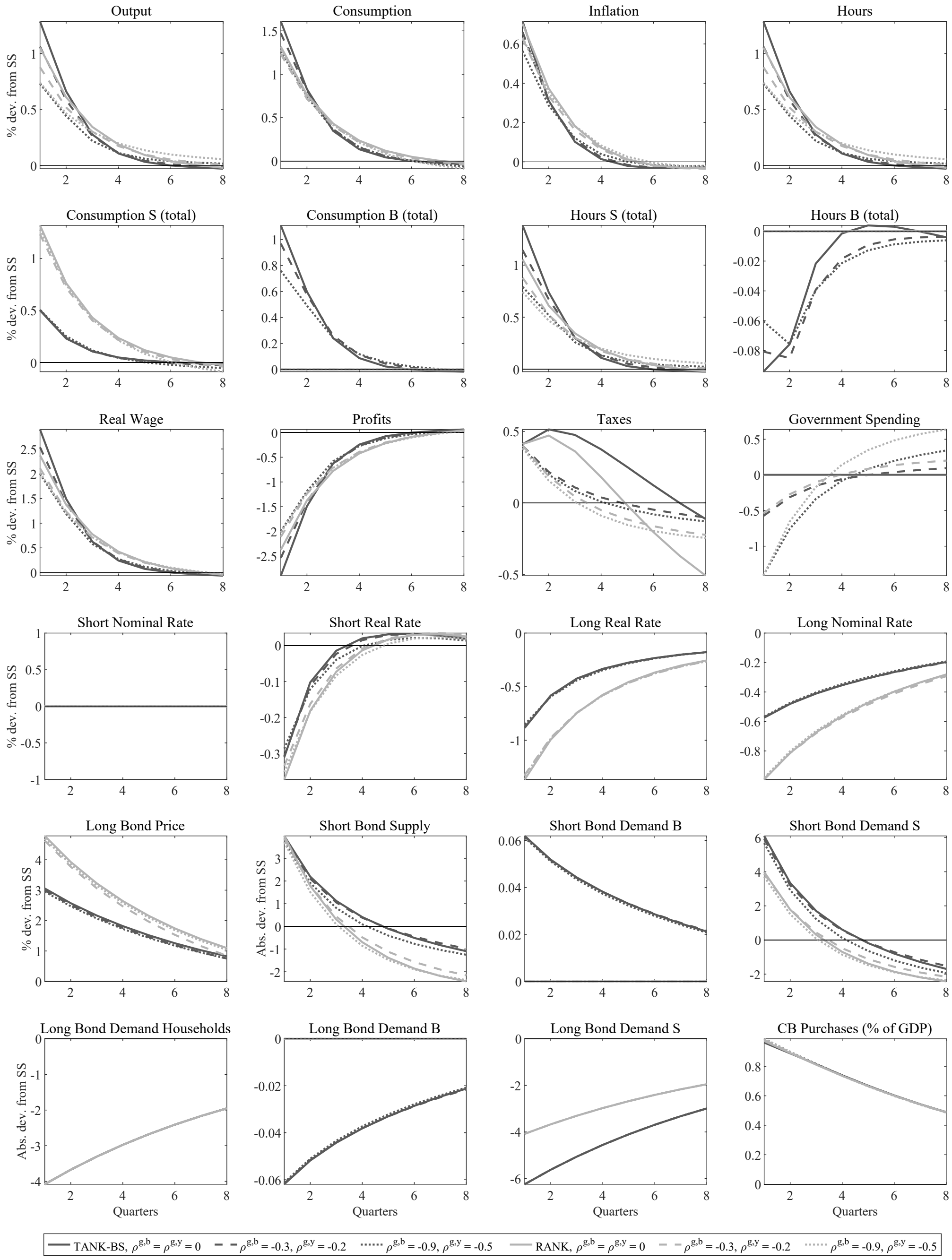
Notes: This figure depicts the impulse responses to a QE shock when the ZLB on the policy rate is binding (gray lines, showing the impact of QE net of a preference shock), and a QT shock occurring far enough above the ZLB (red lines), for the borrower-saver model with a government spending rule. The shock for each simulation is an asset purchase/sale of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

Figure C.19: Impulse responses to a QT shock off the ZLB: Robustness for government spending rule coefficients $\rho^{g,b}$ and $\rho^{g,y}$ in RANK vs. TANK-BS



Notes: This figure depicts the impulse responses to a QT shock occurring far enough above the ZLB, for the borrower-saver model with a government spending rule (TANK-BS, red lines) and its representative-agent counterpart with $\lambda = 0$ (RANK, light red lines). The shock for each simulation is an asset sale of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

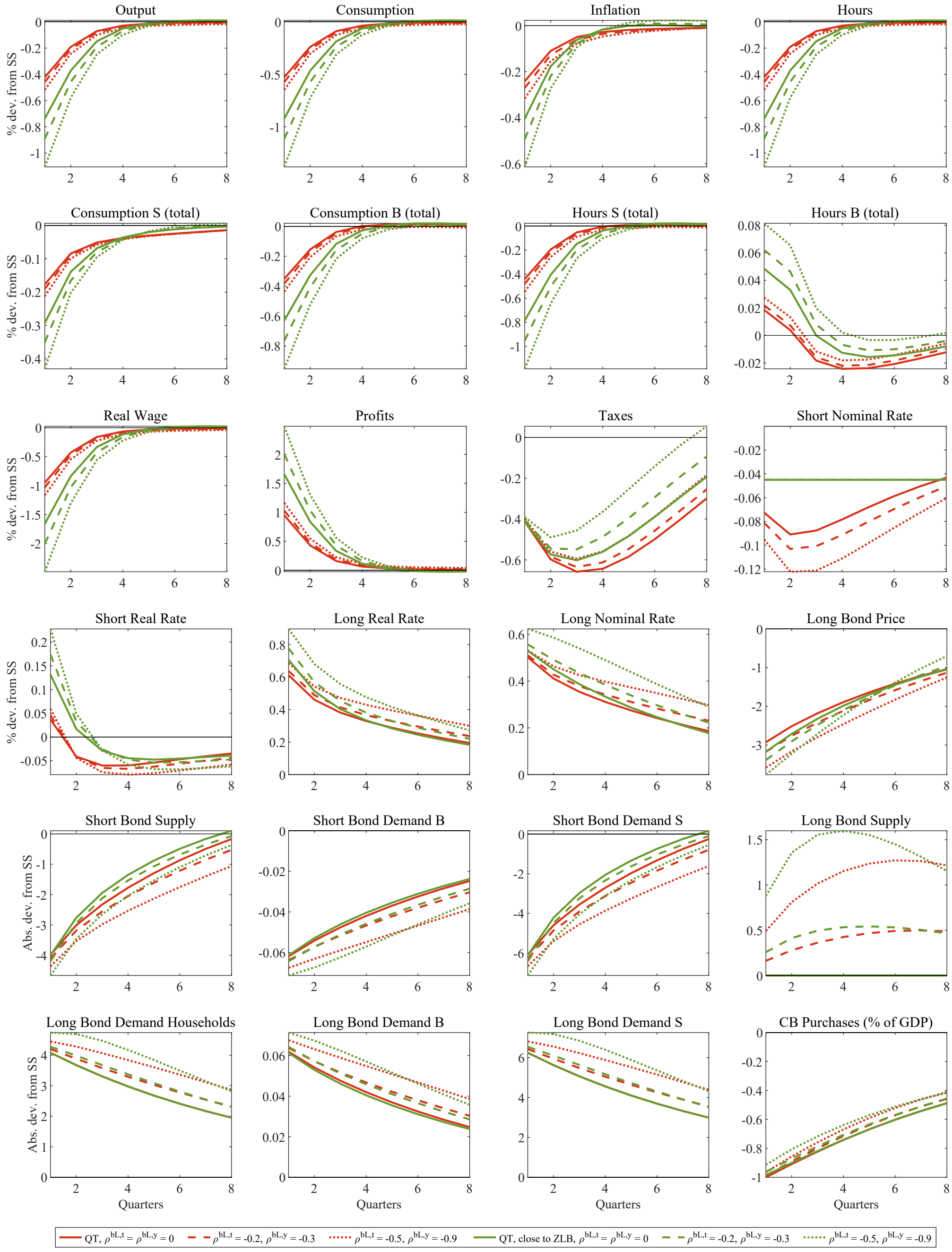
Figure C.20: Impulse responses to a QE shock at the ZLB: Robustness for government spending rule coefficients $\rho^{g,b}$ and $\rho^{g,y}$ in RANK vs. TANK-BS



Notes: This figure depicts the impulse responses to a QE shock net of a negative preference shock when the ZLB on the policy rate is binding, for the borrower-saver model with a government spending rule (TANK-BS, gray lines) and its representative-agent counterpart with $\lambda = 0$ (RANK, light gray lines). The shock for each simulation is an asset purchase of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

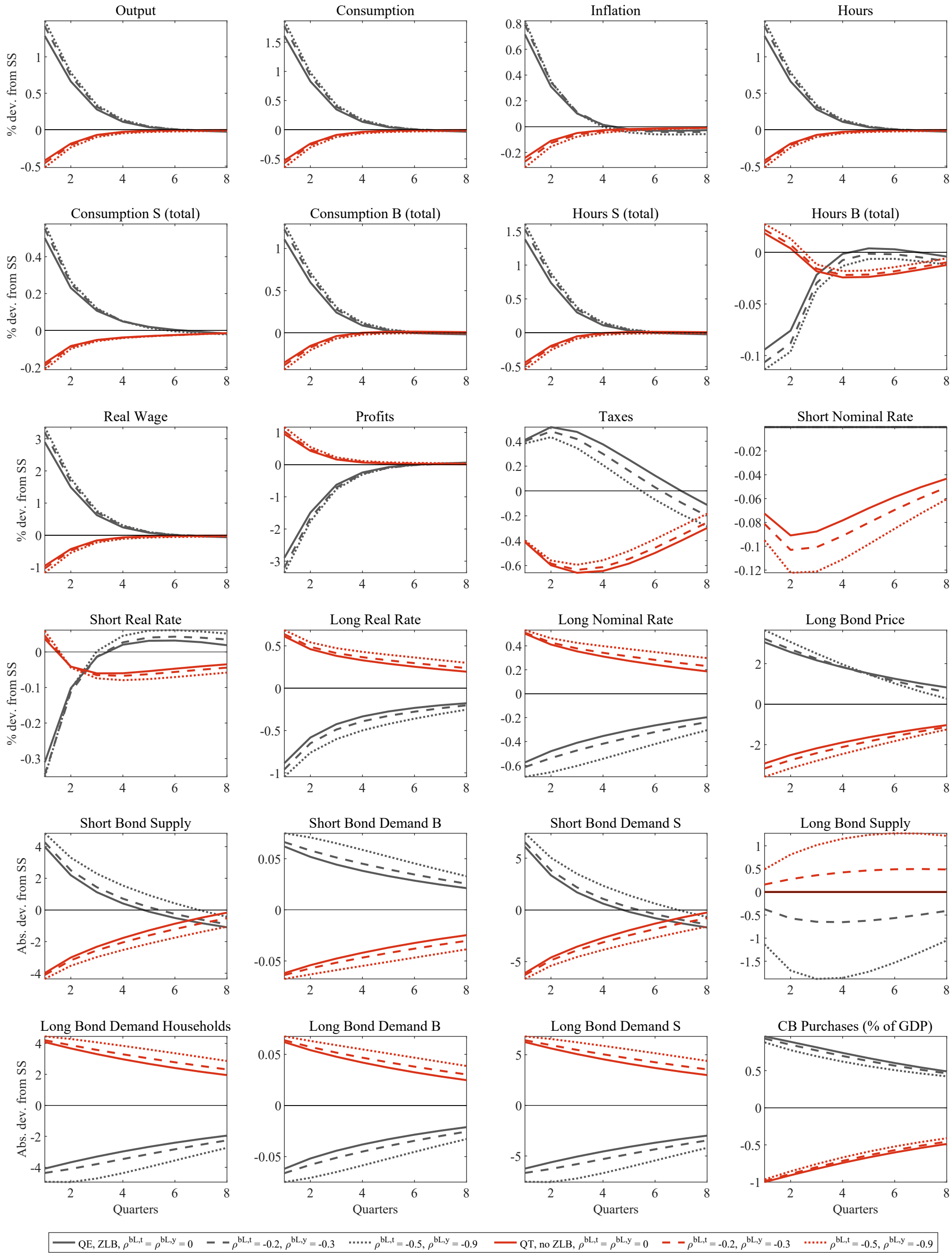
C.2.6 Fiscal rule for long-term debt: Response to taxes $\rho^{bL,t}$ and output $\rho^{bL,y}$

Figure C.21: Impulse responses to a QT shock off and a QT shock near the ZLB: Robustness for long-term debt rule coefficients $\rho^{bL,t}$ and $\rho^{bL,y}$



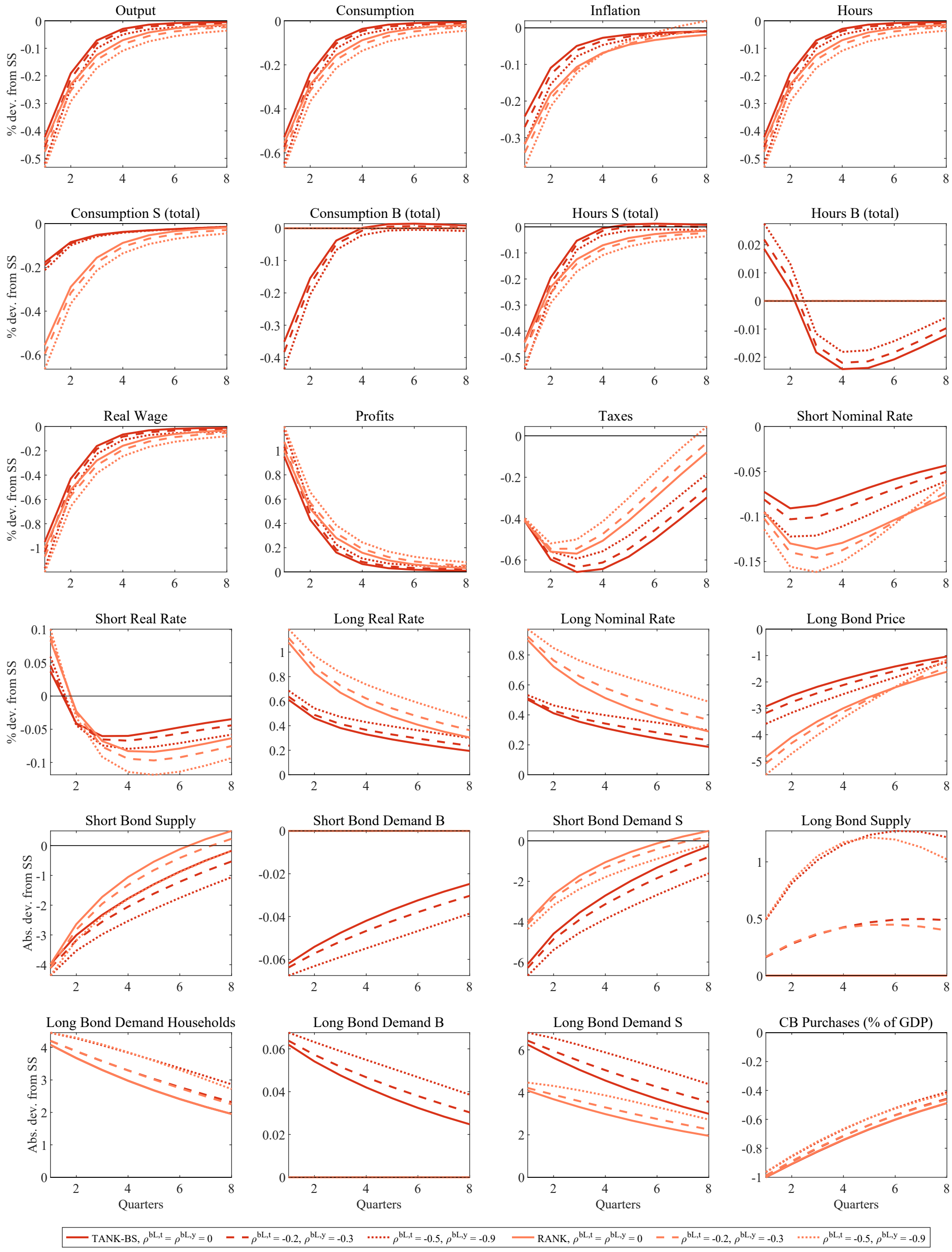
Notes: This figure depicts the impulse responses to a QT shock occurring far enough above the ZLB (red lines) and a QT shock happening close to the ZLB (green lines), for the borrower-saver model with a long-term debt rule. The shock for each simulation is an asset purchase/sale of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

Figure C.22: Impulse responses to a QE shock at the ZLB and a QT shock off the ZLB: Robustness for long-term debt rule coefficients $\rho^{bL,t}$ and $\rho^{bL,y}$



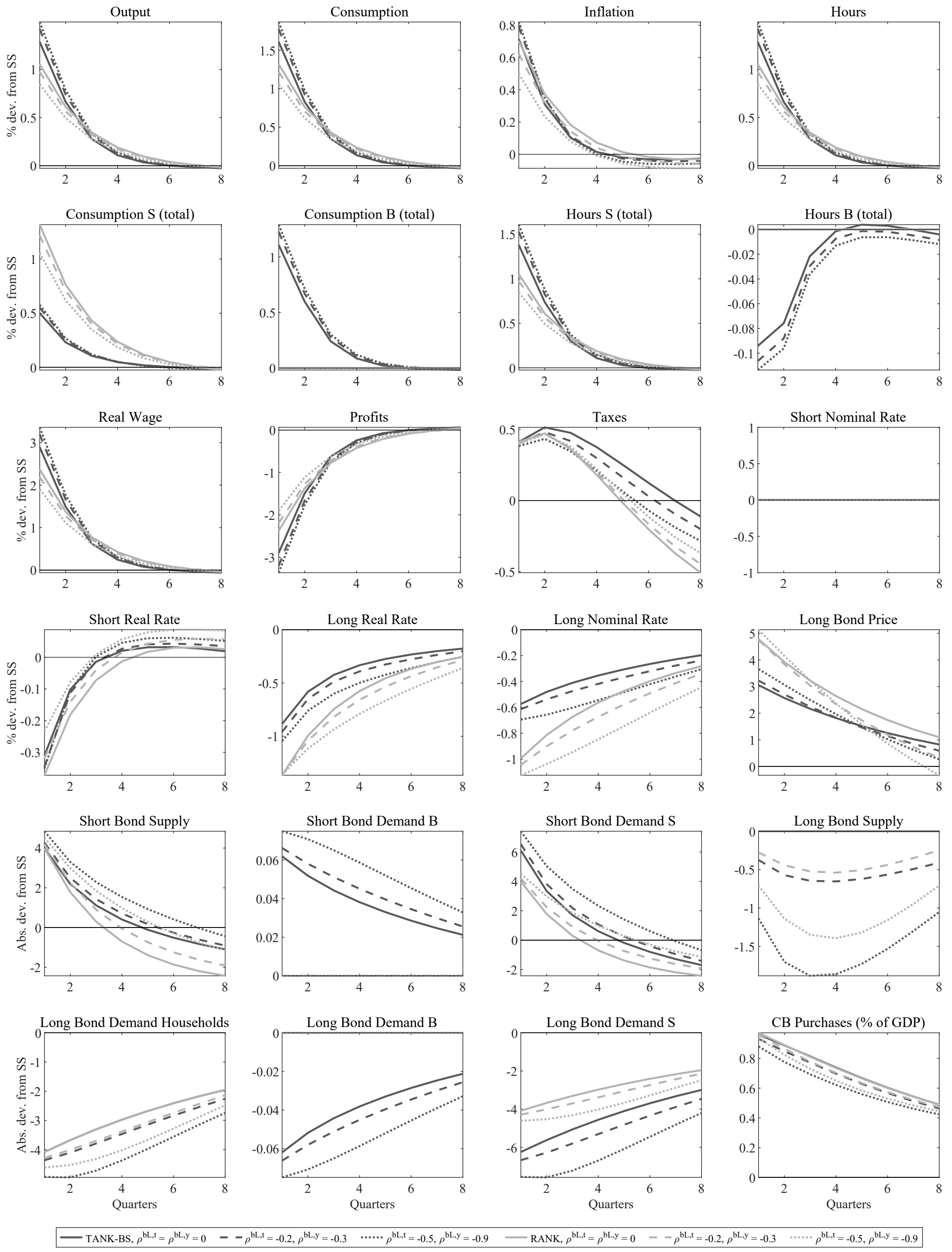
Notes: This figure depicts the impulse responses to a QE shock when the ZLB on the policy rate is binding (gray lines, showing the impact of QE net of a preference shock), and a QT shock occurring far enough above the ZLB (red lines), for the borrower-saver model with a long-term debt rule. The shock for each simulation is an asset purchase/sale of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

Figure C.23: Impulse responses to a QT shock off the ZLB: Robustness for long-term debt rule coefficients $\rho^{bL,t}$ and $\rho^{bL,y}$ in RANK vs. TANK-BS



Notes: This figure depicts the impulse responses to a QT shock occurring far enough above the ZLB, for the borrower-saver model with a long-term debt rule (TANK-BS, red lines) and its representative-agent counterpart with $\lambda = 0$ (RANK, light red lines). The shock for each simulation is an asset sale of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

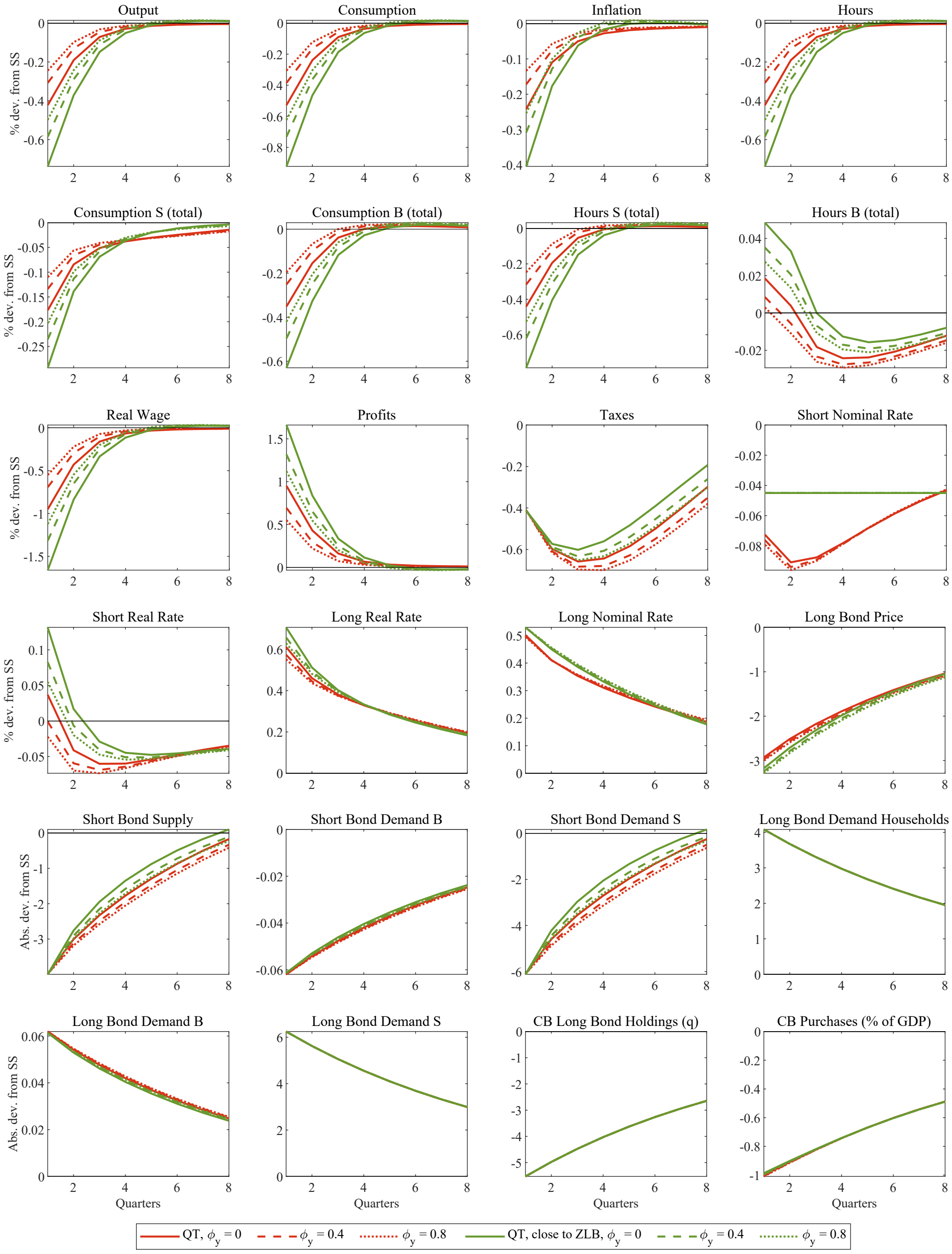
Figure C.24: Impulse responses to a QE shock at the ZLB: Robustness for long-term debt rule coefficients $\rho^{bL,t}$ and $\rho^{bL,y}$ in RANK vs. TANK-BS



Notes: This figure depicts the impulse responses to a QE shock net of a negative preference shock when the ZLB on the policy rate is binding, for the borrower-saver model with a long-term debt rule (TANK-BS, gray lines) and its representative-agent counterpart with $\lambda = 0$ (RANK, light gray lines). The shock for each simulation is an asset purchase of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

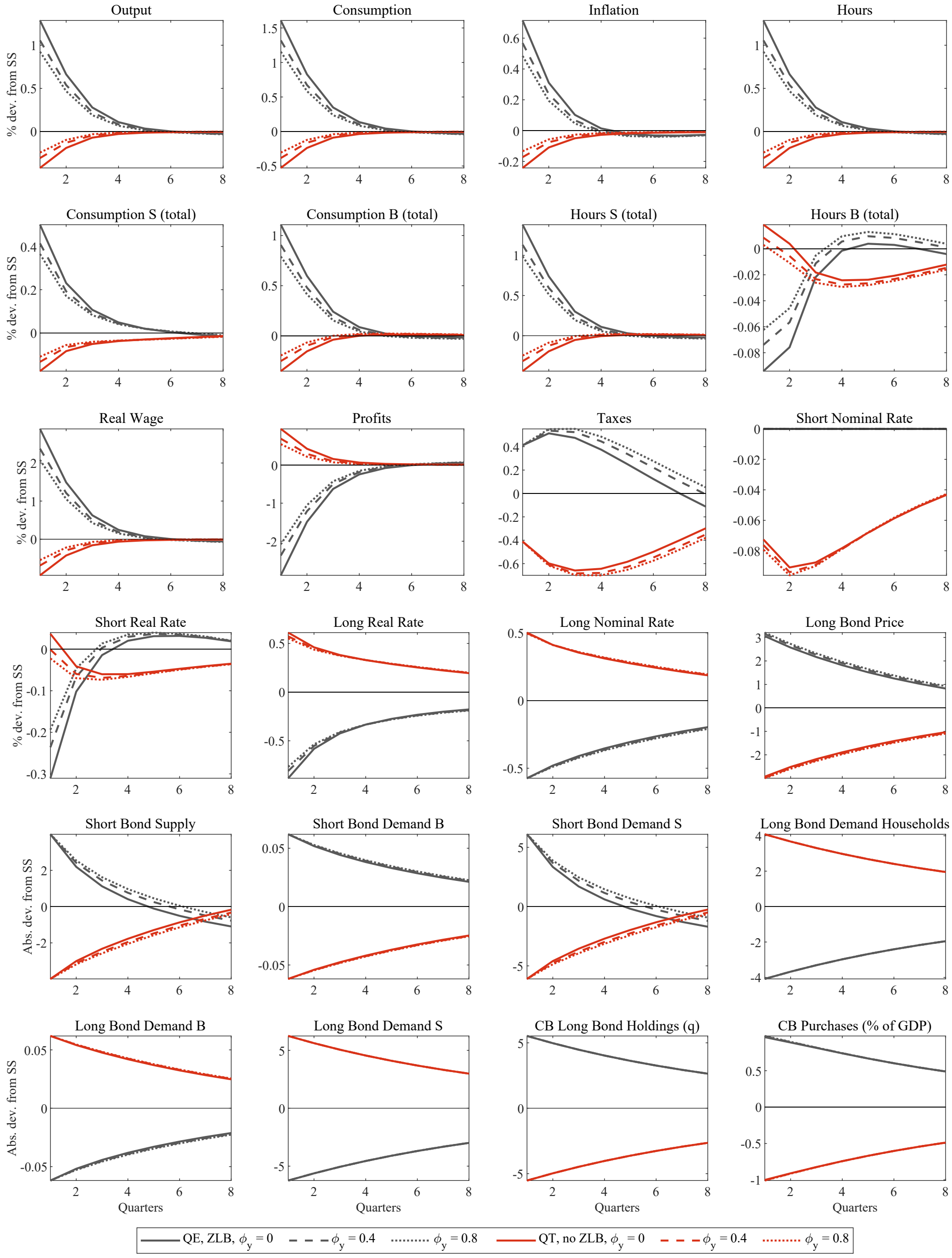
C.2.7 Taylor rule coefficient on output ϕ_y

Figure C.25: Impulse responses to a QT shock off and a QT shock near the ZLB: Robustness for Taylor rule output coefficient ϕ_y



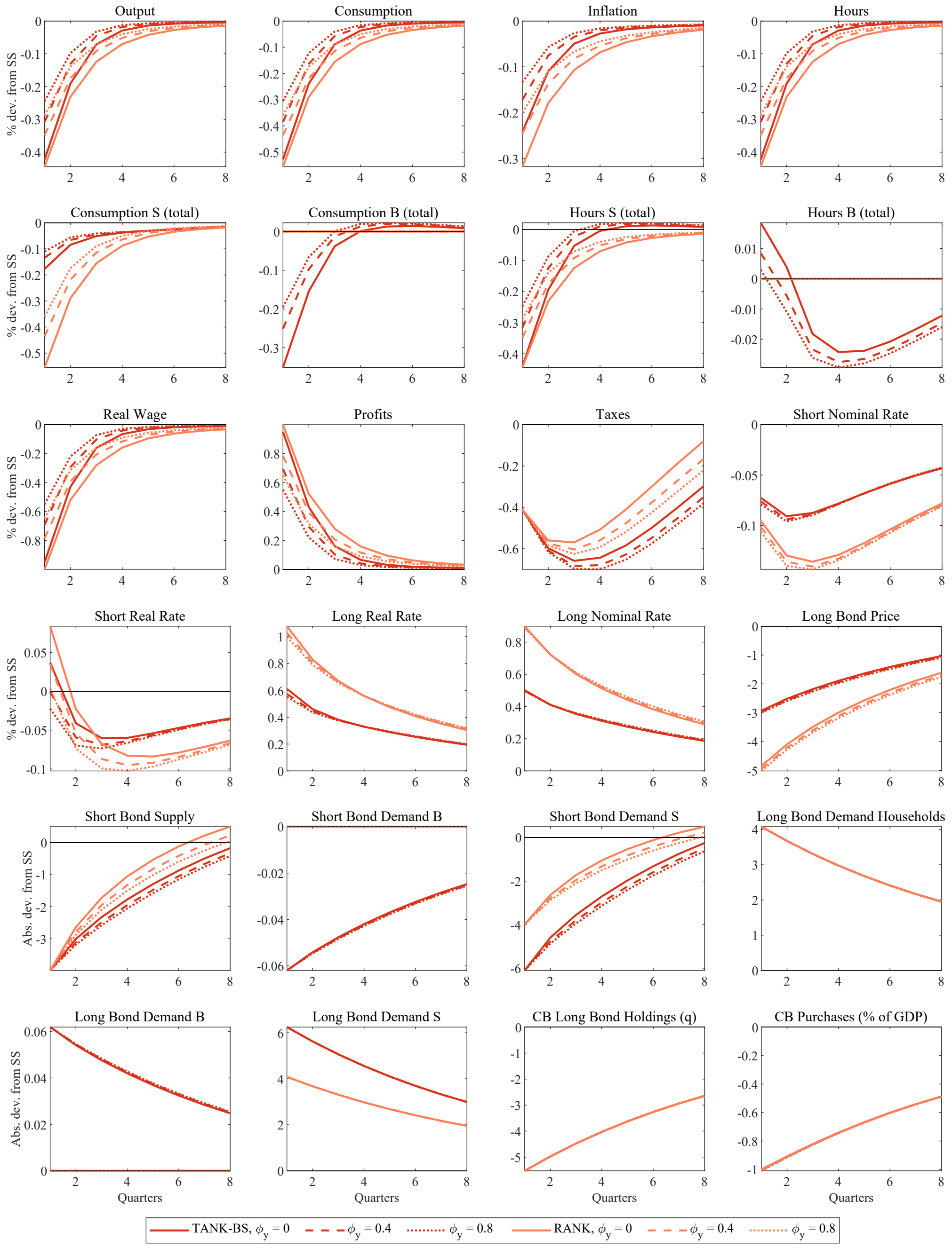
Notes: This figure depicts the impulse responses to a QT shock occurring far enough above the ZLB (red lines) and a QT shock happening close to the ZLB (green lines), for the borrower-saver model with a Taylor rule responding to both inflation and output. The shock for each simulation is an asset purchase/sale of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

Figure C.26: Impulse responses to a QE shock at the ZLB and a QT shock off the ZLB: Robustness for Taylor rule output coefficient ϕ_y



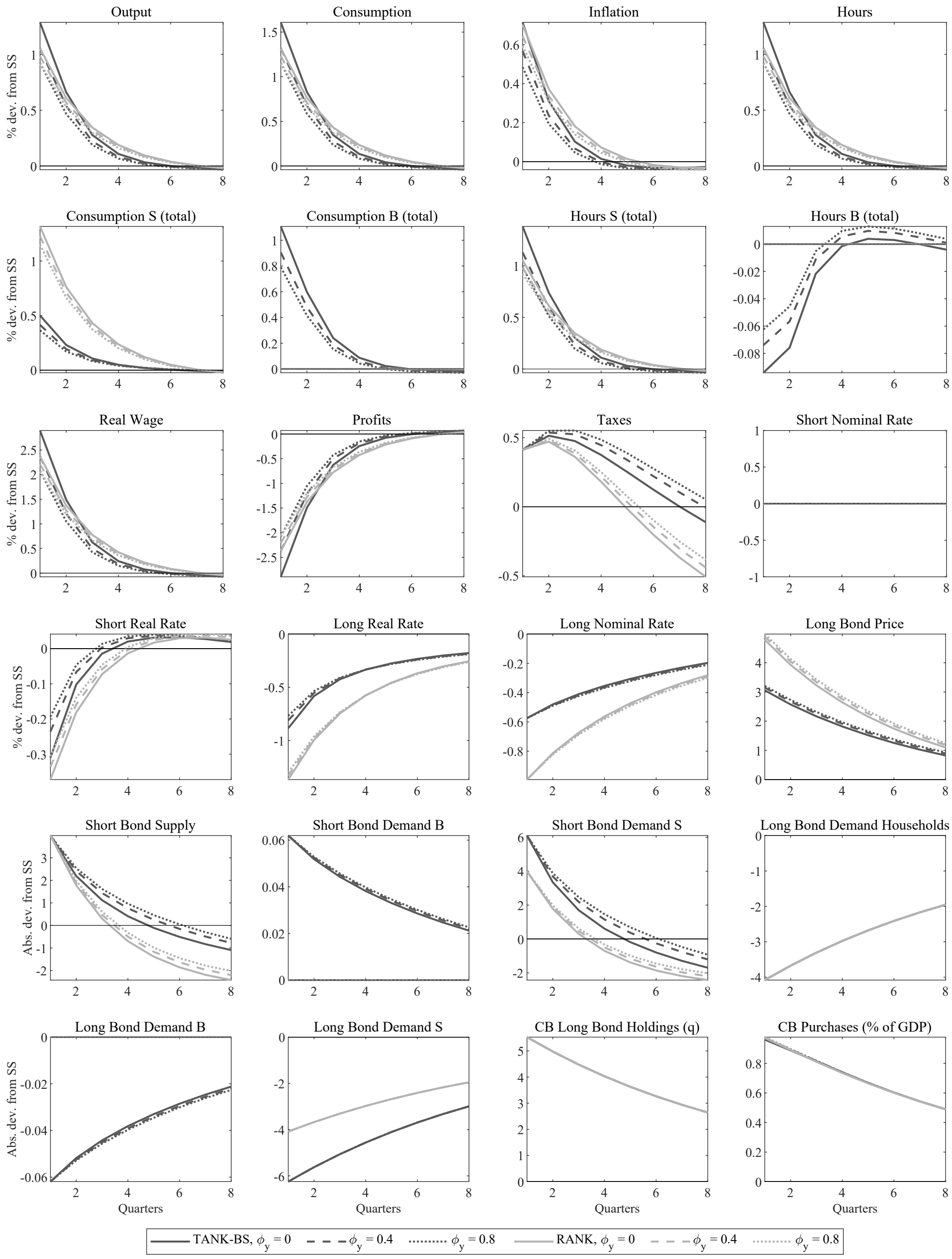
Notes: This figure depicts the impulse responses to a QE shock when the ZLB on the policy rate is binding (gray lines, showing the impact of QE net of a preference shock), and a QT shock occurring far enough above the ZLB (red lines), for the borrower-saver model with a Taylor rule responding to both inflation and output. The shock for each simulation is an asset purchase/sale of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

Figure C.27: Impulse responses to a QT shock off the ZLB: Robustness for Taylor rule output coefficient ϕ_y in RANK vs. TANK-BS



Notes: This figure depicts the impulse responses to a QT shock occurring far enough above the ZLB, for the borrower-saver model with a Taylor rule responding to both inflation and output (TANK-BS, red lines) and its representative-agent counterpart with $\lambda = 0$ (RANK, light red lines). The shock for each simulation is an asset sale of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

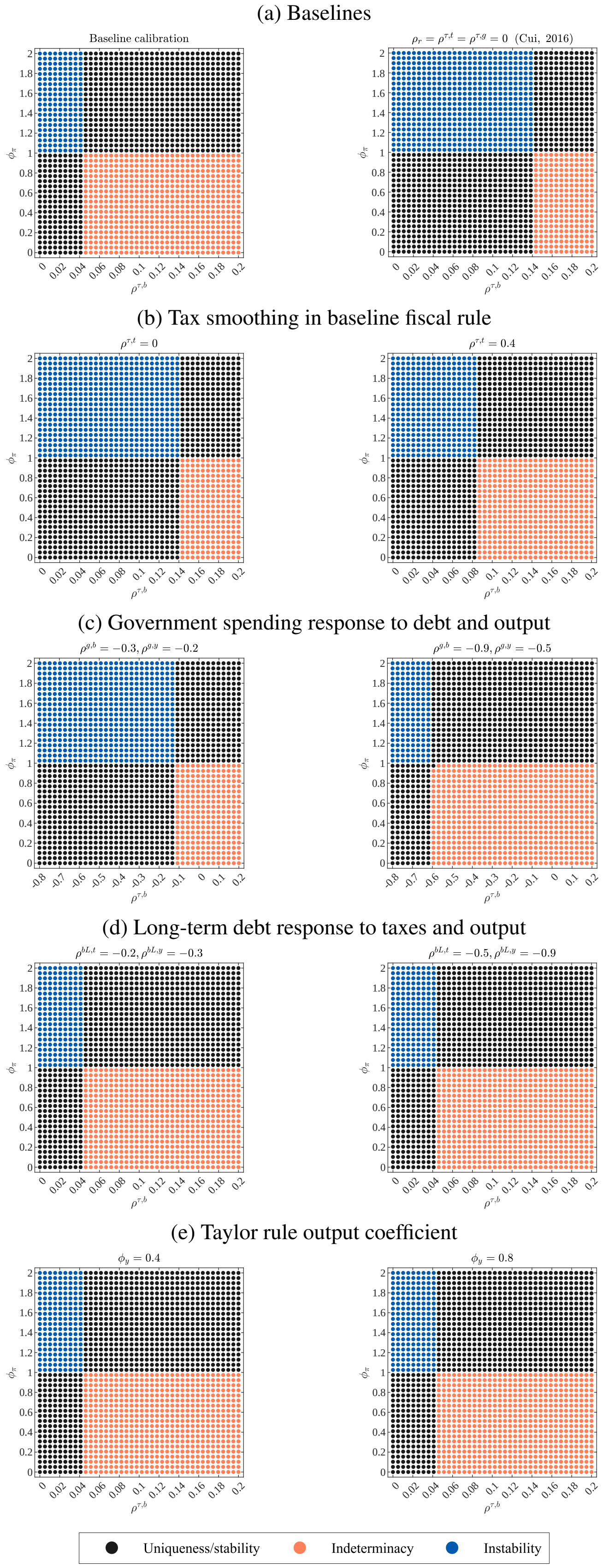
Figure C.28: Impulse responses to a QE shock at the ZLB: Robustness for Taylor rule output coefficient ϕ_y in RANK vs. TANK-BS



Notes: This figure depicts the impulse responses to a QE shock net of a negative preference shock when the ZLB on the policy rate is binding, for the borrower-saver model with a Taylor rule responding to both inflation and output (TANK-BS, gray lines) and its representative-agent counterpart with $\lambda = 0$ (RANK, light gray lines). The shock for each simulation is an asset purchase of size 1% of annualized GDP. Responses for individual consumption levels and hours are weighted by population shares of savers (S) and borrowers (B), respectively.

C.3 Equilibrium dynamics: Sensitivity analysis

Figure C.29: Stability regions for the baseline TANK-BS and alternative policy rules



Notes: These figures show stability and determinacy regions in the parameter space spanned by the Taylor rule coefficient on inflation ϕ_π and the tax response to debt $\rho^{\tau,b}$, for the baseline borrower-saver model and with alternative policy rules. The equilibrium of the model is either unique and stable (black), indeterminate (orange), or unstable (blue) in a neighborhood of the steady state.