



Implications of tax policy for innovation and aggregate productivity growth[☆]



Domenico Ferraro^a, Soroush Ghazi^b, Pietro F. Peretto^{c,*}

^a Department of Economics, W.P. Carey School of Business, Arizona State University, Box 879801, Tempe, AZ 85287, United States

^b Department of Economics, Finance and Legal Studies, Culverhouse College of Business, University of Alabama, Box 870224, Tuscaloosa, AL 35487, United States

^c Department of Economics, Duke University, Box 90097, Durham, NC 27708, United States

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ABSTRACT

We examine the quantitative implications of income taxation for innovation and aggregate productivity growth within the context of a dynamic stochastic general equilibrium model of innovation-led growth. In the model, innovation comes from entrants creating new products and incumbents improving own existing products. The model embodies key features of the U.S. government sector: (i) an individual income tax with differential treatment of labor income, dividends, and capital gains; (ii) a corporate tax; (iii) a consumption tax; (iv) government purchases. The model is restricted to fit observations for the post-war U.S. economy. Our results suggest that endogenous movements in aggregate productivity and endogenous market structure play a quantitatively important role in the propagation of tax shocks.

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1. Introduction

A central question in macroeconomics is how income taxation affects the growth rate of the economy. While there is broad consensus that taxation affects short-term rates of growth, there still is disagreement, both theoretically and empirically, over how and the extent to which taxation affects long-run economic growth. In this paper, we ask two questions: (i) What is the quantitative impact of permanent and temporary changes in individual and corporate income tax rates? (ii) What is the transmission mechanism of tax policy to firms' innovative investments and aggregate productivity growth?

To address these questions, we propose a quantitative general equilibrium model of innovation-led growth. A prominent feature of the theory is the interplay between product and quality innovation: entrants create new products whereas incum-

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* Corresponding author.

E-mail addresses: domenico.ferraro@asu.edu (D. Ferraro), sghazi@culverhouse.ua.edu (S. Ghazi), peretto@econ.duke.edu (P.F. Peretto).

bents improve existing products (see [Garcia-Macia et al., 2016](#), for empirical evidence supporting this model feature). We adopt a formulation of the theory in which market-size effects are sterilized in the long-run through a process of product proliferation that fragments the aggregate market into submarkets whose size does not increase with the size of the workforce ([Peretto, 1998; 1999](#)). Due to the sterilization of the strong scale effect, taxes that operate through market size have no long-run growth effects. Nonetheless, one of the main lessons from our quantitative experiments is that market-size effects remain important for the propagation mechanism of tax policy in the short- and medium-term.

To explain the effects of taxes, it is useful to describe the structure of the model in more detail. The model combines product innovation with quality-improving innovation. As a result, the quantitative theory here nests models based on the variety expansion framework of [Romer \(1990\)](#), such as those discussed in [Grossman and Helpman \(1991a\)](#), and Schumpeterian models based on the quality-ladder framework, such as those in [Grossman and Helpman \(1991b\)](#) and [Aghion and Howitt \(1992\)](#). By using a model in which both types of innovation arise as an equilibrium outcome, one can start to evaluate how and to what extent income taxation alters incentives to innovation more rigorously.

A representative household chooses consumption, labor supply, and savings by borrowing and lending in a spot asset market. Household's income consists of returns on risky financial securities and risk-free bonds, labor income, and government transfers. The government sector purchases final goods and levies proportional tax rates on consumption expenditures, individual income (with differential flat-rate taxes on labor income, dividends, and capital gains), and corporate income.¹ Tax rates vary stochastically over time, which captures the pattern that historically, U.S. federal tax policy has changed unpredictably based on the current state of the economy and concerns about inherited budget deficits and long-term growth (see [Romer and Romer, 2009; 2010](#), for a narrative account of U.S. tax policy).

The production side of the economy consists of a final good and an intermediate good sector. In the final good sector, a competitive firm demands intermediate goods and labor to produce a homogeneous final good. The intermediate good sector is monopolistically competitive and the source of long-run growth. We associate firms in the intermediate good sector with Schedule C corporations in the U.S. federal tax code. For tax purposes, C corporations are considered separate legal entities from their shareholders. As a result, income generated by C corporations is subject to double taxation: it is taxed at the corporate level as profits and again at the individual level as distributed dividends.

The market structure of the intermediate good sector is endogenous: the mass of firms and firm size are jointly determined in free-entry equilibrium. Entry requires the payment of a sunk cost. Upon entry, firms produce intermediate goods that are differentiated by quality. They also invest to improve the quality of their products. Innovative investments at the firm level contribute to the pool of public knowledge that benefits the final good sector via a reduction in unit production costs. This process is self-sustaining and generates exponential growth in the long-run when entry stops and the economy settles into a stable industrial structure. In the model, the long-run growth rate is driven by product quality improvements by incumbents. The introduction of new products by entrants achieves instead sterilization of market-size effects in the long-run.

To examine the quantitative predictions of the theory, we restrict the model to match salient features of post-war U.S. data. We construct measures of average effective tax rates on individual and corporate income, and estimate linear autoregressive processes that we use as model inputs. The results suggest that endogenous movements in aggregate productivity constitute a quantitatively important channel for the transmission of tax policy. Endogenous market structure plays a key role in propagating changes in tax rates.

Long-run growth is un-affected by labor income taxes: given the mass of firms, labor income tax rates affect demand for intermediate goods through the determination of the labor input, which in turn determines the market size faced by producers, and thereby innovative investment at the firm and aggregate level. Everything else equal, this would have long-run growth effects. Yet, as the size and so the profitability of incumbents change, the number of firms endogenously adjusts to bring the economy back to the initial long-run level of firm size, thereby sterilizing the long-run growth effects of labor taxation. By contrast, long-term rates of growth are affected by asset and corporate income taxation: tax rates levied on dividends and capital gains at the individual level and on profits at the corporate level, disturb equilibrium arbitrage conditions that drive household saving, firms' entry, and investment decisions. These effects are quantitatively important.

For example, a 1 percentage point (pp) cut in the tax rate on capital gains raises long-run growth by approximately 0.2 percentage points. The capital gains tax is effectively a tax on firm growth. In the new steady state, the mass of firms is smaller than its previous level before the tax rate cut, leading to a more concentrated market structure. By contrast, an equally-sized 1 pp cut in dividend and corporate income tax rates reduces long-run growth by approximately 0.6 and 0.5 percentage points, respectively. A cut in either tax rate raises the rate of return to entry. The new steady state features a larger number of firms, which stifles investment incentives of incumbents and thereby the growth rate of quality improvement and real GDP per capita.²

Time-varying tax rates on individual and corporate income have quantitatively large effects on aggregate quantities. In the model, quality-improving innovation is driven by the forward-looking investment behavior of the corporate sector. In

¹ Lump-sum transfers adjust to balance the government budget on a period-by-period basis.

² In the model, with constant markups, the equilibrium features a monotonic, inverse relationship between the return to quality-improving innovation and the mass of firms. In a variant of the model with endogenous markups, pro-competitive effects arise, producing a hump-shaped relationship between the return to quality-improving innovation and the mass of firms (see, e.g., [Peretto, 1996; 1999](#)). In this case, whether the effects of dividend and corporate taxation on growth change sign depends on the strength of pro-competitive effects.

deciding how much to invest, a firm trades off the cost of diverting resources from current (before-tax) operating profit with the benefit of reducing unit production costs in the future. Movements in tax rates act as *intertemporal disturbances* to this tradeoff.

To capture the dynamic response of the economy to a temporary tax cut, we rely on impulse response functions (IRFs). IRFs represent a coherent way to describe the propagation mechanism embodied in the model. Temporary changes in tax rates have permanent effects on the level of real GDP per capita. Endogenous technological progress is key to understanding propagation. The response of innovative investments to the tax change feeds into a temporary acceleration or deceleration in the rate of product quality improvement, which translates into permanent gains or losses of output.

In response to a 1 pp cut in the labor tax rate, the labor input raises on impact, it then reverts back to the initial steady-state level mimicking the dynamics of the tax shock. The temporary expansion in equilibrium labor feeds into a temporary expansion in the aggregate demand for intermediate goods production. These transitional market-size effects stimulate aggregate investment in the corporate sector and thereby spur a temporary acceleration of labor productivity and TFP growth. As a result, real GDP sluggishly raises during the transition dynamics and settles on an approximately 1.6% higher level relative to the previous trend. During the transition dynamics, firms' entry rate falls below the steady-state level, such that the number of firms in the corporate sector temporarily declines and slowly reverts back to the initial steady-state level. The response of the number of firms is U-shaped reflecting the internal propagation embodied in the model.

The dynamic responses to the dividend and corporate income tax cuts are comparable both in terms of transmission mechanism and of sign and magnitude of the overall effect on aggregate quantities. In response to a 1 pp cut in either tax rate, aggregate innovative investment temporarily declines below the long-run level, leading to a temporary deceleration in labor productivity and TFP growth. Such a deceleration in aggregate productivity leaves a sizable permanent effect on the level of real GDP, that settles on an approximately 5 percent lower level relative to previous trend. By contrast, in response to an equally-sized cut in the tax rate on capital gains, the economy experiences a temporary acceleration in aggregate productivity growth, that translates into a roughly 5% higher level of real GDP relative to previous trend.

The rest of the paper is organized as follows. In [Section 2](#), we discuss related work. In [Section 3](#), we revisit and update basic facts for post-war U.S. fiscal policy. In [Sections 4 and 5](#), we present the model and discuss the transmission mechanism of tax policy. In [Section 6](#), we present IRFs. In [Section 7](#), we quantitatively evaluate a tax reform based on a flat individual income tax. Finally, [Section 8](#) concludes.

2. Related literature

There is a vast and growing literature studying the short- and long-term impact of taxation. Our paper adds to the theoretical strand of this literature that examines the effects of income taxation in the context of general equilibrium models. More specifically, we contribute to the analysis of the growth effects of taxes with a quantitative model of endogenous growth in which transition dynamics takes center stage. We study permanent as well as temporary changes in taxes through the means of IRFs. Methodologically, we numerically solve the model by applying standard perturbation methods that are widely used in business cycle research, but that to the best of our knowledge, have not been applied to endogenous growth models prior to this work. We note that our model can be solved as easily as workhorse models in the RBC and New Keynesian tradition used in business cycle analysis.

Existing empirical evidence In the context of structural vector autoregressions (SVAR), while there remains disagreement on the magnitude of the effects, the literature finds that changes in tax rates unambiguously affect output growth rates. This literature typically focuses on *temporary* changes in average and marginal individual income tax rates and estimates very long-lasting effects on output growth, that persist well beyond the tax rate has returned to its initial level ([Romer and Romer, 2010](#); [Barro and Redlick, 2011](#); [Mertens and Ravn, 2011](#); [2013](#); [2014](#); [Mertens and Montiel Olea, 2018](#)). These findings are broadly consistent with estimates based on a large sample of OECD countries ([Alesina et al., 2019](#), and references therein). While this body work abstracts from long-run growth effects, it has the merit of taking seriously policy endogeneity and identification of tax shocks (see [Ramey, 2016](#), for a survey article).

Another strand of empirical literature focuses on cross-country growth regressions based on average growth rates of real per capita GDP. This body of work exploits cross-sectional and panel data variation to estimate long-run growth effects of *permanent* changes in taxes ([Easterly and Rebelo, 1993](#); [Easterly et al., 1993](#); [Mendoza et al., 1994](#); [1997](#)). The main finding is that the tax rates adopted by different countries are generally uncorrelated with their growth performance. More recently, however, empirical evidence based on advances in panel data estimation indicates that the composition of taxes affects growth rates over a prolonged period of over 30 years ([Kneller et al., 1999](#); [Gemmell et al., 2011](#)).

Overall, while the recent empirical literature has made considerable progress, challenges remain. To name a few, due to the lack of reliable data, a complete specification of the government budget constraint is often missing from empirical specifications.³ This approach is problematic in that estimates of the growth effects of, say, a tax rate cut can capture the offsetting effects of changes in other fiscal instruments that the regression does not take into account. Relatedly, and equally

³ See [Kneller et al. \(1999\)](#) for a discussion of the bias induced by the omission or misspecification of the government budget constraint in the context of long-run growth regressions. See also [Sims \(1998\)](#) for a more general discussion of the econometric implications of the government budget constraint in models with forward-looking behavior.

important, endogenous growth theory predicts that different types of taxes can have rather different effects on the growth rate of the economy (Peretto, 2003). For example, a generic flat-rate tax on individual income which ignores the differential treatment of labor income vis-à-vis dividends and capital gains confounds distortions that act on very different margins. While these challenges can be readily addressed in the context of our structural model, the empirical literature has not yet provided convincing evidence on the differential impact of the number of tax instruments commonly used by real-world governments.

Existing theoretical work A highly influential body of work identifies labor supply and physical capital accumulation as quantitatively important channels through which fiscal policy affects the economy (Baxter and King, 1993; McGrattan, 1994; 2012; Ohanian, 1997; McGrattan et al., 1997; Prescott, 2004; McGrattan and Prescott, 2005; McGrattan and Ohanian, 2010). This strand of literature views *technology* as exogenous and invariant to government policy. Relative to these papers, the main lesson from our quantitative experiments is that tax rates on labor income, dividends, capital gains, and corporate income have sizable effects on innovative investments and thereby on aggregate labor productivity and TFP growth.

By emphasizing the role of innovation, our work is most closely related to the literature in the endogenous growth tradition, which adopts equilibrium models of innovation to study the effects of government policies. Prior theoretical work has emphasized the difference between growth and level effects of taxation (Stokey and Rebelo, 1995; Peretto, 2003; 2007). While this strand of literature has been instrumental in uncovering new transmission mechanisms of tax policy, quantification has been limited.

Only recently, Atkeson and Burstein (2019) quantify the aggregate impact of innovation policies in an endogenous growth model with product and quality innovation. However, they do not study the role of individual and corporate income taxation, let alone time variation in U.S. tax policy, which are central elements of this paper. Jaimovich and Rebelo (2017) examine nonlinear effects of capital income taxation in the context of an endogenous growth model of variety expansion and heterogeneous entrepreneurs in ability. Our paper is also naturally related to the literature in the Schumpeterian tradition. However, while Schumpeterian growth theory has been fruitfully used to shed light on numerous aspects of the growth process (see Aghion et al., 2014, for a survey article), the quantitative implications of tax policy in this extended class of models are largely unexplored. A notable exception is Akcigit et al. (2017), which quantitatively evaluates the extent to which R&D tax credits change the allocation of resources between basic and applied research. Relative to these papers, we contribute with a quantitative analysis of temporary changes in a realistic set of tax rates.

3. Post-WWII fiscal policy in the United States

To study the effects of tax policy on economic activity, we first need to construct time series for tax rates and government spending. We then need to specify expectations of the private sector about future policy. Here, we describe in detail how we construct these model inputs and relate them to the U.S. fiscal policy since World War II. (See Appendix A for details on data construction, definitions and sources.)

The main source of data is the national income and product accounts (NIPA) released by the Bureau of Economic Analysis (BEA). Our approach of calculating average *effective* tax rates closely follows that of Mendoza et al. (1994). We aggregate all levels of the government (federal, state and local) into one general government sector. We categorize individual income as labor income and asset income (dividends and capital gains) and profits of Schedule C corporations as corporate income.

3.1. Individual income tax

In the model, individual income consists of labor earnings, dividends, and capital gains. In the U.S. tax code, these different sources of income are taxed at different rates.

Labor income tax The tax rate on labor income used in the model, τ_t^l , is the average labor income tax rate (ALITR), that is estimated as

$$\text{ALITR} = \frac{\text{APITR} \times (\text{WSA} + \text{PRI}/2) + \text{CSI}}{\text{CEM} + \text{PRI}/2}, \quad (1)$$

where APITR is the average personal income tax rate, WSA is wages and salaries, PRI is proprietors' income, CSI is contributions for government social insurance, and CEM is compensation of employees. The APITR is estimated as

$$\text{APITR} = \frac{\text{PIT}}{\text{WSA} + \text{PRI}/2 + \text{CI}}, \quad (2)$$

where PIT is personal income taxes, that consists of federal personal income taxes and state and local personal income taxes, $\text{CI} = \text{PRI}/2 + \text{RI} + \text{DI} + \text{NI}$ is capital income, RI is rental income, DI is net dividends, and NI is net interests. As discussed in Joines (1981), the imputation of proprietor's income to capital and labor income is somewhat arbitrary. Here we follow Jones (2002) and split proprietor's income evenly between capital and labor income. The source of the data is NIPA. For the post-war period, 1946–2014, the mean ALITR is 20.6%. Panel A of Fig. 1 shows the time series for ALITR. The series shows a marked upward trend since the early-1950s. The ALITR was 15% in the early-1950s, but it has steadily raised to the 25% in 2014.

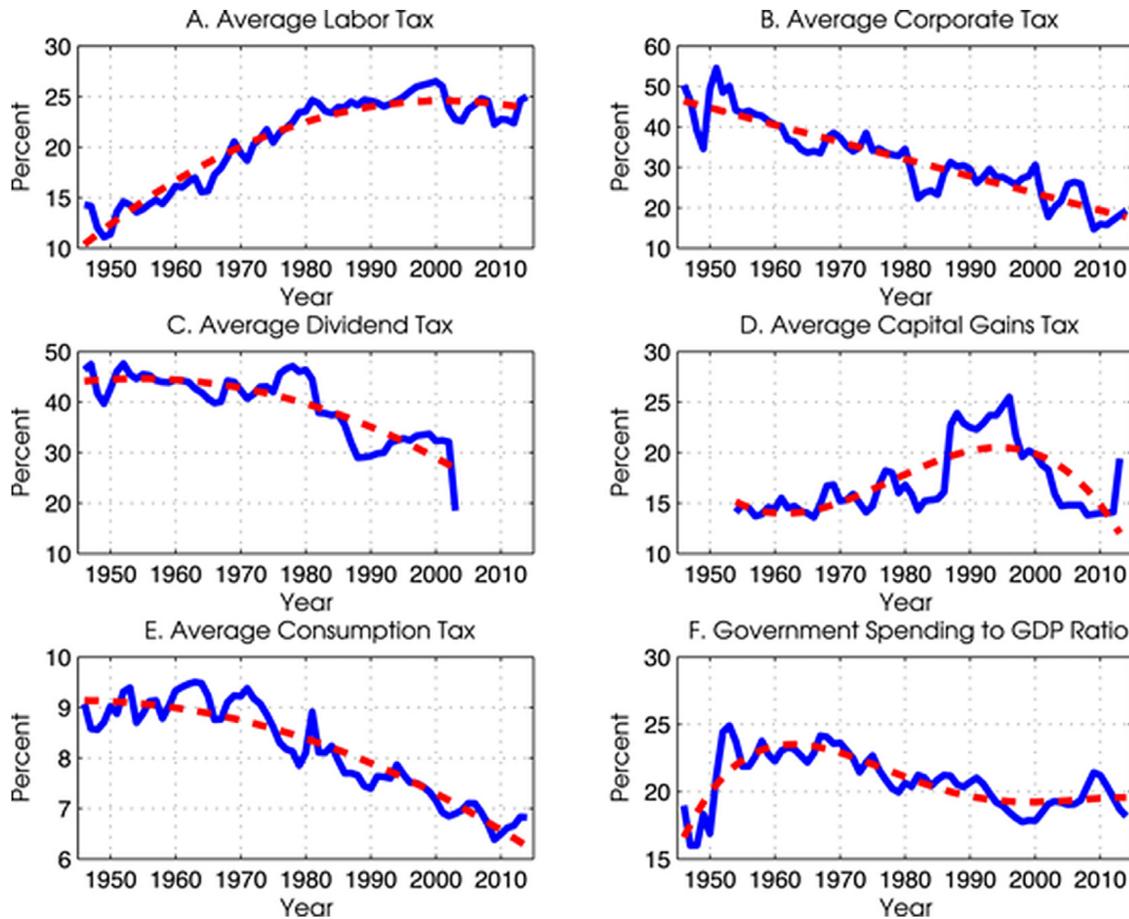


Fig. 1. Post-WWII Fiscal Policy Notes: In all panels, dashed lines show n th-order polynomial trends. Panel A shows the average labor income tax rate (ALITR) for 1946–2014, together with a second-order polynomial trend. Panel B shows the average corporate income tax rate (ACITR) for 1946–2014, together with a linear trend. Panel C shows the average marginal dividend income tax rate (AMDITR) for 1946–2003, as tabulated by [Poterba \(2004, p. 172, Table 1\)](#), together with a second-order polynomial trend. Panel D shows the average capital gains tax rate (ACGTR) for 1954–2013, together with a third-order polynomial trend. Data on capital gains and taxes paid on capital gains are produced by the U.S. Department of the Treasury, Office of Tax Analysis. Panel E shows the average consumption tax rate (ACTR) for 1946–2014, together with a second-order polynomial trend. Panel F shows the government spending to GDP ratio (GRATIO) for 1946–2014, together with a fourth-order polynomial trend. See [Appendix A](#) for further details on data construction, definitions and sources.

Dividend income tax The tax rate on distributed dividends used in the model, τ_t^d , is the average marginal dividend income tax rate (AMDITR). The source of the data is [Poterba \(2004, p. 172, Table 1\)](#). AMDITRs after 1960 are based on tabulations from the NBER TAXSIM model, and on data from the U.S. Department of the Treasury, Statistics of Income (SOI), for earlier years. AMDITR includes the federal marginal income tax rate plus an estimate of the state marginal income tax rate, net of federal income tax deductibility. For the period 1946–2003, the mean AMDITR is 39.5%. Panel C of [Fig. 1](#) shows the time series for AMDITR. The AMDITR was above 40% from 1946 to 1980. It starts declining in the early-1980s; it fluctuates in the 29–34% range until 2002 to reach the post-WWII trough of 18.5% in 2003. This substantial drop in AMDITRs is the result of the cuts in statutory tax rates on dividends prescribed by the Jobs and Growth Tax Relief Reconciliation Act (JGTRRA) of 2003.

Capital gains tax The tax rate on capital gains used in the model, τ_t^v , is the average capital gains tax rate (ACGTR). The source of the data is the U.S. Department of the Treasury, Office of Tax Analysis. For the period 1954–2013, the mean ACGTR is 17%. Panel D of [Fig. 1](#) shows the time series for ACGTR. The ACGTR is approximately constant at the 15% level from the mid-1950s to the mid-1980s. It raises in the late-1980s due to the Tax Reform Act of 1986, which prescribed that capital gains faced the same tax rate as ordinary income. The ACGTR drops from 25% to 20% in 2000 due to the Taxpayer Relief Act of 1997, which reduced the statutory top marginal tax rate on capital gains from 28% to 20%. ACGTRs were further reduced by the Economic Growth and Tax Relief Reconciliation Act (EGTRRA) of 2001 and the JGTRRA of 2003.

3.2. Corporate income tax

The tax rate on corporate profits used in the model, τ_t^π , is the average corporate income tax rate (ACITR), that is estimated as $ACITR = CT/CP$, where CT is federal, state and local taxes on corporate income (excluding Federal Reserve banks)

and CP is the corporate income tax base, that consists of corporate profits (excluding Federal Reserve banks' profits). The source of the data is NIPA. For the post-war period, 1946–2014, the mean ACITR is 32%. Panel B of Fig. 1 shows the time series for ACITR. The series shows a marked downward trend since the early-1950s. The ACITR was as high as 54.5% in 1951, but it has steadily declined since then to a low of 19.3% in 2014.

3.3. Indirect business tax

Included in the analysis are also indirect business taxes on consumption. The tax rate on private consumption used in the model, τ_t^c , is the average consumption tax rate (ACTR), that is estimated as

$$ACTR = \frac{TPI - PRT}{PCE - (TPI - PRT)}, \tag{3}$$

where TPI is taxes on production and imports, PRT is property taxes, and PCE is personal consumption expenditures on durables, nondurables, and services. Taxes on production and imports consists of federal excise taxes and custom duties and of state and local sales taxes, property taxes (including residential real estate taxes), motor vehicle licenses, severance taxes, special assessments, and other taxes. The source of the data is NIPA. Panel E of Fig. 1 shows the time series for ACTR. For the post-war period, the mean ACTR is 8%. The ACTR has been nearly constant at 9% from the early-1950s to the early-1970s, but it has declined since then to 6.8% in 2014.

3.4. Government purchases

In addition to time-varying tax rates, the private sector also faces time-varying government purchases. Government spending is modeled as a share of real GDP per capita. The spending-to-GDP ratio (GRATIO) used in the model, g_t , is estimated as $GRATIO = GOV/GDP$, where GOV is government consumption expenditures and gross investment, that includes federal (national defense plus nondefense), state and local government level, and GDP is gross domestic product. The source of the data is NIPA. Panel F of Fig. 1 shows the time series for GRATIO. For the post-war period, the mean GRATIO is nearly 21%. The GRATIO was below 20% until 1950. It sharply raised from 17% in 1950 to the post-WWII peak of nearly 25% in 1953. Such a surge in government spending is the result of the increase in national defense expenditure due to the Korean War of 1950–1953. To meet the financing needs for defense expenditure, the Revenue Act of 1950 raised the statutory top corporate income tax rate from 38% to 42% in 1950 and to 52% in 1952. Since the mid-1950s, government spending has slowly declined and represents 18% of GDP in 2014.

3.5. Fiscal policy expectations

Before we can simulate equilibrium paths for the model economy, we need to describe private sector's expectations about future government spending and taxes. Thus, here we detail our assumptions, at least for our benchmark policy expectations. Specifically, we fit low-order autoregressive processes to actual data for tax rates ($\tau_t^c, \tau_t^l, \tau_t^d, \tau_t^v$, and τ_t^π) and government spending to GDP ratio, g_t :

$$x_t = d_t + \sum_{j=1}^p \rho_j^x x_{t-j} + \sigma_\epsilon^x \epsilon_t, \quad \text{with } \epsilon_t \stackrel{iid}{\sim} \mathcal{N}(0, 1), \tag{4}$$

where the deterministic term d_t contains a constant, d_0 , and n th-order polynomial trends in time, d_t^n . Lag length p is selected via the Akaike Information Criterion (AIC). For the stochastic process in (4), the autoregressive parameters ρ_j^x control the persistence of the shocks to the tax rates and to the government spending to GDP ratio. The parameter σ_ϵ^x controls the volatility of the innovations ϵ_t . Table 1 summarizes the estimation results.

4. Model

We consider an economy without physical capital. More precisely, there is no capital in the neoclassical sense of a homogenous, durable, intermediate good accumulated through foregone consumption. Instead, there are differentiated, non-durable, intermediate goods. One can think of these goods as capital, albeit with a 100% instantaneous depreciation rate.⁴

Timing convention With the notation here, we adopt the following timing convention: the date t of a generic variable X_t (either control or state variable) indicates the point in time when X_t is chosen. Thus, predetermined variables are dated $t - 1$ in time t equations and dated t in time $t + 1$ equations.

⁴ Following Bilbiie et al. (2012), one can interpret the mass of firms in our setup as the capital stock of the economy. One can rationalize this view by positing that upon its birth the firm sets up an exogenously given stock of capital $k \equiv 1$ (i.e., it builds a plant). It then follows that in this economy the mass of firms stands for the aggregate capital stock, while entry stands for aggregate capital accumulation. The household's decision to purchase shares of entrants amounts then to an extensive-margin investment in physical capital.

Table 1
Post-WWII Fiscal Policy.

	ALITR	AMDITR	ACGTR	ACITR	ACTR	GOV GDP
A. Descriptive statistics:						
Mean	0.206	0.395	0.170	0.320	0.082	0.208
Std. dev.	0.045	0.064	0.034	0.093	0.009	0.021
B. Persistence:						
AR coeff.: ρ_1^x	0.679	1.184	1.132	0.799	0.785	0.910
AR coeff.: ρ_2^x	—	-0.575	-0.308	-0.361	-0.227	-0.378
AR coeff.: ρ_3^x	—	0.139	—	0.021	0.167	—
C. Volatility:						
Std. dev.: σ_ϵ^x	0.008	0.022	0.014	0.028	0.002	0.008
D. Deterministic terms:						
Constant	0.032	0.111	0.020	0.249	0.026	0.087
Polynomial n th-order	2	2	3	1	2	4

Notes: ALITR is the average labor income tax rate for 1946–2014. AMDITR is the average marginal dividend income tax rate for 1946–2003. ACGTR is the average capital gains tax rate for 1954–2013. ACITR is the average corporate income tax rate for 1946–2014. ACTR is the average consumption tax rate for 1946–2014. GOV/GDP (GRATIO) is the government spending to GDP ratio for 1946–2014. The autoregressive (AR) model of order p that we estimate is $x_t = d_t + \sum_{j=1}^p \rho_j^x x_{t-j} + \sigma_\epsilon^x \epsilon_t$, with $\epsilon_t \sim \mathcal{N}^{iid}(0, 1)$, where the deterministic term d_t contains a constant, d_0 , and n th-order polynomial trends in time, d_t^n . Lag length p is selected via the Akaike Information Criterion (AIC). See [Appendix A](#) for further details on data construction, definitions and sources.

4.1. Household sector

The economy is populated by a representative household with a unit mass of infinitely-lived members. Each member is endowed with one unit of time per period. Household preferences are described by

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\ln c_t - \gamma \frac{l_t^{1+\vartheta}}{1+\vartheta} \right), \quad (5)$$

where c_t is per capita consumption, l_t is the fraction of time spent at work, \mathbb{E}_0 denotes the mathematical expectation conditional on the information available at $t = 0$. The parameter β is the subjective time discount factor, γ parametrizes the disutility of work, and ϑ is the inverse of the Frisch elasticity of labor supply.

The household can invest in risky financial assets a_t , that pay a gross *after-tax* rate of return of \tilde{R}_t^a , and in risk-free bonds B_t , that pay a gross interest rate of R_t^b in period $t + 1$. Asset income is then $\tilde{R}_t^a a_{t-1} + R_{t-1}^b B_{t-1}$. Labor income is $w_t l_t$, where w_t is the hourly wage. The household faces a flat-rate tax on consumption expenditure, τ_t^c , on labor income, τ_t^l , on dividend income, τ_t^d , and a capital gains tax, τ_t^v . It also receives lump-sum government transfers Ω_t . The household's flow budget constraint is

$$(1 + \tau_t^c)c_t + a_t + B_t = (1 - \tau_t^l)w_t l_t + \tilde{R}_t^a a_{t-1} + R_{t-1}^b B_{t-1} + \Omega_t. \quad (6)$$

At the start of period t , financial assets $a_{t-1} = s_{t-1} \mathcal{V}_{t-1}$ consist of s_{t-1} shares of an “hedge fund” that aggregates equity of the entire intermediate good sector into an economy-wide portfolio whose ex-dividend market value (or price) is $\mathcal{V}_{t-1} = \int_0^{N_{t-1}} V_{i,t-1} di$, where $V_{i,t-1}$ is the price of firm i 's shares and N_{t-1} is the mass of firms (gross-of-death incumbents) in the intermediate good sector at the start of the period.⁵ At the end of period t , financial assets are $a_t = s_t \mathcal{V}_t$, with $\mathcal{V}_t = \int_0^{N_t} V_{i,t} di$, where N_t is the mass of firms at the end of the period, which is equal to the mass of net-of-death incumbents $\tilde{N}_{t-1} \equiv (1 - \delta)N_{t-1}$ plus the mass of entrants $\Delta_{N,t}$, such that $N_t = (1 - \delta)N_{t-1} + \Delta_{N,t}$, where δ is the per-period (exogenous) probability that each firm exits the intermediate good sector, and $n \equiv \Delta_{N,t}/N_{t-1}$ is the firm's entry rate. Hence, $n - \delta$ is firm's net entry.⁶

The gross after-tax rate of return to the market portfolio is the *average* of the gross after-tax rates of return to firm-level equity:

$$\tilde{R}_t^a \equiv \frac{1}{N_{t-1}} \int_0^{N_{t-1}} R_{i,t}^a di, \quad \text{with} \quad R_{i,t}^a \equiv 1 + \frac{(1 - \tau_t^d)D_{i,t} + (1 - \tau_t^v)(V_{i,t} - V_{i,t-1})}{V_{i,t-1}}, \quad (7)$$

where $D_{i,t}$ indicates firm i 's distributed dividends.

Household's problem The household takes the stochastic processes for tax rates $(\tau_t^c, \tau_t^l, \tau_t^d, \tau_t^v)$, and prices $(w_t, \tilde{R}_t^a, R_t^b)$ as given, and chooses the time path for consumption, c_t , labor supply, l_t , equity shares, s_t , and bond holdings, B_t , given

⁵ The fictitious hedge fund charges no fees. Alternatively, one could think of a competitive environment where the hedge fund charges fees, but it breaks even in a zero-profit equilibrium.

⁶ $\delta > 0$ is required for the model to have symmetric dynamics in the neighborhood of the non-stochastic steady state.

financial assets, a_{t-1} , and risk-free bonds, B_{t-1} , from the previous period, to maximize lifetime utility (5) subject to the budget constraint (6). (Standard no-Ponzi game conditions on equity and bonds hold.)

The household's maximization problem yields: (i) an intratemporal condition,

$$\frac{u_l(c_t, l_t)}{u_c(c_t, l_t)} = -\frac{(1 - \tau_t^l)}{(1 + \tau_t^c)} w_t; \tag{8}$$

(ii) an intertemporal condition for bond holdings,

$$1 = \mathbb{E}_t \left[\beta \frac{u_c(c_{t+1}, l_{t+1})}{u_c(c_t, l_t)} \left(\frac{1 + \tau_t^c}{1 + \tau_{t+1}^c} \right) R_t^b \right]; \tag{9}$$

(iii) an intertemporal condition for equity shares,

$$1 = \mathbb{E}_t \left[\beta \frac{u_c(c_{t+1}, l_{t+1})}{u_c(c_t, l_t)} \left(\frac{1 + \tau_t^c}{1 + \tau_{t+1}^c} \right) \tilde{R}_{t+1}^a \right]. \tag{10}$$

Optimality conditions (9) and (10) are asset pricing equations that drive the consumption-saving decisions of the household, that we parsimoniously rewrite as $1 = R_t^b \mathbb{E}_t [M_{t,t+1}]$ and $1 = \mathbb{E}_t [M_{t,t+1} \tilde{R}_{t+1}^a]$, respectively, where $M_{t,t+1}$ is the consumption-tax-adjusted stochastic discount factor (SDF) between period t and $t + 1$:

$$M_{t,t+1} \equiv \beta \frac{u_c(c_{t+1}, l_{t+1})}{u_c(c_t, l_t)} \left(\frac{1 + \tau_t^c}{1 + \tau_{t+1}^c} \right). \tag{11}$$

As evident from (11), intertemporal disturbances in consumption tax rates directly affect the valuation of the risk-free bond and of risky claims on the intermediate good sector. Note that if $\tau_t^c = \tau_{t+1}^c$ for all $t \geq 0$ then consumption taxes have no intertemporal distortion.

4.2. Final good sector

The final good sector is competitive and consists of a representative final producer that uses intermediate inputs, $X_{i,t}$, that are vertically differentiated by quality, $Z_{i,t}$, and labor, L_t , to produce a final good, Y_t , that we take as the numéraire. The price of the final good is then set to one. The final good has four different uses: (i) private and government consumption; (ii) production of intermediate goods; (iii) investment in the improvement of the quality of existing intermediate goods; (iv) investment in the creation of new intermediate goods (variety expansion).

The technology for the production of the final good (gross output) is

$$Y_t = \int_0^{\tilde{N}_{t-1}} X_{i,t}^\theta \left(Z_{i,t-1}^\alpha Z_{t-1}^{1-\alpha} \frac{L_t}{\tilde{N}_{t-1}^\eta} \right)^{1-\theta} di, \tag{12}$$

where \tilde{N}_{t-1} is the mass of active firms at the start of period t , that also corresponds to the mass of intermediate goods available for purchase at the start of the period, and $X_{i,t}$ is the quantity of intermediate good i used in production. The parameter $\eta \leq 1$ captures the degree of congestion (or rivalry) of labor services across intermediate goods. On the one hand, for $\eta = 0$ there is no congestion as labor services can be shared by all intermediate goods with no productivity loss. This is a case of extreme economies of scope in the use of the labor input that in equilibrium manifest themselves as strong social increasing returns to product variety. On the other hand, for $\eta = 1$ there is full congestion. This is the case of no economies of scope and no social returns to variety.

The contribution of intermediate good i into the production process depends on good i 's own quality, at the start of the period, $Z_{i,t-1}$, as well as on the average quality of intermediate goods, $Z_{t-1} = (1/\tilde{N}_{t-1}) \int_0^{\tilde{N}_{t-1}} Z_{i,t-1} di$. Productivity of the labor input depends on the overall quality of the intermediate goods used in production. This is the defining feature of *vertical product innovation*: higher-quality intermediate goods perform similar functions to those performed by lower-quality goods, but they increase the efficiency of the production process and, as a result, they reduce unit costs of production.

Final producer's problem The final producer takes intermediate good i 's own quality, $Z_{i,t-1}$, and average quality of intermediate goods, Z_{t-1} , as given and sets the value marginal product of each intermediate good i equal to its price, $p_{i,t}$, and the value marginal product of labor equal to the wage rate, w_t . As a result, the demand curve for intermediate goods is

$$X_{i,t} = \left(\frac{\theta}{p_{i,t}} \right)^{\frac{1}{1-\theta}} Z_{i,t-1}^\alpha Z_{t-1}^{1-\alpha} \frac{L_t}{\tilde{N}_{t-1}^\eta}. \tag{13}$$

In Eq. (13), the quality indexes $Z_{i,t-1}$ and Z_{t-1} are multiplicative demand shifters: quality improvements of existing intermediate goods shift the demand curves for intermediate goods outward.

The demand curve for labor is

$$L_t = \left(\frac{1 - \theta}{w_t} \right) Y_t. \tag{14}$$

Finally, perfect competition in the final good sector and the production technology (12) imply that the parameter θ pins down the share of intermediate goods in gross output:

$$\int_0^{\tilde{N}_{t-1}} p_{i,t} X_{i,t} di = \theta Y_t. \quad (15)$$

We stress that in the model gross output differs from gross domestic product (GDP). The value of θ alongside other deep parameters, then, jointly determines the value of intermediate goods and labor income as a share of GDP.

4.3. Intermediate good sector

The intermediate good sector is a monopolistically competitive industry and consists of firms that produce intermediate goods that are vertically differentiated by quality. The market structure of the industry is endogenous: the total mass of firms and firm size are jointly determined in free-entry equilibrium. Intermediate producers undertake investments that improve the quality of existing goods. Indeed, such quality improvements are the source of long-run growth in per capita income.

Incumbents An incumbent operates a technology that requires one unit of final good per unit of intermediate good produced and the payment of a fixed operating cost, ϕZ_{t-1} , in units of the final good.⁷ Hence, firm i 's gross cash flow (revenues minus production costs) is $F_{i,t} = X_{i,t}(p_{i,t} - 1) - \phi Z_{t-1}$, with $\phi > 0$, where $X_{i,t}$ and $p_{i,t}$ are output and unit output price, respectively. Intermediate producers take the average quality index Z_t as given. An incumbent can also upgrade the quality of the own intermediate good by investing $I_{i,t} \geq 0$ units of the final good:

$$Z_{i,t} = Z_{i,t-1} + I_{i,t}. \quad (16)$$

At the individual firm level, incentives to quality-improving investments stem from the shape of the demand curve in Eq. (13): quality upgrading shifts the demand curve for the intermediate good outward which, everything else being equal, raises firm's profit. Before-tax operating profit is $\Pi_{i,t} = F_{i,t} - \sigma_t I_{i,t}$, where $0 \leq \sigma_t \leq 1$ allows for full/partial deductibility of investment.⁸ Operating profit $\Pi_{i,t}$ represents the tax base for the corporate income tax, τ_t^π . Hence, distributed dividends are $D_{i,t} \equiv (1 - \tau_t^\pi)F_{i,t} - (1 - \sigma_t \tau_t^\pi)I_{i,t}$.

The incumbent takes the demand curve for the intermediate good (13), law of motion for quality upgrading (16), and tax rates (τ_t^d, τ_t^v) as given and it chooses the time path for output prices, $p_{i,t}$, and investment, $I_{i,t}$, given quality indexes $Z_{i,t-1}$ and Z_{t-1} , to maximize the cum-dividend value of the firm $(1 - \tau_t^d)D_{i,t} + V_{i,t} - \tau_t^v(V_{i,t} - V_{i,t-1})$. The ex-dividend value of the firm $V_{i,t}$ is the present discounted value (PDV) of net-of-tax rate dividends:

$$V_{i,t} = \left(\frac{1}{1 - \tau_t^v} \right) \mathbb{E}_t \sum_{j=1}^{\infty} \left(\prod_{k=1}^j \tilde{M}_{t+k-1,t+k} \right) (1 - \tau_{t+j}^d) D_{i,t+j}, \quad (17)$$

where $\tilde{M}_{t+k-1,t+k} \equiv \frac{(1-\delta)M_{t+k-1,t+k}(1-\tau_{t+k-1}^v)}{1-\mathbb{E}_{t+k-1}[(1-\delta)M_{t+k-1,t+k}\tau_{t+k}^v]}$ and $M_{t+k-1,t+k}$ is the SDF as defined in (11).

Given the expression for the ex-dividend value of the firm (17), the incumbent maximizes the following cum-dividend firm value:

$$(1 - \tau_t^d)D_{i,t} + \mathbb{E}_t \sum_{j=1}^{\infty} \left(\prod_{k=1}^j \tilde{M}_{t+k-1,t+k} \right) (1 - \tau_{t+j}^d) D_{i,t+j} + \tau_t^v V_{i,t-1}. \quad (18)$$

Note that the last term $\tau_t^v V_{i,t-1}$ on the right-hand side of (18) is irrelevant for the firm's maximization problem as it is independent of current firm's choices.⁹ The maximization problem yields (i) a constant markup over the marginal cost pricing rule,

$$p_{i,t} = \frac{1}{\theta}, \quad (19)$$

and (ii) an intertemporal condition that drives the firm's investment decision,

$$1 = \mathbb{E}_t \left\{ (1 - \delta) M_{t,t+1} \left[\frac{(1 - \tau_t^v)(1 - \tau_{t+1}^d)(1 - \tau_{t+1}^\pi)}{(1 - \tau_t^d)(1 - \tau_t^\pi)} \left[\left(\frac{1 - \theta}{\theta} \right) \frac{\alpha X_{i,t+1}}{Z_{i,t}} + 1 \right] + \tau_{t+1}^v \right] \right\}. \quad (20)$$

Entrants Setting up a firm requires to sink νX_t units of the final good where $X_t = (1/\tilde{N}_{t-1}) \int_0^{\tilde{N}_{t-1}} X_{i,t} di$. Specifically, the economy starts out with a given range of intermediate goods, each supplied by one firm. Because of the sunk cost, new firms cannot supply an existing good in Bertrand competition with the incumbent monopolists but must instead introduce

⁷ If $\phi = 0$, variety expansion becomes a source of long-run growth as in first-generation models of endogenous growth à la Romer (1990).

⁸ In the U.S. tax code R&D expenditure is fully deductible from taxable corporate income, i.e. $\sigma_t = 1$.

⁹ See Appendix B for details on the derivation of the cum-dividend value of the firm.

a new intermediate good that expands product variety. Entry is positive insofar as the ex-dividend value of the firm equals the sunk entry cost, i.e. $V_{i,t} = \nu X_t$ for all $t \geq 0$. The mass of new firms that enters the intermediate good sector in period t starts operating and paying out dividends from period $t + 1$ onward. Entrants finance entry by issuing equity and enter at the average quality level. (The latter is a simplifying assumption that preserves symmetry of equilibrium.)

4.4. Government sector

The government sector purchases final goods and finances spending by levying distortionary taxes. The government’s budget constraint is $G_t + \Omega_t = T_t$, where G_t is government spending, Ω_t is lump-sum transfers and T_t denotes total tax revenues. Government spending is modeled as a share of real GDP, such that $G_t = g_t \mathcal{Y}_t$, with $0 \leq g_t < 1$, where \mathcal{Y}_t denotes real GDP. Government purchases of final goods are modeled as a “pure waste,” as they do not affect either marginal utility of private consumption or production. We focus then on the effects of distortionary taxation. Proportional tax rates are levied on individual income (labor income, dividends, and capital gains), on corporate income (operating profits net of investment), and on private consumption expenditures. In the model, tax rates are modeled as low-order autoregressive (AR) stochastic processes to capture the inherent uncertainty in post-war U.S. tax policy. As discussed in Section 3, we fit these AR processes to U.S. tax data. As a result, the expectations of the household and firms in the model about future policy changes are tightly linked to the expectations of the private sector in the United States. Such a consistency between model and actual policy expectations is key to understanding the dynamic adjustment of the economy in response to changes in tax rates.

5. Tax policy in general equilibrium

We now turn to the general equilibrium of the model. Specifically, we focus on the symmetric equilibrium where firm-level variables equal their corresponding mean values. As a result, we next adopt a more parsimonious notation where we drop the i subscript from the variables at the firm level. As an example, $X_t \equiv X_{i,t}$ denotes average intermediate good production. Market clearing in labor and asset markets requires $l_t = L_t$ and $a_t = \mathcal{Y}_t$, respectively. Note that the aggregate market value of the corporate sector equals $\mathcal{Y}_t = N_t V_t$, whereas the after-tax return to the market portfolio is $\tilde{R}_t^a = (1 - \delta)R_t^a$. Market clearing in the goods market yields the aggregate resource constraint of the economy, such that output is either consumed or invested in activities that generate future income and product:

$$C_t + G_t + \mathcal{I}_t + Q_t = Y_t, \tag{21}$$

where C_t and G_t are private and public consumption, respectively, \mathcal{I}_t indicates investment (quality-improving investments and entry costs), and Q_t denotes intermediate expenses (i.e. intermediate inputs and operating costs).

5.1. National income and product accounts

In the model, the aggregate resource constraint yields the following decomposition of gross output between GDP and intermediate expenses:

$$\underbrace{C_t + G_t + \tilde{N}_{t-1} I_t + \nu X_t \Delta_{N,t}}_{\text{GDP}} + \underbrace{\tilde{N}_{t-1} X_t + \phi \tilde{N}_{t-1} Z_{t-1}}_{\text{intermediate expenses}} = Y_t. \tag{22}$$

private+public consumption
product quality investment
firm creation investment
inputs cost
operating costs
gross output

We include quality-improving investments in the calculation of GDP.¹⁰ This is consistent with the current NIPA approach. Since the 2013 NIPA release, BEA recognizes expenditures by business, government, and nonprofit institutions on R&D as fixed assets, which are then recorded as investment in GDP. In the previous NIPA approach, expenditures on R&D by business – whether purchased from others or carried out in-house – were treated as intermediate expenses used up during production of other goods and services rather than as capital expenses that generate future income and product. (See Appendix B for further details on the calculation of GDP in the model related to the U.S. national accounts.)

5.2. Determinants of the labor input

We now turn to discuss the intratemporal trade-offs that drive the determination of the labor input. In setting the supply of labor services, the representative household equates the marginal rate of substitution (MRS) between consumption and leisure to the effective price of leisure. In the economy here, the consumption good is the numéraire such that the wage rate

¹⁰ Research and development (R&D) is defined in the System of National Accounts (SNA) as “creative work undertaken on a systematic basis to increase the stock of knowledge, and use of this stock of knowledge for the purpose of discovering or developing new products, including improved versions or qualities of existing products, or discovering or developing new or more efficient processes of production” (see <http://unstats.un.org/unsd/nationalaccount/docs/SNA2008.pdf>).

represents the relative price of leisure to consumption. Consumption and labor income tax rates introduce a wedge between MRS and the wage rate:

$$\gamma L_t^\vartheta C_t = \left(\frac{1 - \tau_t^l}{1 + \tau_t^c} \right) w_t. \quad (23)$$

Eq. (23) describes an upward-sloping labor supply curve, with a Frisch elasticity of $\epsilon^F \equiv d \ln L_t / d \ln w_t = 1/\vartheta$. Notice that in the baseline formulation of model, tax revenues are only partially rebated to the household sector as they finance government consumption. Thus, changes in consumption and labor income tax rates have income effects.¹¹

To provide insight into the determination of the labor input, and thereby its equilibrium response to tax changes, it is useful to combine the household's intratemporal condition for labor supply in Eq. (23) with the intratemporal condition for labor demand of the final good producer in Eq. (14), which yields

$$L_t^{1+\vartheta} = \frac{1 - \theta}{\gamma} \left(\frac{1 - \tau_t^l}{1 + \tau_t^c} \right) \frac{Y_t}{\bar{C}_t}. \quad (24)$$

Changes in tax rates levied on consumption and labor income have a direct impact on the aggregate labor input through labor supply considerations, and an indirect equilibrium effect through the aggregate consumption-to-output ratio. The extent to which C_t/Y_t responds to changes in either τ_t^l or τ_t^c , or both, depends on the response of the intermediate good sector, which takes place through changes in entrants' investment in firm creation (net firms' entry/exit) and incumbents' innovative investment. Notice that the tax rates levied on individual asset income and corporate profits also affect the labor input, but only through the determination of the aggregate consumption-to-output ratio.

5.3. Determinants of product and quality innovation

Next, we turn to study the *intertemporal* trade-offs that drive product and quality innovation. In the model, quality-improving innovation is driven by the forward-looking investment behavior of the intermediate good sector. In deciding how much to invest, a typical firm trades off the cost of diverting resources from current (before-tax) operating profit with the benefit of reducing unit production costs in the future. Movements in tax rates act as intertemporal disturbances to this trade-off.

In symmetric equilibrium, the intertemporal first-order condition for quality-improving investment in Eq. (20) becomes

$$1 = \mathbb{E}_t \left\{ (1 - \delta) M_{t,t+1} \left[\frac{(1 - \tau_t^v)(1 - \tau_{t+1}^d)(1 - \tau_{t+1}^\pi)}{(1 - \tau_t^d)(1 - \tau_t^\pi)} \left[\left(\frac{1 - \theta}{\theta} \right) \alpha x_{t+1} + 1 \right] + \tau_{t+1}^v \right] \right\}, \quad (25)$$

where $x_{t+1} \equiv X_{t+1}/Z_t$ is the quality-adjusted measure of firm size, which determines firm's gross profitability through its relationship with the quality-adjusted gross cash flow (revenues minus variable and fixed production costs), $f_{t+1} \equiv F_{t+1}/Z_t$: $f_{t+1} = (p_{t+1} - 1)x_{t+1} - \phi$, where $p_{t+1} = 1/\theta$ is the unit output price of the typical firm in the corporate sector, and ϕ is the parameter governing the extent of fixed operating costs. Notice that the investment decision at the individual firm-level is a bang-bang problem, such that the intertemporal condition in Eq. (25) is to be interpreted as an investment "indifference" condition at the aggregate level. Everything else equal, unexpected changes in future tax rates mandate adjustment in current aggregate investment.

Consumption tax rates (through the effective SDF) and tax rates levied on dividends and profits distort innovative investments insofar as they vary over time. Put differently, the tax rates τ_t^c , τ_t^d , and τ_t^π drop from Eq. (25) to the extent that they are constant across two consecutive periods. This observation points to the potentially important role played by the private sector's expectations about the future path of tax rates. Volatile tax rates on consumption, dividends, and taxable corporate income directly distort the intertemporal allocation of quality-improving investment.

By contrast, the tax rate levied on capital gains represents an intertemporal distortion irrespective of its variation over time. Intuitively, this happens because the capital gains tax applies to *changes* in the market value of the firm, and the current investment decision indeed affects the value of the firm tomorrow relative to today's level. Hence, in the steady-state of the model with constant tax rates, the capital gains tax remains the only tax instrument determining the incentives to quality-improving innovation.

We further stress that the presence of consumption, asset, and corporate income tax rates, and the lack of the labor income tax rate in Eq. (25), reflects the different transmission channels of tax policy embodied in the model. First, changes in consumption tax rates directly affect the timing of investment decisions through changes in the effective SDF applied to risky cash flows. Everything else equal, a higher consumption tax rate tomorrow relative to today's level reduces the effective discount factor to current consumption, which deters current aggregate investment.

Second, tax rates levied on asset income (dividends and capital gains) directly affect the rate of return demanded by the household sector in order to hold claims on the corporate sector. The corporate sector as a whole needs then to change

¹¹ The Hicksian elasticity determines the impact of taxes in steady-state if tax revenues are rebated to the household sector as lump-sum transfers. If tax revenues are not rebated, or only partially rebated, tax changes have income effects and the Marshallian elasticity becomes the relevant parameter.

investment policy accordingly to guarantee the required rate of return to investors, as mandated by the equilibrium in the asset market. Third, changes in the corporate income tax rate affect the rate of return to the market portfolio held by the household sector by changing the intertemporal distribution of dividends.

Fourth, the tax rate levied on labor income has no direct effect on aggregate corporate investment, but only an indirect effect on firm size, and thereby on the gross profitability of the corporate sector through the determination of the labor input per active firm $f_{t+1} \propto L_{t+1}/\tilde{N}_t^\eta - \phi$. Few considerations are in order. Next period labor input, L_{t+1} , and number of active firms in the corporate sector, \tilde{N}_t , are equilibrium variables, that are out of control of the individual firm. Firms in the corporate sector take then future gross profitability, f_{t+1} , as a signal about the future prospects of aggregate demand for their products, X_t , and thereby of quality-adjusted firm size, $x_{t+1} \propto L_{t+1}/\tilde{N}_t^\eta$. The transmission of changes in the labor income tax rate, τ_t^l , to aggregate corporate investment operates through two channels: (i) changes in τ_t^l directly affect labor supply as intratemporal disturbances to the consumption-leisure trade-off; and (ii) equilibrium dynamics in the labor input drives entry in the corporate sector, thus determining the number of active firms. The implied dynamics in the labor input per active firm acts then as a disturbance to the intertemporal allocation of R&D investment.

Intertemporal tax disturbances Next, we study how variation over time in tax rates alters the intertemporal allocation of R&D investment. By timing R&D expenditures, the corporate sector accomplishes intertemporal shifting of tax burden. Corporate R&D is tax deductible, such that the intertemporal allocation of R&D investment effectively alters the time path of taxable corporate income.

To this goal, we consider the rate of return to incumbents (RRI) investment and the rate of return to entrants (RRE) investment. We interpret RRI and RRE as investment schedules as represented in the (i_t, r_{t+1}^a) space, where $i_t \equiv I_t/Z_{t-1}$ is the current R&D investment rate and r_{t+1}^a is the rate of return to corporate equity one period ahead. The intersection of RRE and RRI schedules describes the investment decision of the private sector as implied by no arbitrage. To sharpen intuition, we rely on perfect foresight and so abstract from uncertainty about the future path of tax rates. (See Appendix B for details on the derivation of the RRI and RRE schedules.)

In symmetric equilibrium, the household's intertemporal condition for equity in (10) jointly with the intertemporal condition for R&D investment in (25), yields the RRI investment schedule:

$$r_{t+1}^a = \frac{(1-\tau_t^v)(1-\tau_{t+1}^d)(1-\tau_{t+1}^\pi) - (1-\tau_{t+1}^v)(1-\tau_t^d)(1-\tau_t^\pi)}{(1-\tau_t^d)(1-\tau_t^\pi)} + \frac{(1-\tau_t^v)(1-\tau_{t+1}^d)(1-\tau_{t+1}^\pi)}{(1-\tau_t^d)(1-\tau_t^\pi)} \left(\frac{1-\theta}{\theta}\right) \alpha x_{t+1}. \tag{26}$$

Note that the RRI investment schedule in (26) is a flat line in the (i_t, r_{t+1}^a) space. This reflects the bang-bang property of the investment problem at the individual firm-level. At the aggregate level, the RRI schedule represents an indifference condition, that jointly with the RRE schedule below, describes the trade-off driving the intertemporal allocation of R&D investment in the corporate sector.

In symmetric equilibrium, the expression for the after-tax rate of return to equity in (7) jointly with the free-entry condition $V_t = vX_t$ yields the RRE investment schedule:

$$r_{t+1}^a = \underbrace{(1-\tau_{t+1}^d)(1-\tau_{t+1}^\pi) \left[\frac{\left(\frac{1-\theta}{\theta}\right)x_{t+1} - \phi - i_{t+1}}{vX_t} \right]}_{\text{dividend-price ratio channel}} (1+i_t) + \underbrace{(1-\tau_{t+1}^v) \left[\frac{x_{t+1}(1+i_t)}{x_t} - 1 \right]}_{\text{capital gains channel}}. \tag{27}$$

Note that the RRE schedule in (27) is an upward-sloping line in the (i_t, r_{t+1}^a) space. Higher rates of return to corporate equity next period are associated to higher rates of investment in R&D today. Such a positive relationship materializes through two channels. Everything else equal, a higher investment rate today is associated to (i) a higher dividend-price ratio tomorrow, and to (ii) an appreciation of the market value of the corporate sector.

Explaining the effects of intertemporal disturbances in tax rates hinges on understanding if, how, and to what extent the RRI and the RRE schedules shift in response to tax changes. Next, we discuss a few experiments in tax policy that illustrate the transmission mechanisms embodied in the model. First, we stress that *current* tax rates only enter the RRI schedule in Eq. (26). Thus, changes in current tax rates, keeping fixed future ones, affect the R&D investment rate today by shifting the RRI investment schedule either upward or downward. As an example, let us consider a reduction in either the dividend tax, or the corporate tax, or both, while keeping future tax rates fixed at their current values. In this scenario, the RRI schedule shifts downward, whereas the RRE schedule remains unchanged. As a result, the current investment rate unambiguously declines, implying a lower return to corporate equity tomorrow.

Second, changes in *future* tax rates disturb both the RRI and RRE investment schedules. Let us consider next a reduction in either next period dividend tax, or corporate tax, or both, while keeping current tax rates unchanged. The RRI schedule shifts upward. Holding the RRE fixed, this upward shift in the RRI schedule would imply an unambiguous increase in the current investment rate. However, the RRE moves to the left, such that the overall effect is in principle ambiguous.

Third, we consider changes in current and next period tax rates on capital gains. A reduction in the current tax rate on capital gains, relative to tomorrow's value, shifts the RRI schedule upward while leaving the RRE schedule unchanged. As a result, the current investment rate unambiguously raises implying a higher return to corporate equity. By contrast, a reduction in next period tax rate relative to its current value unambiguously reduces the current investment rate. Holding the RRE fixed, the downward shift in the RRI schedule implies an unambiguous reduction in the current investment rate. This effect is further amplified by the leftward shift of the RRE investment schedule.

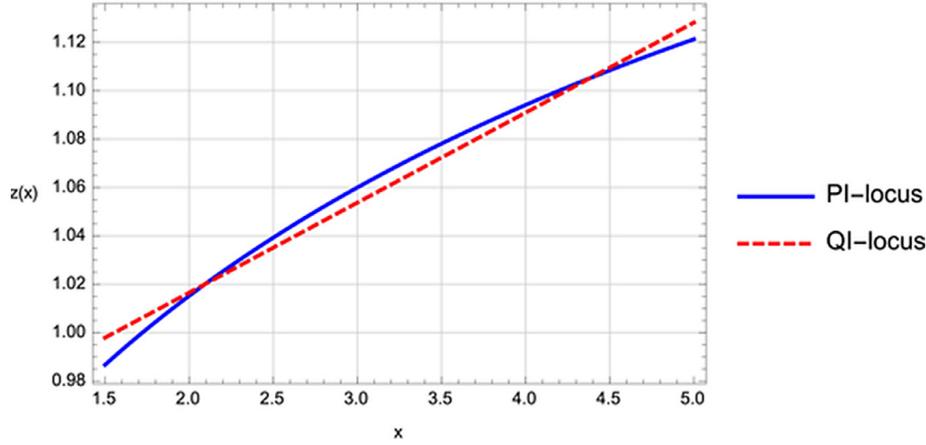


Fig. 2. Determination of Steady-State Growth Rate of Quality Improvement Notes: On the horizontal axis, $x_t \equiv X_t/Z_{t-1}$ is the quality-adjusted firm size, whereas on the vertical axis, $z_t \equiv Z_t/Z_{t-1}$ is the gross growth rate of quality improvement. The PI locus (solid line) describes the gross growth rate of quality improvement, z_t , needed to equalize the rate of return to entry to the rate of return to quality-improving investment, given the value of x_t that both entrants and incumbents expect to achieve in equilibrium. The QI locus (dashed line) describes the gross growth rate of quality improvement, z_t , that incumbents generate given the quality-adjusted firm size, x_t , that they expect to achieve in equilibrium. See Section 6.1 for further details on the baseline parametrization of the model.

5.4. Determinants of growth

To understand the role of tax policy for the determination of long-term rates of economic growth, we use the equations that describe the steady state of the model. In the steady state with constant tax rates (and $\sigma_t = 1$, for all $t \geq 0$), the steady-state growth rate of output per capita is determined by a low-dimensional system, that links the quality-adjusted firm size in the corporate sector, $x_t \equiv X_t/Z_{t-1}$, to the steady-state gross growth rate of quality improvement, $z_t \equiv Z_t/Z_{t-1}$. Along the balanced growth path (BGP), the gross growth rate of quality z_t and firm size x_t are constant. (Henceforth, we omit time subscripts unless needed for clarity.)

The system consists of a product innovation (PI) locus that captures the incentives to firms' entry in the corporate sector:

$$z = \beta(1 - \delta) \left[(1 - \tau^d)(1 - \tau^\pi) \left(\frac{1 - \theta}{\theta v} - \frac{z - 1 + \phi}{v x} \right) z + (1 - \tau^v)(z - 1) + 1 \right]. \quad (28)$$

And of a quality innovation (QI) locus that captures the incentives to investment in quality improvement of incumbents in the corporate sector:

$$z = \beta(1 - \delta) \left[(1 - \tau^v) \left(\frac{1 - \theta}{\theta} \right) \alpha x + 1 \right]. \quad (29)$$

The PI locus in (28) describes the steady-state quality-adjusted R&D investment rate $I_t/Z_{t-1} = z_t - 1$ that equalizes the rate of return to entry to the rate of return to quality investment, given the value of x that both entrants and incumbents expect to achieve in equilibrium. The QI locus in (29) describes instead the steady-state investment rate that incumbents generate given the quality-adjusted firm size, x , that they expect to achieve in equilibrium. (See Appendix B for details on the derivation of the PI and QI locus.) The steady state is the intersection of these two locus in the (x, z) space. Fig. 2 illustrates the determination of the steady state of the model based on our baseline parametrization, which we discuss at length in Section 6.1 below.

Few remarks are in order. First, the corporate tax rate does not enter the QI locus as the R&D expensibility parameter is set to $\sigma_t = 1$ at all times. This approach replicates in the model the full expensibility of R&D investment granted by the U.S. tax code to incorporated firms. Second, the dividend tax rate does not enter the QI locus as corporate investment is financed by retained earnings instead of equity. This accords with the "new view" of corporate finance (Auerbach, 2002).

Existence and stability of the steady state require an intercept condition that the PI curve starts out below the QI curve and a slope condition that the PI curve is steeper than the QI curve. Together they imply that a stable steady state (x^*, z^*) exists with the PI curve cutting the QI curve from below. In order to see the stability of such steady state, notice that if the system starts at a slightly higher $x > x^*$, then the return to product innovation is higher than the return to quality innovation (since the PI curve is above the QI line to the immediate right of the intersection). This spurs entry and increases the number of firms. Since x is inversely related to the number of firms, x then falls forcing the system to revert back to steady-state value x^* . Note that because the QI locus is a line and PI is an inverted parabola, there will be another intersection at higher values of x and z . Yet, such steady state is unstable. The baseline parameter values in Section 6.1 yield local stability of equilibrium dynamics around the stable steady-state.

In the model, the steady-state growth rate of quality improvement, z^* , is the only driver of aggregate TFP and real GDP growth. This result is due to the presence of fixed operating costs. An ever expanding number of products puts pressure on the economy's aggregate resources by duplicating fixed costs, which in turn makes firm's entry, and so expanding-variety innovation, irrelevant for long-run productivity growth. The irrelevance of product innovation for long-term rates of economic growth has important implications for tax policy.

In the system (28) and (29), the corporate income tax, τ^π , and the individual income tax on dividends, τ^d , and capital gains, τ^v , jointly determine the steady-state growth rate of quality improvements and thereby of output per capita. In the model, tax rates on corporate income and individual asset income affect equilibrium behavior through two channels: (i) tax rates change budget sets; (ii) tax rates change entry and investment decisions by distorting intertemporal first-order conditions. Yet, we emphasize that the steady-state growth effects of corporate and asset income taxation remain even if tax revenues are lump-sum rebated to the household. This happens because *constant* tax rates affect steady-state relative rates of return to entrants' and incumbents' investment and thereby the "great ratio" of the theory, quality-adjusted firm size, leading then to substitution effects. Tax rates on individual asset income play a key role in corporate investment decisions.

Next, we emphasize that neither the consumption tax rate nor the labor income tax rate enter the determination of the steady-state rate of quality improvement, z^* , in the system (28) and (29). Explaining why this happens is key to understanding the transmission mechanism of tax policy embodied in the model. The PI and QI curves capture the insight that firms' entry and R&D investment decisions by incumbents do not directly respond to changes in consumption and labor income tax rates, but only indirectly through changes in quality-adjusted firm size. A permanent change in either τ^c or τ^l , or both, affects the equilibrium labor input, and thereby the aggregate demand for intermediate goods. These market-size effects are nevertheless sterilized in the long-run by net entry/exit of firms. To see this, (1) fix the number of firms, then a change in either tax rate affects the quality-adjusted firm's size, x , and thereby incentives to quality-improving innovation. Everything else equal, this would have steady-state growth effects. (2) Now, let the mass of firms vary as in free-entry equilibrium; as the profitability of incumbents varies, the mass of firms endogenously adjusts (net entry/exit) to bring the economy back to the initial steady-state level of firm size, x^* . As a result, the adjustment process through firms' entry fully sterilizes the long-run growth effects of the initial tax change.

6. Quantitative implications for the U.S. economy

In this section, we study the quantitative predictions of the model. Specifically, we feed the U.S. post-war fiscal policy along with empirical estimates of policy expectations into the model and compute the equilibrium. We implement two types of policy analysis: (i) analysis of long-run effects of tax changes, through steady-state comparisons; and (ii) analysis of short-run effects of tax changes, through computation of approximate equilibrium dynamics in the neighborhood of the steady state, with no shocks to either government spending or tax rates. As a first step, we next choose parameter values, such that the model economy is consistent with salient features of the post-war U.S. economy. (See Appendix B for the list of equilibrium conditions used to compute the approximate equilibrium of the model and a discussion of the solution method.)

6.1. Parametrization

We now turn to the parametrization of the model. Each time period is taken to represent a year. As for the calibration strategy, we exogenously set the value of a subset of parameters based on previous work and micro data, whereas we calibrate the rest of parameters to match specific moments in U.S. data. While none of the parameters has a one-to-one relationship to a moment, we can provide a heuristic description of identification.

6.1.1. Internally calibrated parameters

Next, we discuss parameter values that are exogenously set.

Congestion of labor services in production The reduced-form aggregate production function of the final good (gross output) reduces to:

$$Y_t = \tilde{N}_{t-1}^{1-(1-\theta)\eta} X_t^\theta (Z_{t-1} L_t)^{1-\theta}, \quad (30)$$

where the parameter $0 \leq \eta \leq 1$ captures the degree of congestion of labor services across intermediate goods. For $\eta = 0$ there is no congestion as labor services can be shared across intermediate goods with no productivity loss. For $\eta = 1$ there is instead full congestion. In the United States, population growth averaged 1.2% per year over the period 1977–2013, and the number of firms has grown at approximately 1.1% per year on average over the same time period. Importantly, these two figures are not statistically different from each other, which suggests that population and the number of firms indeed move in lockstep in the United States. Thus, we set $\eta = 1$. Data on the population of active firms in the U.S. business sector is from the Business Dynamics Statistics (BDS) dataset produced by the Census and available at <http://www.census.gov/ces/dataproducts/bds/index.html>.

Arguably, the calibration of the congestion parameter, and so the implied social return to variety, represents a challenging task. Hard evidence backing up a specific parameter value is scarce and often open to criticism. To address this concern, we

check the sensitivity of our results to an alternative parametrization with partial congestion, based on a value of $\eta = 0.75$ —labor congestion of 75%.

Government spending and taxes We set \bar{g} equal to 20.8 percent so that the mean of the government spending to GDP ratio in the model matches that in post-war data for 1946–2014. In the model, taxes are levied on (i) individual income, which consists of labor income, dividends of Schedule C corporations distributed to their owners, and capital gains on equity shares of the corporate sector, (ii) corporate income, which consists of profits of Schedule C corporations, and (iii) consumption expenditures. For the taxes levied on individual income, we set $\bar{\tau}^l$ equal to 20.6% to match the average labor income tax rate (ALITR) in the data for 1946–2014; $\bar{\tau}^d$ equal to 39.5% to match the average marginal dividend income tax rate (AMDITR) in the data for 1946–2003; and $\bar{\tau}^v$ equal to 17% to match the average capital gains tax rate (ACGTR) in the data for 1954–2013. For the tax levied on corporate profits, we set $\bar{\tau}^\pi$ equal to 32% to match the average corporate income tax rate (ACITR) in the data for 1946–2014. In the U.S. tax code, R&D expenditure is fully deductible from taxable corporate income so we set $\sigma_t = 1$ at all times. For the consumption tax, we set $\bar{\tau}^c$ equal to 8.2% to match the average consumption tax rate (ACTR) in the data for 1946–2014. The parameter estimates that govern the persistence of the deviations of the fiscal instruments from the long-run deterministic trends are reported in [Table 1](#).

6.1.2. Externally calibrated parameters

Next, we discuss parameter values that are calibrated to targeted moments of U.S. data.

Preferences Using data from the Current Population Survey (CPS), [McGrattan and Prescott \(2013\)](#) find that total hours of work relative to the working-age population averaged 1442 h per year in United States. If discretionary time per week is 100 h, then the fraction of time spent at work is 0.277. Given our specification of preferences,

$$u(c_t, l_t) = \ln c_t - \gamma \frac{l_t^{1+\vartheta}}{1+\vartheta}, \quad (31)$$

we set γ equal to 9.33 to get the same predicted fraction of time spent at work for the model. Also, we set $\vartheta = 1$ so that the Frisch elasticity of labor supply equals one ([Chetty et al., 2012](#), see). In addition, we set the discount factor $\beta = 0.98$, so that in the model the risk-free interest rate r_t^b along the balanced growth path (BGP) is 4 percent, consistent with recent findings by [Gomme et al. \(2011\)](#).

Technology The value of the parameter θ uniquely pins down the markup at $1/\theta$. The available evidence for the United States provides estimates of markups in value added data ranging from 1.1 by [Basu and Fernald \(1997\)](#) to 1.2 by [Bils and Klenow \(2004\)](#). Instead of settling on one specific value for the markup, we report results for two alternative economies featuring a price markup of 10 and 20%. We set then θ equal to 0.83 for a 20% markup and to 0.91 for a 10% price markup.

The firm's private return to quality improvement α is set equal to 0.31, so that along the BGP the R&D expenditure to GDP ratio in the model matches the average R&D-to-GDP ratio of 2.6% in the data for the period 1996–2012. Data on R&D expenditure as percent of GDP are from the World Development Indicators (WDI) produced by the World Bank and available at <http://data.worldbank.org/indicator/GB.XPD.RSDV.GD.ZS>.

Firms' exit We set the death rate of the firm to $\delta = 6.18$ percent such that the firm's exit probability in the model matches the mean of firms' exit rates in the data for 1977–2013, conditional on surviving for the first five years. Specifically, we calculate the firm's death rate as the number of firm deaths in the current period divided by the number of active firms in the previous period. All establishments owned by the firm must exit to be considered a firm death. Data on the population of active firms and on the number of firms' deaths in the United States are from the BDS dataset. In addition to the relatively high firms' death rate parametrization of 6.18 percent, we also experiment with $\delta = 3.94$ percent, which is the exit rate for mature firms of 25 years of age and older in the BDS dataset.

Entry and fixed operating costs We finally set ϕ to 0.15 and ν to 0.54, such that the model matches the average growth rate of real GDP per capita of 2% in the data for the period 1948–2014, and the average labor share of GDP of 0.653 for the period 1948–2013 based on [Koh et al. \(2016\)](#).

6.1.3. Parameter identification

The analytical tractability of the model BGP allows for a heuristic description of parameter identification. As standard in dynamic equilibrium models, none of the parameters has a one-to-one relationship to a specific moment. Yet, the cross-equation restrictions implied by the theory highlight key relationships between model parameters and targeted moments.

We consider the non-stochastic steady state of the model with constant tax rates. Tax rates along the BGP are calibrated to match the corresponding average values in the United States. Given our specification of preferences, the steady-state version of the household's intertemporal condition for bond holdings in (9) yields:

$$z_t = \beta R_t^b, \quad (32)$$

where $z_t \equiv Z_t/Z_{t-1}$ is the gross growth rate of quality improvement along the BGP, that is incidentally the steady-state growth rate of consumption. Given a target of 2% for real GDP growth and 4% for the risk-free interest rate, the relationship in (32) yields the calibrated value of $\beta = 1.02/1.04 \approx 0.98$. Recall that the pricing equation of the intermediate producers in (19) yields the unit price $p_t = 1/\theta$ for all $t \geq 0$. A target mark-up of 20% implies then the calibrated value of $\theta = 1/1.2 \approx 0.83$.

Notice that the production technology in (12) and price-taking behavior in the final good sector implies a constant labor share of gross output $w_t L_t / Y_t = 1 - \theta$. Next, we use the aggregate resource constraint $Y_t = \mathcal{Y}_t + \mathcal{Q}_t$ to derive an expression

for the GDP-to-output ratio, $\mathcal{Y}_t/Y_t = 1 - \theta^2(1 + \phi/x_t)$, such that the labor share of GDP reduces to:

$$\frac{w_t L_t}{\mathcal{Y}_t} \equiv \frac{w_t L_t}{Y_t} \left(\frac{1}{\mathcal{Y}_t/Y_t} \right) = \frac{1 - \theta}{1 - \theta^2(1 + \phi/x_t)}. \quad (33)$$

Few remarks are in order. First, the value of the parameter θ is uniquely pinned down at 0.83 by the 20% target for the price mark-up. Second, along the BGP, quality-adjusted firm size x_t is determined by the PI and QI locus in (28) and (29), respectively, jointly with the steady-state growth rate of quality improvement, z_t . Holding x_t fixed, there exists then a one-to-one relationship between the parameter governing the extent of fixed operating costs, ϕ , and the labor share of GDP. Notice that ϕ enters the expression for the PI locus as well, such that x_t is an implicit function of ϕ alongside other parameters of the model. Yet, we stress that though different parametrizations can produce the same numerical value for quality-adjusted firm size, x_t , different calibrations of ϕ imply drastically different implications for the labor share of GDP in the model. This argument suggests that the observed labor share of GDP indeed has relevant identifying information.

In the model, the R&D-to-GDP ratio is related to the labor share of GDP in (33) through a simple relationship:

$$\frac{\text{R\&D}_t}{\mathcal{Y}_t} = \frac{\theta^2(z_t - 1)/x_t}{1 - \theta^2(1 + \phi/x_t)} = \frac{w_t L_t}{\mathcal{Y}_t} \left(\frac{\theta^2}{1 - \theta} \right) \frac{z_t - 1}{x_t}. \quad (34)$$

Given our targets of 65.3% for the labor share of GDP, and of 2% for real GDP growth, the expression in (34) restricts x_t . As a result, the remaining three parameters entering the PI and QI locus, (ϕ, ν, α) , need to be jointly calibrated to reproduce the three targeted moments for the labor share of GDP, the R&D-to-GDP ratio, and the growth rate of real GDP.

Next, we highlight that the value of the labor input does not enter any of the steady-state relationships above. This feature of the equilibrium represents a cross-equation exclusion restriction, that reflects the sterilization of market-size effects along the BGP: Rates of return to firms' entry and incumbents' quality-improving innovation are independent of equilibrium labor. Yet, the parameters determining the BGP restrict the calibrated value of the steady-state labor input. This block recursive structure allows us to calibrate the economy to the targeted moments for the risk-free interest rate, the labor share of GDP, R&D-to-GDP ratio, and the growth rate of real GDP, independently of the labor input. Then, given the values for the exogenously set and calibrated parameters, the target of 0.277 for time spent at work implies the calibrated value for the disutility of work parameter of $\gamma = 9.33$.

Finally, we discuss identification of the parameter η governing congestion of labor services into the production of gross output. To this goal, we consider the equilibrium relationship $x_{t+1} = \theta^{\frac{2}{1-\theta}} L_{t+1} / \tilde{N}_t^\eta$ to derive an expression for the number of firms per capita (population size is normalized to one):

$$N_t^\eta = \frac{\theta^{\frac{2}{1-\theta}}}{(1 - \delta)^\eta} \left(\frac{L_{t+1}}{x_{t+1}} \right). \quad (35)$$

The expression in (35) delivers a revealing cross-equation exclusion restriction implied by the equilibrium of the model. On the right-hand side of (35), the parameters θ and δ are uniquely pinned down by our targets for the price mark-up and firms' exit probability. In addition, the targeted value for the labor input and the implied steady-state value for quality-adjusted firm size are both determined independently of the equilibrium relationship in (35). There exists, then, a one-to-one relationship between the congestion parameter η and the number of firms per capita. The equilibrium of the model suggests that statistics on the number of firms per capita, and alike, indeed contain relevant identifying information for calibrating the congestion parameter.

In BDS data for 1977–2013, the ratio of civilian noninstitutional population (16 years of age and older) to the total number of firms in the U.S. business sector is approximately 45. This figure translates into a firms-to-population ratio of 0.02. In the baseline parametrization based on full congestion with $\eta = 1$, the model delivers a firms-to-population ratio of 0.016, which is strikingly close to the data for being an untargeted moment. If one restricts attention to firms of 5 years of age and older, instead, the ratio of population to the number of firms in that age group is approximately 77. This figure implies a firms-to-population ratio of 0.013, that can be exactly matched by setting the congestion parameter to 0.95. Furthermore, if we only consider mature firms of 25 years of age and older, then the ratio of population to the number of firms in that age group is 299. This figure implies a firms-to-population ratio of 0.003 that can be matched with a congestion parameter of roughly 0.75.

6.2. Growth effects of income taxation

We now turn to investigate the quantitative effects of *permanent* changes in tax rates. Specifically, we compare the steady states of the model before and after the change in a specific tax rate, while keeping the remaining tax rates fixed at their steady-state values. In each experiment, the government budget constraint is balanced with the required change in lump-sum transfers.

We consider steady-state responses of real GDP/TFP growth and the R&D-to-GDP ratio to a 1 percentage point (pp) permanent cut in tax rates. To gauge the magnitude of these effects, we consider numerical solutions for the shifts in the equilibrium steady-state growth rates arising from small perturbations in each tax rate.

Table 2
Long-Run Responses to Permanent Tax Cuts with 20% Price Markup.

	old steady-state	new steady-state (1 pp tax cut)				
		$\tau^d \downarrow$	$\tau^v \downarrow$	$\tau^\pi \downarrow$	$\tau^c \downarrow$	$\tau^l \downarrow$
A. Firms' exit probability of 6.18%:						
Real GDP/TFP growth	2%	0.9%	2.57%	1%	2%	2%
R&D-to-GDP ratio	2.6%	1.34%	3.17%	1.47%	2.6%	2.6%
B. Firms' exit probability of 3.94%:						
Real GDP/TFP growth	2%	1.41%	2.22%	1.47%	2%	2%
R&D-to-GDP ratio	2.6%	2.02%	2.83%	2.08%	2.6%	2.6%

Notes: 1 percentage point (pp) tax cut from steady-state value. See Section 6.1 for details on the baseline parametrization of the model.

Table 3
Long-Run Responses to Permanent Tax Cuts with 10% Price Markup.

	old steady-state	new steady-state (1 pp tax cut)				
		$\tau^d \downarrow$	$\tau^v \downarrow$	$\tau^\pi \downarrow$	$\tau^c \downarrow$	$\tau^l \downarrow$
A. Firms' exit probability of 6.18%:						
Real GDP/TFP growth	2%	1.44%	2.30%	1.50%	2%	2%
R&D-to-GDP ratio	2.6%	2.02%	2.93%	2.08%	2.6%	2.6%
B. Firms' exit probability of 3.94%:						
Real GDP/TFP growth	2%	1.65%	2.16%	1.69%	2%	2%
R&D-to-GDP ratio	2.6%	2.28%	2.78%	2.31%	2.6%	2.6%

Notes: 1 percentage point (pp) tax cut from steady-state value. See Section 6.1 for details on the baseline parametrization of the model.

We next discuss two key predictions of the model for the long-run transmission mechanism of tax changes. First, permanent changes in the tax rate on consumption expenditures and on labor income have no effect on either the long-run growth rate of TFP or the level of the R&D-to-GDP ratio. This neutrality result stems from the interaction of firms' entry and quality-improving innovation. Changes in labor and consumption tax rates propagate through the economy by changing the scale of economic activity. Market-size effects are irrelevant for the long-term incentives to quality-improving innovation, and thereby neutral in terms of long-term rates of TFP and real GDP growth.

Second, permanent changes in tax rates on individual asset income (dividends and capital gains) and corporate income have, instead, a quantitatively large impact on aggregate TFP growth. The magnitude of this effect is sensitive to the parametrization of the firm's exit probability and of the price markup. We report then results for alternative parametrizations: Table 2 shows results for the economy with a price markup of 20%, whereas Table 3 shows results based on a price markup of 10%. Panel A of each table considers a high exit probability of 6.18%, which is the exit rate of firms of 5 years of age and older in the U.S. business sector. Panel B of each table considers a low exit probability of 3.94%, which corresponds to the exit rate of firms of 25 years of age and older.

20% price markup The quantitative effects of a dividend and of a corporate tax cut have the same sign and are comparable in magnitude. Specifically, for the high-exit economy, a 1 pp cut in either tax rate halves the steady-state growth rate of the economy from 2% to approximately 1%. For the low-exit economy, instead, an equally-sized tax cut reduces growth by roughly 0.6 percentage points. By contrast, a 1 pp cut in the capital gains tax raises steady-state growth by nearly 0.6 percentage points in the high-exit economy, and by 0.2 percentage points in the low-exit economy. Overall, these are sizable effects.

The sensitivity of the growth effects of income taxation to the value of the firm's exit probability hinges on the following insight. Product quality is an asset that generates future income and product. The capitalized value of this asset depends on the total income expected to be realized over its economic life span and the market discount rate applied to this stream of generated income. A higher probability of firm's death/exit lowers the expected economic life span of its product, which implies a higher effective discount rate applied to the future income generated by the firm. Everything else equal, a higher discount rate reduces then the capitalized value of product quality, such that a tax cut of a given size has a disproportionately large impact on the total asset value of the firm.

10% price markup The quantitative effects of a dividend and of a corporate tax cut have again the same sign and are comparable in magnitude. For the high-exit economy, a 1 pp cut in either tax rate reduces the steady-state growth rate of the economy by approximately 0.5 percentage points. For the low-exit economy, an equally-sized tax cut reduces growth by roughly 0.3 percentage points. By contrast, a 1 pp cut in the capital gains tax raises steady-state growth by nearly 0.3 percentage points in the high-exit economy, and by 0.15 percentage points in the low-exit economy. Notice that reducing the price markup from 20% to 10% nearly halves the steady-state responses to tax cuts across the board. The extent of market power is indeed a key conditioning variable for understanding the transmission of asset and corporate income taxation to long-term growth rates of TFP.

Table 4
Variance Decomposition of Aggregate TFP Growth.

	full congestion	partial congestion	
	$\eta = 1$	$\eta = 0.95$	$\eta = 0.75$
A. Variances/covariances:			
$\text{Var}(d \ln A_t)$	0.169	0.166	0.153
$\text{Var}(d \ln Z_t)$	0.169	0.173	0.190
$\text{Var}(d \ln N_t)$	0.043	0.045	0.054
$\text{Cov}(d \ln Z_t, d \ln N_t)$	-0.061	-0.065	-0.081
B. Unconditional shares:			
$\text{share}_{\text{quality}}^{\text{TFP}}$	100%	99.9%	98%
$\text{share}_{\text{entry}}^{\text{TFP}}$	0%	0.1%	2%

Notes: Panel A reports the theoretical variances and covariances from the model (in percent). Panel B reports the corresponding variance decompositions, where the shares of the unconditional variance of TFP growth attributed to product quality and firm entry are calculated as $\text{share}_{\text{quality}}^{\text{TFP}} \equiv \frac{\text{Var}(d \ln Z_t)}{\text{Var}(d \ln Z_t) + (1-\eta)^2 \text{Var}(d \ln N_t)}$ and $\text{share}_{\text{entry}}^{\text{TFP}} \equiv \frac{(1-\eta)^2 \text{Var}(d \ln N_t)}{\text{Var}(d \ln Z_t) + (1-\eta)^2 \text{Var}(d \ln N_t)}$, respectively.

Shutting down firms' entry To understand the role played by firms' entry, we next consider a variant of the model in which the number of firms is held fixed, and thus by construction invariant to changes in the economic environment.

To shut down firms' entry, we proceed in two steps: (i) we eliminate from the model the free-entry condition $V_t = \nu X_t$ ("firm creation technology"); and (ii) we make the incumbents live forever, such that $\delta = 0$ at all times. This eliminates two parameters, (δ, ν) , from the model. (Notice that this formulation of the model can be viewed as the limit case of a large enough sunk entry cost, which effectively deters entry in the corporate sector.) Also, we re-calibrate the parameters $\alpha = 0.12$ and $\gamma = 8.15$ to match the baseline targets of 2% for real GDP growth and 0.277 for the time spent at work, respectively.

In [Appendix C, Table C.1](#) shows the steady-state responses to tax cuts in the economy with a fixed number of firms. An immediate consequence of firms' entry shutdown is that the model now displays market-size effects in the long-run: steady-state growth depends on the level of the labor input. As a result, changes in labor income tax rates affect the steady-state growth rate of quality improvement, and thereby aggregate TFP and real GDP growth.

6.3. Level effects of income taxation

We now turn to study the dynamic adjustment of the economy in response to a *temporary* changes in tax rates. To this goal, we rely on IRFs to tax shocks as they illustrate the propagation mechanisms embodied in the model.¹² Specifically, we study the dynamic effects of a temporary change in a specific tax rate, while keeping the other tax rates fixed at their baseline steady-state values, and the government budget constraint balanced at all times through lump-sum transfers. We consider a 1 pp cut in a given tax rate, which is (in expectation) known to last for several periods. In the model, the expectations about the persistence of tax shocks are disciplined by reduced-form estimates based on autoregressive processes fitted to U.S. tax data. The dynamic responses to a tax shock are computed as deviation from the steady-state *trend* for growing variables and from the steady-state *level* for stationary variables.

Dynamic responses to tax cuts [Figs. 3](#) through [6](#) show IRFs to individual and corporate income tax cuts. Two main quantitative results stand out: (i) temporary tax cuts have a sizable permanent effect on the level of real GDP per capita, labor productivity, and TFP; and (ii) the model displays substantial internal propagation.

In response to a 1 pp cut in the labor tax rate, the labor input raises on impact, it then reverts back to the initial steady-state level mimicking the dynamics of the tax shock. The temporary expansion in equilibrium labor feeds into a temporary expansion in the aggregate demand for intermediate goods production. These transitional market-size effects stimulate aggregate R&D investment in the corporate sector and thereby spur a temporary acceleration of labor productivity and TFP growth. As a result, real GDP sluggishly raises during the transition dynamics and settles on an approximately 1.6% higher level relative to the previous trend. During the transition dynamics, firms' entry rate falls below the steady-state level, such that the number of firms in the corporate sector temporarily declines and slowly reverts back to the initial steady-state level. The response of the number of firms is U-shaped reflecting the internal propagation embodied in the model.

Next, we discuss the dynamic responses to the dividend and corporate tax cut. We lump together the discussion as the responses are indeed comparable both in terms of transmission mechanism and of sign and size of the overall effect on aggregate quantities. The adjustment dynamics in response to the dividend and corporate tax cut is rather complex, reflecting the dynamics of the tax shock itself. In the data, dividend and corporate tax shocks follow third-order AR processes, such that the reversion to the initial steady-state value need not be monotonic. In response to a 1 pp cut in the tax rate, aggregate

¹² We follow the tradition of endogenous growth theory of omitting neoclassical capital in order to keep the dynamical system low dimensional. [Bilbiie et al. \(2012\)](#) show that adding neoclassical capital to the production function of intermediate goods does not change in any significant way the propagation mechanism of temporary shocks.

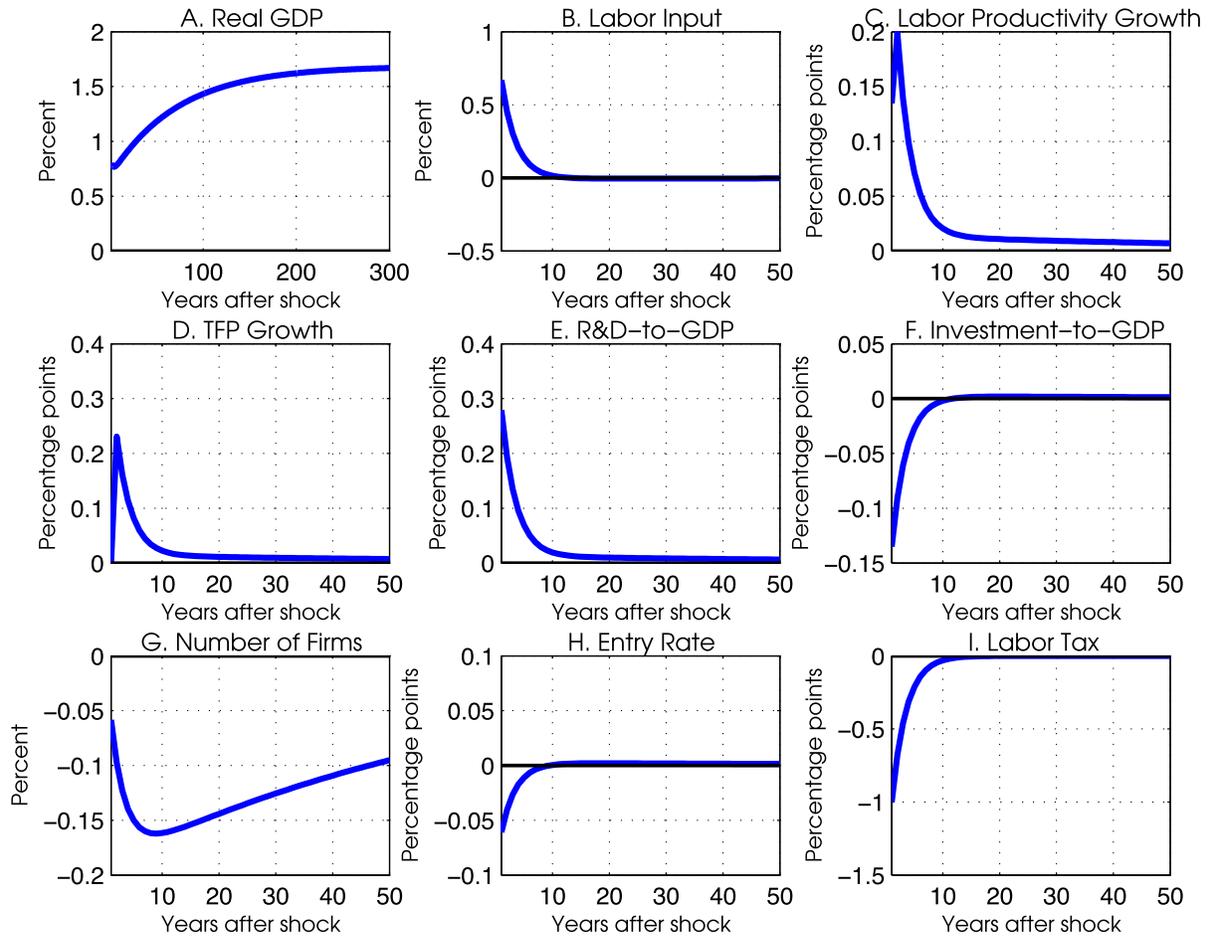


Fig. 3. IRFs to a Labor Tax Cut.

R&D investment temporarily declines below the long-run level, leading to a temporary deceleration in labor productivity and TFP growth. Such a deceleration in aggregate productivity leaves a sizable permanent effect on the level of real GDP, that settles on an approximately 5 percent lower level relative to previous trend. By contrast, in response to an equally-sized cut in the tax rate on capital gains, the economy experiences a temporary acceleration in aggregate productivity growth, that translates into a roughly 5 percent higher level of real GDP relative to previous trend.

Overall, the IRF analysis points to a quantitatively important effect of income taxation on aggregate innovation and thereby on aggregate productivity and real GDP per capita.

Robustness In Appendix C, Figs. C.1 through C.12 show additional IRFs based on several parametrizations of the model (higher firm’s exit probability and partial congestion of labor services in production) and for a variant of the model with a fixed number of firms.

6.4. Sources of aggregate productivity growth

We now turn to quantify the role played by firms’ entry and incumbents’ quality improvement in determining the dynamics of aggregate productivity growth. Specifically, we ask how much of the variation in productivity growth can be attributed to variation in the number of firms/products as opposed to variation in product quality. To this goal, we consider the expression for TFP implied by the model:

$$A_t \propto Z_t N_t^{1-\eta}, \tag{36}$$

where A_t denotes current TFP, Z_t and N_t are respectively the stock of knowledge and number of firms inherited from the previous period, and η parametrizes the degree of congestion of labor services in production. In the model, aggregate TFP is proportional to a composite of number of products and product quality. Variation over time of these two equilibrium quantities, and their dynamic interactions, determine the overall variation in TFP growth.

Note that under full congestion, the number of firms drops out of the expression for TFP in (36). As a result, all variation in TFP is due to the aggregate dynamics in product quality. Next, we provide results based on variance decompositions under partial congestion of labor services. We consider *unconditional* variance decompositions based on simulated time-series from the economy where all tax shocks are turned on.

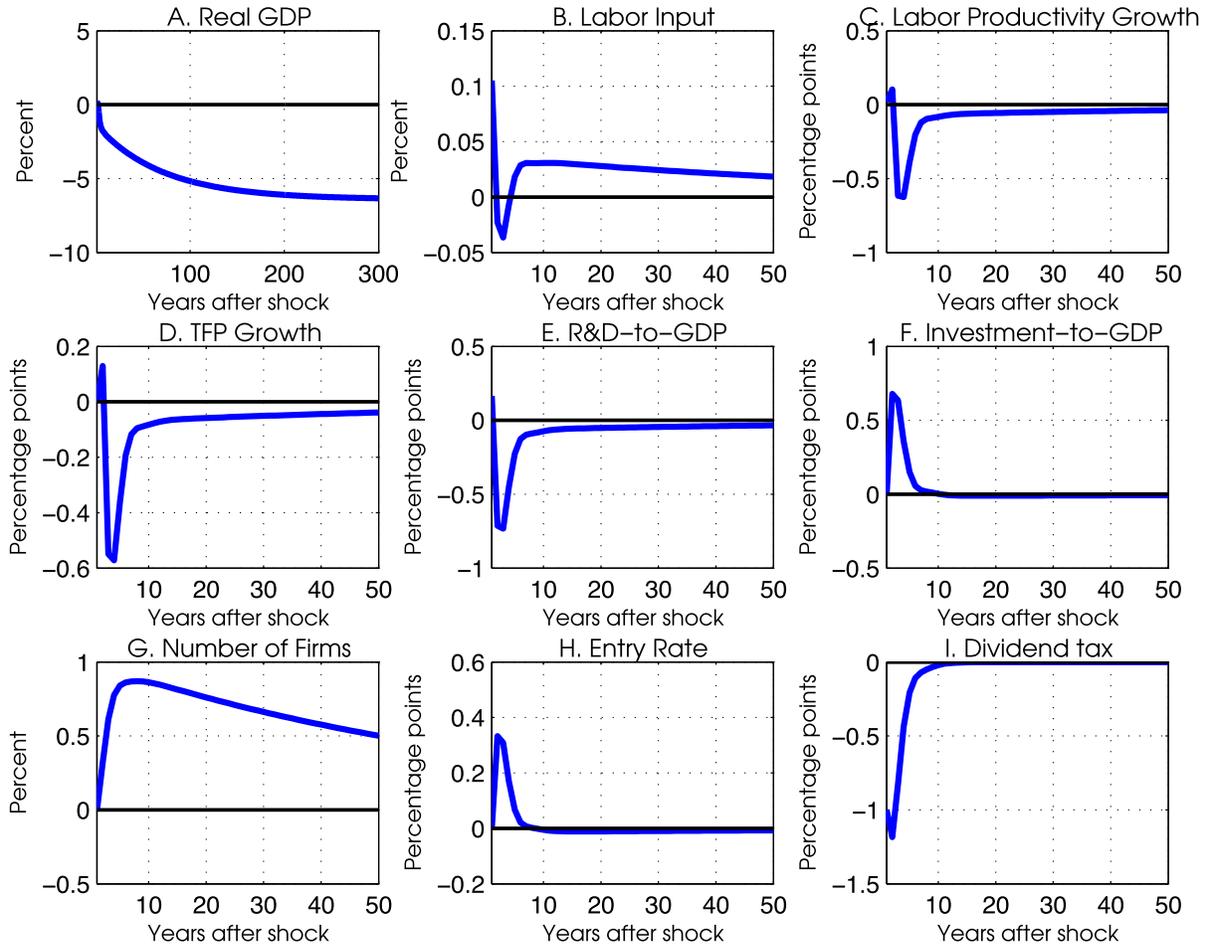


Fig. 4. IRFs to a Dividend Tax Cut.

Aggregate TFP growth Using the expression in (36), we next consider growth rates:

$$d \ln A_t = d \ln Z_t + (1 - \eta)d \ln N_t, \tag{37}$$

where $d \ln A_t \equiv \ln A_t - \ln A_{t-1}$ indicates the percentage growth rate in TFP. Then, we apply the textbook variance/covariance decomposition formula to Eq. (37), which yields $\text{Var}(d \ln A_t) = \text{Var}(d \ln Z_t) + (1 - \eta)^2 \text{Var}(d \ln N_t) + 2(1 - \eta)\text{Cov}(d \ln Z_t, d \ln N_t)$. Using such an additive decomposition, we measure the relative contribution of product quality and number of products as follows:

$$\text{share}_{\text{quality}}^{\text{TFP}} \equiv \frac{\text{Var}(d \ln Z_t)}{\text{Var}(d \ln Z_t) + (1 - \eta)^2 \text{Var}(d \ln N_t)}; \tag{38}$$

$$\text{share}_{\text{entry}}^{\text{TFP}} \equiv \frac{(1 - \eta)^2 \text{Var}(d \ln N_t)}{\text{Var}(d \ln Z_t) + (1 - \eta)^2 \text{Var}(d \ln N_t)}. \tag{39}$$

Table 4 shows the results for the variance decomposition of TFP growth. Panel A reports the theoretical variances and covariances of TFP and its components. The unconditional variance of growth in product quality and in the number of firms raises as we reduce the degree of labor congestion in production. Specifically, the variance of product quality growth raises by 12.4% from the full congestion case to partial labor congestion of 75%. The variance of growth in the number of firms raises by approximately 25.6%. Yet, the unconditional variance of aggregate TFP declines as product quality and number of firms co-move more negatively as labor congestion decreases. The covariance between product quality growth and the growth in the number of firms raises in absolute terms by nearly 33 percent. Panel B shows the relative contribution of product quality and number of firms to TFP growth.

7. Evaluation of tax reforms

In this section, we quantitatively evaluate proposals for reforming the U.S. tax system. Each proposal aims at achieving a growth rate of real GDP per capita of 3%. Our approach to evaluating tax reforms consists of four steps. First, (i) we

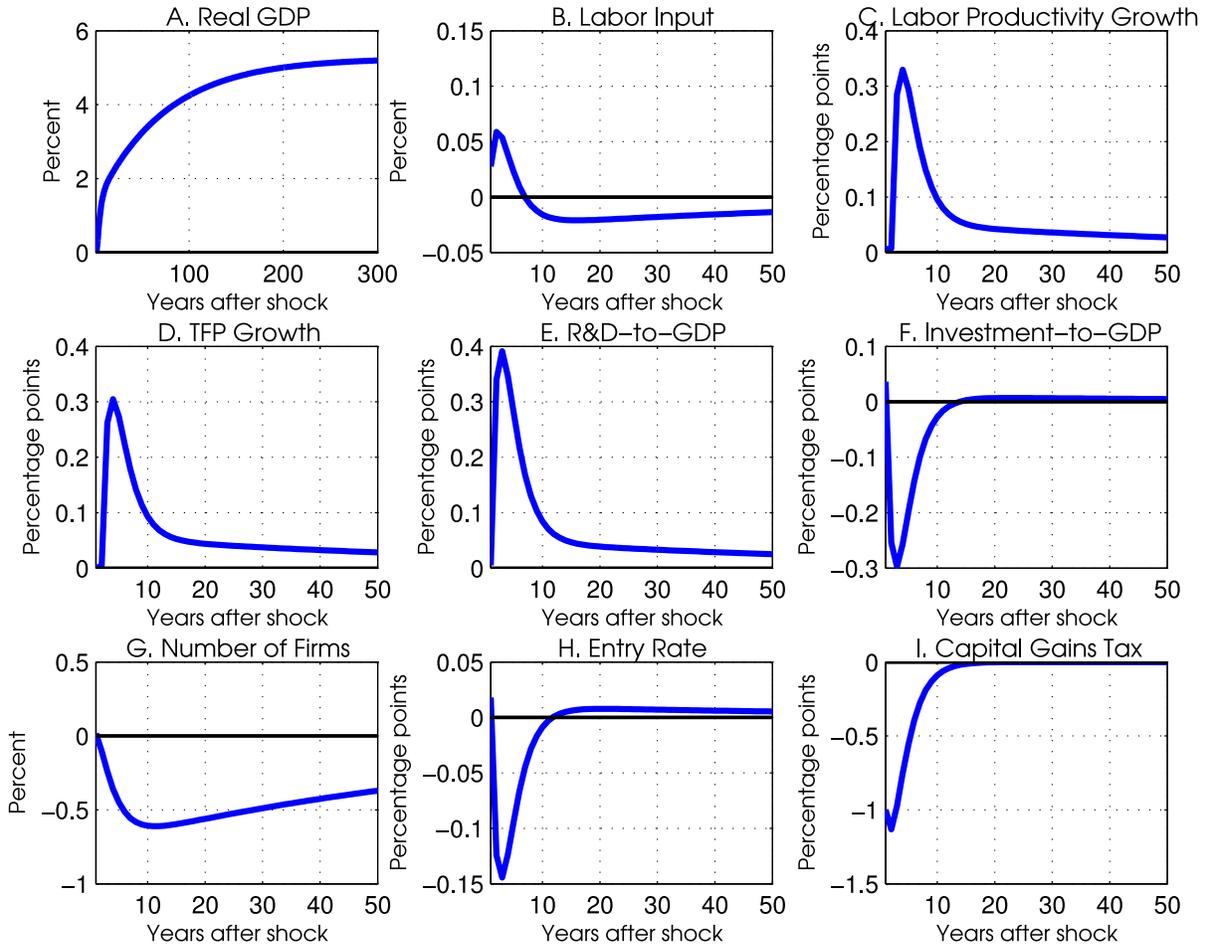


Fig. 5. IRFs to a Capital Gains Tax Cut.

discipline the model by using the parameter values calibrated to match targeted moments in U.S. annual data. In doing so, we rely on the assumption that parameters are invariant to the tax reform. (ii) We explicitly set a 3% target for real GDP growth, that the tax reform is required to achieve to be viewed as successful. (iii) We restrict the range of values that some tax instruments can take, such that the reform proposal broadly mimicks tax reforms enacted in the United States in the near past. This restriction on tax rates arguably provides realism to the counterfactual analysis: If the reform proposal was already enacted in the near past, it may as well receive enough political support to be enacted in the near future. Finally, (iv) we keep the government spending-to-GDP ratio fixed at 21% and let transfer payments to the household sector adjust to balance the government budget.

7.1. Government receipts and expenditures account

We now turn to the details of government outlays and revenues. In the model, the government budget constraint implies the receipts and expenditures account of the government sector:

$$\underbrace{\frac{G_t}{GDP_t} + \frac{\Omega_t}{GDP_t}}_{\text{current expenditures}} = \underbrace{\tau_t^c \left(\frac{C_t}{GDP_t} \right) + \tau_t^l \left(\frac{w_t L_t}{GDP_t} \right) + \tau_t^d \left(\frac{\tilde{D}_t}{GDP_t} \right) + \tau_t^v \left(\frac{\Delta \tilde{V}_t}{GDP_t} \right) + \tau_t^\pi \left(\frac{\tilde{\Pi}_t}{GDP_t} \right)}_{\text{current tax receipts}}. \tag{40}$$

Expression (40) reminds us that tax receipts inherently depend on both tax rates and the tax base. And that the tax base consists of several sources of taxable income: labor income, $w_t L_t$, dividends, \tilde{D}_t , and capital gains, $\Delta \tilde{V}_t$, in the household sector; and operating profits, $\tilde{\Pi}_t$, in the corporate sector. Hence, the quantitative impact of a given tax reform ultimately depends on both the mix of tax instruments, and the short- and long-term taxable income elasticities.

In implementing a tax reform proposal, we maintain the government spending-to-GDP ratio (GRATIO) fixed at $\bar{g} = 20.8\%$, as in our baseline calibration in Section 6. Note that in the United States, the GRATIO has been fluctuating about a 21% level since the early-1980s, whereas average effective tax rates have experienced substantial variation over the same period. It would then seem plausible to keep the size of the government sector (as measured by the GRATIO) invariant to the specific

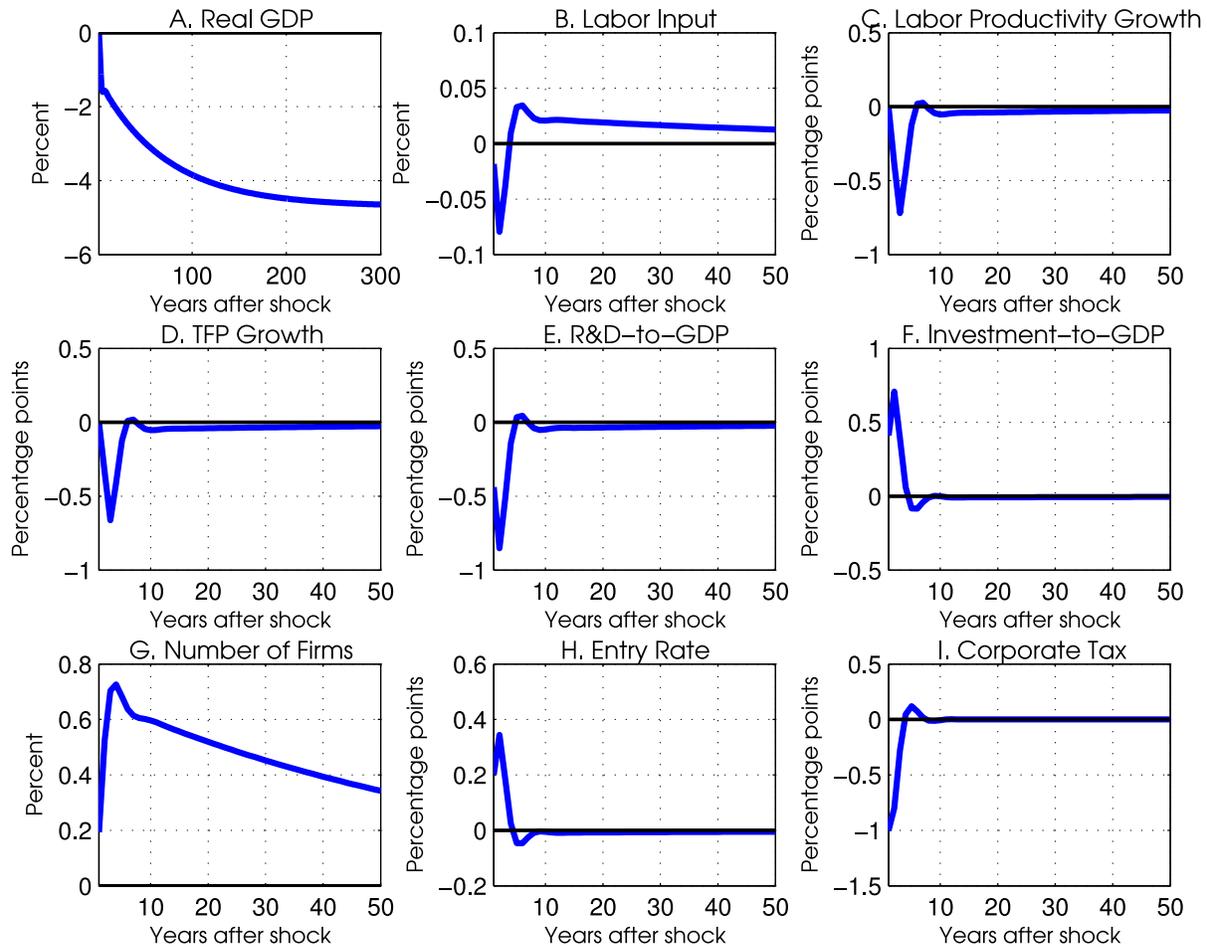


Fig. 6. IRFs to a Corporate Tax Cut.

tax reform implemented. Also, the implementation of the proposals forces transfers to bear all the adjustment needed to balance the government budget.

7.2. Flat individual income tax

We stress that the tax reforms implemented in the model, by construction, achieve the 3% target for real GDP per capita growth in the long-run. In evaluating the impact of a tax reform proposal, then, we rely on two metrics. First, we look at the implied labor and profit income shares of GDP. Historically, the implications of tax policy for functional income distribution have been key to arguments either in support or against tax reform proposals. Second, we compute the implied share of private consumption in GDP as a simple measure of welfare gains/losses implied by the reform.

Tax Reform Act of 1986 revisited The salient feature of the tax reform proposal is the simplification of the individual income tax. In this respect, the reform shares key features of the Tax Reform Act of 1986 (TRA86). The proposal consists of three components:

- (i) Flat tax rate on individual income (earnings, dividends, and capital gains);
- (ii) Keep the government spending-to-GDP ratio at 21% ;
- (iii) Adjust lump-sum transfers to balance the government budget.

We acknowledge that TRA86 was not designed to keep the size of the government sector fixed at the value of year 1986. However, the government spending-to-GDP ratio remained nearly constant at 21% over the 10-year period 1980–1990 around the reform.

Isogrowth tax frontier The equilibrium of the model implies that the 3% target for real GDP growth is achieved by several combinations of individual and corporate income tax rates. These different combinations of tax rates form an *isogrowth tax frontier* (ITF).

In Fig. 7, panel A shows the ITF: All feasible combinations of individual income tax rates τ^y on the x -axis and corporate income tax rates τ^π on the y -axis, that achieve the 3% long-term growth target in real GDP per capita. The ITF is

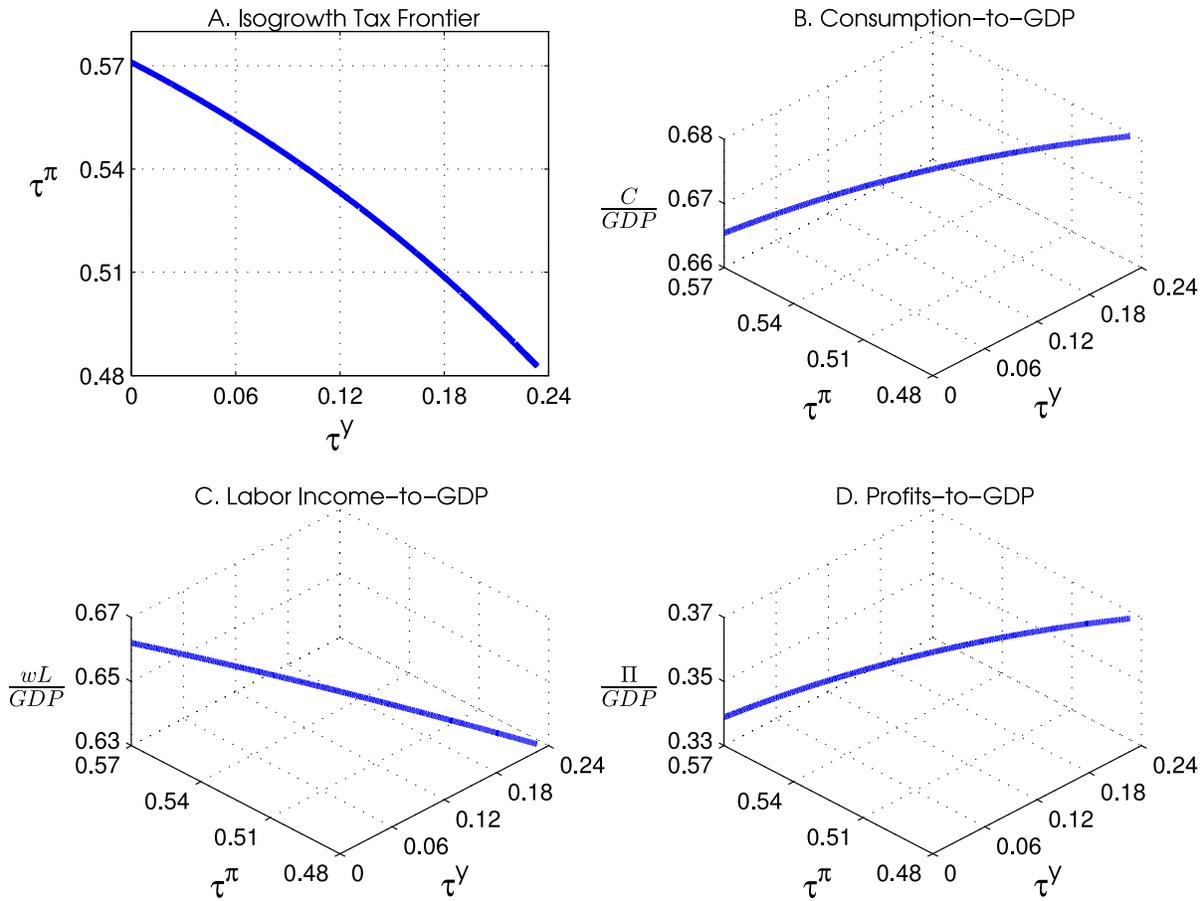


Fig. 7. Flat Individual Income Tax Notes: Panel A shows the combinations of individual income tax rates τ^y on the x-axis and corporate income tax rates τ^π on the y-axis that achieve the 3 percent target for real GDP growth. Panel B through D show the implied share of private consumption in GDP, and the labor and profit income shares of GDP, respectively. The government budget is balanced by lump-sum transfers. See Section 6.1 for details on the baseline parametrization of the model.

downward-sloping implying a trade-off between individual and corporate income taxation. Higher taxation of corporate income mandates lower taxation of individual income. Panel B through D show the share of private consumption in GDP and the labor and profit income shares of GDP along the ITF.

8. Conclusion

In this paper, we develop a quantitative theory of innovation-led growth. Prominent feature of the theory is the interplay between product and quality innovation: entrant firms create new products whereas incumbents improve own existing products. Market structure is endogenous in that firm size and the mass of firms are jointly determined in equilibrium. We restrict the theory to fit annual data for the post-war U.S. economy. In addition, the model embodies key features of the U.S. government sector: (i) an individual income tax with differential treatment of labor income, dividends, and capital gains; (ii) a corporate income tax; (iii) a consumption tax; and (iv) government purchases.

Overall, our results indicate that endogenous movements in aggregate productivity and the dynamic adjustment in market structure are quantitatively important channels for the transmission mechanism of tax policy. While studying optimal tax policy was beyond the scope of this paper, we view the normative implications of our results as an important and promising topic for future research. Indeed, while there is an extensive literature on optimal tax policy in the context of the neoclassical growth model, to the best of our knowledge, research on optimal taxes in models with endogenous market structure and innovation remains limited.

Appendix A. Data

In this appendix, we provide details on data definitions and sources, and describe how we construct average effective and marginal tax rates. The main source of data is the national income and product account (NIPA) tables by the Bureau of Economic Analysis (BEA). All data items are indexed by table and line numbers. Our approach of calculating average effective

tax rates closely follows that of [Mendoza et al. \(1994\)](#). We aggregate all levels of the government (federal, state and local) into one general government sector.

The **average corporate income tax rate (ACITR)** is defined as $ACITR \equiv CT/CP$, where CT is federal, state and local taxes on corporate income (NIPA Table 3.1 line 5), excluding Federal Reserve banks (NIPA Table 3.2 line 8), and CP is the **corporate income tax base**, that consists of corporate profits (NIPA Table 1.12 line 13), excluding Federal Reserve banks profits (NIPA Tables 6.16 A-B-C-D line 11). [Mertens and Ravn \(2013\)](#) follow a similar methodology but they restrict their calculations to the federal government.

The **average consumption tax rate (ACTR)** is defined as

$$ACTR \equiv \frac{TPI - PRT}{PCE - (TPI - PRT)}, \quad (A.1)$$

where TPI is **taxes on production and imports** (NIPA Table 3.1 line 4), PRT is **property taxes** (NIPA Table 3.3 line 8), and PCE is **personal consumption expenditures** on durables, nondurables, and services (NIPA Table 1.1.5 line 2).¹³

The **average personal income tax rate (APITR)** is defined as

$$APITR \equiv \frac{PIT}{WSA + PRI/2 + CI}, \quad (A.2)$$

where PIT is **personal income taxes**, that consists of federal personal income taxes (NIPA Table 3.2 line 3) and state and local personal income taxes (NIPA Table 3.3 line 4), WSA is **wage and salaries** (NIPA Table 1.12 line 3), PRI is **proprietors' income** (NIPA Table 1.12 line 9), $CI \equiv PRI/2 + RI + DI + NI$ is **capital income**, RI is **rental income** (NIPA Table 1.12 line 12), DI is **net dividends** (NIPA Table 1.12 line 16), and NI is **net interest** (NIPA Table 1.12 line 18). As discussed in [Joines \(1981\)](#), the imputation of proprietor's income to capital and labor income is somewhat arbitrary. We here follow [Jones \(2002\)](#) and split proprietor's income evenly between capital and labor income.

The **average labor income tax rate (ALITR)** is then defined as

$$ALITR \equiv \frac{APITR \times (WSA + PRI/2) + CSI}{CEM + PRI/2}, \quad (A.3)$$

where CSI is **contributions for government social insurance** (NIPA Table 3.1 line 7), and CEM is **compensation of employees** (NIPA Table 1.12 line 2). The calculations of APITR and ALITR are based on [Jones \(2002\)](#). [Leeper et al. \(2010\)](#) follow a similar methodology but they restrict their calculations to the federal government.

The **average marginal dividend income tax rate (AMDITR)** is from [Poterba \(2004, p. 172, Table 1\)](#). AMDITRs after 1960 are based on tabulations from the NBER TAXSIM model, and on data from the U.S. Department of the Treasury, Statistics of Income, for earlier years. AMDITR includes the federal marginal income tax rate plus an estimate of the state marginal income tax rate, net of federal income tax deductibility. The **average capital gains tax rate (ACGTR)** is based on data from the U.S. Department of the Treasury, Office of Tax Analysis, and available at <https://www.treasury.gov/resource-center/tax-policy/Pages/Tax-Analysis-and-Research.aspx>.

The **government spending to GDP ratio (GRATIO)** is defined as $GRATIO \equiv GOV/GDP$, where GOV is **government consumption expenditures and gross investment**, that includes federal (national defense plus nondefense), state and local government level (NIPA Table 1.1.5 line 22) and GDP is **gross domestic product** (NIPA Table 1.1.5 line 1). The **tax revenues to GDP ratio (TRATIO)** is calculated as $TRATIO \equiv TR/GDP$, where $TR \equiv PCT + TPI + CT + CSI$, and PCT is federal, state and local **personal current taxes** (NIPA Table 3.1 line 3). [Blanchard and Perotti \(2002\)](#) and [Mertens and Ravn \(2014\)](#), among others, follow a similar methodology but they restrict their calculations to the federal government. Consumption expenditures (durables, nondurables, and services) to GDP ratio (CRATIO) is calculated as PCE/GDP , where PCE is **personal consumption expenditures** (NIPA Table 1.1.5 line 2).

Appendix B. Model derivations

In this appendix, we first provide details on the derivation of the equations presented in the main text of the paper and then discuss how we solve the model.

B1. Cum-dividend value of the firm

In symmetric equilibrium, after-tax gross return to the market portfolio is $\tilde{R}_t^a = (1 - \delta)R_{i,t}^a$, where $R_{i,t}^a = [(1 - \tau_t^d)D_{i,t} + (1 - \tau_t^v)V_{i,t} + \tau_t^v V_{i,t-1}]/V_{i,t-1}$ and $V_{i,t}$ denotes the value of the firm after dividends payout (ex-dividend value). The asset pricing equation for corporate equity shares is

$$1 = \mathbb{E}_t[(1 - \delta)M_{t,t+1}R_{i,t+1}^a], \quad \text{with} \quad M_{t,t+1} \equiv \beta \frac{u_c(c_{t+1}, l_{t+1})}{u_c(c_t, l_t)} \left(\frac{1 + \tau_t^c}{1 + \tau_{t+1}^c} \right). \quad (B.1)$$

¹³ Taxes on production and imports consists of federal excise taxes and custom duties and of state and local sales taxes, property taxes (including residential real estate taxes), motor vehicle licenses, severance taxes, special assessments, and other taxes.

Using the expression for $R_{i,t}^a$, the asset pricing equations for corporate equity shares in period t and $t + 1$ are, respectively:

$$V_{i,t} = \frac{\mathbb{E}_t \left\{ (1 - \delta) M_{t,t+1} \left[(1 - \tau_{t+1}^d) D_{i,t+1} + (1 - \tau_{t+1}^v) V_{i,t+1} \right] \right\}}{1 - \mathbb{E}_t \left[(1 - \delta) M_{t,t+1} \tau_{t+1}^v \right]}, \quad (\text{B.2})$$

$$V_{i,t+1} = \frac{\mathbb{E}_{t+1} \left\{ (1 - \delta) M_{t+1,t+2} \left[(1 - \tau_{t+2}^d) D_{i,t+2} + (1 - \tau_{t+2}^v) V_{i,t+2} \right] \right\}}{1 - \mathbb{E}_{t+1} \left[(1 - \delta) M_{t+1,t+2} \tau_{t+2}^v \right]}. \quad (\text{B.3})$$

Iterating Eq. (B.2) one period forward and using (B.3) yields:

$$V_{i,t} = \frac{1}{(1 - \tau_t^v)} \mathbb{E}_t \left[\frac{(1 - \delta) M_{t,t+1} (1 - \tau_t^v)}{1 - \mathbb{E}_t \left[(1 - \delta) M_{t,t+1} \tau_{t+1}^v \right]} (1 - \tau_{t+1}^d) D_{i,t+1} \right] \quad (\text{B.4})$$

$$+ \frac{1}{(1 - \tau_t^v)} \mathbb{E}_t \left[\frac{(1 - \delta) M_{t,t+1} (1 - \tau_t^v)}{1 - \mathbb{E}_t \left[(1 - \delta) M_{t,t+1} \tau_{t+1}^v \right]} \times \frac{(1 - \delta) M_{t+1,t+2} (1 - \tau_{t+1}^v)}{1 - \mathbb{E}_{t+1} \left[(1 - \delta) M_{t+1,t+2} \tau_{t+2}^v \right]} (1 - \tau_{t+2}^d) D_{i,t+2} \right] \quad (\text{B.5})$$

$$+ \mathbb{E}_t \left[\frac{(1 - \delta) M_{t,t+1} (1 - \tau_{t+1}^v) \mathbb{E}_{t+1} \left[(1 - \delta) M_{t+1,t+2} (1 - \tau_{t+2}^v) V_{i,t+2} \right]}{1 - \mathbb{E}_t \left[(1 - \delta) M_{t,t+1} \tau_{t+1}^v \right]} \times \frac{1}{1 - \mathbb{E}_{t+1} \left[(1 - \delta) M_{t+1,t+2} \tau_{t+2}^v \right]} \right]. \quad (\text{B.6})$$

Continuing with forward iteration, and using the standard transversality condition on the terminal value of the firm, yields:

$$V_{i,t} = \left(\frac{1}{1 - \tau_t^v} \right) \mathbb{E}_t \sum_{j=1}^{\infty} \left(\prod_{k=1}^j \tilde{M}_{t+k-1,t+k} \right) (1 - \tau_{t+j}^d) D_{i,t+j}, \quad (\text{B.7})$$

where the factor $\tilde{M}_{t,t+k}$ is defined as

$$\tilde{M}_{t+k-1,t+k} \equiv \frac{(1 - \delta) M_{t+k-1,t+k} (1 - \tau_{t+k-1}^v)}{1 - \mathbb{E}_{t+k-1} \left[(1 - \delta) M_{t+k-1,t+k} \tau_{t+k}^v \right]}, \quad (\text{B.8})$$

and $M_{t+k-1,t+k}$ is the consumption-tax-adjusted SDF, as defined in (B.1). Next, using the ex-dividend value of the firm in Eq. (B.7), the incumbent intermediate producer maximizes the following cum-dividend firm value:

$$(1 - \tau_t^d) D_{i,t} + \mathbb{E}_t \sum_{j=1}^{\infty} \left(\prod_{k=1}^j \tilde{M}_{t+k-1,t+k} \right) (1 - \tau_{t+j}^d) D_{i,t+j} + \tau_t^v V_{i,t-1}. \quad (\text{B.9})$$

Note that in the expression (B.9), the last term $\tau_t^v V_{i,t-1}$ on the right-hand side is irrelevant for the firm's value maximization problem, as it is independent of current firm's choices.

B2. Equilibrium conditions and solution method

Here we list the equilibrium conditions that we use to compute the equilibrium of the model. Specifically, we consider a first-order log-linear approximation of the equilibrium around the non-stochastic steady state of the model.

The list of equilibrium conditions is:

$$C_t + G_t + \tilde{N}_{t-1} I_t + \nu X_t \left(\frac{\tilde{N}_t}{1 - \delta} - \tilde{N}_{t-1} \right) + \tilde{N}_{t-1} X_t + \phi \tilde{N}_{t-1} Z_{t-1} = Y_t, \quad (\text{B.10})$$

$$Y_t = \theta \frac{2\theta}{1-\theta} L_t Z_{t-1} \tilde{N}_{t-1}^{1-\eta}, \quad (\text{B.11})$$

$$\gamma L_t^\theta C_t = \frac{(1 - \tau_t^l)}{(1 + \tau_t^c)} w_t, \quad (\text{B.12})$$

$$1 = \mathbb{E}_t \left[M_{t,t+1} R_t^b \right], \quad \text{with} \quad M_{t,t+1} \equiv \beta \frac{C_t}{C_{t+1}} \left(\frac{1 + \tau_t^c}{1 + \tau_{t+1}^c} \right), \quad (\text{B.13})$$

$$1 = \mathbb{E}_t \left[M_{t,t+1} \tilde{R}_{t+1}^a \right], \quad (\text{B.14})$$

$$\tilde{R}_{t+1}^a \equiv (1 - \delta) \left[(1 - \tau_{t+1}^d) \frac{D_{t+1}}{V_t} + (1 - \tau_{t+1}^v) \left(\frac{V_{t+1} - V_t}{V_t} \right) + 1 \right], \quad (\text{B.15})$$

$$w_t = (1 - \theta)\theta^{\frac{2\theta}{1-\theta}} Z_{t-1} \tilde{N}_{t-1}^{1-\eta}, \quad (\text{B.16})$$

$$\tilde{N}_{t-1}^\eta X_t = \theta^{\frac{2}{1-\theta}} Z_{t-1} L_t, \quad (\text{B.17})$$

$$Z_t = Z_{t-1} + I_t, \quad (\text{B.18})$$

$$V_t = \nu X_t, \quad (\text{B.19})$$

$$1 = \mathbb{E}_t \left\{ (1 - \delta) M_{t,t+1} \left[\frac{(1 - \tau_t^\nu)(1 - \tau_{t+1}^d)(1 - \tau_{t+1}^\pi)}{(1 - \tau_t^d)(1 - \tau_t^\pi)} \left[\left(\frac{1 - \theta}{\theta} \right) \frac{\alpha X_{t+1}}{Z_t} + 1 \right] + \tau_{t+1}^\nu \right] \right\}, \quad (\text{B.20})$$

$$F_t = \left(\frac{1 - \theta}{\theta} \right) \theta^{\frac{2}{1-\theta}} \left(\frac{L_t}{\tilde{N}_{t-1}^\eta} \right) Z_{t-1} - \phi Z_{t-1}, \quad (\text{B.21})$$

$$D_t = (1 - \tau_t^\pi)(F_t - I_t), \quad (\text{B.22})$$

$$G_t + \Omega_t = T_t, \quad (\text{B.23})$$

$$G_t = g_t [Y_t - \tilde{N}_{t-1}(X_t + \phi Z_{t-1})], \quad (\text{B.24})$$

$$T_t = \tau_t^c C_t + \tau_t^l w_t L_t + \tilde{N}_{t-1} [\tau_t^d D_t + \tau_t^\nu (V_t - V_{t-1}) + \tau_t^\pi (F_t - I_t)]. \quad (\text{B.25})$$

To compute the approximate equilibrium of the model around the steady state, in the system (B.10)–(B.25), we divide the variables with positive steady-state growth by Z_{t-1} . For example, $\hat{c}_t \equiv C_t/Z_{t-1}$. Variables with hats indicate series detrended by the quality index.

B3. Rate of return to equity and R&D investment schedules

Here we provide details on the derivation of the rate of return to incumbents' investment (RRI) and the rate of return to entrants' investment (RRE), or analogously to firm creation investment. We interpret RRI and RRE as investment schedules as represented in (i_t, r_{t+1}^a) space, where $i_t \equiv I_t/Z_{t-1}$ is the current R&D investment rate and r_{t+1}^a is the rate of return to corporate equity one period ahead.

Rate of return to incumbents' investment (RRI) Dropping expectations and using the household's first-order intertemporal condition for equity in (B.14), it yields:

$$\frac{1}{\tilde{R}_{t+1}^a} = M_{t,t+1}. \quad (\text{B.26})$$

Replacing the relationship in (B.26) into the first-order intertemporal condition for R&D investment in (B.20), and dropping expectations, it yields:

$$R_{t+1}^a = \frac{(1 - \tau_t^\nu)(1 - \tau_{t+1}^d)^2}{(1 - \tau_t^d)^2} \left[\left(\frac{1 - \theta}{\theta} \right) \alpha x_{t+1} + 1 \right] + \tau_{t+1}^\nu, \quad (\text{B.27})$$

where $R_{t+1}^a \equiv 1 + r_{t+1}^a$ is the gross rate of return to corporate equity and $x_{t+1} \equiv X_{t+1}/Z_t$ is the quality-adjusted firm size. In Eq. (B.27), we use the restriction $\tau_t^d = \tau_t^\pi$ for all $t \geq 0$ to simplify notation, but it is inessential for the derivations here. We refer to the expression in Eq. (B.27) as the incumbents' investment schedule (RRI schedule). We stress that the RRI schedule is a flat line in the (i_t, r_{t+1}^a) space. This reflects the "bang-bang" property of the investment problem at the individual firm-level.

Rate of return to entrants' investment (RRE) The expression in (B.15) yields the after-tax rate of return to corporate equity in symmetric equilibrium:

$$r_{t+1}^a = (1 - \tau_{t+1}^d) \frac{D_{t+1}}{V_t} + (1 - \tau_{t+1}^\nu) \left(\frac{V_{t+1} - V_t}{V_t} \right). \quad (\text{B.28})$$

Next, using the expression for dividends $D_t = (1 - \tau_t^\pi)(F_t - I_t)$ in (B.22), it yields:

$$r_{t+1}^a = (1 - \tau_{t+1}^d)^2 \left(\frac{F_{t+1} - I_{t+1}}{V_t} \right) + (1 - \tau_{t+1}^\nu) \left(\frac{V_{t+1} - V_t}{V_t} \right). \quad (\text{B.29})$$

In Eq. (B.29), we use again the restriction $\tau_t^d = \tau_t^\pi$ for all $t \geq 0$ to simplify notation, but it is inessential for the derivations here. Using the free-entry condition $V_t = \nu X_t$ in (B.19), and multiplying and dividing by Z_t the first two terms on the right-hand side of (B.29), it yields:

$$r_{t+1}^a = (1 - \tau_{t+1}^d)^2 \left[\frac{F_{t+1}/Z_t - I_{t+1}/Z_t}{\nu X_t/Z_t} \right] + (1 - \tau_{t+1}^\nu) \left[\frac{X_{t+1}/Z_t - X_t/Z_t}{X_t/Z_t} \right]. \tag{B.30}$$

Using the expression for the gross cash flow $F_t = (p_t - 1)X_t - \phi Z_{t-1}$, jointly with the constant markup pricing rule $p_t = 1/\theta$, it yields the schedule linking the rate of return to equity one period ahead, r_{t+1}^a , to the current R&D investment rate, i_t :

$$r_{t+1}^a = (1 - \tau_{t+1}^d)^2 \left[\frac{\left(\frac{1-\theta}{\theta}\right)X_{t+1} - \phi - i_{t+1}}{\nu X_t} \right] (1 + i_t) + (1 - \tau_{t+1}^\nu) \left[\frac{X_{t+1}(1 + i_t) - 1}{X_t} - 1 \right]. \tag{B.31}$$

We refer to the expression in Eq. (B.31) as the entrants' investment schedule (RRE schedule). We stress that the RRE schedule is upward sloping in the (i_t, r_{t+1}^a) space. The intersection of the RRI and RRE schedules describes the investment rate and the rate of return to equity as implied by the no-arbitrage condition between incumbents' investment and firm creation investment.

B4. Production innovation and quality innovation locus

Here we provide details on the derivation of the product (PI) and quality innovation (QI) locus. The PI and QI locus jointly determine the gross growth rate, $z_t \equiv Z_t/Z_{t-1}$, and the quality-adjusted firm size, $x_t \equiv X_t/Z_{t-1}$, in the steady state of the model with constant tax rates. In steady state, Eq. (B.27) reduces to

$$R^a = (1 - \tau^\nu) \left[\left(\frac{1 - \theta}{\theta} \right) \alpha x + 1 \right] + \tau^\nu. \tag{B.32}$$

Next, using the relationship in (B.26), and the expression for the effective SDF in (B.13), and realizing that in the steady state aggregate consumption grows at the same rate of quality improvement, it yields the QI locus in the (x, z) space:

$$z = \beta(1 - \delta) \left\{ (1 - \tau^\nu) \left[\left(\frac{1 - \theta}{\theta} \right) \alpha x + 1 \right] + \tau^\nu \right\}. \tag{B.33}$$

Next, in the steady state, Eq. (B.31) reduces to

$$R^a = (1 - \tau^d)^2 \left[\left(\frac{1 - \theta}{\nu\theta} \right) - \frac{\phi + i}{\nu x} \right] (1 + i) + (1 - \tau^\nu) i + 1. \tag{B.34}$$

Again, using the relationship in (B.26), and the steady-state expression for the effective SDF in (B.13), and $z = 1 + i$, it yields the PI locus in the (x, z) space:

$$z = \beta(1 - \delta) \left\{ (1 - \tau^d)^2 \left[\left(\frac{1 - \theta}{\nu\theta} \right) - \frac{\phi + z - 1}{\nu x} \right] z + (1 - \tau^\nu) z + \tau^\nu \right\}. \tag{B.35}$$

B5. National income and product accounts

Here we provide details on the calculation of gross domestic product (GDP) in the model in relation to the U.S. national income and product accounts (NIPA). In NIPA's accounting methodology, GDP can be measured as: (i) the sum of the value added generated at each stage of production ("value-added approach"); (ii) the sum of goods and services sold to final users ("expenditures approach"); and (iii) the sum of income payments and other costs incurred in the production of goods and services ("income approach"). Next, we calculate GDP in the model according to these three different approaches.

Value-added approach According to the value-added approach, GDP equals the sum of the valued added generated at each stage of production. In the product side of the model accounts, there are two stages of production: (i) production of the final good in the final good sector, and (ii) production of the intermediate good in the corporate sector. Value-added (VA) in the final good sector is $VA_t^{FS} = Y_t - p_t \tilde{N}_{t-1} X_t$, where Y_t is sales of final goods and $p_t \tilde{N}_{t-1} X_t$ is the value of intermediate inputs used up in production. (Note that we take the final good as the numeraire, whose price is then normalized to one.) Value-added in the corporate sector is $VA_t^{CS} = p_t \tilde{N}_{t-1} X_t - \tilde{N}_{t-1} X_t - \phi Z_{t-1}$, where $p_t \tilde{N}_{t-1} X_t$ is sales of intermediate goods and $\tilde{N}_{t-1} X_t + \phi Z_{t-1}$ is production costs. The production technology in the corporate sector requires one unit of final good per unit of intermediate good produced, such that $\tilde{N}_{t-1} X_t$ is intermediate expenses on goods used up as inputs into the production of intermediate goods. Note that we treat R&D expenditures in the corporate sector as fixed assets, which is consistent with the current NIPA approach. As a result, in the model, $GDP_t = VA_t^{FS} + VA_t^{CS} = Y_t - \tilde{N}_{t-1} X_t - \phi Z_{t-1}$.

Expenditures approach According to the expenditures approach, GDP equals the sum of (i) *personal consumption expenditures*, (ii) *gross private fixed investment*, (iii) *change in private inventories*, (iv) *net exports of goods and services*, (v) *government consumption expenditures and gross investment*. (Note that, in the model, change in private inventories and net exports of

goods and services are identically zero.) Consistently with the current NIPA approach, we treat R&D expenditures as fixed assets, such that R&D is recorded as gross private fixed investment. Also, according to the System of National Accounts, 2008, (2008 SNA), R&D is defined as “creative work undertaken on a systematic basis to increase the stock of knowledge, and use of this stock of knowledge for the purpose of discovering or developing new products, including improved versions or qualities of existing products, or discovering or developing new or more efficient processes of production.” (See <http://unstats.un.org/unsd/nationalaccount/docs/SNA2008.pdf> for further details on the treatment of R&D in national accounts.) We classify investment in quality improvements, $\tilde{N}_{t-1}I_t$, as R&D expenditures, and sunk entry costs, $\nu X_t \Delta_{N,t}$, as private fixed investment. As a result, in the model, $GDP_t = C_t + G_t + \tilde{N}_{t-1}I_t + \nu X_t \Delta_{N,t}$, where C_t and G_t are personal and government consumption expenditures, respectively, and $\tilde{N}_{t-1}I_t + \nu X_t \Delta_{N,t}$ is gross private fixed investment.

Income approach According to the income approach, GDP equals the sum of income payments and other costs incurred in the production of goods and services. In the model, labor income represents a constant share of gross output: $w_t L_t = (1 - \theta)Y_t$. The recognition of R&D expenditures as gross private fixed investment also affects the income side of the accounts (both in the model and NIPA data), as gross domestic income (GDI) equals gross domestic product (GDP). According to the current NIPA approach, R&D expenditures are entirely attributed to corporate profits. Thus, in the income side of the model accounts, we calculate corporate profits as $\tilde{N}_{t-1}\Pi_t + \tilde{N}_{t-1}I_t$, where Π_t is operating profit. Note that, in the model, $p_t \tilde{N}_{t-1}X_t = \theta Y_t$. As a result, in the model, $GDI_t \equiv GDP_t = Y_t - \tilde{N}_{t-1}X_t - \phi Z_{t-1}$.

Appendix C. Additional results

In this appendix, we provide additional results based on IRFs to tax shocks under alternative parameterizations of the model, and steady-state responses to tax cuts in the variant of the model with a fixed number of firms.

C1. IRFs to Tax Shocks with Higher Firm’s Exit Probability

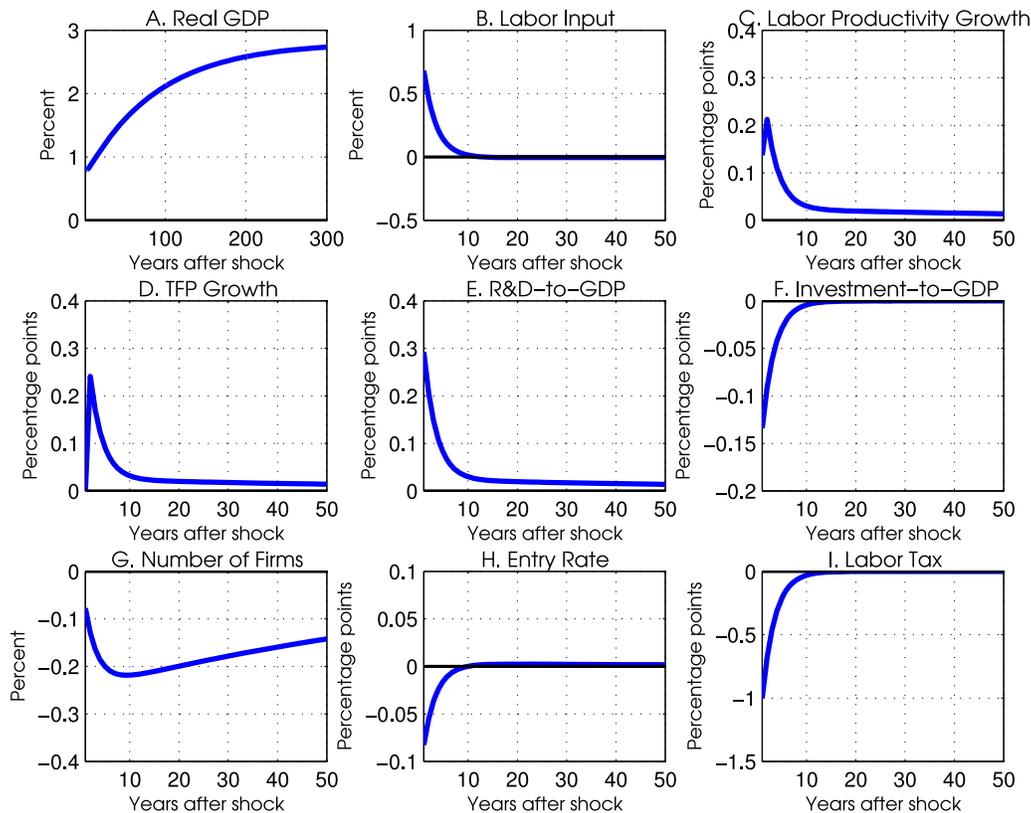


Fig. C.1. IRFs to a Labor Tax Cut *Notes:* Firm’s exit probability of 6.18 percent. See Section 6.1 for details on the baseline parameterization of the model.

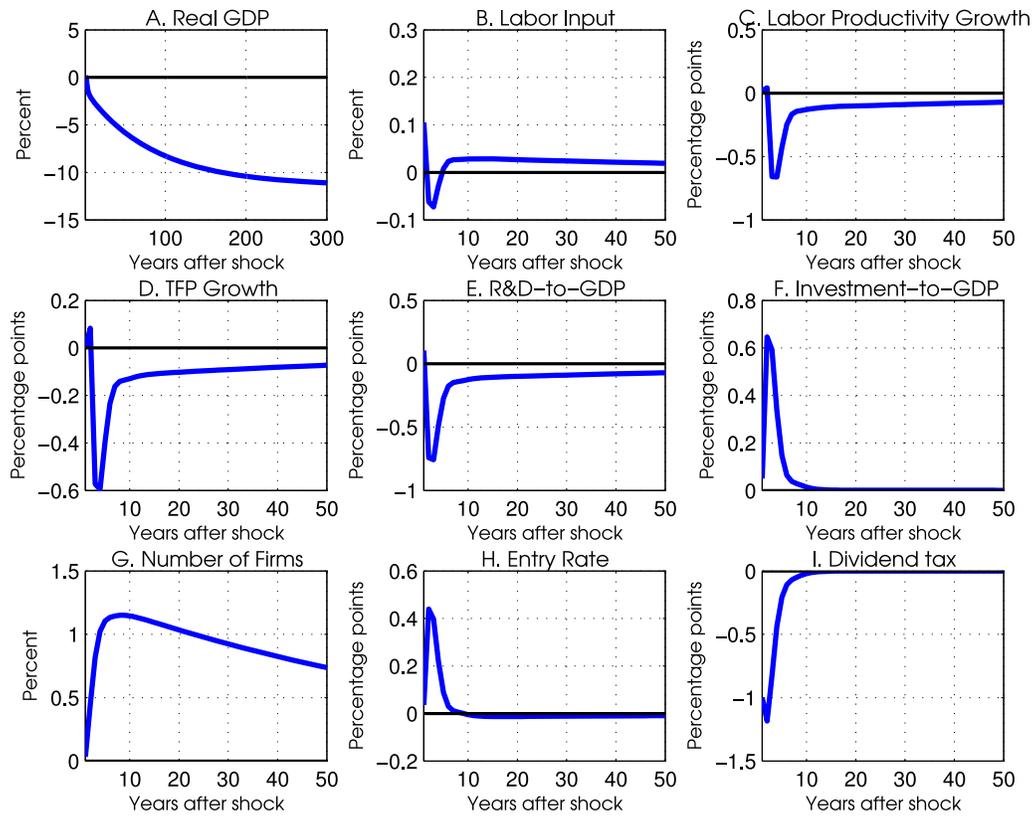


Fig. C.2. IRFs to a Dividend Tax Cut Notes: Firm’s exit probability of 6.18 percent. See Section 6.1 for details on the baseline parameterization of the model.

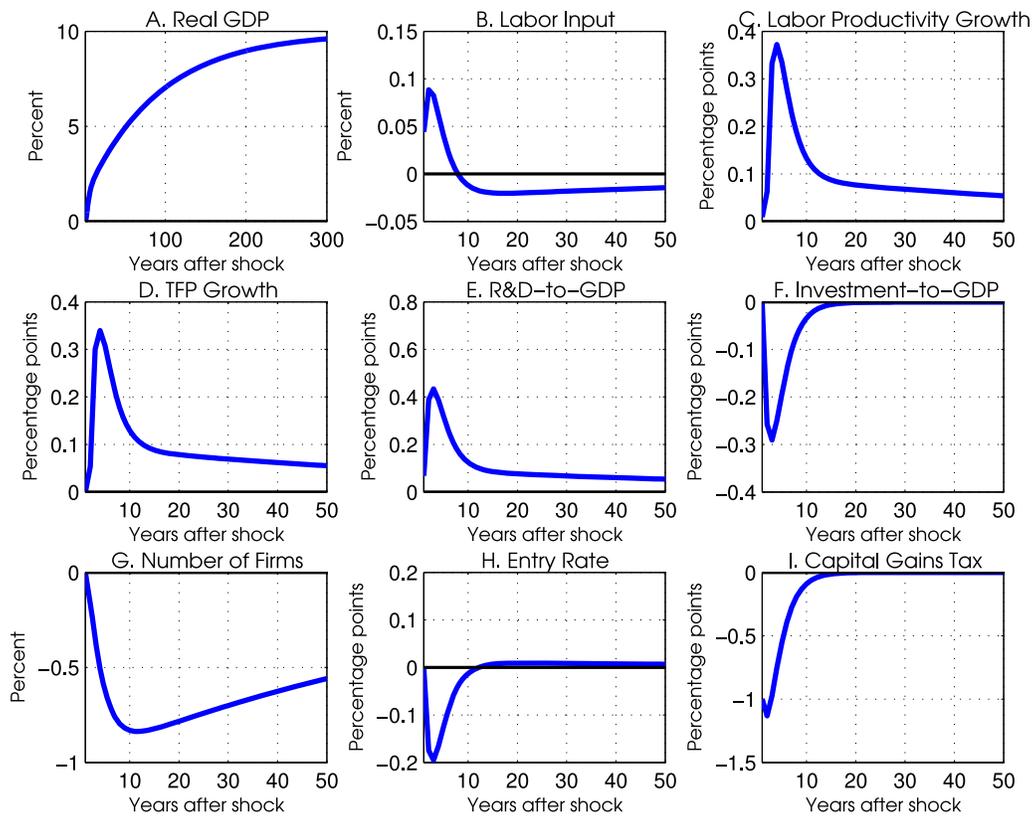


Fig. C.3. IRFs to a Capital Gains Tax Cut Notes: Firm’s exit probability of 6.18 percent. See Section 6.1 for details on the baseline parameterization of the model.

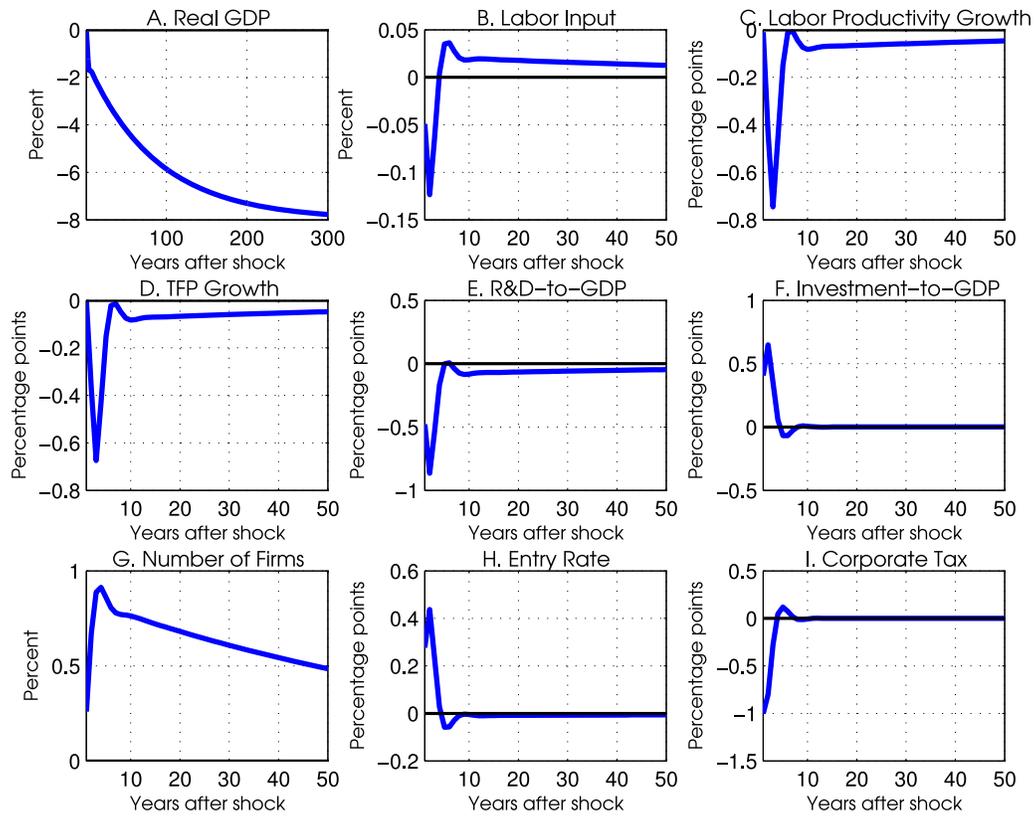


Fig. C.4. IRFs to a Corporate Tax Cut Notes: Firm's exit probability of 6.18 percent. See Section 6.1 for details on the baseline parameterization of the model.

C2. IRFs to Tax Shocks with a Fixed Mass of Firms

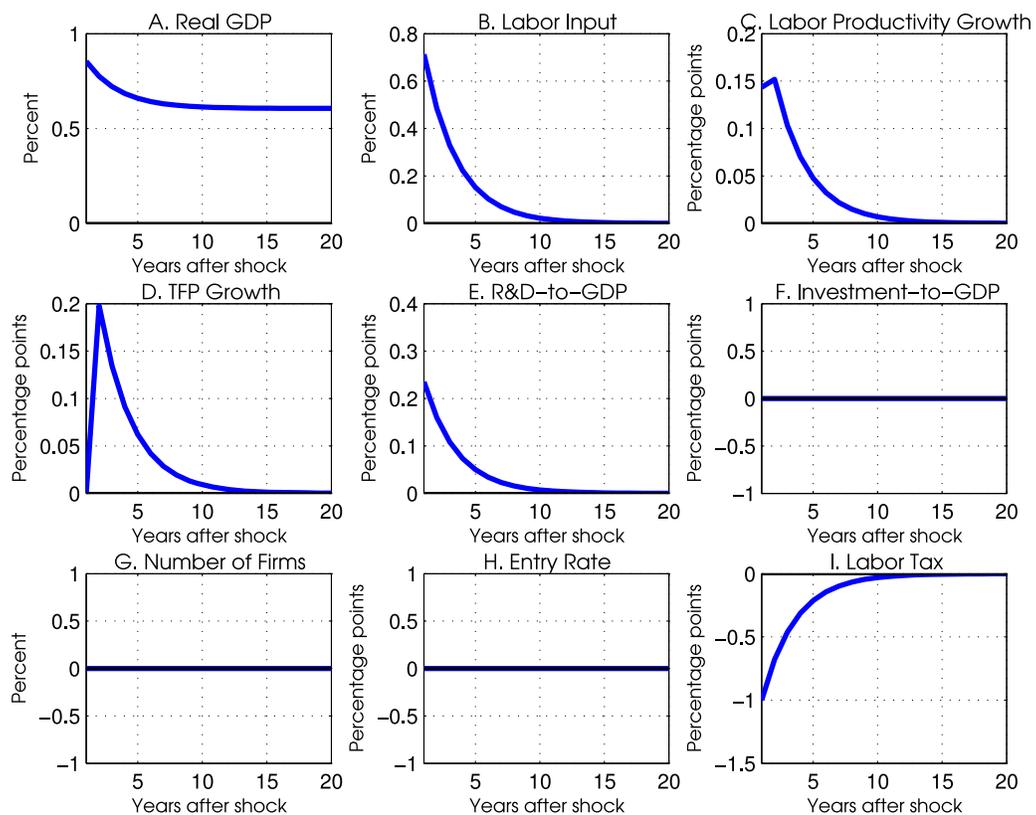


Fig. C.5. IRFs to a Labor Tax Cut Notes: Fixed number of firms. See Section 6.1 for details on the baseline parameterization of the model.

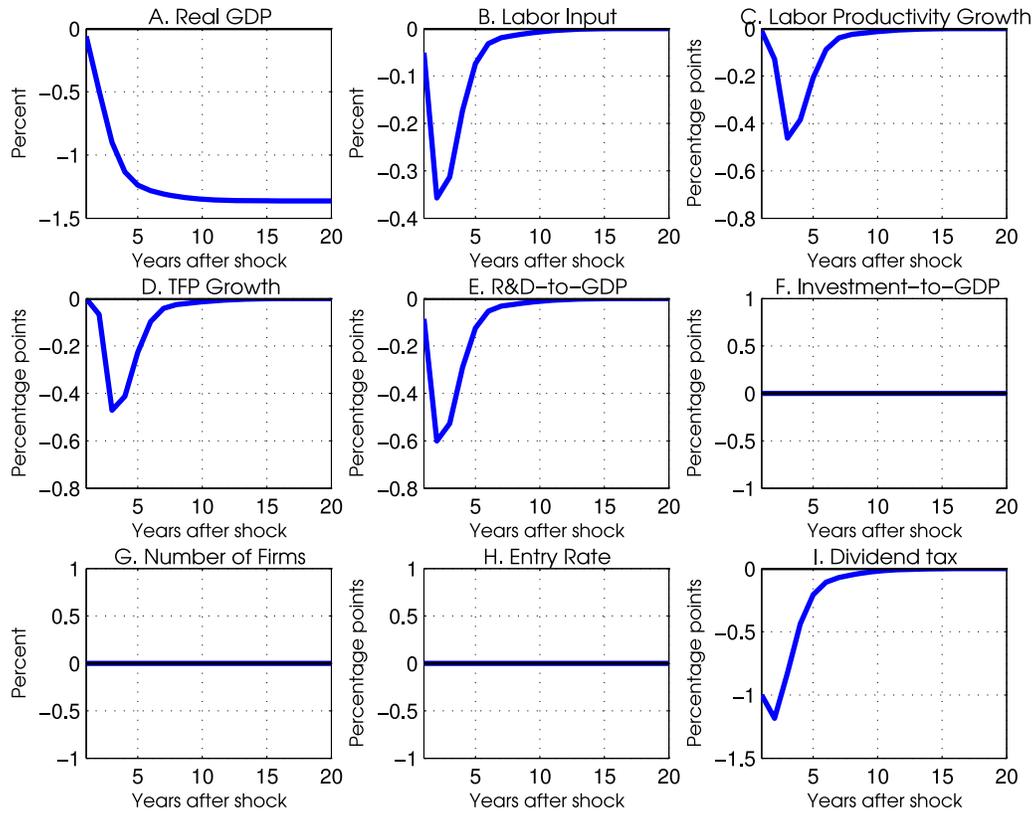


Fig. C.6. IRFs to a Dividend Tax Cut Notes: Fixed number of firms. See Section 6.1 for details on the baseline parameterization of the model.

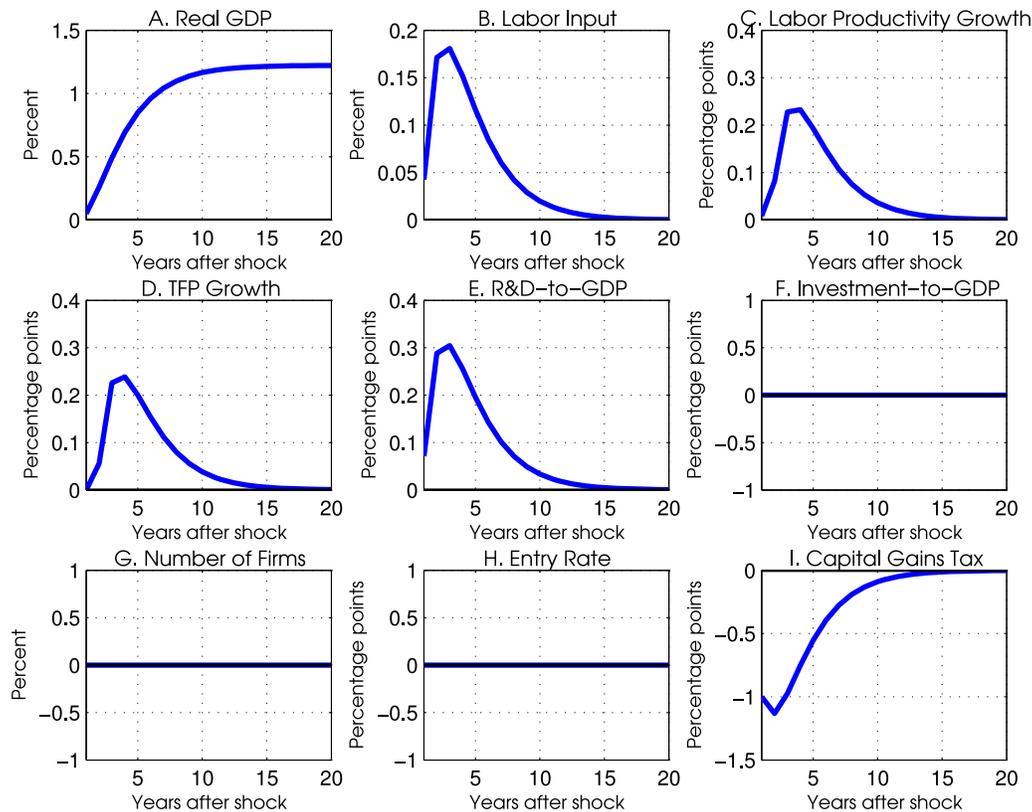


Fig. C.7. IRFs to a Capital Gains Tax Cut Notes: Fixed number of firms. See Section 6.1 for details on the baseline parameterization of the model.

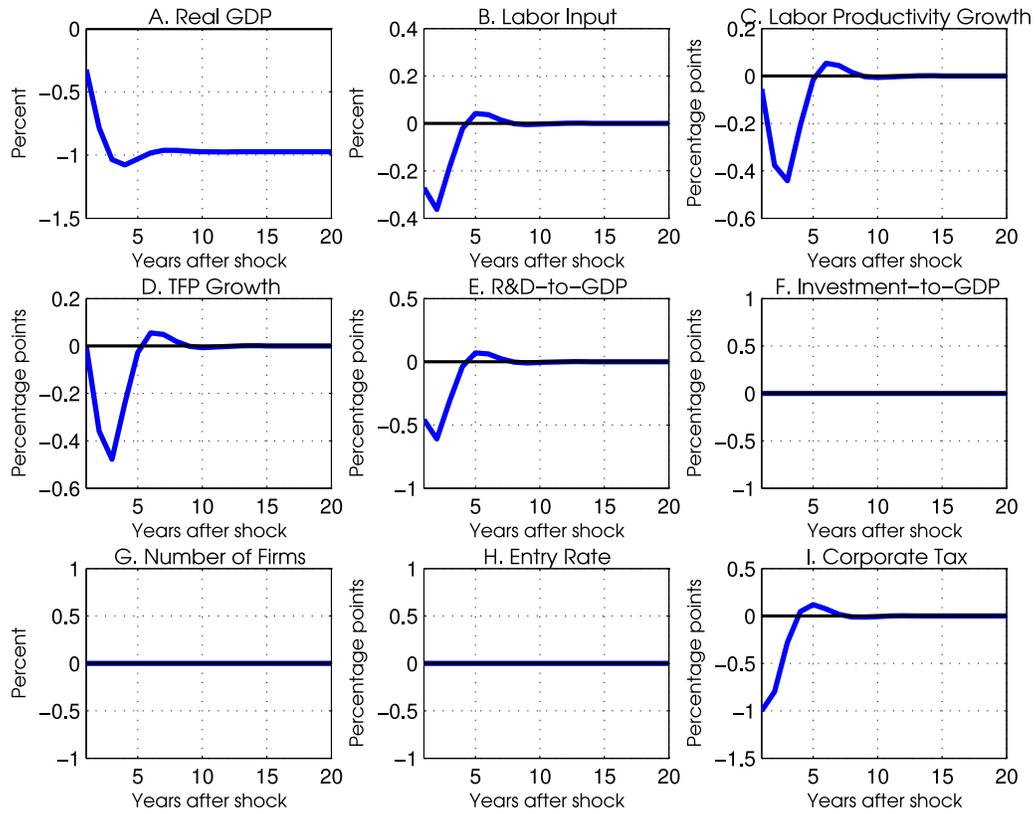


Fig. C.8. IRFs to a Corporate Tax Cut Notes: Fixed number of firms. See Section 6.1 for details on the baseline parameterization of the model.

C3. IRFs to Tax Shocks with Partial Congestion

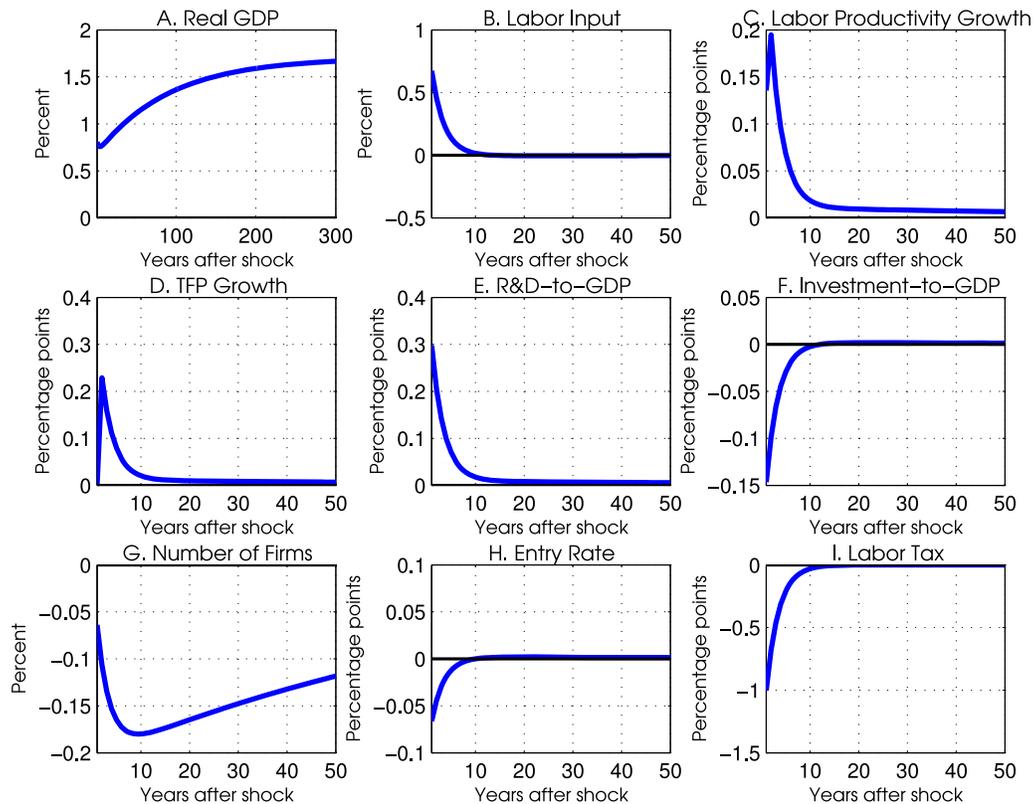


Fig. C.9. IRFs to a Labor Tax Cut Notes: Labor congestion of 75 percent. See Section 6.1 for details on the baseline parameterization of the model.

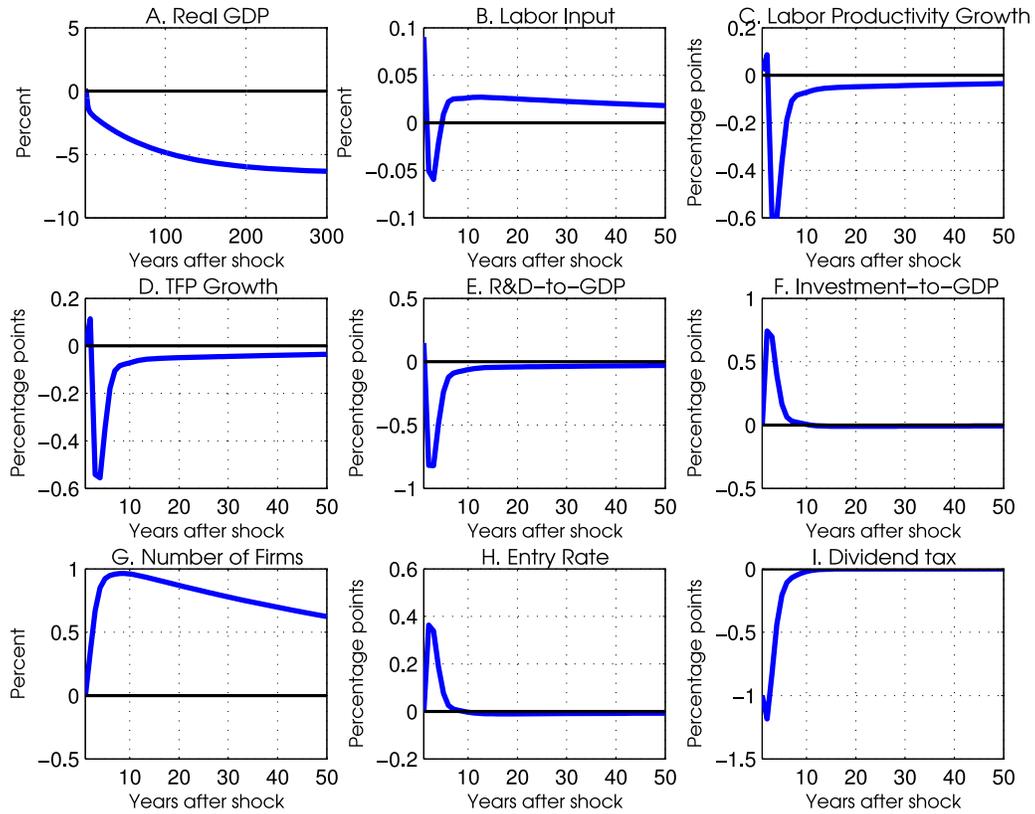


Fig. C.10. IRFs to a Dividend Tax Cut Notes: Labor congestion of 75 percent. See Section 6.1 for details on the baseline parameterization of the model.

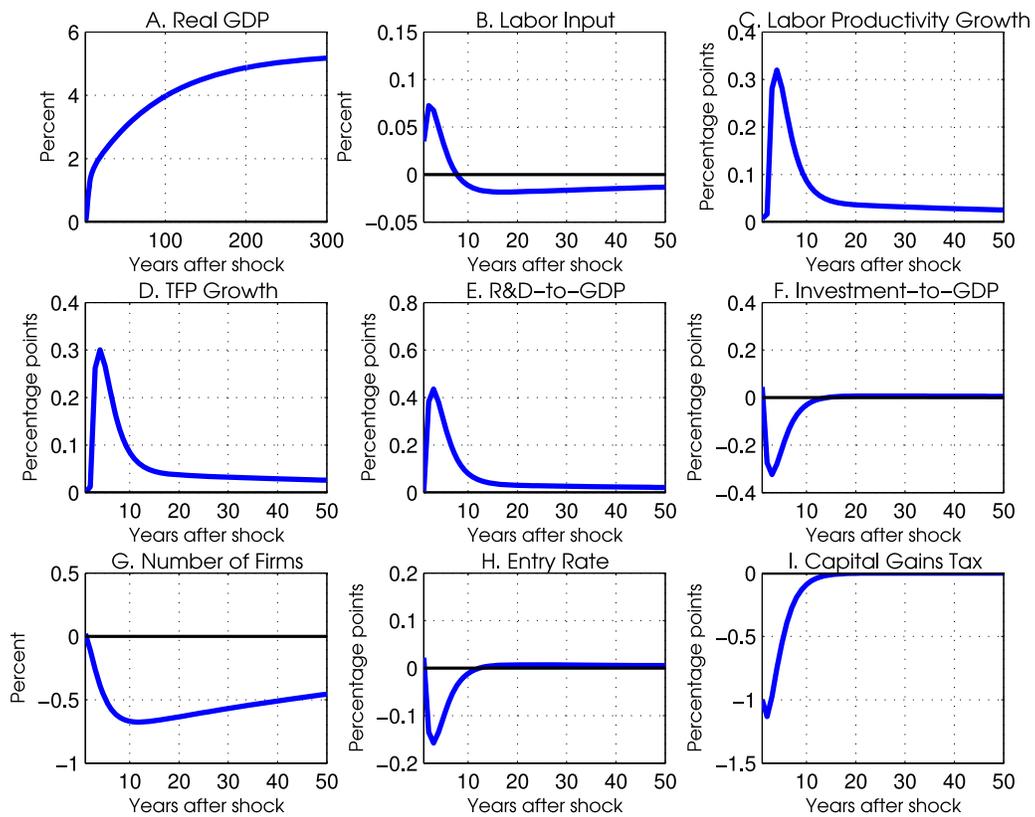


Fig. C.11. IRFs to a Capital Gains Tax Cut Notes: Labor congestion of 75 percent. See Section 6.1 for details on the baseline parameterization of the model.

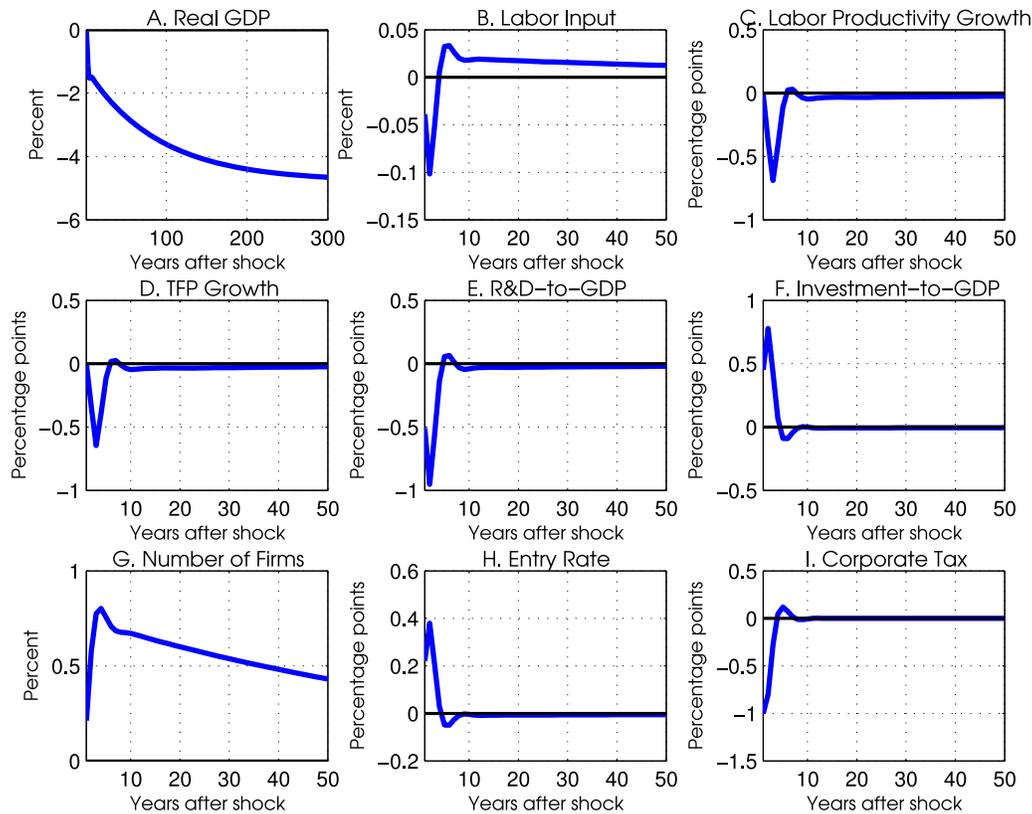


Fig. C.12. IRFs to a Corporate Tax Cut Notes: Labor congestion of 75 percent. See Section 6.1 for details on the baseline parameterization of the model.

C4. Steady-state Responses with a Fixed Mass of Firms

Table C.1 Long-Run Responses to Permanent Tax Cuts with a Fixed Number of Firms.

	old steady-state	new steady-state (1 pp tax cut)				
		$\tau^d \downarrow$	$\tau^v \downarrow$	$\tau^\pi \downarrow$	$\tau^c \downarrow$	$\tau^l \downarrow$
A. Unitary Frisch elasticity of labor supply:						
Real GDP/TFP growth	2%	2%	2.05%	2%	2.02%	2.02%
R&D-to-GDP ratio	2.6%	2.6%	2.66%	2.6%	2.61%	2.61%
B. Labor indivisibility:						
Real GDP/TFP growth	2%	2%	2.05%	2%	2.03%	2.04%
R&D-to-GDP ratio	2.6%	2.6%	2.66%	2.6%	2.62%	2.62%

Notes: 1 percentage point (pp) tax cut from steady-state value. In panel A, a unitary Frisch elasticity of labor supply is pinned down by setting $\vartheta = 1$. In panel B, we set $\vartheta = 0$ for the labor indivisibility case. In both panels, we re-calibrate the disutility of work parameter γ such that the steady-state target of time spent at work of 0.277 is achieved: $\gamma = 8.15$ for the parametrization $\vartheta = 1$ in panel A, whereas $\gamma = 2.26$ for $\vartheta = 0$ in panel B. See Section 6.1 for further details on the baseline parameterization of the model.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.euroecorev.2020.103590

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