Volatility costs of R&D

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Abstract

This paper incorporates endogenous growth into a New Keynesian DSGE framework to investigate the effects of R&D on economic volatility. It identifies a mechanism through which the cyclicality of R&D and its effects on volatility depend on the cyclicality of production. R&D activity becomes more procyclical, thereby amplifying economic volatility when labor supply is procyclical. The conclusions are reversed if labor supply is countercyclical. Alternative calibrations show that this link between R&D and production labor is weaker when R&D intensity, the spillover rate of innovation, and R&D adjustment costs are higher. In these cases, R&D tracks economic activity more closely which in turn magnifies economic volatility. The higher volatility has considerable welfare consequences and it implies that the steeper path of growth resulting from higher R&D activity comes at a price.

Keywords: Research and development, business cycles, endgenous growth, DSGE.

JEL Classification: E30, E32, O30, O33.

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1 Introduction

There is an undisputed positive link between innovative activities such as research and development (R&D) and long-term economic growth. The short-term behavior of these activities and how they influence business cycles, however, are far less clear. On the first of these two subjects, there is a considerable amount of research, mostly attributing the cyclicality of R&D spending to how the opportunity costs of these activities change along the business cycle for financially constrained firms. While some studies (such as Aghion and Saint-Paul, 1998 and Aghion et al., 2012) find that the opportunity costs of allocating funds to innovation is smaller during economic downturns, there is just as much evidence (Himmelberg and Petersen, 1994; Hall and Lerner, 2010; Barlevy, 2007) indicating otherwise. By contrast, the latter subject, whether or not R&D has any quantitatively important effects on economic fluctuations, has received little attention and there is relatively small amount of evidence some of which I mention below. In this paper, I identify a mechanism through which R&D, despite its small share of economic activity, can have a sizeable impact on the amplitude of business cycles. From a reasonable calibration to the U.S. economy, I find that this effect is mostly positive and large enough to cause a considerable loss of welfare. The important inference here is that innovative activities which clearly increase our living standards come at the price of higher economic volatility.

To investigate the tradeoff between growth and volatility, I incorporate endogenous growth into a medium-scale New Keynesian dynamic stochastic general equilibrium (DSGE) framework. R&D in this framework is a labor-intensive process that complements a labor-augmenting technology, it does not have diminishing returns, and it directly determines the growth rate of the economy. Firms in the economy decide to allocate labor/resources between production and R&D activities each period. If they choose to increase the level of R&D, the efficiency of production labor (and the growth rate of the economy at the symmetric equilibrium) increases but there are fewer labor units left over for production. Firms make this choice by comparing the marginal returns to each activity. Since production exhibits diminishing returns to production labor but not R&D, firms increase (decrease) the intensity/share of R&D in the production process when there is more (less) production labor. The cyclicality of R&D and its impact on output, therefore, depends on the cyclicality of labor supply. When the economy experiences a favorable shock that also increases labor supply (when labor supply is procyclical), for example, firms increase the relative share of R&D in production, farther increasing labor efficiency and output. Conversely, the R&D process has a mitigating effect on output if a shock prompts a countercyclical behavior in labor supply. These inferences are based on model responses to shocks that originate in different sides of a conventional Ney Keynesian, economy (e.g. Christiano et al., 2005; Smets and Wouters, 2007).

R&D in my baseline calibration, as in the data, constitutes only 2 percent of total spending in the economy. I proceed by examining how the short-run dynamics change if this percentage were to rise. The results indicate that when the economy is more R&D intense at steady state, the link between labor supply and R&D spending mentioned above is weaker and R&D instead follows output more closely (becomes more procyclical). The reason is that when R&D has a larger role in production, (through its effects on the growth rate of capital and the efficiency of labor), it becomes less sensitive to changes in labor supply. In this setting, a smaller change in R&D is sufficient to offset any disparity that forms between the marginal returns to production labor and R&D. Simply put, when R&D becomes a more important factor of production, its levels become less sensitive to the other factors and it follows the demand for firms' goods more closely. For a majority of the shocks in my model this stronger procylicality of R&D also implies higher output volatility. Simulated model moments suggest that if the steady state level of R&D is adjusted so that GDP growth rate is doubled, output volatility increases by 37 percent.

There are two other aspects of R&D that have important implications for this paper as they can significantly change short-term dynamics. First, R&D can affect productivity and growth not only through the change in its levels within firms but also through the cross-firm diffusion rate of the innovations it creates. This channel of transmission, for example, is argued to be one of the determinants of the productivity slowdown after the 2008 recession (e.g. Anzoategui et al., 2018). The second aspect is the cost of adjusting the levels of R&D within a firm. If these costs are much larger/lower than the costs of adjusting physical capital then this would directly affect the strength of the mechanisms mentioned above as it would considerably alter the sensitivity of R&D to production labor. As I discuss below there is no clear indication whether R&D adjustment costs are high or low as there is evidence for both. I incorporate both aspects into my model separately and I find a positive relationship between these aspects and output volatility. Specifically, I find that output is most volatile in economies in which innovation is transfered across firms at a higher rate and the costs of adjusting the level of R&D is high. When a higher share of the innovation that a firm adopts is created externally, its R&D spending once again becomes less sensitive to production labor and more procyclical which in turn increases output volatility. R&D similarly becomes less sensitive to production labor when cost of adjusting its levels is higher. For a majority of the shocks that I consider in my model, labor is countercyclical due to strong income effects (labor supply drops in response to a positive shock, for example), implying that R&D has a mitigating effect on output. When adjustment costs are high, this mitigation mechamism becomes weaker and output volatility is higher. The higher output volatility that is a byproduct of higher rate of diffusion and large adjustment costs, unlike the volatility generated by R&D intensity, is not offset by a higher economic growth rate.

In further computations, I find that the positive relationships between R&D intesity, innovation spillover, adjustment costs and volatility also applies to other macroeconomic variables such as inflation, consumption, investment and labor supply and I find that this volatility has substantial welfare consequences. The households in the economy, for example, are willing to give up 13 percent more of their steady state consumption to avoid the higher volatility that is generated by increasing R&D intensity by 50 percent (corresponding roughly to a 50 percent rise in annual GDP growth rate).

In the last part of the paper, I discuss two natural extentions of the baseline framework. First, I add skilled and unskilled labor to the model and I identify a negative relationship between R&D and the skilled-unskilled wage gap. Second, I assume that R&D contributes to a capital augmenting technology (instead of a labor augmenting technology) and I find that the amplification/mitigation mechanisms described above depend on the unit and adjustment costs of R&D relative to those of physical capital.

1.1 Evidence and theory

Studies based on microdata reveal several facts about R&D in the United States. First, it is mostly large firms with multiple production processes that conduct the majority of R&D (c.f., Foster and Grim, 2010; Foster et al., 2016). There are many explanations, dating back to Schumpeter (1942), of why this may be so such as the greater ability of large firms to reap the returns from R&D and their cost and risk diversification advantages relative to smaller firms (e.g. Cohen and Klepper, 1996). While I do not test the different explanations, the construction of the production process in my model is informed by these studies. Specifically, I assume that the firms engage in both production and R&D, and the interaction between production labor and R&D plays a critical role in the model. This interaction would not take place if the firm was a small innovator with a negligible level of non-R&D activity.

Second, there is evidence revealing a positive trend in R&D-outsourcing and the diffusion rate of innovation (e.g. Azoulay, 2004; Cassiman and Veugulers, 2006; Chesbrough, 2003; Knott, 2017). This trend, also referred to as open innovation, implies that firms rely more heavily external R&D and they adopt innovations of other firms at a higher rate then they did before. To incorporate this critical aspect of R&D, I allow for innovation, that is a byprodcut of R&D, to diffuse across firms and I study the implications of this diffusion for short-term dynamics.

Third, there are different views on the costs of adjusting R&D compared to those associated with physical capital adjustment. On the one hand, studies such as Brown et al. (2012), Hall et al. (2016) and Aysun and Kabukcuoglu (2019) point to high adjustment costs, mainly since knowledge input that goes into R&D cannot be separated across time, and corroborate this with the high level of R&D smoothing behavior of firms. This is consistent with the relatively low volatility of R&D over the business cycle in Figure 1 that depicts the growth rate of real GDP, real fixed investment and real R&D spending across time. The same figure also shows that employment in non-R&D activities tracks output much more closely than employment in R&D activities (such as science and engineering). On the other hand, studies such as Saint-Paul (1993) find a significant drop in the share of R&D spending within firms, especially those that are financially constrained, during recessions. Comin and Gertler (2006) and Rafferty and Funk (2008) find similar evidence. These findings goes against the lower opportunity costs of risky activties such as R&D during recessions pointed out by Aghion and Saint-Paul (1998) and it implies that these risky activities are more rapidly shed during downturns. It is, therefore, useful to accomodate these different views and test how the short-term behavior of the economy changes under different scenarios.

There has a been a resurgence of studies on the latter point mentioned above after the 2008 crisis (e.g. Fernald, 2014; Queraltó, 2013; Christiano et al., 2015). These studies explain and replicate the productivity slow-down following during the recession period. I adopt some elements from these studies when constructing my model. The basic New-Keynesian DSGE framework, for example, follows the one in Anzoategui et. al (2018) and it allows me incorporate multi-unit firms, and include various nominal and real rigidities that generate short-term fluctuations. I follow the structure in Bianchi et al. (2018) to include R&D into the production process. The evolution of R&D is different from these two studies, however, as it follows, the endogenous growth mechanism in Barlevy (2007). There is a more fundamental difference between my analysis and the papers mentioned above, including the empirical studies on the cylicality of R&D. While these studies focus on the behavior of R&D and how it is affected by the business cycle, I take the opposite direction by investigating the effects of R&D on the business cycle. There are only a few studies that provide macroeconomic evidence that sheds light on this subject. Comin and Gertler (2006), for example, find that R&D plays an important role for the persistence of economic fluctuations. Kung and Schmid (2015) find and empirical link between the fluctuations in the trend output growth rate and asset prices, and R&D-driven innovation. There is no direct microevidence, to the best of my knowledge, how R&D intensity affects economic volatility. Yet there is indirect evidence suggesting that R&D activity may be associated with higher volatility. Table 1, for example, shows that the volatilty of gross output, value added, intermediate input purchases, and the number of production workers is considerably larger in the most R&D intensive sectors relative to low-R&D sectors.[1] These observations and the predictions from my model go against the well-established negative relationship between economic growth and volatility (e.g., Ramey and Ramey, 1995; Aghion and Banerjee, 2005) and they imply that the said negative relationship may not hold for every growth-enhancing activity; R&D for instance can generate high volatility and growth at the same time.

2 The economy and calibration

The economy follows a medium-scale DSGE framework and it is populated by households, labor intermediaries, final and intermediate goods producers, capital goods producers, a central bank, and a government. Below, I describe these agents and their optimization problems.

2.1 Households

The households, indexed by $i \, \varepsilon \, [0,1]$, are infinitely-lived and they have external habit persistence over comsumption. These agents maximize their life-time utility given by,

$$U_0 = E_0 \sum_{t=0}^{\infty} \beta^t \left\{ \ln \left(C_{i,t} - \rho \bar{C}_{t-1} \right) + \tilde{\varphi}_{b,t} B_{i,t+1} - \tau \frac{L_{i,t}^{1+\sigma_l}}{1+\sigma_l} \right\}, \tag{1}$$

where ρ is the habit persistence parameter, β is the time discount factor and the parameter τ is used to ensure that labor supply is equal to 1 at steady state. Household i derives utility from consumption, $C_{i,t}$ (relative to aggregate consumption $\bar{C}_{t-1}$), disutility from working, with $L_{i,t}$ and σ_l denoting labor supply and the inverse of the Frisch-elasticity of labor supply respectively, and she holds risk-free government bonds, $B_{i,t}$. $\tilde{\varphi}_{b,t}$ is a liquidity demand shock that, as in Anzoategui et al. (2018), generates a wedge between the rental rate of capital and the risk-free rate and it

[1] According to the BRDIS 2013 survey the chemical products, computers, information, professional services, and transportation industries constitute roughly 82% of total U.S. R&D (total funds for R&D). This share is much larger than the total output share of these sectors in the U.S. (in 2017 22% according to BEA real gross output data during). Also while the output share of the industries has remained relatively constant in the past decades the R&D share of the 5 industries above have increased (the share was 68.4 % in 1999).

provides a convenient way to track how credit spread shocks propagate through the economy. All shocks in the model follow an AR(1) process. A complete list of these shocks are reported in Appendix A.

In maximizing her life-time utility function, the household faces the following budget constraint:

$$P_tC_{i,t}+T_t=W_{i,t}L_{i,t}+\Pi_{i,t}+R_t^kQ_{t-1}K_{i,t}-Q_tK_{i,t+1}+R_tB_{i,t}-B_{i,t+1}-\frac{\phi_w}{2}\left(\frac{W_{i,t}/W_{i,t-1}}{\pi_{t-1}^{\iota_w}\pi^{1-\iota_w}}-1\right)^2W_tL_t \tag{2}$$

where P_t is the price of the final good and T_t is the nominal value of the lump-sum taxes collected by the government. Households purchase capital goods $K_{i,t+1}$ from capital producers by paying a price of Q_t and rent these to intermediate goods producers at the rate of R_t^k. Besides capital rent, households also collect profits, $\Pi_{i,t}$, from the intermediate goods producers. The two other sources of revenue for household i are her wage earnings (with $W_{i,t}$ denoting the wage rate), and her returns from holding risk-free bonds, R_t. Households face quadratic wage adjustment costs similar to the Rotemberg (1982) formulation where wages are partially indexed to past inflation, $\pi_{t-1}=P_{t-1}/P_{t-2}$. ι_w and ϕ_w in this formulation represent the degree of wage indexation and the probability of adjusting wages, respectively.

Households' labor services are heterogenous and they are hired by perfectly competitive labor intermediaries. These firms produce homogenous labor services accoding to the aggregator below and rent them out to intermediate goods producers.

$$L_t=\left[\int_0^1 L_{i,t}^{1/\varphi_{w,t}}di\right]^{\varphi_{w,t}} \tag{3}$$

Here $\varphi_{w,t}$ represents the elasticity of substitution between labor services. The profit maximization problem of the intermediaries yields the following labor demand function:

$$L_{i,t}=\left(\frac{W_{i,t}}{W_t}\right)^{-\frac{\varphi_{w,t}}{\varphi_{w,t}-1}}L_t \tag{4}$$

where $W_t = \left[\int_0^1 W_{i,t}^{-\frac{1}{\varphi_{w,t-1}}} di\right]^{\varphi_{w,t-1}}$. Given this setup, households maximize their life-time utility by choosing the amount of consumption, capital purchases, bond holdings, labor supply and wages.

The first order necessary conditions for capital and risk-free bonds are given by,

$$\Lambda_t = \beta E_t \left\{ \Lambda_{t+1} R_{t+1}^k \right\} \tag{5}$$

$$\Lambda_t = \beta E_t \left\{ \Lambda_{t+1} R_{t+1} \right\} + \varphi_{b,t} \tag{6}$$

where $\Lambda_t = \left[P_t(C_t - \rho C_{t-1})\right]^{-1}$ is the Lagrange multiplier corresponding to the budget constraint and $\varphi_{b,t} = \tilde{\varphi}_{b,t}/\Lambda_t$ is the liquidity shock in consumption units. The two conditions above can be combined to derive the following relationship between credit spreads and liquidity demand shocks:

$$\beta E_t \left\{ \frac{\Lambda_{t+1}}{\Lambda_t} \left(R_{t+1}^k - R_{t+1} \right) \right\} = \varphi_{b,t} \tag{7}$$

The optimality conditions with respect to labor supply and wages are:

$$\tau L_{i,t}^{\sigma_l} = \Lambda_t \Omega_{h,t} W_{i,t} \tag{8}$$

$$\begin{aligned} \phi_w \left(\frac{\pi_{i,t}^w}{\pi_{t-1}^{\iota_w} \pi^{1-\iota_w}} - 1 \right) \frac{\pi_{i,t}^w}{\pi_{t-1}^{\iota_w} \pi^{1-\iota_w}} - \frac{L_{i,t}}{L_t} \left(1 + \left(1 - \Omega_{h,t}\right) \frac{\varphi_{w,t}}{\varphi_{w,t} - 1} \right) \\ = E_t \left\{ \phi_w \beta \frac{\Lambda_{t+1}}{\Lambda_t} \left(\frac{\pi_{i,t+1}^w}{\pi_t^{\iota_w} \pi^{1-\iota_w}} - 1 \right) \frac{\left(\pi_{i,t+1}^w\right)^2}{\pi_t^{\iota_w} \pi^{1-\iota_w}} \frac{L_{t+1}}{L_t} \right\}. \end{aligned} \tag{9}$$

where $\Omega_{h,t}$ is the Lagrange multipler for the household's labor supply and wage inflation is given by $\pi_{i,t}^w = W_{i,t}/W_{i,t-1}$. These two conditions are combined after log-linearizing the model to derive the New-Keynesian wage Phillips curve (see Appendix A).

2.2 Final and intermediate goods producers

Final consumption goods are produced by a representative, perfectly competitive firm. This firm uses the following CES technology to combine a continuum of intermediate goods, $Y_{j,t}$, to yield the final good, Y_t:

$$Y_t = \left(\int_0^1 Y_{j,t}^{1/\varphi_{p,t}} dj \right)^{\varphi_{p,t}} \tag{10}$$

where $\varphi_{p,t}$ captures the elasticity of substitution between the intermediate goods and it is modelled as an AR(1) process to introduce cost-push/mark-up shocks in the model. The profit maximization problem of the final goods firm produces the following demand for intermediate good j:

$$Y_{j,t} = Y_t \left(\frac{P_{j,t}}{P_t} \right)^{-\varphi_{p,t}/\left(\varphi_{p,t}-1\right)} \tag{11}$$

The focal point of the model is the decision problem of the intermediate goods producers. These firms, indexed by j, are monopolistically competitive and they produce intermediate goods by using the following Cobb-Douglas technology:

$$Y_{j,t} = A_t \left(Z_{j,t} K_{j,t} \right)^{\alpha} M_{j,t}^{1-\alpha} \tag{12}$$

where A_t is a systematic productivity shock that follows an AR(1) process, $Z_{j,t}$ is the utilization rate of capital and α is the share of capital. The firm rents capital from consumers and the labor input, $M_{j,t}$, is a product of two components: physical units of labor that are used in production, $L_{j,t}^p$ and a variable that measures the effectiveness of this type of labor, $\mu_{j,t}$ so that,

$$M_{j,t} = \mu_{j,t} L_{j,t}^p. \tag{13}$$

Each period, the firm allocates its total labor force, $L_{j,t}$, to the production of the intermediate good and R&D type activities, $RD_{j,t}$:

$$RD_{j,t} = L_{j,t} - L_{j,t}^p. \tag{14}$$

Here I denote the share of R&D in total labor as $SRD_{j,t} = RD_{j,t}/L_{j,t}$. I will use this variable to observe how the R&D intensity of firms change in response to various shocks.

The effectiveness of labor is positively related to the share of labor allocated to R&D. This relationship is specified by a formulation similar to that in Barlevy (2007):

$$\mu_{j,t} = \left(\lambda^{\nu RD_{j,t}}\right)^{\eta} (\mu_t)^{1-\eta} \tag{15}$$

where the parameter λ governs the growth rate of the economy and it is assumed to be greater than one. Along the balanced growth path, the economy grows at the rate of $\mu = \lambda^{\nu RD}$.The parameter ν here can be interpreted as the probability that R&D activity is successfull in creating an innovation or as the "stepping on toes" effects of R&D (as in Jones and Williams, 1998). In addition to these firm-specific effects of R&D, I assume that labor effectiveness can also increase due to R&D activities and discoveries of other firms. The second term on the right hand side of equation (15) captures this positive externality and it is given by,

$$\mu_t = \int_0^1 \mu_{k,t} dk \quad for \;\; k \neq j. \tag{16}$$

Overall, effectiveness is a Cobb-Douglas aggregate of the firm-level and industry-level effects of R&D, where $1-\eta$ captures the degree to which a firm's labor effectiveness depends on new industry-level technologies/discoveries versus firm-level discoveries. To ensure stability along a balanced growth path, I assume that $\eta\nu < 1$.

The intermediate good producer j's profit function is given by:

$$\begin{aligned}\Pi_{j,t} = {} & P_{j,t} A_t \left(Z_{j,t} K_{j,t}\right)^{\alpha} M_{j,t}^{1-\alpha} - W_t \lambda^{\nu RD_{j,t}} F_j - \frac{\phi_{rd}}{2}\left(RD_{j,t}/RD_{j,t-1} - 1\right)^2 W_t RD_{j,t} - W_t L_{j,t} \\ & - R_t^k Q_{t-1} K_{j,t} - \frac{\phi_p}{2}\left(\frac{P_{j,t}/P_{j,t-1}}{\pi_{t-1}^{\iota_p}\pi^{1-\iota_p}} - 1\right)^2 P_t Y_t - \frac{\kappa_z}{1+\varpi}\left(Z_{j,t}^{1+\varpi} - 1\right) Q_{t-1} K_{t,j}\end{aligned} \tag{17}$$

The firm faces two frictions in maximizing its life-time profits. The first of these, quadratic costs of adjusting prices, allows me to produce price stickiness. ϕ_p and ι_p in the cost function captures the probablity of changing prices and the degree of indexation to past inflation, respectively. The second, quadratic costs of adjusting R&D activities (with ϕ_{rd} governing the level of R&D adjustment costs) is more central to the analysis in this paper. As I describe below, the model also features quadratic costs of adjusting physical capital. It is the difference between the two types of adjustment costs that play a key role in the model by generating an asymmetric response of R&D and fixed investment to shocks. Another non-standard cost component in the maximization problem are the fixed costs associated with R&D, F_j, that is scaled by the growth rate of the economy. This scaling of fixed costs ensures that it does not diminish in importance as the economy grows and it is a reasonable representation of how fixed costs evolve.[2]

The more standard features of the maximization problem are that the intermediate firm pays wages for labor and incurs capital borrowing and utilization costs (with κ_z and ϖ regulating the level and elasticity of this cost, respectively). The realized return from capital holdings here is given by,

$$R_t^k = \frac{(1-\delta)\,Q_t + MPK_t}{Q_{t-1}} \tag{18}$$

where MPK_t is the marginal product of capital.

The optimality conditions derived from the maximization of discounted life-time profits with respect to prices, capital, production labor, R&D activity, and capital utilization are as follows:

Prices:

$$\begin{aligned} &\phi_p \left(\frac{\pi_{j,t}}{\pi_{t-1}^{\iota_p} \pi^{1-\iota_p}} - 1 \right) \frac{\pi_{j,t}}{\pi_{t-1}^{\iota_p} \pi^{1-\iota_p}} + \Omega_{p,t} \frac{Y_{j,t}}{Y_t} \left(1 - \frac{\varphi_{p,t}}{\varphi_{p,t} - 1} \right) \\ &= E_t \left\{ \phi_p \beta \frac{\Lambda_{t+1}}{\Lambda_t} \left(\frac{\pi_{j,t+1}}{\pi_t^{\iota_p} \pi^{1-\iota_p}} - 1 \right) \frac{\pi_{j,t+1}}{\pi_t^{\iota_p} \pi^{1-\iota_p}} \frac{Y_{t+1}}{Y_t} \right\} \end{aligned} \tag{19}$$

Capital:

$$\alpha \Omega_{p,t} \frac{P_{j,t} Y_{j,t}}{K_{j,t}} = R_t^k Q_{t-1} + \frac{\kappa_z}{1+\varpi} \left(Z_{j,t}^{1+\varpi} - 1 \right) Q_{t-1} \tag{20}$$

[2] Barlevy (2007), for example, attributes the growth of labor overhead costs when there is higher productivity to the rising level of fixed R&D costs.

Production labor:

$$(1-\alpha)\,\Omega_{p,t}\frac{P_{j,t}Y_{j,t}}{L^{p}_{j,t}}=W_t \tag{21}$$

R&D (combined with the demand for production labor):

$$\begin{aligned}W_tL^{p}_{j,t}\eta\nu\ln(\lambda)=&\left[\nu\ln(\lambda)\,\lambda^{\nu RD_{j,t}}F_j+1\right]W_t+\phi_{rd}W_t\left(\frac{RD_{j,t}}{RD_{j,t-1}}-1\right)\left(\frac{RD_{j,t}}{RD_{j,t-1}}\right)\\&+\beta\phi_{rd}E_t\left(W_{t+1}\right)\left(\frac{E_t\left(RD_{j,t+1}\right)}{RD_{j,t}}-1\right)\left(\frac{E_t\left(RD_{j,t+1}\right)}{RD_{j,t}}\right)^2+\frac{\phi_{rd}}{2}W_t\left(\frac{RD_{j,t}}{RD_{j,t-1}}-1\right)^2\end{aligned} \tag{22}$$

Capital utilization:

$$\alpha\Omega_{p,t}\frac{P_{j,t}Y_{j,t}}{Z_{j,t}}=\kappa_z Z^{\varpi}_{j,t}Q_{t-1}K_{t,j} \tag{23}$$

where $\pi_{j,t}=P_{j,t}/P_{j,t-1}$ and $\Omega_{p,t}$ is the Lagrange multiplier corresponding to the relative demand for the intermediate good producers' output. This variable is identical for each firm and it is equal to the marginal cost of production below.[3]

$$\Omega_{p,t}=\alpha^{-\alpha}(1-\alpha)^{\alpha-1}\left(\frac{W_t}{P_t}\right)^{1-\alpha}\left(Q_{t-1}R^{k}_{t}\right)^{\alpha}Z_t^{-\alpha}A_t^{-1}\lambda^{-\nu(1-\alpha)RD_t}+\frac{W_t}{P_t}\frac{RD_t}{Y_t} \tag{24}$$

2.3 Capital producers

Capital producers are perfectly competitive firms that purchase capital investment goods from final goods producers and the undepreciated part of capital from consumers at relative prices $P_{I,t}$ and Q_t, respectively, to produce new capital goods. As in Anzoategui et al. (2018), it is assumed that the price of investment goods, $P_{I,t}$, follows an AR(1) process. The new capital goods are sold to consumers, at the installed-capital price of Q_t, who in turn rent them out to intermediate good producers. Capital producers maximize profits subject to the law-of-motion of capital as follows:

$$\max\ E_0\sum_{t=0}^{\infty}\beta^t\frac{\Lambda_t}{\Lambda_0}\left[Q_{t-1}K_t-Q_{t-1}(1-\delta)K_{t-1}-\frac{P_{I,t}}{P_t}I_t\right] \tag{25}$$

[3] $\Omega_{p,t}$ is obtained by setting output to unity and by expressing L^{p}_{t}/K_t in terms of real wages and returns to capital.

$$s.t. \qquad K_t = (1-\delta) K_{t-1} + \left[1 - \frac{\phi_k}{2} \left(\frac{I_t}{I_{t-1}} - 1 \right)^2 \right] \varphi_{I,t} I_t \tag{26}$$

where future profits are discounted at the households' stochastic discount factor. In maximizing profits, capital producers face quadratic costs when adjusting investment. These costs have the same functional form as the R&D adjustment costs that intermediate good producers face. The adjustment cost parameter, ϕ_k, however is different from the R&D adjustment cost parameter. The parameter δ in the evolution of capital represents the depreciation rate and the shock variable $\varphi_{I,t}$ follows an AR(1) process and it represents shifts in investment-specific technologies. The first order condition corresponding to the maximization with respect to investment is given by,

$$\begin{aligned} & Q_{t-1} \varphi_{I,t} \left[1 - \frac{\phi_k}{2} \left(\frac{I_t}{I_{t-1}} - 1 \right)^2 - \phi_k \left(\frac{I_t}{I_{t-1}} - 1 \right) \frac{I_t}{I_{t-1}} \right] \\ & \qquad + E_t \left\{ \beta \phi_k \frac{\Lambda_{t+1}}{\Lambda_t} Q_t \varphi_{I,t+1} \left(\frac{I_{t+1}}{I_t} - 1 \right) \frac{I_{t+1}^2}{I_t^2} \right\} - \frac{P_{I,t}}{P_t} = 0 \end{aligned} \tag{27}$$

2.4 Monetary and fiscal policy, and market clearing

I assume that there is a central bank that sets nominal policy interest rate, R_t, according to the following Taylor rule:

$$R_t = (R_{t-1})^{r_s} \left[R \left(\pi_t / \pi \right)^{r_\pi} \left(Y_t / y \right)^{r_y} \left(Y_t / \mu Y_{t-1} \right)^{r_{\Delta y}} \right]^{1-r_s} \varphi_{r,t} \tag{28}$$

where R is the steady state policy rate, r_s is the interest rate smoothing term, and parameters r_π, r_y, $r_{\Delta y}$, determine the weight of inflation, output gap and output growth in the Taylor rule. $\varphi_{r,t}$ is a monetary policy shock that follows an AR(1) process. y is the detrended level of output at steady state.

Let $\varphi_{g,t}$ denote a shock that follows an AR(1) process then real government spending is given by,

$$G_t = \varphi_{g,t}. \tag{29}$$

This expenditure is financed through taxes and borrowing:

$$G_t = \frac{T_t}{P_t} + \frac{B_{t+1}}{P_t} - \frac{R_t B_t}{P_t}. \tag{30}$$

The resource constraint for the economy as a whole is given by,

$$Y_t = C_t + \frac{P_{I,t}}{P_t}\left(I_t + \frac{\phi_k}{2}\left(\frac{I_t}{I_{t-1}} - 1\right)^2 \varphi_{I,t} I_t\right) + G_t \tag{31}$$

Also in equilibrium bond markets clear so that there is no net supply of bonds.

2.5 Calibration

To calibrate the nonstandard features of the model I make two initial assumptions. First, I assume that the real GDP growth rate is 3% which approximately matches the average growth rate of U.S. real GDP over the past 50 years. Second, I assume that the technology diffusion parameter $\eta = 0.25$ which implies that R&D spillover is 3 times that of internal R&D. This spillover effect is similar to the spillover effect in Bianchi et al. (2018) whose estimate for the diffusion parameter is 0.28. These restrictions imply that along the balanced growth path, R&D spending as a share of GDP is 2% and that the labor units allocated to R&D activities is approximately 3% of those allocated to production. The 2% R&D-spending-to-GDP ratio matches the approximate average in U.S. data in the past 35 years when R&D spending is measured as the total domestic R&D spending in the NSF, BRDIS database.

Matching the share of workers engaging in R&D is not as straightforward. According to BRDIS statistics the number of scientists and engineers employed for R&D activities is 1.6% of the production workers in the whole country (the mean value between 2000 and 2015) this share rises to 8% in sectors with high R&D activity (Chemicals, Transportation, Information Professional scientific and technical services, Computer and electronic products). The 3% figure in my model is higher than the former average yet it is not unreasonable given that scientists and engineers are not the only types of labor employed for R&D. In this calibration exercise, the implied value for λ is 1.624 and the fixed cost parameter F takes the value 0.239 when it is set equal to $(\varphi_p - 1)$ times the detrended level of output so that economic profits are zero at steady state. The calibration above also implies that $\nu = 0.514$, so that there is roughly a 50% chance that R&D activity successfully creates an innovation.[4] This parameter is linked to the intensity of R&D in the economy and its value in alternative calibrations will change as I attempt to gauge the behavior of the economy when it becomes more and less R&D intensive. The adjustment cost parameters for investment and R&D spending, ϕ_k and ϕ_{rd}, are set equal to 4 initially (a commonly used value for investment adjustment costs). I do, however, make the adjustment of R&D more costly in alternative calibrations of the model to reflect the fact that R&D spending is less cyclical than investment in the data.

The rest of the parameters are set equal to values commonly used or estimated in the literature (e.g., Smets and Wouters, 2007). The habit persistence parameter ρ, for example, takes the value of 0.7. The discount factor β is fixed to 0.995 which corresponds to a 2% annualized interest rate. At steady state, the spread between returns to capital and the risk-free interest rate $R^k - R = \Theta$ is 2% (see Appendix A for a description of Θ) on an annual basis. σ_l is set equal to 2 so that Frisch-elasticity of labor supply is 0.5. The labor parameter in the utility function, τ, is set equal to $\tau = \frac{(1-\alpha)}{\xi_w(1-\rho)c/y}$ so that the steady state labor is equal to 1. The share of capital in the production function α is set equal to 0.3, implying a 30% share of income for capital. Wage and price indexation parameters ι_w and ι_p are both set equal to 0.5, so that wages and prices adjust every two quarters. The parameters capturing the probability of adjusting wages and prices (Calvo parameters), ϕ_p and ϕ_w, are both set equal to 0.5, implying a 6 month duration for wage and price contracts. The price and wage mark-ups, φ_p and φ_w are set equal to 1.25 and 1.5, respectively. The depreciation rate, δ, is fixed to 0.025 so that the steady state depreciation rate is 10% on an annual basis. The elasticity parameter governing the costs of chaning capacity utilization, ϖ, is fixed to 1.[5] The Taylor rule parameters, $r_\pi, r_y, r_{\Delta y}$ and r_s are set equal to 1.5, 0.125, 0.125 and 0.75,

[4]Success rate of roughly 50% is not an unreasonable assumption given the wide range of estimates in the literature. Evidence shows that the success rate varies across industries and countries, and it ranges between 8% and 90% (e.g. Cooper, 1983; Cozijnsen et al., 2000; DiMasi et al., 2016; Välikangas et al. 2009).

[5]This is the same value used in Smets and Wouters (2007), except in their formulation the elasticity parameter

respectively. The spending shares, $G/Y, C/Y$ and I/Y are fixed to 0.18, 0.67 and 0.15, respectively. For every shock process the parameters representing persistence and the standard deviation of the i.i.d. innovations are set equal to 0.9 and 0.01, respectively. When solving the model, the variables Y_t, C_t, I_t, K_t are normalized by the stochastic growth rate of the economy $\mu_t = \lambda^{\nu RD_t}$ to ensure stationarity.

Under this calibration, the model provides a reasonable fit to the data as shown in Table 2. Specifically, the correlation of simulated macroeconomic variables with output and their standard deviations relative to output are close to the respective values in the data.

3 Results

Below I describe the impulse responses obtained from the model under different parameterizations. These parameterizations alter R&D's intensity in production, its adjustment costs, and its diffusion rate across firms. At the end of the section, I discuss the model's inherent growth-volatility tradeoff mechanism and I quantify the mechanism's welfare effects.

Before I begin describing how parameters governing the R&D process affect the model, it is instructional to report some baseline responses. Figure 2 displays the responses of the main variables in the economy to a one percent shock to productivity and government spending, two shocks that represent supply and demand shocks in the economy. The behavior of the standard variables in the model is consistent with the inferences from conventional dynamic new-Keynesian frameworks and macroeconometric evidence. In response to a productivity shock there is higher production prompted by higher productivity of capital and labor, and there is a decline in labor, wages and prices. Despite the higher level of output, policy rates are lowered mainly due to the lower level of inflation. The positive government spending shock represents a positive demand shock which can also be captured through shocks to consumption investment and the risk premium. This demand shock generates the usual increase in output, inflation, policy rate and labor, and a

$\psi = \varpi/(1+\varpi)$.

decrease in investment spending.

The non-standard components of the figures are the responses of R&D, the efficiency and the amount of production labor, labor input (effective labor, M_t) and the share of R&D in total labor. In the model, the marginal product of R&D, $(1-\alpha)\eta\nu\ln(\lambda)P_tY_t$, is proportional to the level of output and the labor income of production workers. As output, labor and wages decline in response to a positive productivity shock, the amount of R&D activity also declines, causing a drop in the efficiency of production labor. Since the great majority of firms' work force is allocated to production, production labor follows the response of total labor supply closely. There is, however, a reallocation of labor from R&D activities to production as evinced by the declining share of R&D in total labor. The reason for this cross-subsidization of production labor is that while the marginal product of R&D is proportional to output as mentioned above, the marginal product of labor ($(1-\alpha)Y/L^p$) is propotional to output per labor. The productivity shock in the model that generates a drop in production labor, for example, causes a more pronounced decline in the returns to R&D, which in turn skews the allocation of total labor to production activities. Conversely, a government spending shock that increases labor supply, increases the level of R&D and the intensity of R&D in the production process due to the same mechanism as displayed in the bottom panel of Figure 2.

The more general inference in these baseline results, however, is that the cyclicality of R&D activity and R&D's effects on output volatility depend on the type of shock or more specifically on how the shock affects total labor supply. If an adverse shock decreases labor supply and output at the same time, for example, R&D would decrease as well (making it procyclical), amplifying the negative response of output. This positive relationship between labor and R&D is also observed in the responses to a broader set of shocks displayed in Figure 3. The additional insight in this figure is that the magnitude of R&D responses is much larger compared to that of labor supply. This disparity depends on the adjustment costs of R&D which I kept the same as physical capital adjustment costs in the baseline calibration. As I discuss below, R&D becomes less volatile if its adjustment costs are higher. The exercises below test how various features of the R&D process affect its cyclicality and overall macroeconomic volatility.

3.1 R&D intensity

In this section I compare the responses from the model when R&D plays a greater and a lesser role in the production process. In the former calibration exercise, 5 percent of the total labor supply is allocated to R&D functions, 2.5 times the amount under the baseline calibration. This also implies that the share of R&D in total income is 7.5 percent, the annual GDP growth rate is 7.8 percent, and λ, F and ν are 1.59, 0.226, 0.53 respectively. To lessen the role of R&D in production, I set the share of R&D in labor and income to a very small number (0.0001 times its value in the baseline calibration). The GDP growth rate, λ, F and ν corresponding to this exercise are 0 percent, 1.64, 0.249, and 0.5011 respectively. The diffusion parameter remains the same under both exercises.

Figure 4 illustrates that the responses to a one percent productivity shock, corresponding to the two alternative scenarios, yield qualitatively similar responses for the most part. These responses do, however, reveal a larger (smaller) output response in the more R&D intense (deficient) economy. When R&D is more substantial for production, it becomes less sensitive to both the changes in production labor (and also capital).[6] It instead becomes more closely related to output. As output increases, for example, the marginal returns to R&D increase and firms allocate a larger share of funds to R&D processes. The reason is that when there is more R&D and thus less production labor at steady state, a small change in R&D is sufficient to counteract any changes in production labor and to restore the parity between the marginal returns to labor and R&D. By contrast, when R&D does not play a significant role in production, it follows production labor more closely. The decline in labor generated by the positive productivity shock in Figure 4 prompts a smaller negative response of R&D and a larger positive response of output in the more R&D intense economy. This mechanism is also observed when the economy faces the broader set of shocks in Figure 5 and R&D becomes more (less) procyclical in the economy with higher (lower) R&D intensity. When

[6] Equation (A.9) in Appendix A illustrates the relationship between steady state level of R&D and R&D's sensitivity to production labor. As the steady state level of R&D increases, the aforementioned sensitivity declines due to an increase in μ and a decrease in L^p. A similar mechanism applies to the allocation of funds between capital and R&D.

R&D intensity is higher, the initial increase in labor caused by positive government spending and price shocks have smaller positive impacts on R&D and output, and the negative responses of labor during monetary policy, investment and bond spread shocks have smaller negative impacts on R&D and output. While the amplitude of output in response to monetary and fiscal shocks is smaller in the R&D-intense economy, the difference compared to the baseline responses is relatively small.

In general, these results suggest that the higher procylicality of R&D in the R&D-intense economy implies larger output fluctuations. The amplitudes of the other variables, reported in Table 3, suggest that this property of R&D intensity applies more broadly to macroeconomic fluctuations. More specifically, the maximum amplitudes of the responses are mostly larger (smaller) in the R&D-intense (deficient) economy compared those obtained from the baseline economy. These observations are consistent with the standard deviations of the simulated variables reported in Panel B. It should be noted that while R&D intensity causes higher volatility, it also generates higher growth. The last row in Panel B, helps to quantify this inherent growth-volatility tradeoff in the model. The reported numbers roughly imply that if growth rate doubles, output becomes 37 percent more volatile.

3.2 R&D spillover

As mentioned above, recent evidence links the productivity slow-down during the Great Recession to not only the drop in the level of innovation but also its slower diffusion across companies/sectors. The latter mecahism is what I investigate in this section. Specifically, I set the diffusion rate parameter, η, to high and low levels to determine how diffusion affects the cyclicality of R&D. In the high-diffusion economy, I assume that nearly all of the innovation a firm uses (99%) is created externally. By contrast, in the low-diffusion economy, firms rely mostly on internal innovation (97%).

The results are displayed in Figures 6 and 7 and Table 4. These results generally point to higher macroeconomic volatility in the economy that has a high rate of diffusion. When the diffusion rate is high, a firm is less-relient on internal R&D. Its decision to change the level of internal R&D has a smaller impact on the effectiveness of production labor. The relative returns to R&D, therefore, becomes less sensitive to the level of production labor as in the case of the R&D intense economy above. This mechanism, as before, makes R&D more procyclical and magnifies macroeconomic volatility. This time, however, the high diffusion rate of innovation does not increase the growth rate of the economy so that there are no qualifying benefits to the higher macroeconomic volatility that results from the higher rate of diffusion.

3.3 R&D adjustment costs

In the baseline model, I took a neutral stance on R&D adjustment costs by setting the R&D adjustment cost parameter equal to the investment adjustment cost parameter. While it is not clear that this is an empirically accurate description of the cost structure of firms, there are several reasons why one could postulate that R&D adjustment costs are higher. First, in my model, R&D is a labor intensive process and changing the level of R&D would amount to shedding labor. Given that investment is roughly 4 times as volatile as labor in the past 40 years, it is reasonable to assume that there are higher costs associated with changing the level of R&D. This disparity is magnified by the fact that it is more costly to fire or hire high-skill labor (such as scientists and engineers) that engage in R&D activities. Nevertheless, several studies (Ouyang 2011; Archibugi et al., 2013; Fabrizio and Tsolmon 2014; Fatas, 2000; Sedgley et al., 2018) identify alternative mechanisms showing that the opportunity costs of R&D may be larger(smaller) during economic expansions(downturns) which makes R&D more flexible and sensitive to the business cycle. In this section, I compare the responses from my model when the R&D adjustment cost parameter is set equal to lower and higher values. To make the R&D adjustment process less and more costly, I set the adjustment paramater ϕ_{rd} to 1 and 7, respectively. This makes R&D adjustment 75 percent less and more costly than adjusting physical capital.[7]

The results from these alternative calibrations are displayed in Figures 8 and 9, and in Table

[7] I choose these values to make the exercise symmetric. The lower value is chosen as 1 since impulse response do not change by much when $\phi_{rd} < 1$. I should, however, note that the wedge between the high-adjustment cost economy responses and the baseline calibration responses becomes much larger if I set ϕ_{rd} to higher values.

5. When the economy faces a positive productivity shock and adjustment costs are high, the sensitivity of R&D to production labor is smaller and there is a smaller negative response of R&D that in turn generates a larger response of output. Conversely, R&D becomes more sensitive to production labor when it is more flexible and the larger drop in its levels suppresses the positive response of output by more. This mechanism operates when the economy is exposed to the other shocks. In response to fiscal and monetary policy shocks, for which production labor is procylical, the smaller response of R&D mitigates the response of output. By contrast, the smaller response of R&D to productivity, bond spread, investment and price shocks, amplifies the response of output. The statistics in Table 5 indicate that the amplification mechanism under high adjustment costs is stronger and that macreconomic volatility is higher compared to the calibration with lower adjustment costs.

3.4 Welfare analysis

In this section, I investigate the welfare implications of the inherent R&D-volatility relationship in my model. To do so, I approximate the model's objective function and the decision rules to the second order. I then measure welfare effects by computing the percent of steady state consumption that households are willing to give up to avoid the volatility generated by the shocks in my model.

To quantify welfare effects, I use the following second order approximation to the utility function:

$$EU_t = E\left(c_t\right) - \tau E\left(l_t\right) - \frac{(1+\rho\mu)}{2\left(1-\rho\mu\right)} var\left(c_t\right) - \frac{\tau\sigma_l}{2} var(l_t) - \frac{\rho\mu}{\left(1-\rho\mu\right)^2} cov(c_t, c_{t-1}) - \frac{\tau\sigma_l\rho\mu}{\left(1-\rho\mu\right)} cov(c_t, l_t) \tag{32}$$

where $E\left(c_t\right)$, $E\left(l_t\right)$ and $var\left(c_t\right)$, $var\left(l_t\right)$ are the unconditional means and variances of consumption and labor, respectively. $cov(c_t, c_{t-1})$ and $cov(c_t, l_t)$ are the covariance of consumption and its lag value and the consumption-labor covariance, respectively. c_t and l_t represent the deviation of consumption and labor around their steady state values.

I classify the effects of shocks on the expected utility into two parts. The first part captures the effects that feed through the unconditional means of consumption and labor (denoted by u^{mean}). In other words, the additional steady state level of consumption that consumers are willing to give up not to sustain the effects of the shocks that feed through the mean values of consumption and labor. The second part measures the additional steady state level of consumption needed to avoid the effects that feed through the unconditional variances of the two variables (denoted by u^{var}). u^{mean} and u^{var} are obtained from the following two equations:

$$\ln[(1+u^{mean})(1-\rho\mu)C]-\tau = U+E(c_t)-\tau E(l_t) \tag{33}$$

$$\begin{aligned}\ln[(1+u^{var})(1-\rho\mu)C]-\tau = U &- \frac{(1+\rho\mu)}{2(1-\rho\mu)}var(c_t)-\frac{\tau\sigma_l}{2}var(l_t)\\ &-\frac{\rho\mu}{(1-\rho\mu)^2}cov(c_t,c_{t-1})-\frac{\tau\sigma_l\rho\mu}{(1-\rho\mu)}cov(c_t,l_t)\end{aligned} \tag{34}$$

where $U=\ln[(1-\rho\mu)C]-\tau$ and C are the steady state values of the utility function and consumption, respectively. Notice here that bond holdings do not enter welfare calculations as it is the usual procedure in welfare analysis, and the steady state level of labor is equal to 1. Solving for u^{mean} and u^{var} yields:

$$u^{mean}=\exp[E(c_t)-\tau E(l_t)]-1 \tag{35}$$

$$u^{var}=\exp\left[-\frac{(1+\rho)\,var(c_t)}{2(1-\rho)}-\frac{\tau\sigma_l var(l_t)}{2}-\frac{\rho\mu cov(c_t,c_{t-1})}{(1-\rho\mu)^2}-\frac{\tau\sigma_l\rho\mu cov(c_t,l_t)}{(1-\rho\mu)}\right]-1 \tag{36}$$

To demonstrate the relationship between welfare and growth, I first obtain the unconditional moments of the model variables (that are also consistent with the data). I then use these moments to compute u^{mean} and u^{var}. I also measure the total welfare loss due to the shocks in the model as $u^{total}=u^{mean}+u^{var}$. I then repeat this exercise for the calibrations with different degrees of R&D intensity.

The results are reported in Table 6. The two extreme calibrations in the table, produce the following quantitative implications: When R&D's share in labor and income is 2 times its share in the baseline scenario, growth rate also roughly doubles. This, however, comes at the price of higher volatility and consumers are willing to give up roughly one-third of their steady state consumption to avoid this added volatility. If, on the other hand, R&D's share in production and income is much lower, 5 percent of the shares under the baseline calibration, growth rate and welfare losses both fall. The relative welfare gain that is equivalent to 10 percent of steady state consumption costs the economy 2.85 percent of annual growth. The comparison of u^{mean} and u^{var} reveal that a larger portion of welfare effects feed through the variances of the variables. This implies that welfare exercises using only the second-order approximation to the utillity function, while underestimating welfare effects, would also uncover the negative relationship between welfare and growth produced by R&D.

4 Other considerations

In this section, I discuss how the model can be extended to investigate high-low skill wage gap and the tradeoff between the stock of physical capital and the stock of R&D. For brevity and to keep the paper focused, I do not solve these extended versions of the model. I instead discuss some potential inferences that may come out of these alternative frameworks.

4.1 High skill - low skill labor wage gap

In the baseline model, workers engaged in R&D activities and production received the same wage rate. Assume instead that workers are of two types, high-skilled and low-skilled. High-skilled and low-skilled workers are hired by intermediate goods producers to work on R&D and production activities, and they receive the wage rates, $W^h_{j,t}$ and $W^l_{j,t}$, respectively. This reconfiguration allows one to infer the cyclicality of high-low skill wage gap and how this gap relates to the scale of R&D in the economy.

To accomodate heterogenous agents on the supply side of the labor market, first assume that households consist of families with members who possess high and low skills. Assuming disutility of labor is separable across high and low skill workers and letting $L^h_{i,t}$ and $L^l_{i,t}$ denote the amount of labor supplied by these members of family i then the utility function of the household i can be represented as:

$$U_{i,t} = E_t \sum_{t=0}^{\infty} \beta^t \left\{ \ln\left(C_{i,t} - \rho \bar{C}_{t-1}\right) + \tilde{\varphi}_{b,t} B_{i,t+1} - \tau^h \frac{\left(L^h_{i,t}\right)^{1+\sigma_l}}{1+\sigma_l} - \tau^l \frac{\left(L^l_{i,t}\right)^{1+\sigma_l}}{1+\sigma_l} \right\}, \tag{37}$$

In this economy, family i would choose how much high-skill and low-skill labor to supply and would consider family-wide consumption when deciding how much to consume or save. Next, assume that the supply of high and low skill labor are aggregated separately by labor intermediaries and rented out to the intermediate goods producers, and that the wage adjustment costs that households face apply to their composite wage rate given by $W_t = W^h_t L^h_{i,t}/L_{i,t} + W^l_t L^l_{i,t}/L_{i,t}$.[8],[9]

In the symmetric equilibrium, the shares of members with high and low skills would be the same for each family. Assuming that the remaining components of the model are unchanged, the intermediate goods optimality conditions with respect to production labor and R&D can be combined to produce the following:

$$\begin{aligned} W^l_t \eta \nu \ln(\lambda) L^p_{j,t} &= W^h_t \nu \ln(\lambda) \lambda^{\nu RD_{j,t}} F_j + W^h_t + \phi_{rd} W^h_t \left(\frac{RD_{j,t}}{RD_{j,t-1}} - 1\right)\left(\frac{RD_{j,t}}{RD_{j,t-1}}\right) \\ &+ \phi_{rd} E_t\left(W^h_{t+1}\right)\left(\frac{E_t\left(RD_{j,t+1}\right)}{RD_{j,t}} - 1\right)\left(\frac{E_t\left(RD_{j,t+1}\right)}{RD_{j,t}}\right)^2 + \frac{\phi_{rd}}{2} W^h_t \left(\frac{RD_{j,t}}{RD_{j,t-1}} - 1\right)^2 \end{aligned} \tag{38}$$

where $\int_0^1 L^p_{j,t} dj = \left[\int_0^1 \left(L^l_{i,t}\right)^{1/\varphi_{w,t}} di\right]^{\varphi_{w,t}}$ and $\int_0^1 RD_{j,t} dj = \left[\int_0^1 \left(L^h_{i,t}\right)^{1/\varphi_{w,t}} di\right]^{\varphi_{w,t}}$. Here I assume that the fixed cost associated with R&D is monetized by the high-skill labor wage rate. The condi-

[8]One could also assume that wage adjustment costs apply separately to high-skill and low-skill wages. This alternative formulation produces two separate wage Phillips curves that is very similar, when aggregated, to the Phillips curve in my model.

[9]In the optimality conditions with respect to the two different types of labor , $\varphi_{c,t}\varphi_{l,t}\tau^h\left(L^h_{i,t}\right)^{\sigma_h} = \Lambda_t \Omega_{h,t} W^h_{i,t}$ and $\varphi_{c,t}\varphi_{l,t}\tau^l\left(L^l_{i,t}\right)^{\sigma_l} = \Lambda_t \Omega_{h,t} W^l_{i,t}$, the parameters τ^h and τ^l can be fixed as follows to ensure that the steady state supply of high-skilled and low-skilled labor are equal to RD and L^p: $\tau^h = \frac{\Omega_h(1-\alpha)W^h}{RD^{\sigma_l} PC(1-\rho)}$ and $\tau^l = \frac{\Omega_h(1-\alpha)W^l}{(L^p)^{\sigma_l} PC(1-\rho)}$.

tion above then can be used to derive the following expression for the high-low skill wage gap:

$$\frac{W_t^h}{W_t^l} = \frac{\eta \nu \ln(\lambda) L_{j,t}^p}{1 + \nu \ln(\lambda) \lambda^{\nu RD_{j,t}} F_j + AC_{j,t}} \tag{39}$$

where $AC_{j,t}$ represents the adjustment costs associated with R&D. Equation (39) shows that the relative wages of the two types of labor are inversely related to their levels. Specifically, if intermediate goods producers use a higher amount of production labor, the wage gap widens. Conversely, wage gap shrinks when firms hire more R&D workers. The cyclicality of wage gap would, therefore, depends on the relative cyclicality of R&D and production labor. If a shock prompts a stronger procyclical response of R&D compared to production labor, for example, wage gap would become countercyclical. While I do not simulate this model, I should mention that the baseline parameter values imply that the high-skill wage rate to low-skil wage rate ratio (my measure of the wage gap) is 1.73. This figure is similar to, albeit slightly lower than, the wage gap in Bureau of Labor Statistics (2017) , 2.05 for men and 2.39 for women, if high-skills and low-skills correspond to a bachelor's degree (and above), and a high school diploma, respectively.[10]

4.2 Physical capital - R&D stock tradeoff

Throughout the paper R&D process is modeled as a labor intensive process. In this section, I consider the other extreme scenario where R&D uses only investment. Here R&D investment can be interpreted as spending on research labs that include various machinery, tools and software used in the R&D process. While it is more reasonable to assume that R&D requires both high-skill labor and investment, the framework I offer here can be combined with my baseline model to obtain broader inferences. The objective of this section is to gauge the tradeoff that firms face between physical and R&D capital.

To observe this tradeoff, first assume that the efficiency of labor, μ_t', and hence the growth rate of the economy is now determined by the rate at which R&D capital, K_t^{rd}, is accumulated so that

[10]The disparity is smaller if wage gap is measured across a broader time period in the BLS data and if high-skilled workers are the ones with a bachelor's degree only.

the production function and the efficiency of labor are given by,

$$Y_t = A_t K_t^{\alpha} \left(\mu_t' L_t\right)^{1-\alpha} \tag{40}$$

$$\mu_t' = \frac{K_t^{rd}}{K_{t-1}^{rd}} = \left(1-\delta^{rd}\right) + \nu \frac{RD_t}{K_{t-1}^{rd}} \tag{41}$$

where δ^{rd} represents the depreciation rate of R&D capital. To simplify the description of the symmetric equilibrium in the economy, I drop the subscript j, I assume that intermediate goods producers do not face any adjustment costs when changing the level of R&D and that the capital utilization rate Z_t is equal to 1. I do, however, discuss the potential effects of R&D adjustment costs below. Combining the optimality conditions with respect to physical capital and R&D in this economy would yield the following expression:

$$\frac{K_t}{K_t^{rd}} = \frac{\alpha}{(1-\alpha)\,\nu} \frac{Q_t^{rd}}{Q_{t-1} R_t^k} \left(1 + \frac{\nu F}{K_{t-1}^{rd}} + AC_t\right) \tag{42}$$

where Q_t^{rd} represents the cost that firms face when converting R&D spending to R&D capital and it is assumed to be exogenously determined for simplicity. I assume again that the intermediate good producers face a fixed cost with F representing the scale parameter and that these costs are monetized by Q_t^{rd}. The tradeoff expression above implies that an economy shifts funds away from capital investment to R&D and it accumates more R&D stock relative to capital stock when the unit costs of R&D, $Q_t^{rd}\left(1+\nu F/K_{t-1}^{rd}\right)$, drop relative to the unit costs of physical capital, $Q_{t-1}R_t^k$. In addition to the costs incurred when converting R&D investment to capital, firms also incur higher fixed costs when they do more R&D relative to their R&D stock. Also, the production process becomes more R&D intense if the success rate of R&D, ν, and the share of labor is higher. If the firm incurs an additional R&D adjustment cost (captured by AC_t above), R&D would be more costly. Shocks that have an asymmetric effect on the returns to capital and the price of capital relative to R&D conversion costs would also cause a shifting of funds away from or towards R&D spending. This would slow-down or accelerate economic growth.

5 Concluding remarks

In this paper, I identified a mechanism that forms a positive link between R&D activity and labor supply. According to this mechanism, the cyclicality of R&D and the amplitude of output responses to structural shocks depend on the cyclicality of labor supply. R&D activity becomes more strongly procyclical and amplifies the reponse of output for shocks that generate a procyclical response of labor supply. The conclusions are reversed if labor supply is countercyclical. Further simulations revealed that this link between R&D and labor supply becomes weaker when the steady state share of R&D expenditures in the economy is higher (when R&D intensity is higher), the rate at which innovations spillover across firms is higher, and when costs required to adjust the levels of R&D within firms is larger. In these cases, R&D follows total output/spending more closely, becoming more procyclical and increasing output volatility. The first relationship mentioned above (relationship between R&D intensity and output volatility) implies that the steeper path of growth resulting from higher R&D activity entails higher economic volatility. Further exercises showed that this higher volatility had substantial welfare consequences.

In the last part of the paper, I elaborated on two natural extentions to my paper: alternative formulations that distinguish between high-skill and low-skill labor, and that treat R&D as a capital intensive process instead of a labor-intensive process. While I offer suggestions on how model dynamics could change in these alternatie economies, it would be interesting for future work to study the quantitative implications of these formulations not only for tradeoff between growth and output volatility but also for income distribution.

I should point out that by investigating the effects of R&D, I am focusing on only the input part of the innovation process. While my model includes a parameter that captures the success rate of R&D, this parameter value is implicitly determined in the caibration exercises. Modelling the relationship between innovation input and output more rigorously could lead to unique inferences. For example, one could postulate that if an economy allocates more resources to R&D, the chances that the R&D activity is successful in producing a useful innovation increases. It could be interesting to incorporate these potential mechanisms into DSGE models to study short-term dynamics and test their strength empirically.

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Appendix A.The Log-linearized Model

This appendix lists the log-linearized equations that describe the optimality conditions, resrource constraints and the evolution of variables in the model. These equations are derived by log-linearizing all the variables in the equilibrium conditions around their steady state values. Below, lower case letters with time subscripts represent deviations from steady state and capital letters without time subscripts denote steady state values. The linearized equations can be listed as follows:

Consumption demand and labor supply:

$$\begin{aligned} c_t = {} & \left(\frac{1}{1+\rho\mu}\right) E_t c_{t+1} + \left(\frac{\rho\mu}{1+\rho\mu}\right) c_{t-1} \\ & - \left(\frac{1-\rho\mu}{1+\rho\mu}\right) \left[r_{t+1} - E_t \pi_{t+1} + \Theta \varphi_{b,t}\right] - \left(\frac{\rho\mu}{1+\rho\mu}\right) (\mu_t - \mu_{t-1}) \end{aligned} \tag{A.1}$$

$$\frac{1}{1-\rho\mu} \left[c_t - \rho\mu \left(c_{t-1} + \mu_{t-1}\right)\right] + \sigma_l l_t = w_t - p_t \tag{A.2}$$

where Θ is the steady state risk spread.

External finance premium:

$$E_t r^k_{t+1} = E_t r_{t+1} + \varphi_{b,t} \tag{A.3}$$

Wage inflation:

$$\begin{aligned} \pi^w_t - \iota_w \pi_{t-1} = {} & \beta \left(E_t \pi^w_{t+1} - \iota_w \pi_t\right) \\ & + \frac{\varphi_w}{\phi_w (\varphi_w - 1)} \left[\sigma_l l_t + \frac{\left[c_t - \rho\mu \left(c_{t-1} + \mu_{t-1}\right)\right]}{1-\rho\mu} - (w_t - p_t) + (1 - \Omega_h) \varphi_w \varphi_{w,t}\right] \end{aligned} \tag{A.4}$$

where φ_w represents the gross mark-up of real wages over the steady state marginal rate of substitution.

Production function:

$$y_t = a_t + \alpha \left(z_t + k_t\right) + (1-\alpha) m_t \tag{A.5}$$

Labor input:

$$m_t = \mu_t + l_t^p \tag{A.6}$$

Labor in production related activities:

$$\frac{L^p}{L} l_t^p = l_t - \frac{RD}{L} rd_t \tag{A.7}$$

Effectiveness of labor:

$$\mu_t = \nu \ln(\lambda) RDrd_t \tag{A.8}$$

R&D:

$$\eta \nu \ln(\lambda) l_t^p = [\nu \ln(\lambda)]^2 \mu F \frac{RD}{L^p} rd_t + \frac{\phi_{rd}}{L^p} [rd_t - rd_{t-1} + \beta E_t (rd_t - E_t rd_{t+1})] \tag{A.9}$$

Phillips curve:

$$\begin{aligned} \pi_t - \iota_p \pi_{t-1} = {} & \beta (E_t \pi_{t+1} - \iota_p \pi_t) + \frac{(W/P)RD/Y}{\phi_p(\varphi_p - 1)} (rd_t + w_t - p_t) \\ & + \frac{\Omega_p - \frac{W}{P} RD/Y}{\phi_p(\varphi_p - 1)} \left[(1-\alpha)(w_t - p_t) + \alpha \left(r_t^k + q_{t-1} \right) - \alpha z_t - a_t - \nu (1-\alpha) \ln(\lambda) \mu^{\alpha - 1} rd_t \right] \\ & + \frac{\Omega_p}{\phi_p(\varphi_p - 1)} \frac{\varphi_p}{(\varphi_p - 1)} \varphi_{p,t} \end{aligned} \tag{A.10}$$

where φ_p represents the gross mark-up of prices over marginal cost. Combining the linearized conditions for labor and capital demand yields the relative demand for these factors as a function of their relative cost:

$$w_t - (r_t^k + q_{t-1}) = k_t - l_t^p + z_t \tag{A.11}$$

where the steady state utilization rate is equal to 1 and the capacity utilization level parameter κ_z is equal to the steady state level of returns to capital, R^k. Combining the linearized version of the optimality conditions with respect to capital and the utilization rate produces the following:

$$z_t = \frac{1}{\varpi} r_t^k \tag{A.12}$$

Returns to capital:

$$r_t^k = [1-(1-\delta)]/R^k mpk_t + (1-\delta)/R^k q_t - q_{t-1} \tag{A.13}$$

Marginal product of capital:

$$mpk_t = [-(z_t + k_t - m_t) + w_t] \tag{A.13}$$

Investment Euler equation:

$$i_t = \frac{1}{(1+\beta\mu)} i_{t-1} + \frac{\beta\mu}{(1+\beta\mu)} E_t i_{t+1} + \frac{q_{t-1} - p_{I,t} + \varphi_{I,t}}{\phi_k(1+\beta\mu)} + \frac{\mu(\mu_{t-1} - \beta\mu_t)}{(1+\beta\mu)} \tag{A.13}$$

Evolution of capital stock:

$$k_t = \left(\frac{1-\delta}{\mu}\right)(k_{t-1} - \mu_{t-1}) + \frac{\mu - (1-\delta)}{\mu}(i_t - \mu_t + \varphi_{I,t}) + \mu_t \tag{A.14}$$

Taylor rule:

$$r_t = r_s r_{t-1} + (1-r_s)\left[r_\pi \pi_t + r_y y_t + r_{\Delta y}(y_t - y_{t-1})\right] + \varphi_{r,t} \tag{A.15}$$

Feasibility condition:

$$y_t = \frac{C}{Y} c_t + \frac{G}{Y} \varphi_{g,t} + \frac{I}{Y}(i_t + p_{I,t}) \tag{A.16}$$

The evolution of shocks to liquidity demand, investment specific technology, monetary policy, government spending, respectively:

$$\varphi_{b,t} = (1-\rho_b)\Theta + \rho_b \varphi_{b,t-1} + \eta_{b,t} \tag{A.17}$$

$$\varphi_{I,t} = \rho_I \varphi_{I,t-1} + \eta_{I,t} \tag{A.18}$$

$$\varphi_{r,t} = \rho_r \varphi_{r,t-1} + \eta_{r,t} \tag{A.19}$$

$$\varphi_{g,t} = \rho_g \varphi_{g,t-1} + \eta_{g,t} \tag{A.20}$$

where parameters ρ represent the persistence of the shocks and η_t are the i.i.d innovations. The two elasticity of substitution variables, $\varphi_{w,t}$ and $\varphi_{p,t}$, and the relative price of investment goods $p_{I,t}$ and the productivity shock evolve as follows:

$$\varphi_{w,t} = (1-\rho_w)\,\varphi_w + \rho_w \varphi_{w,t-1} + \eta_{w,t} \tag{A.21}$$

$$\varphi_{p,t} = (1-\rho_p)\,\varphi_p + \rho_p \varphi_{p,t-1} + \eta_{p,t} \tag{A.22}$$

$$p_{I,t} = \rho_{pi} p_{I,t-1} + \eta_{pi,t} \tag{A.23}$$

$$a_t = \rho_a a_{t-1} + \eta_{a,t} \tag{A.24}$$

Table 1. R&D and industry-level volatility

	Production	Total value added	Compensation of employees	Taxes on production and imports less subsidies	Gross operating surplus	Total intermediate inputs	Energy inputs	Materials inputs	Purchased-services inputs	non-R&D employees
All industries	3.15	1.68	2.34	2.26	1.69	5.35	17.03	8.08	3.43	1.57
Low-R&D industries	3.04	1.62	1.95	2.10	2.16	5.25	15.95	7.86	3.27	1.40
High-RD industries	3.79	2.36	3.95	4.68	4.80	6.26	24.78	9.85	4.75	2.62
Chemical products	6.46	3.85	2.17	8.73	6.83	11.23	26.41	12.54	10.30	1.99
Computers	7.34	8.04	6.43	5.07	22.96	11.68	34.47	12.93	11.91	4.36
Information	3.62	4.61	5.38	4.09	10.11	7.97	29.45	9.82	7.73	2.30
Professional services	3.18	3.08	4.14	13.25	6.18	5.01	22.05	10.63	4.81	2.65
Transportation	5.21	3.53	3.23	14.35	8.28	8.08	28.31	9.86	4.74	2.06

Notes: The statistics in the first nine columns are based on data from the Bureau of Economic Analysis, Integrated Industry-Level Production Account (KLEMS) database. These statistics correspond to the standard deviation of the growth rates of the annual variables listed in the column headings. The time period is 1997 to 2017. Before measuring the standard deviations, the nominal variables are deflated by using the GDP deflator. The last column is measured by using the total number of all employees in production and non-supervisory roles (source: Bureau of Labor Statistics data from the Current Employment Statistics database, quarterly sample period: 1964Q3-2017Q3). The high R&D industries are the ones listed in the bottom rows. All remaining industries are designated as low-R&D.

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Table 2. Model versus data moments

	Data	Model
Correlations with output		
Investment	0.80	0.76
Consumption	0.90	0.86
Labor	0.00	-0.15
Interest rates	0.50	0.19
Inflation	0.03	-0.03
Standard deviation relative to output		
investment	3.619	3.569
consumption	0.927	0.949
labor	0.474	0.693
interest rates	0.744	0.87
inflation	0.43	0.643

Notes:The data moments are computed by using quarterly data (spanning 1990Q1 to 2018Q3) from the Federal Reserve Bank of St. Louis, FRED database. Output, investment and consumption are measured as the Real Gross Domestic Income, Real Private Domestic Investment and Real Personal Consumption Expenditures, respectively. Labor, interest rates and inflation are measured as total number of civilian workers, the effective federal funds rate, and the GDP deflator, respectively. All data series are seasonally adjusted, first-differenced and demeaned.

Table 3. Growth and volatility

Panel A. Amplitude of Impulse Responses

		Shocks					
		Productivity	Gov. Spending	Bond Spread	Investment	Monetary policy	Price
Baseline	Output	0.58	0.16	1.21	0.27	0.57	1.29
	Inflation	0.53	0.03	0.58	0.02	5.33	0.91
	Consumption	0.52	0.05	1.81	0.22	0.77	1.72
	Investment	1.82	0.28	11.04	1.45	0.74	0.95
	Labor	0.62	0.07	0.28	0.08	0.20	0.75
High R&D	Output	1.05	0.15	4.05	0.72	0.53	2.09
	Inflation	0.66	0.03	0.16	0.10	5.32	1.21
	Consumption	0.62	0.03	2.33	0.17	0.69	1.49
	Investment	4.99	0.46	28.75	4.48	0.86	7.80
	Labor	0.76	0.09	0.92	0.16	0.24	0.83
Low R&D	Output	0.50	0.16	0.80	0.20	0.60	1.13
	Inflation	0.54	0.03	0.62	0.03	5.35	0.82
	Consumption	0.36	0.12	1.88	0.26	0.84	1.73
	Investment	2.20	0.42	9.75	1.09	0.51	1.00
	Labor	0.53	0.06	0.16	0.06	0.18	0.66

Panel B. Volatility and Growth

	Baseline	High R&D	Low R&D
Output volatility	0.157	0.231	0.142
Inflation volatility	0.101	0.127	0.102
Consumption volatility	0.149	0.157	0.132
Investment volatility	0.562	1.150	0.627
Labor volatility	0.109	0.154	0.095
Quarterly growth	0.75%	1.89%	0%

Notes: The numbers in Panel A represent the absolute value of the minimum/maximum responses of the variables (listed in the rows) to 1 percent structural shocks (shocks listed in the columns). In the high R&D and low R&D economies the share of R&D in total labor is 2.5 times and 0.0001 times its share in the baseline economy, respectively. The variance and persistence parameters of the shock processes are calibrated to 0.01 and 0.9m, respectively, to obtain the simulated variances displayed in Panel B.

Table 4. R&D Diffusion and volatility

Panel A. Amplitude of Impulse Responses

		Shocks					
		Productivity	Gov. Spending	Bond Spread	Investment	Monetary policy	Price
Baseline	Output	0.58	0.16	1.21	0.27	0.57	1.29
	Inflation	0.53	0.03	0.58	0.02	5.33	0.91
	Consumption	0.52	0.05	1.81	0.22	0.77	1.72
	Investment	1.82	0.28	11.04	1.45	0.74	0.95
	Labor	0.62	0.07	0.28	0.08	0.20	0.75
High diffusion	Output	0.86	0.15	1.47	0.32	0.54	1.61
	Inflation	0.63	0.04	0.55	0.02	5.35	1.04
	Consumption	0.82	0.04	1.48	0.25	0.73	2.04
	Investment	2.25	0.31	11.77	1.60	0.69	1.64
	Labor	0.82	0.10	0.48	0.10	0.27	0.88
Low diffusion	Output	0.19	0.19	1.02	0.21	0.56	0.46
	Inflation	0.03	0.03	0.74	0.06	5.49	0.15
	Consumption	0.48	0.13	2.16	0.18	0.74	0.74
	Investment	0.97	0.20	10.63	1.32	0.75	0.35
	Labor	0.11	0.01	0.07	0.01	0.04	0.13

Panel B. Volatility and Growth

	Baseline	High diffusion	Low diffusion
Output volatility	0.157	0.209	0.073
Inflation volatility	0.101	0.117	0.059
Consumption volatility	0.149	0.202	0.111
Investment volatility	0.562	0.633	0.425
Labor volatility	0.109	0.151	0.025

Notes: The numbers in Panel A represent the absolute value of the minimum/maximum responses of the variables (listed in the rows) to 1 percent structural shocks (shocks listed in the columns). In the high diffusion and low diffusion economies the diffusion rate parameter η is set equal to 0.01 and 0.97, respectively. The variance and persistence parameters of the shock processes are calibrated to 0.01 and 0.9m, respectively, to obtain the simulated variances displayed in Panel B.

Table 5. R&D adjustment costs and volatility

Panel A. Amplitude of Impulse Responses

		Shocks: Productivity	Gov. Spending	Bond Spread	Investment	Monetary policy	Price
Baseline	Output	0.58	0.16	1.21	0.27	0.57	1.29
	Inflation	0.53	0.03	0.58	0.02	5.33	0.91
	Consumption	0.52	0.05	1.81	0.22	0.77	1.72
	Investment	1.82	0.28	11.04	1.45	0.74	0.95
	Labor	0.62	0.07	0.28	0.08	0.20	0.75
High adjustment costs	Output	0.81	0.16	0.08	0.29	0.42	1.32
	Inflation	0.57	0.04	0.26	0.02	3.57	1.28
	Consumption	0.75	0.02	0.20	0.23	0.57	1.52
	Investment	2.40	0.02	0.97	1.49	0.56	2.01
	Labor	0.67	0.15	0.01	0.09	0.18	0.49
Low adjustment costs	Output	0.19	0.19	1.02	0.21	0.56	0.46
	Inflation	0.03	0.03	0.74	0.06	5.49	0.15
	Consumption	0.48	0.13	2.16	0.18	0.74	0.74
	Investment	0.97	0.20	10.63	1.32	0.75	0.35
	Labor	0.11	0.01	0.07	0.01	0.04	0.13

Panel B. Volatility and Growth

	Baseline	High adjustment costs	Low adjustment costs
Output volatility	0.157	0.180	0.073
Inflation volatility	0.101	0.109	0.059
Consumption volatility	0.149	0.172	0.111
Investment volatility	0.562	0.590	0.425
Labor volatility	0.109	0.127	0.025

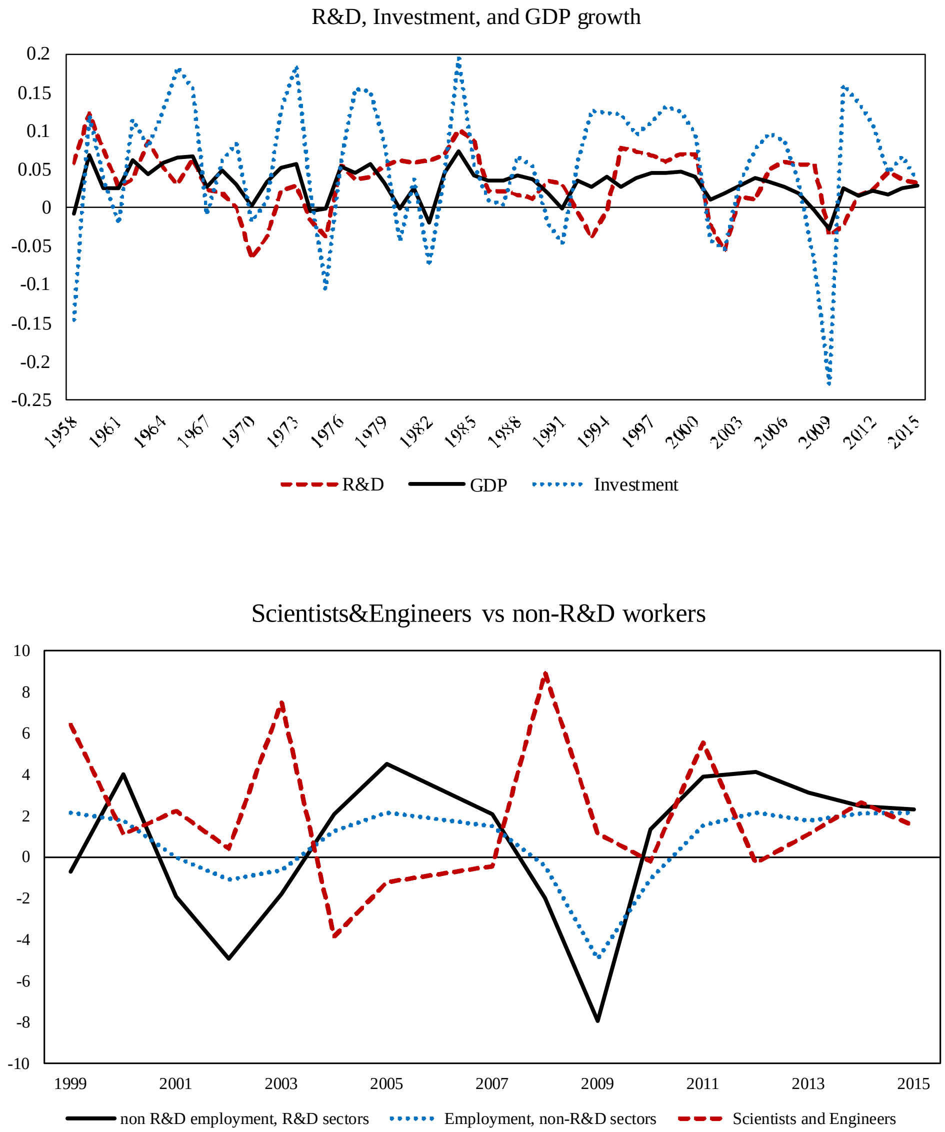
Notes: The numbers in Panel A represent the absolute value of the minimum/maximum responses of the variables (listed in the rows) to 1 percent structural shocks (shocks listed in the columns). In the high and low adjustment cost economies the R&D adjustment cost parameter ϕ_{rd} is set equal to 7 and 1, respectively. The variance and persistence parameters of the shock processes are calibrated to 0.01 and 0.9m, respectively, to obtain the simulated variances displayed in Panel B.

Table 6. Welfare loss versus growth

R&D intensity/Baseline R&D intesity	u-mean	u-var	u-total	annualized growth rate
5%	-0.002	-0.029	-0.031	0.15%
25%	-0.0131	-0.0413	-0.0544	0.75%
50%	-0.029	-0.062	-0.090	1.51%
75%	-0.046	-0.087	-0.133	2.27%
100% (baseline)	-0.067	-0.118	-0.184	3%
125%	-0.092	-0.152	-0.244	3.8%
150%	-0.124	-0.190	-0.314	4.59%
200%	-0.225	-0.275	-0.500	6.16%

Notes: u- mean and u-var denote the effects of shocks on the utility of consumers that feed through the unconditional means and variances, respectively, of consumption and labor. The rows correspond to economies with higher and lower shares of R&D in labor compared to the baseline economy. In the 5% percent economy, for example, R&D's share in total labor is 5% its share in the baseline case. The last column shows the steady state output growth rates that correspond to the different shares of R&D.

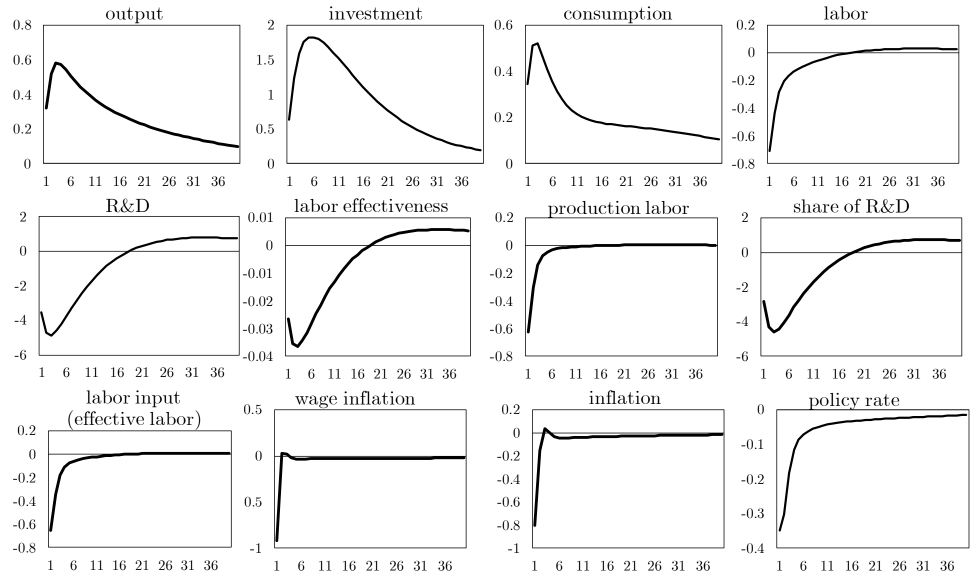
Figure 1. Cyclicality of R&D and employment by type



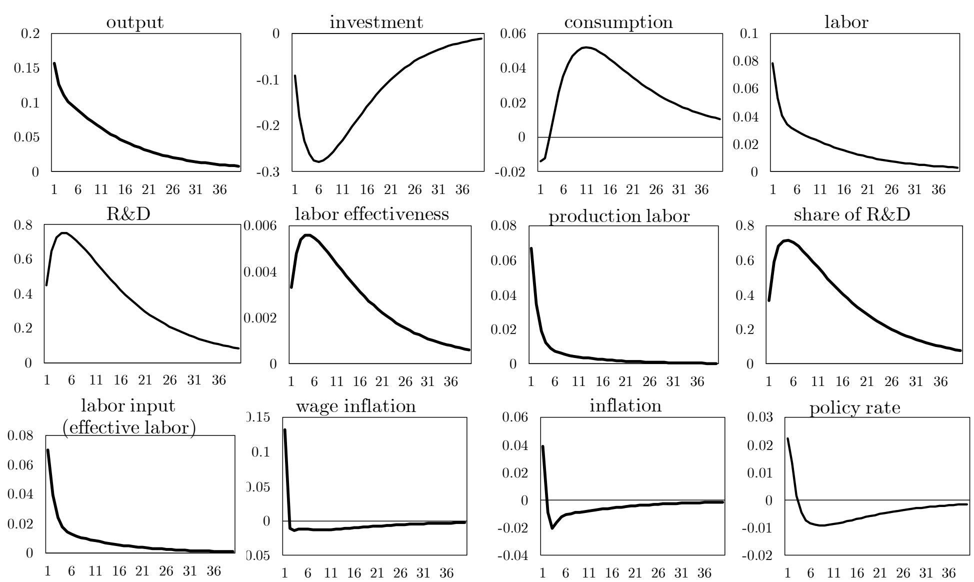
Notes: R&D data and the number of scientists are obtained from the National Science Foundation's BRDIS and SIRD databases. GDP and Investment are in real terms and total R&D spending is deflated by using the GDP deflator. GDP, Investment and the non-R&D workers (workers employed in production and non-supervisor roles) are obtained from the Federal Reserve Bank of St. Louis, FRED database.

Figure 2. Responses to productivity and government spending shocks

Productivity shock

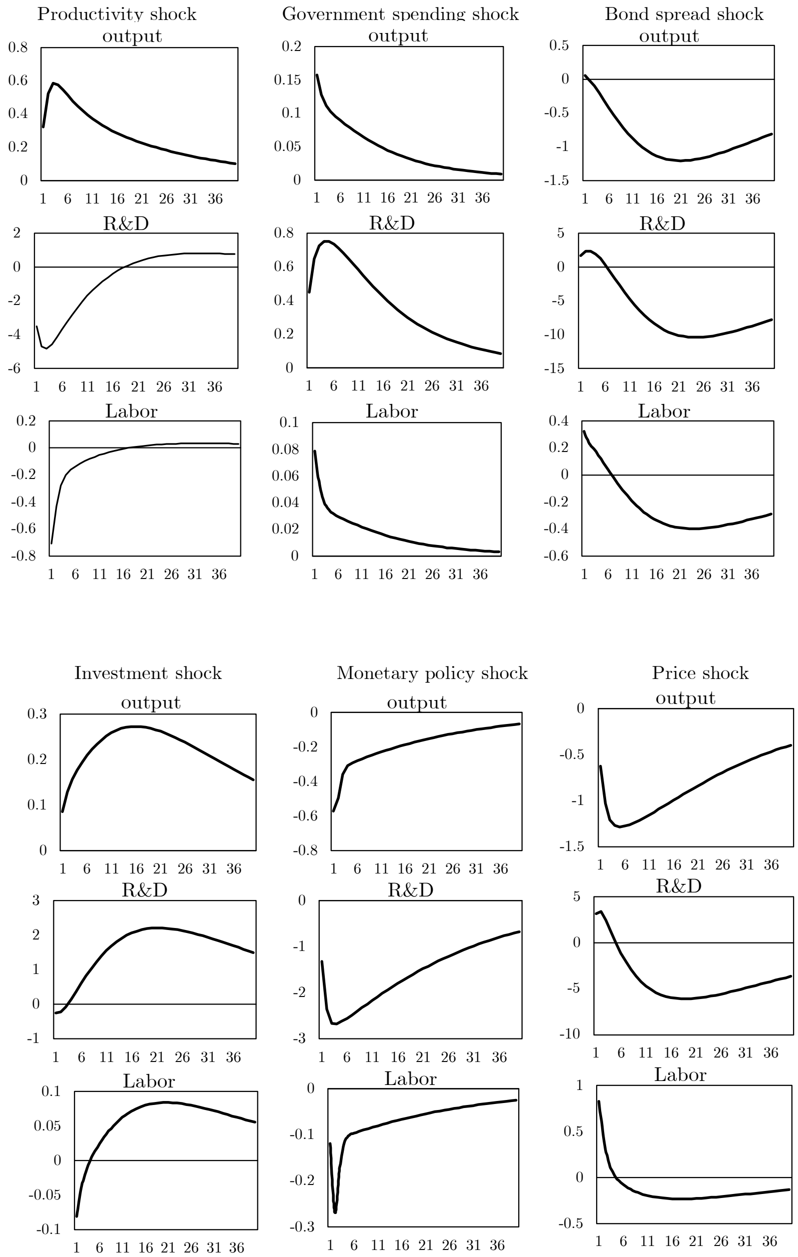


Government spending shock



Note: The figure displays the responses (percentage deviations from steady state) of model variables to a one percent productivity and government spending shock.

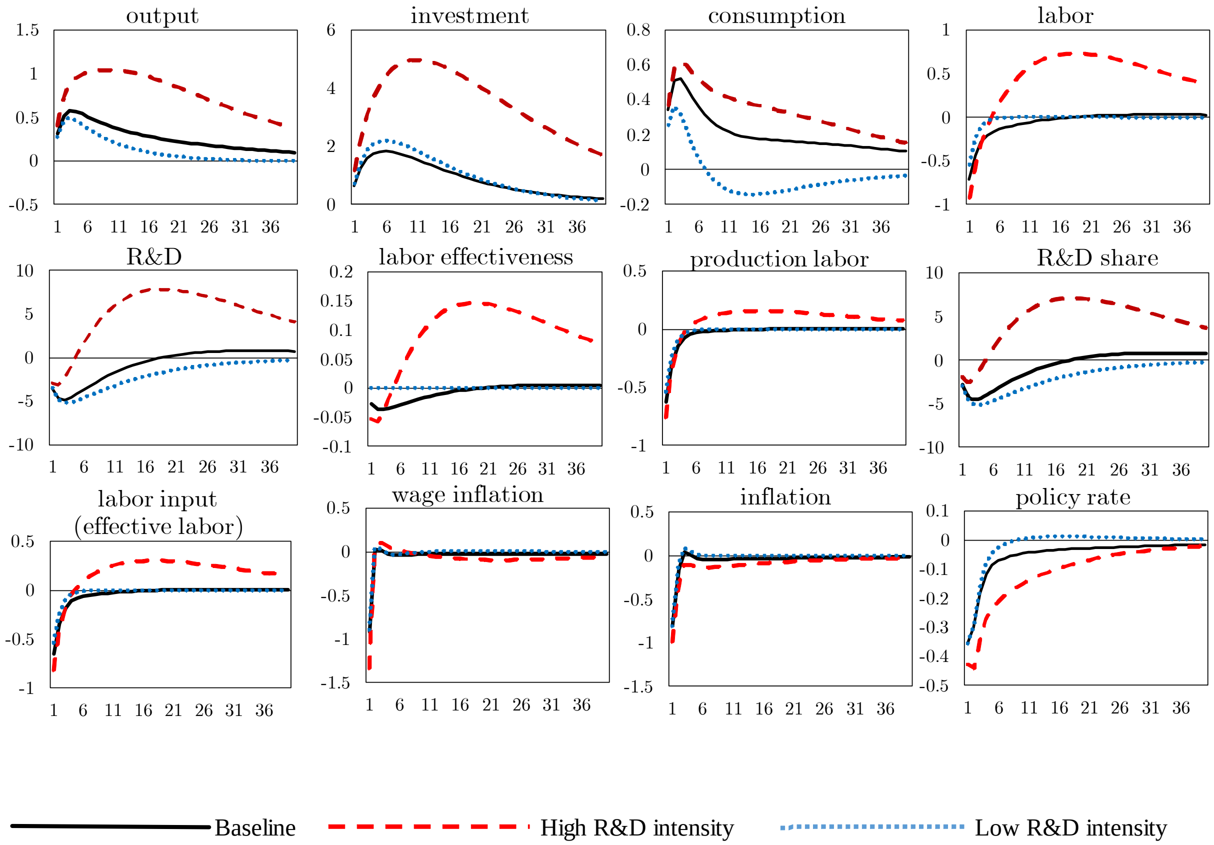
Figure 3. Other shocks



Note: The figure displays the responses (percentage deviations from steady state) of variables to a one percent shock.

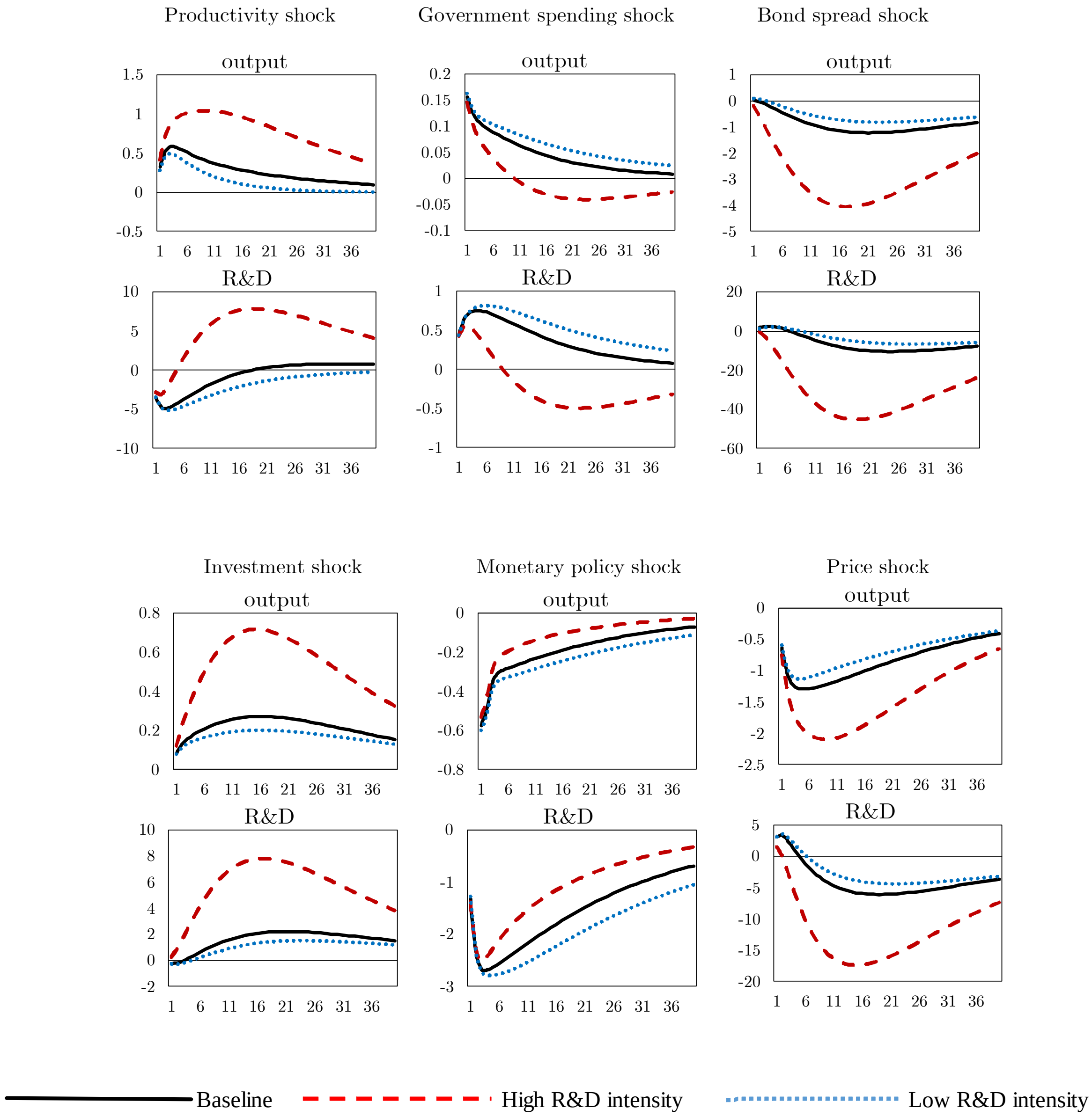
Figure 4. R&D intesity

Productivity shock



Note: The figure displays the responses (percentage deviations from steady state) of variables to a one percent productivity shock. In the high R&D and low R&D economies the share of R&D in total labor is 2.5 times and 0.0001 times its share in the baseline economy, respectively.

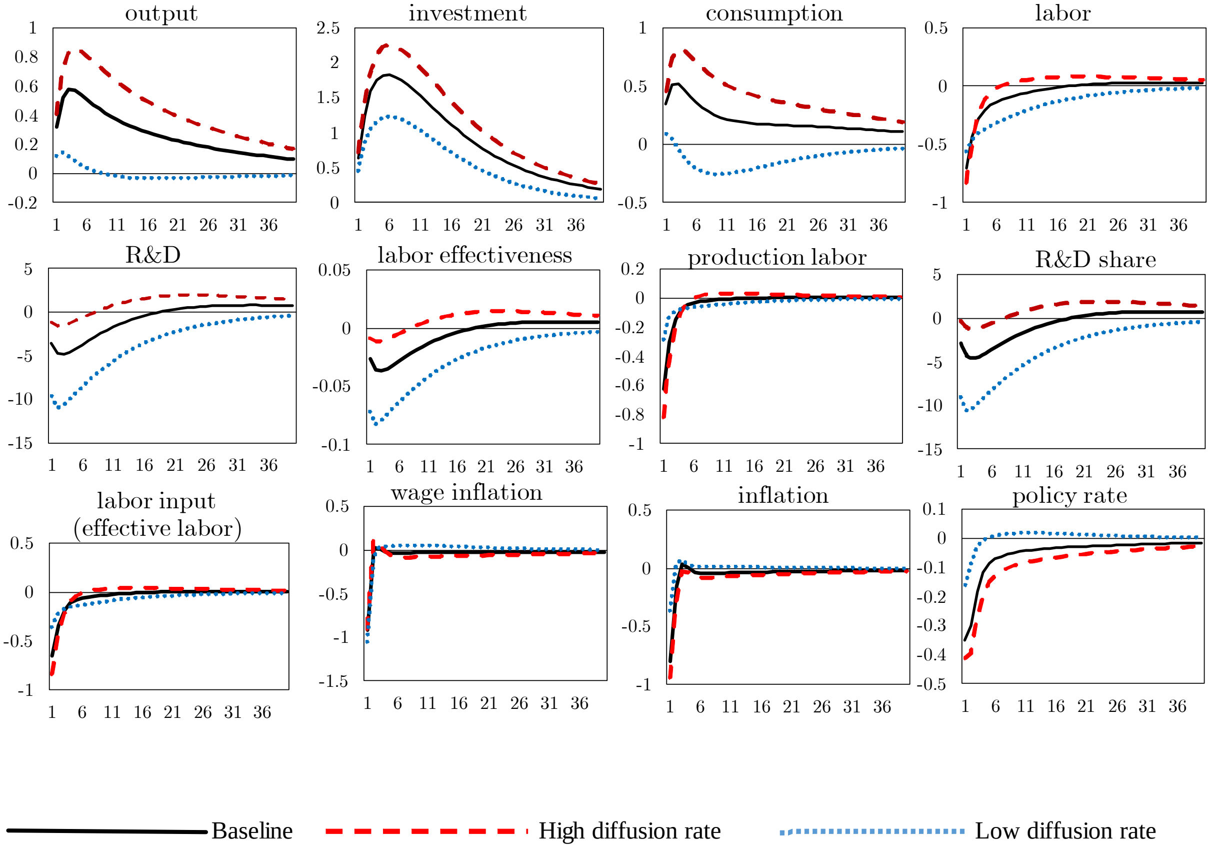
Figure 5. R&D intensity, other shocks



Notes: The figure displays the responses (percentage deviations from steady state) of variables to a one percent shock. In the high R&D and low R&D economies the share of R&D in total labor is 2.5 times and 0.0001 times its share in the baseline economy, respectively.

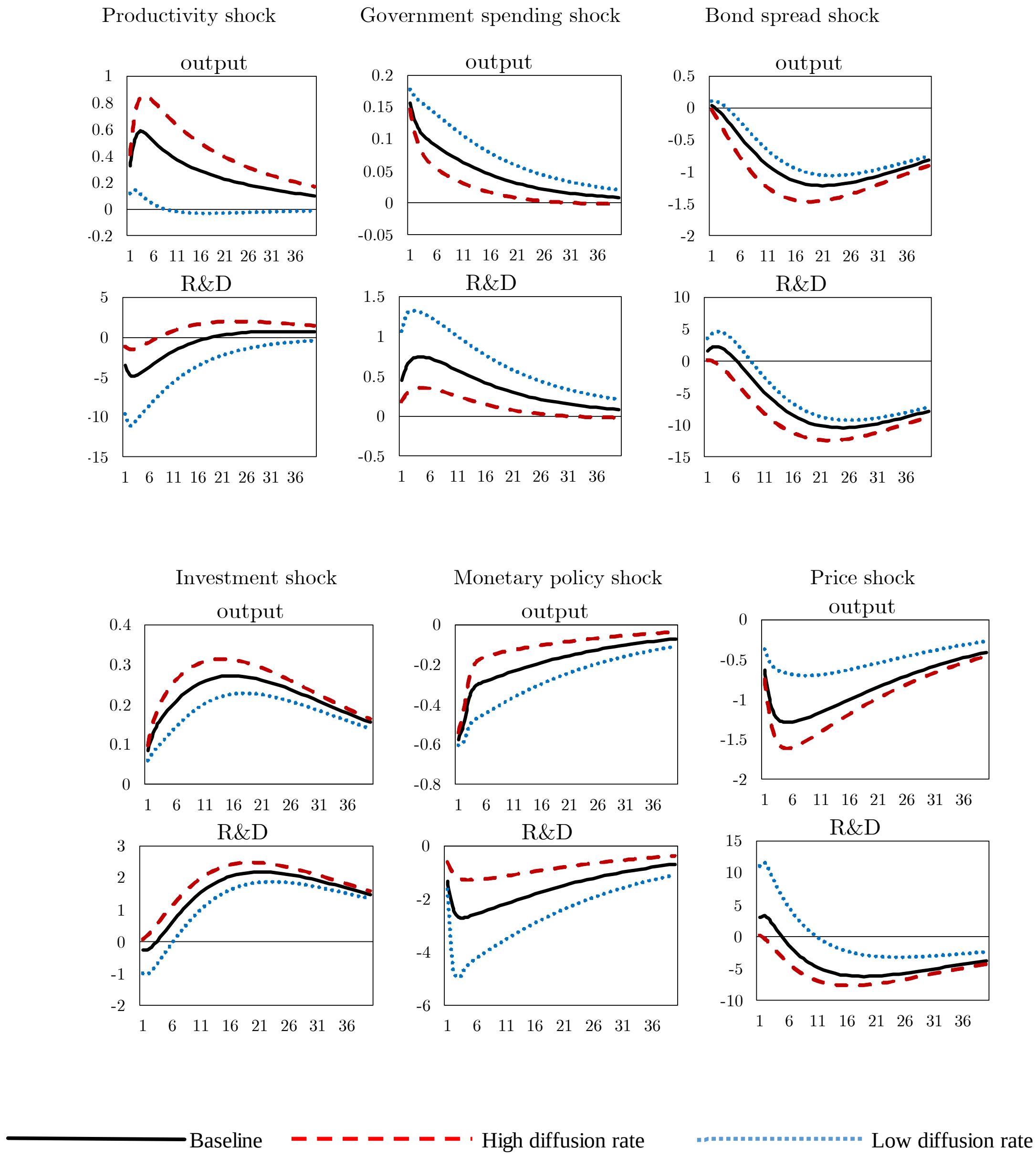
Figure 6. R&D diffusion

Productivity shock



Notes: The figure displays the responses (percentage deviations from steady state) of variables to a one percent productivity shock. In the high diffusion and low diffusion economies the diffusion rate parameter η is set equal to 0.01 and 0.97, respectively.

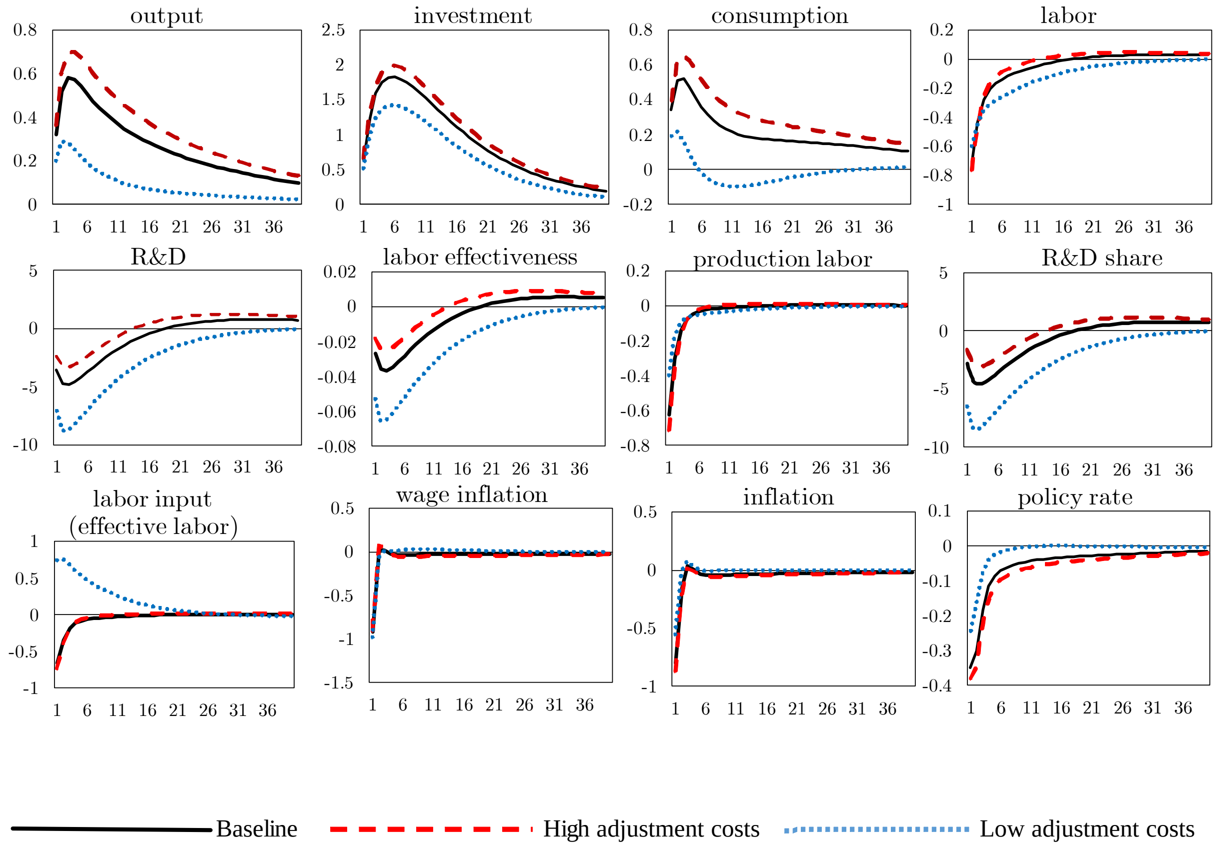
Figure 7. R&D diffusion, other shocks



Notes: The figure displays the responses (percentage deviations from steady state) of variables to a one percent shock. In the high diffusion and low diffusion economies the diffusion rate parameter η is set equal to 0.01 and 0.97, respectively.

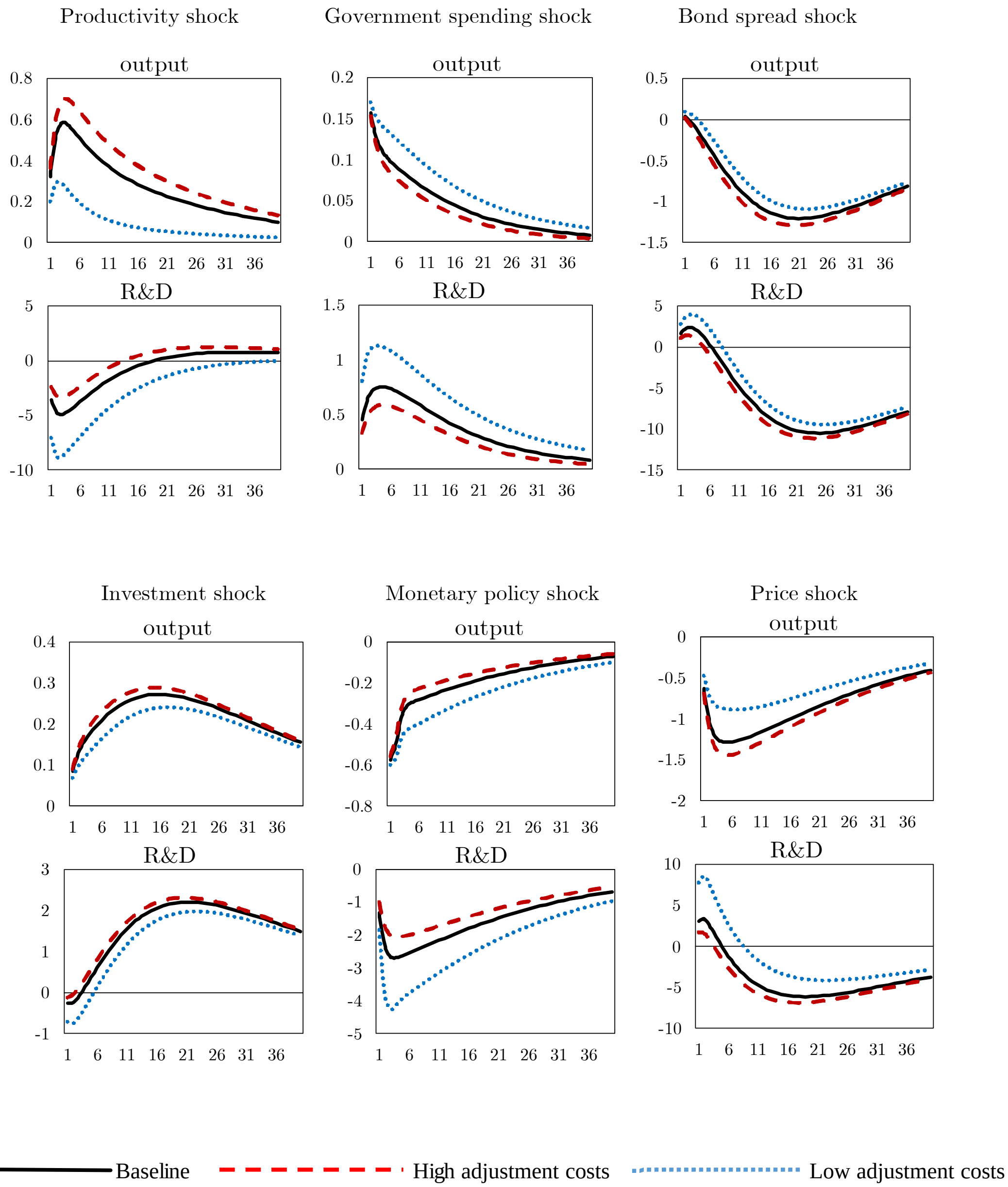
Figure 8. R&D adjustment costs

Productivity shock



Notes: The figure displays the responses (percentage deviations from steady state) of variables to a one percent productivity shock. In the high and low adjustment cost economies the R&D adjustment cost parameter ϕ_{rd} is set equal to 7 and 1, respectively.

Figure 9. R&D adjustment costs, other shocks



Notes: The figure displays the responses (percentage deviations from steady state) of variables to a one percent shock. In the high and low adjustment cost economies the R&D adjustment cost parameter ϕ_{rd} is set equal to 7 and 1, respectively.