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R&D, innovation spillover and business cycles

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Abstract

This paper shows that technology shocks have the largest impact on economies when industries adopt innovations of other industries at a high rate, if costs of adopting new technologies and adjusting R&D expenditures are low, and if innovators face a high degree of competition. It is not the level but the spillover of innovations across industries that is the key determinant of these findings. Under the conditions mentioned above, R&D becomes less procyclical and smoother along the business cycle yet R&D driven innovations have a larger impact on output since these innovations spillover at a higher rate. These inferences are drawn from a dynamic stochastic general equilibrium framework describing a real economy with endogenous growth. The latter feature allows us to infer the welfare implications of R&D processes.

Keywords: Research and development, spillover effects, endogenous growth.

JEL Classification: E30, E32, O30, O33.

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1 Introduction

The past five decades of evidence has revealed that Research and Development (R&D) plays a critical role in productivity growth and the overall growth of economies (c.f. Griliches, 1973). This inference, now a stylized fact, originating mostly in the growth literature, has also influenced research on short-term macroeconomic dynamics as studies have analyzed the fluctuations of R&D, and the implications for productivity, along the business cycle. The findings for the cyclicality of R&D in this literature are inconclusive. While some studies (Aghion and Saint-Paul, 1998 and Aghion et al., 2012) find that R&D is counter-cyclical, others (Himmelberg and Petersen, 1994; Hall and Lerner, 2010; Barlevy, 2007) find otherwise. These studies are also different in terms of the main factor that generates R&D cyclicality. Regardless of these differences, the direction of casuality in all these studies is from the stage of the business cycle to R&D spending. In this paper, we approach the subject from the opposite direction and investigate how R&D activity affects business cycles. In so doing, we incorporate various features of R&D processes that are inferred from microdata into a general equilibrium framework. Out of these features, the diffusion of innovation that results from R&D type activities plays the central role. The recent trend towards R&D outsourcing motivate this emphasis (see below for a discussion).

We model a two-tier, vertically-related, industrial system consisting of innovators and intermediate good producers in which innovation not only passes-through within an industry but also across industries. The inter-industry transfer of technology occurs through both embodied and disembodied technologies. The innovators sell input goods to intermediate goods producers. These input goods embody the improvement in technology that is a product of the innovators' R&D activity. At the same time, intermediate good producers directly adopt the disembodied technologies from innovators. These adopted technologies supplement the intermediate goods producers' existing R&D process and allows them to increase their own efficiency in producing the input good. This internal production is larger than the external purchases of input goods. To visualize our model, imagine a producer, say Apple, hires engineers and scientists to develop software and conduct R&D type activities while at the same time outsourcing some of the software development to technology companies such as Infosys. The downstream spillover of innovation (from Infosys to Apple) then can work through Apples's purchases of the new software or via Apple directly adopting some of the innovations of Infosys (for example, the ability to input data into a hand-held device when a retailer sells a product) in its own software development process. The question we are interested in here is how a company such as Apple reacts to an increase in the rate of successful innovations by a company such as Infosys? Does it adopt the new technologies or does it outsource a larger fraction of software development to the now more efficient technology producer, Infosys? More central for our paper, how do these decisions and inter-industry linkages affect the response of overall economic activity?

Examining the effects of a technology shock that originates in the innovators' production process, we find a larger output response, yet a decline in overall R&D activity when, at steady state, innovation spills over more rapidly from innovators to intermediate goods producers. The reason is that intermediate goods producers substitute externally purchased input goods with internal goods as they become more efficient at input production. Since internal production constitutes to largest share, this increase in efficiency generates a larger positive response of intermediate goods and output. The decrease in the price of innovators' output due to lower demand from intermediate goods producers decreases the returns to and the level of R&D by innovators. Also, the higher level of technology adoption by intermediate goods producers curbs their need for R&D and thus overall R&D activity declines. These results are reversed when inter-industry innovation spillover is weaker. There are several inferences here. First, the main channel through which technology shocks propagate is through technology adoption (disembodied technology) and not through inputs that embody the new technologies. Second, to the extent that business cycles are driven by technology shocks, higher spillover across industries can increase the amplitude of business cycles (boosting expansions and increasing the severity of recessions). Third, R&D becomes countercyclical as the rate of spillover across industries increase. A positive technology shock that increases output, therefore, can restrain the ability to create new technologies if the technology shock spreads very rapidly. Finally, the positive technology shock also prompts labor to migrate away from innovative activities to intermediate and final goods production.

One feature of R&D that has been put under great scrutiny is the level of competition amongst innovators. Studies, some of which we discuss below, have attempted to determine how R&D spending and rate of innovations depend on innovators' market power. As a second exercise we, therefore, investigate this feature of R&D. Increasing the market power of innovators produces results that are similar to those obtained by increasing the rate of spillover. When innovators are less competitive, they restrict the production of the input good and charge a higher price relative to the baseline scenario with more competition. This results in a lower level of R&D by innovators and innovation spillover to intermediate good producers. Although this prompts higher levels of R&D, labor demand and input production by intermediate good producers, the weaker spillover and the overall drop in labor efficiency generates a more mitigated positive output response in the economy. Similar to simulations under high innovation spillover, the economy becomes less volatile under a monopoly but it also engages in less innovative activities and the labor force shifts away from innovators to intermediate goods producers.

We incorporate two other realistic features of R&D process to gain further insights from our model. First, we assume that firms incur costs when changing the level of R&D. We then test how the economy responds to a technology shock when these costs are lowered. Although there is a disagreement in the literature (see below) about the size of these costs (especially in relation to physical capital adjustment costs), according to firm-level observations they are nontrivial. Second, we realistically assume that intermediate goods producers incur costs when adopting new technologies from innovators. By contrast, they pay no cost when adopting innovations that result from internal R&D activities. Our findings indicate that if firms pay a lower cost to adjust R&D, the amplitude of overall R&D spending and output increases. Amplitude of output also increases when adoption costs are lower. The increase in overall R&D activity, however, is more subdued relative to the baseline case since intermediate goods firms, in response to higher labor efficiency, lower their demand for innovators' input goods. They instead produce these goods internally. The lower demand for input goods decreases innovators' labor demand and R&D spending. Putting this together with our central finding mentioned above, we draw the following inference: if innovation is successfully transferred between industries either, due to a more rapid spillover rate or due to lower technology adoption and R&D adjustment costs, technology shocks generate a larger positive response of output yet a smaller positive response of R&D activity.

We incorporate different types of shocks and find that the above characteristics of R&D processes are most impactful for technology shocks that originate in the innovation industry. Using these shocks we also conduct a welfare analysis and uncover large welfare costs of economic volatility in an economy that has lower innovation spillover, higher adjustment and adoption costs and less competition in the innovation industry (i.e., R&D averse economy) relative to that under the benchmark calibration. In this exercise, we keep the steady state growth rate of the economy constant. When we allow the balanced growth rate of economy to change with R&D intensity, we observe a trade-off between welfare costs and R&D intensity. The additional welfare costs due to higher R&D activity, however, are small compared to the gains in economic growth. In the high-growth-high-R&D economy, for example, while the households are willing to give up 2.2% more of their *annual* consumption to avoid volatility (relative to the baseline case), their consumption grows 3% more than it does along the benchmark balanced growth path on a *quarterly* basis.

Our methodology is similar in spirit to those that identify the cyclicality of R&D and productivity along the business cycle and explain the productivity slow-down following the 2008 crisis (e.g. Fernald, 2015; Queraltó, 2019; Christiano et al., 2016, Bianchi et al., 2019; Anzoategui et al., 2019). Some components of the R&D process in our model, for example, follows the structure in Bianchi et al. (2019) and the basic dynamic stochastic general equilibrium (DSGE) framework is similar to Anzoategui et al. (2019).[1],[2] Yet our approach is fundamentally different in several ways. First, as mentioned above, we investigate the effects of R&D and R&D spillover on the

[1]We abstain from modeling entry/exit dynamics of firms that we see in Schumpeterian models (e.g., Bilbiie et al., 2012). Aghion et al., 2005, Comin and Gertler (2006) and Queralto (2019) are some of the papers that also do not have firm entry/exit in their models, however unlike our paper these papers have expanding varieties model which suggests that innovations lead to new varieties which in turn increase productivity and economic growth.

[2]Similar to Anzoategui et al. (2019), we model labor as the main input for R&D. This approach is motivated by the fact that labor costs constitute the largest share of R&D expenditures in most countries (see for example, OECD, 2015; Goolsbee, 1998; Wolf and Reinthaler, 2008). We should note, however, that there are other studies that treat R&D as a physical investment (e.g., Bianchi et al., 2019; Queralto, 2019; Comin and Gertler, 2006).

business cycle, in contrast to the studies above that take the opposite direction. We should mention here that our paper is not the only one that has taken this direction. Earlier studies such as Comin and Gertler (2006) and Kung and Schmid (2015) have analyzed the effects of R&D and innovation on the persistence of business cycles and growth of economies. These papers, however, are very few in number and they are different in scope and methodology compared to our analysis. Second, we deviate from the studies mentioned above by incorporating vertically-related industries into our model. This allows us to capture the business cycle effects of innovation spillover across industries. Third, our model represents a real economy without the nominal rigidities in a standard New-Keynesian framework, a framework that is used by most of the studies mentioned above. The model also includes endogenous growth which allows to incorporate growth-enhancing characteristics of R&D and innovation. To the best of our knowledge, there have only been few attempts at merging endogenous growth with a DSGE framework (e.g. Bilbiie et al., 2012, 2008; Bilbiie et al. 2014). The relationship between endogenous growth and R&D in our model follows the structure in Barlevy (2007) and it allows us to determine the volatility implications of R&D driven growth. We find that higher growth due to higher R&D is associated with higher economic volatility. While this finding goes against the common negative relationship in international data (e.g., Ramey and Ramey, 1995; Aghion et al., 2005), we find that the welfare costs of the higher economic volatility are very small compared to the gains from higher consumption spurred by the higher growth.[3]

The more central contribution of our modeling approach is that it allows us to reconcile two seemingly detached features of R&D. R&D is strongly related to business cycles yet it is a relatively smooth form of expenditure (especially compared to investment). We show that it is not the overall level of R&D activity but the cross-industry spillover of R&D-driven innovations that drives business cycles.

[3]We should also mention that there is micro-evidence that positively relate R&D to economic volatility. Comin and Philippon (2005) show that there has been an increase in firm-level volatility in the U.S. between 1950-2000, which might be related to the increase in R&D activities. Castro et al. (2015) provide supporting evidence for increased volatility that idiosyncratic shocks are larger than aggregate shocks, and this a more common phenomenon for R&D intensive manufacturing industries. Similarly, Li (2011) shows that R&D intensive firms are subject to higher risk and uncertainty when they face binding financing constraints. Czarnitzki and Toole (2011) state that patent protection can spur innovation and growth by reducing the adverse effect of this risk.

Our paper is mostly motivated by evidence for higher rate of innovation spillover that has emerged in the past two decades. Studies such as Azoulay (2004), Cassiman and Veugulers (2006), Chesbrough (2003), Knott (2017) and Higón (2016) find/show a positive trend in the outsourcing of R&D (also referred to as open innovation). While the scope and the quantitative findings of these studies are different, they unequivocally point to an increasing rate of innovation spillover and the adoption of external technologies.[4]

Microevidence also reveals several other characteristics of R&D. Studies such as Foster and Grim (2010) and Foster et al. (2016) for example show, using U.S. data, that R&D is mostly conducted by large firms that have sizeable production processes in addition to R&D type activities. This is the reason both types of firms in our model, intermediate goods producers and innovators, do both R&D and production at the same time and they have market power. We should however mention that there are opposing views on how market power affects R&D and innovation.[5] In our analysis, we address these different views by investigating how our results depend on market power.

R&D adjustment costs play a critical role in our model as they directly determine how smooth R&D is. While there is a general agreement that adjusting R&D is costly, it is less clear how big these costs are, especially with respect to physical capital adjustment costs. On the one hand, studies such as Brown et al. (2011), Hall et al. (2016), and Aysun and Kabukcuoglu (2019) favor high adjustment costs as they argue that high fixed costs (setting up a lab for example) and

[4]Azoulay (2004), for example, finds that it is data-intensive projects that are mostly outsourced to other companies. Veugelers (1997) finds that R&D-intense firms are more likely to experience R&D/innovation spillovers. Cassiman and Veugelers (2006) shows that internal and external R&D activities are complements and Berchicci (2013) finds that this complementarity can play a role in achieving higher innovative performance. Part of this literature also compares the relative importance of in-house R&D and external R&D. Based on a dataset populated by Spanish firms' investment in basic research between 2006-2012, Higón (2016) finds that while 22 percent of firms conduct external R&D, 6 percent of the firms conduct in-house R&D.

[5]Schumpeterian growth models (Schumpeter, 1942) suggest that firms with market power are the engines of innovation for reasons such as greater economies of scale, easier access to R&D funding, risk management practices, large fixed costs pertaining to R&D and the ability to internally finance R&D. There is mixed empirical evidence for this theory (Symeonidis, 1996 provides an extensive review of studies that test the Schumpeterian hypothesis). Geroski (1990), for example, shows that market power cannot increase innovation using U.K. data. Acemoglu and Linn (2004) reach the opposite conclusion. Different from these findings, Aghion et al. (2005) and Hashmi (2013) uncover an inverted-U shaped relationship between market power and innovation. Peretto (1999) takes a different angle and shows that R&D investment can increase market power.

knowledge input is insensitive to short-term fluctuations and thus R&D expenditures are smoothed across the business cycle. On the other hand, studies such as Saint-Paul (1993), Comin and Gertler (2006), Rafferty and Funk (2008) find that R&D is more volatile implying that adjustment costs may be low. Some of the explanations for this result are that since R&D conducting firms are dependent on external finance and R&D is a risky activity, firms face more difficulty in funding R&D and they are more likely to shed these risky activities during economic downturns.[6] The application and evidence for technology adoption costs mostly come from the international trade literature. Bustos (2011), Yeaple (2005) and Bresnahan et al. (2002), for example, argue/find that there are fixed costs to adopting external technologies such as costs of IT and general employee training and organizational restructuring. It is, therefore, critical to address these issues related to R&D. This is what we do in Section 3. In so doing, we use different calibrations to determine how our results depend on the level of adjustment and adoption costs.

2 Model

Our model economy is populated by final and intermediate goods producers, innovators, an innovation aggregator, a labor intermediary and households. Below we describe the optimization problem of each agent, the linkages between them and our calibration exercise.

2.1 Final goods producers

We assume that a representative perfectly competitive firm produces the final consumption good, Y_t. It does so by combining intermediate goods, $Y_{k,t}$, via a constant elasticity of substitution (CES) technology. Let φ^m and N^M denote the elasticity of substitution between intermediate goods and

[6] In Hall and Lerner (2010) large R&D adjustment costs are explained by the fact that firms smooth out their R&D expenditures as a large share of this spending is on skilled labor. A large drop in R&D expenditure during a recession then implies a loss of human capital which in turn can shrink firms' knowledge base for a long period of time. Therefore, firms protect their R&D spending at the cost of curbing other expenditures during economic downturns (Brown and Petersen, 2011, 2015).

the number of intermediate goods, respectively, then this technology can be represented as below:[7]

$$Y_t = \left(N^M\right)^{1-\varphi^m} \left(\sum_{k=1}^{N^M} Y_{k,t}^{1/\varphi^m}\right)^{\varphi^m} \tag{1}$$

The profit maximization problem of the firm yields the following inverse demand function for intermediate good k:

$$P_{k,t} = \left(\frac{Y_{k,t}}{Y_t}\right)^{(1-\varphi^m)/\varphi^m} \tag{2}$$

where the price of the final consumption good, P_t, is normalized to 1.

2.2 Intermediate goods producers

Intermediate goods are produced by imperfectly competitive firms. These firms, indexed by k, maximize their life-time profits subject to the inverse demand function in equation (2), and their profits are represented as,

$$\Pi_{k,t}^{l} = P_{k,t} M_{k,t} \left(L_{k,t}^{p}\right)^{1-\alpha} - W_t \left(L_{k,t}^{p} + L_{k,t}^{m} + L_{k,t}^{rd}\right) - P_t^I X_{k,t}^I - \frac{\phi^{rd}}{2} \left(\frac{L_{k,t}^{rd}}{L_k^{rd}} - 1\right)^2 W_t L_{k,t}^{rd} \tag{3}$$

The firms face quadratic costs when adjusting the allotment of R&D labor (with ϕ^{rd} regulating adjustment costs) away from its steady state level. They combine production labor, $L_{k,t}^{p}$ (with α denoting the share parameter for production labor) and input good $M_{k,t}$ to produce the intermediate good, $Y_{k,t}$. $M_{k,t}$ is the following CES aggregate of goods produced internally, $X_{k,t}^M$ and those purchased from innovators $X_{k,t}^I$ (with P_t^I denoting the price of the input good $X_{k,t}^I$):

$$M_{k,t} = \left[\left(\gamma^M\right)^{\lambda^M} \left(X_{k,t}^M\right)^{1-\lambda^M} + \left(1-\gamma^M\right)^{\lambda^M} \left(X_{k,t}^I\right)^{1-\lambda^M}\right]^{1/(1-\lambda^M)} \tag{4}$$

[7] The coefficient $\left(N^M\right)^{1-\varphi^m}$ is included to execute our symmetric equilibrium. In this equilibrium $Y_{k,t} = Y_t/N^m$.

where parameters γ^M and λ^M represent the share of the internally produced inputs and the elasticity of substitution between the two types of input goods, respectively, and $X_{k,t}^M$ is given by:

$$X_{k,t}^M = \mu_{k,t}\left(L_{k,t}^m\right)^{1-\alpha}. \tag{5}$$

$L_{k,t}^m$ is the labor services allocated to the production of the input good. We assume that the efficiency of $L_{k,t}^m$, represented by $\mu_{k,t}$, is positively related to the amount of R&D that firm k does as well as the R&D of other firms. This relationship is given by,

$$\mu_{k,t} = \left(\lambda^{\upsilon^m L_{k,t}^{rd}}\right)^{\eta^m}\left(\lambda^{u^M \upsilon^m L_t^{'M,rd}}\right)^{\eta^M}\left[\left(\mu_t^I\right)^{u^I}\right]^{1-\eta^m-\eta^M} \tag{6}$$

where $L_{k,t}^{rd}$ and $L_t^{'M,rd}$ are the amounts of labor allocated R&D activities by firm k and all firms other than firm k, respectively. The parameter λ is greater than 1 and it allows us to capture growth effects of R&D.

We assume that not all R&D efforts result in successful innovations. The hazard parameter υ^m allows us to incorporate this aspect of the R&D process in the industry. In addition to internal innovation, intermediate goods producers can also adopt the innovation of other intermediate goods producers and innovators (see below for a description). These two external determinants of efficiency are represented by the second and third expression on the right-hand-side of equation (6), respectively.

We assume here that firms incur costs when adopting external innovation, with parameters u^M and u^I representing the costs of adopting innovation from intermediate goods producers and innovators, respectively. The share parameters η^m and η^M regulate the importance of internal versus external R&D and they capture innovation spillover effects.

The R&D process parameters are assumed to be the same for every firm. We defer the derivation of μ_t^I to the next section where we introduce the innovators in the economy. It is important to note here that μ_t, under a symmetric equilibrium, also represents the growth rate of output in the economy.[8]

The maximization of firm k's profits (taking other firms' production as given) with respect to production labor, $L^p_{k,t}$, input good labor, $L^m_{k,t}$, and R&D labor, $L^{rd}_{k,t}$, yields the following conditions:

$$\frac{(1-\alpha)}{\varphi^m}\frac{Y_{k,t}^{1/\varphi^m}Y_t^{(\varphi^m-1)/\varphi^m}}{L^p_{k,t}} = W_t \tag{7}$$

$$\frac{\left(\gamma^M\right)^{\lambda^M}(1-\alpha)}{\varphi^m}\frac{Y_{k,t}^{1/\varphi^m}Y_t^{(\varphi^m-1)/\varphi^m}}{L^m_{k,t}}\left(M_{k,t}\right)^{\lambda^M-1}\left(X^M_{k,t}\right)^{1-\lambda^M} = W_t \tag{8}$$

$$\begin{aligned}\frac{\eta^m \upsilon^m \ln(\lambda)\left(\gamma^M\right)^{\lambda^M}}{\varphi^m}Y_{k,t}^{1/\varphi^m}Y_t^{(\varphi^m-1)/\varphi^m}\left(M_{k,t}\right)^{\lambda^M-1}\left(X^M_{k,t}\right)^{1-\lambda^M} = W_t + \phi^{rd}W_t\left(\frac{L^{rd}_{k,t}}{L^{rd}_k}-1\right)\left(\frac{L^{rd}_{k,t}}{L^{rd}_k}\right) \\ +\frac{\phi^{rd}}{2}W_t\left(\frac{L^{rd}_{k,t}}{L^{rd}_k}-1\right)^2\end{aligned} \tag{9}$$

[8] We use the formulation in equation (6) to simplify the illustration. The inherent growth mechanism in the model can be described as follows: Assume that firms accumulate stock of knowledge that are a product of R&D activities and that this stock improves labor efficiency. The evolution of the said stock variables for the intermediate good producer k, all other intermediate firms, and innovators, $RD^{s,M}_{k,t}$, $RD'^{s,M}_t$ and $RD^{s,I}_t$, respectively, can be represented as,

$$RD^{s,M}_{k,t} = RD^{s,M}_{k,t-1} + \nu^m L^{rd}_{k,t}, \quad RD'^{s,M}_t = RD'^{s,M}_{t-1} + \nu^m L'^{rd}_{k,t}, \quad RD^{s,I}_t = RD^{s,I}_{t-1} + \Psi_t L^{I,rd}_t$$

where Ψ_t is derived below. Labor efficiency for intermediate good producer k depends on these variables as follows:

$$\mu^s_{k,t} = \left(\lambda^{RD^{s,M}_{k,t}}\right)^{\eta^m}\left(\lambda^{u^M RD'^{s,M}_t}\right)^{\eta^M}\left[\lambda^{u^I RD^{s,I}_t}\right]^{1-\eta^m-\eta^M}$$

The growth rate of labor efficiency, also the source of growth in the economy, at time t is then given by,

$$\mu^g_{k,t} = \mu^s_{k,t}/\mu^s_{k,t-1} = \left(\frac{\lambda^{\eta^m RD^{s,M}_{k,t}}}{\lambda^{\eta^m RD^{s,M}_{k,t-1}}}\right)\left(\frac{\lambda^{\eta^M u^M RD'^{s,M}_t}}{\lambda^{\eta^M u^M RD'^{s,M}_{t-1}}}\right)\left(\frac{\lambda^{(1-\eta^m-\eta^M)u^I RD^{s,I}_t}}{\lambda^{(1-\eta^m-\eta^M)u^I RD^{s,I}_{t-1}}}\right)$$

$$\mu^g_{k,t} = \left(\lambda^{\upsilon^m L^{rd}_{k,t}}\right)^{\eta^m}\left(\lambda^{u^M \upsilon^m L'^{M,rd}_t}\right)^{\eta^M}\left[\left(\mu^I_t\right)^{u^I}\right]^{1-\eta^m-\eta^M}$$

where $\mu^I_t = \lambda^{\Psi_t L^{I,rd}_t}$ as described below and notice that $\mu^g_{k,t}$ equals the efficiency term in equation (6). We assume that under symmetric equilibrium $\mu^g_{k,t}$ is the same for all intermediate goods producers. Furthermore, the parameterization that describes this symmetric equilibrium (explained in Section 2.7) also ensures that innovators' production and the overall output in the economy also grow at the same rate along the steady state balanced growth path. To ensure that our model is stationary, we detrend some variables in our model with their corresponding stochastic growth rates. As a result, the stock variables drop out and the formulation of the model is simplified to the form that we use.

As mentioned above, firm k takes other firms' decisions as given when maximizing profits. It, therefore, only takes into account its marginal effect on the growth rate of the economy when maximizing with respect to $L_{k,t}^{rd}$. Maximizing profits with respect to $X_{k,t}^{I}$ produces the following demand function:

$$\frac{\left(1-\gamma^{M}\right)^{\lambda^{M}}}{\varphi^{m}} Y_{k,t}^{1/\varphi^{m}} Y_{t}^{(\varphi^{m}-1)/\varphi^{m}} \left(M_{k,t}\right)^{\lambda^{M}-1} \left(X_{k,t}^{I}\right)^{-\lambda^{M}} = P_{t}^{I} \tag{10}$$

We should note here that the above expression can be used to show that the growth rate of $P_{t}^{I} X_{k,t}^{I}$ is equal to the growth rate of output. This ensures that the revenue of intermediate goods producers does not outpace or lag the costs of input goods purchased from innovators as the economy grows. The real wages (equal to nominal wages since price is normalized to 1) also grow at the rate of output in equilibrium.

2.3 Innovation aggregator

The economy has a representative perfectly competitive innovation aggregator that combines innovations to produce the input good X_{t}^{I} that is in turn sold to intermediate goods producers. Innovations are aggregated through the following CES technology:

$$X_{t}^{I} = \left(\sum_{j=1}^{N^{I}} X_{j,t}^{1/\varphi^{I}}\right)^{\varphi^{I}} \tag{11}$$

where N^{I} and φ^{I} denote the number of innovators and the elasticity of substitution between the input goods. The price of innovator j's good, $P_{j,t}$, can be derived from the maximization problem of the aggregator as follows:

$$P_{j,t} = P_{t}^{I} \left(\frac{X_{j,t}}{X_{t}^{I}}\right)^{\left(1-\varphi^{I}\right)/\varphi^{I}} \tag{12}$$

2.4 Innovators

We assume that the economy is populated by N^I imperfectly competitive innovators who only use labor to produce an input good that is in turn sold to the intermediate goods producers. These agents allocate their labor input to production and R&D activities, and the efficiency of production labor depends on the amount of R&D that innovators conduct. This R&D process too is labor intensive. Given this setup the profit function that innovator j maximizes can be represented as follows:

$$\Pi_{j,t} = A_t^I P_{j,t} X_{j,t} - W_t \left(L_{j,t}^p + L_{j,t}^{rd} \right) - \frac{\phi^{rd}}{2} \left(\frac{L_{j,t}^{rd}}{L_j^{rd}} - 1 \right)^2 W_t L_{j,t}^{rd}. \tag{13}$$

where $L_{j,t}^p$ and $L_{j,t}^{rd}$ denote the amount of labor allocated to production and R&D, respectively.

Innovators face similar costs associated with changing the level of R&D labor. These costs are also regulated by the same parameter, ϕ^{rd}. The production function and the efficiency variable have a simpler structure for innovators since we assume that labor is the only input and innovation does not spillover from intermediate goods producers to innovators.

These two are given by,

$$X_{j,t} = \mu_{j,t} \left(L_{j,t}^p \right)^{1-\alpha}, \tag{14}$$

$$\mu_{j,t} = \left(\lambda^{\varepsilon_t^I L_{j,t}^{rd}} \right)^{\eta^i} \left(\lambda^{u^s \upsilon^i L_t^{\prime I,rd}} \right)^{1-\eta^i}. \tag{15}$$

As expressed in the second term on the right-hand-side of the efficiency variable, innovation spillsover across innovators and the adoption of external innovation is costly, with u^s representing the cost parameter. The innovation shock, ε_t^I, follows an AR(1) process and it is systematic across all innovators. This shock is the focal point of our analysis and it can be interpreted as an exogenous change in the success rate of R&D activity in creating new innovations. Hereafter, we refer to this as a "standing on shoulders" shock to simplify the discussion. In our simulations, we track how this shock is transmitted throughout the economy and to other firms' innovation processes.

In each period, innovator j decides how much labor to hire for production and R&D, and takes the production of other firms as given in maximizing profits. This maximization with respect to $L_{j,t}^{p}$ and $L_{j,t}^{rd}$ produces the following first order conditions, respectively:

$$\frac{(1-\alpha)}{\varphi^I} P_t^I X_{j,t}^{1/\varphi^I} \left(X_t^I\right)^{\frac{\varphi^I-1}{\varphi^I}} \frac{1}{L_{j,t}^{p}} = W_t \tag{16}$$

$$\begin{aligned} \frac{\eta^i \upsilon^i \ln(\lambda)}{\varphi^I} P_t^I X_{j,t}^{1/\varphi^I} \left(X_t^I\right)^{\frac{\varphi^I-1}{\varphi^I}} = W_t + \phi^{rd} W_t \left(\frac{L_{j,t}^{rd}}{L_j^{rd}} - 1\right)\left(\frac{L_{j,t}^{rd}}{L_j^{rd}}\right) \\ + \frac{\phi^{rd}}{2} W_t \left(\frac{L_{j,t}^{rd}}{L_j^{rd}} - 1\right)^2 \end{aligned} \tag{17}$$

2.5 Symmetric equilibrium

We assume that in equilibrium every firm is identical within each type so that they hire the same amount of workers, allocate this labor to different activities in a similar way and produce the same amount of output. Under this symmetric equilibrium, growth rate of input goods X_t^M and X_t^I are respectively given by,

$$\mu_t^M = \lambda^{\upsilon^m L_t^{M,rd}\left(\eta^m + u^M \eta^M \left(N^M - 1\right)\right)/N^M} \left(\mu_t^I\right)^{u^I\left(1-\eta^m-\eta^M\right)} \tag{18}$$

$$\mu_t^I = \lambda^{\varepsilon_t^I L_t^{I,rd}\left[\frac{\eta^i + u^s\left(1-\eta^i\right)\left(N^I-1\right)}{N^I}\right]} \tag{19}$$

The growth rate of total output in the economy can be derived as the following aggregate of the two growth rates above:

$$\mu_t = \left(\gamma^M\right)^{\lambda^M} \left(\frac{X^M}{M}\right)^{1-\lambda^M} \mu_t^M + \left(1-\gamma^M\right)^{\lambda^M} \left(\frac{X^I}{M}\right)^{1-\lambda^M} \mu_t^I \tag{20}$$

2.6 Households and market clearing

The households, indexed by $h\,\varepsilon\,[0,1]$, are infinitely-lived and they maximize the following life-time utility function,

$$U_0 = E_0 \sum_{t=0}^{\infty} \beta^t \left\{ \ln C_{h,t} - \tau \frac{L_{h,t}^{1+\sigma_l}}{1+\sigma_l} \right\}, \tag{21}$$

where $C_{h,t}$ and $L_{h,t}$ are the consumption and labor supply of household h. β is the time discount factor and the parameter τ ensures that total labor supply is equal to 1 at steady state and σ_l is the inverse of the Frisch-elasticity of labor supply. In maximizing their life-time utility function, households face the following budget constraint:

$$P_t C_{h,t} + T_t = W_{h,t} L_{h,t} + \Pi_{h,t} + R_t B_{h,t} - B_{h,t+1} \tag{22}$$

where the price of the final good, $P_t = 1$, and $B_{h,t}$ and T_t are the risk-free bonds holdings of households and the lump-sum taxes they pay to the government, respectively. In addition to nominal wages and interest ($W_{h,t}$ and R_t), households also receive profits, $\Pi_{h,t}$, from the intermediate goods producers. To maximize their life-time utility, households choose the amount of consumption, bond holdings and labor supply.

Households' heterogenous labor services are hired by perfectly competitive labor intermediaries who in turn rent them out to the intermediate goods producers and innovators. The intermediaries combine labor services to produce homogenous labor as follows:

$$L_t = \left[\int_0^1 L_{h,t}^{1/\varphi_w} dh \right]^{\varphi_w} \tag{23}$$

where φ_w is the elasticity of substitution between labor services. The demand for households' labor services is derived from the profit maximization problem of the labor intermediaries as,

$$L_{h,t} = \left(\frac{W_{h,t}}{W_t} \right)^{-\frac{\varphi_w}{\varphi_w - 1}} L_t \tag{24}$$

where the aggregate wage rate is given by $W_t = \left[\int_0^1 W_{h,t}^{-\frac{1}{\varphi_w - 1}} dh\right]^{\varphi_w - 1}$.

Utility maximization with respect to bond holdings and labor supply produce the following two conditions, respectively

$$\Lambda_t = \beta E_t \left\{\Lambda_{t+1} R_{t+1}\right\} \tag{25}$$

$$\varphi_w \tau L_{h,t}^{\sigma_l} = \Lambda_t W_{i,t} \tag{26}$$

where $\Lambda_t = (P_t C_t)^{-1}$ is the Lagrange multiplier corresponding to the budget constraint.

The taxes that households pay, together with their bond purchases, finance government expenditures, G_t such that

$$G_t = T_t + B_{h,t+1} - R_t B_{h,t} \tag{27}$$

Government spending is subject to a shock that follows an AR(1) process. This formulation allows us to investigate the effects of demand-side shocks on R&D spillover. While there are alternative ways to introduce demand shocks, this was the most straightforward approach. The resource constraint for the economy is then given by,

$$Y_t = C_t + G_t \tag{28}$$

Finally, we assume that there is a central bank that sets real interest rates to stabilize the economy by using the following rule:

$$R_t = R_{t-1}^{\rho} Y_t^{\pi_y} \tag{29}$$

where the parameters ρ and π_y govern interest rate smoothing and responsiveness to output growth (the deviation of output from its balanced growth path).

2.7 Calibration

There are several conventions that we follow and assumptions that we make when solving the model. First, we assume that the steady state balanced growth path of the economy is characterized by a single growth rate, implying that the two input goods, X_t^M and X_t^I , and the total output in the economy, grow at the same rate. This restriction ensures that the intermediate goods producers use both types of input goods at all times. The parity in growth rates implies the following steady state condition:

$$\frac{L^{M,rd}}{L^{I,rd}} = \frac{\upsilon^i N^M}{\upsilon^m N^I} \frac{\left[\eta^i + u^s\left(1-\eta^i\right)\left(N^I-1\right)\right]}{\left[\eta^m + u^M \eta^m\left(N^M-1\right)\right]}\left[1-u^I\left(1-\eta^m-\eta^M\right)\right] \tag{30}$$

Second, we solve the model by log-linearizing all the variables in the equilibrium conditions around their steady state values. Before doing so, we detrend variables that grow along the steady state by using the respective growth rates. To detrend aggregate variables such as total output and consumption, for example, we use the total growth rate μ_t. To detrend the two input goods, X_t^M and X_t^I, we use μ_t^M and μ_t^I, respectively.

Third, we set the standard parameters in the model equal to their commonly used or estimated values. The time discount factor, for example, is set equal to 0.995, implying that annualized risk-free interest rates are roughly 2%. We fix the labor share parameter α to 0.35. Setting $\sigma_l = 2$ produces a Frisch-elasticity of labor supply of 0.5. To ensure that total labor supply is equal to 1, we set τ such that $\tau = \frac{(1-\alpha)N^M Y}{\varphi_w^2 L^p C}$. The price mark-up parameters φ_p^M and φ_p^I, and the wage mark-up parameter φ_w are set equal to 1.5. We assume that the share of government spending share in total spending is equal to 20 percent at steady state, and that the monetary policy parameters, ρ and π_y, are equal to 0.7 and 0.15. For the shock processes, the persistence parameters and the standard deviations are all set equal to 0.9 and 0.01, respectively.

Fourth, we choose parameter values that allow us to construct a simple foundation that forms the basis for our sensitivity analyses that are the focal point of our paper. We initially assume, for example, that the adoption cost parameters are all equal to 1, implying that firms adopt the innovations of other firms without paying a cost. For simplicity, we initially assume that the number of intermediate goods producers and innovators are equal to 2. Later, we deviate from this duopolistic structure to gauge the impact of market power on our results. We set the diffusion parameters, η^m, η^i, η^M, equal to 1/3 implying that externally-adopted innovations is roughly two times that of innovations from internal R&D. This composition of R&D/innovations is close to that in Bianchi et al. (2019), where the diffusion parameter is estimated as 0.28.

To determine the composition of labor at steady state, we assume that the economy grows at 3 percent on an annual basis. We also assume that the intertemporal elasticity of substitution parameter, λ^M, equals 0.5 and that the share parameter γ^M equals 0.9 so that the intermediate good firms mostly use internally produced input goods and the two types of goods are imperfect substitutes. Under this parameterization, the share of labor allocated to R&D activities of innovators, $L^{I,rd}/(L^{I,rd} + L^{I,p})$ is roughly 1.5 percent. This value also describes the share of R&D labor in total labor allocated to R&D and input production by intermediate good producers, $L^{M,rd}/(L^{M,rd} + L^{M,m})$. The share of labor in R&D activities in our baseline calibration matches the shares obtained from data fairly well. The BRDIS statistics, for example, show that the number of scientists and engineers in R&D activities is 1.6% of workers in production. This statistic describes the whole country and the period between 2000 and 2015. Fixing γ^M to 0.9 generates a $L^{M,p}/L^{M,m}$ ratio of roughly 1.11. In our baseline calibration we assume that the "standing on shoulders" effects of R&D offset its "stepping on toes effects" for both innovators and intermediate goods producers so that the parameters, υ^i and υ^m, are equal to 1. Under this calibration, the innovators and intermediate goods producers hire one-third and two-thirds of the total labor supply at steady state, respectively, and the value of λ equals 21.4.

3 Results

In this section, we first present our baseline results obtained by using the calibration methodology above. We then change several model features such as the degree of innovation spillover, R&D adjustment and adoption costs, and market power to determine how these features affect output responses and spillover effects.

3.1 Baseline results

We begin our analysis by investigating how a "standing on shoulders" shock to the innovators R&D process propagates throughout the economy. In so doing, we initially assume that R&D adjustment costs are small (ϕ^{rd} is set equal to 0.01).

Figure 1 shows the impulse responses to a one-standard deviation shock to ε_t^I. The shock generates an increase in both the marginal returns to innovators' R&D and production labor which in turn prompts an increase in the demand for these services. The positive supply shock, notwithstanding the increase in labor demand, decreases the price of innovators' input good.

The shock that originates in the innovators' production process affects intermediate good producers through two channels. First, lower input good prices supplied by innovators cause an increase in the demand for these goods and an overall increase in intermediate good production. Moreover, the composition of the input goods used by intermediate goods producers also becomes more skewed towards innovators' input. We infer this by the larger response of innovators' production relative to intermediate goods producers' input production. Second, the additional innovations are partially adopted by intermediate goods firms which increases the efficiency of input labor. In our baseline calibration, R&D, input and production labor for intermediate good producers all fall to match the returns to these services to the higher marginal benefits to purchasing input goods from innovators. Despite the fall in labor demand, the positive innovation spillover from innovators generates an increase in intermediate firms' input production.

Overall, we find that the growth of the innovation sector outpaces that of the intermediate goods sector and that there is a shift in the labor force away from the latter to the former. While these results demonstrate the basic workings of our model, some features such as R&D adjustment costs and external innovation adoption costs were ignored and others such as market power were simplified in our baseline calibration. Below, we analyze how or if these features change our results by putting the emphasis on innovation spillover. We should note here that there is mixed evidence on the magnitudes/degrees of these features and the effects on R&D in the literature. In our analysis below we, therefore, use different values to gain insights.

3.2 Innovation adoption costs

So far, we assumed that firms adopt the innovations of other firms without paying a cost. In this section, we relax this assumption and assume that there is an imperfect pass-through of innovations across firms. Another way of interpreting this imperfection is that firms pay a cost to adopt the innovations of other firms.

To execute this strategy, we set all the adoption cost parameters to 0.5. This implies that only 50 percent of the externally adopted innovations improve labor efficiency. The impulse responses corresponding to this alternative calibration are displayed in Figure 2. With adoption costs, innovators conduct more of their own R&D compared to the baseline scenario. Despite the imperfect passthrough from other innovators, this additional R&D generates an increase in labor efficiency and the returns to production labor. This prompts a larger supply of input goods from innovators and a sharper drop in the prices of these goods. Intermediate firms face opposing forces related to R&D efforts. On the positive side, it is more costly for them to adopt external R&D and thus they, similar to innovators, conduct more internal R&D. They do, however, have access to cheaper input goods from innovators, and thus less incentive to increase the production of their own input goods or to bolster the efficiency by doing so. This is reinforced by the more steep adoption costs that intermediate firms face. Specifically, intermediate firms face costs of adopting innovations from innovators, in addition to the costs of adopting the innovations of other intermediate firms. This additional layer of costs causes their labor's efficiency to fall by more than that of innovators. We find that the latter set of negative effects are larger and the shift in the labor force away from intermediate firms (to innovators) is stronger with adoption costs. Overall, we find that there is a smaller increase in output when there are costs to adopting external innovations.

3.3 Rate of inter-industry technology diffusion

In our baseline calibration, the intermediate firms' labor efficiency depended mostly on internal and intra-industry R&D with the share of inter-industry adoption of innovations constituting one-thirds ($1-\eta^m-\eta^M = 0.33$). In this section, we examine how the impulse responses change under a higher rate of inter-industry diffusion of innovations and when there is no inter-industry diffusion at all. To approximate the former case, we set η^m and η^M equal to 0.05, implying that 90 percent of the gains in efficiency in intermediate firms' input labor are a result of the R&D efforts of innovators. To shut-down the inter-industry diffusion we set $1-\eta^m-\eta^M$ to zero.

The impulse responses obtained from these alternative economies are displayed in Figure 3. When positive technology shocks, originating in the innovators production process, flow at a higher rate to intermediate firms, these firms become more efficient in producing input goods and their demand for input goods from innovators is smaller relative to the baseline scenario. The innovators, therefore, spend less on R&D and production labor. While the higher level of intermediate goods production increases the demand for labor, only production labor increases since the higher inflow of external innovations decreases the demand for internal R&D and input labor. Overall, we find that the net effect of the technology shock on output is larger than its effects under the baseline scenario. Simply put, the higher rate technology diffusion is growth-enhancing. In contrast, when diffusion is shut-down, intermediate firms' demand for labor drops given the lower efficiency of labor. The intermediate firms substitute internal input production to some extent with the inputs from innovators yet this is not enough to offset the negative effects on input production and there is a decline in the supply of intermediate goods which in turn suppresses the positive output response. It is important to mention here that the latter mechanism reveals a central result in our paper as it points out that the main channel through which technology shocks are transmitted across the economy is external technology adoption and not the purchasing of inputs that embody the new technologies.

3.4 Market power

In this section, we change the competitive structure of the innovation industry to investigate the effect of market power on the diffusion and the overall effects of R&D. In so doing, we keep the number of intermediate good producers at 2 and set the number of innovators to 1.01 and 1,000 to approximate the two extreme forms of competition: monopoly and perfect competition.

The responses to the innovators' "standing on shoulders shock" that correspond to these two forms of competition are displayed in Figure 4. The positive response of innovators' output and the negative response of price of the input good that we observe under the baseline scenario are also observed when there is perfect competition. These results are, however, reversed when the innovator is a monopoly. Under perfect competition, innovators obtain almost all of their innovations externally and thus their R&D spending is relatively irresponsive to the shock. The intermediate firms' R&D labor demand does not decrease since there is a smaller amount of R&D that spillsover from the innovators.

When the innovator is a monopoly, it increases the price of the input good and curtails production and labor demand, especially R&D labor, in response to a technology shock. Faced with higher input prices from innovators and lower amount of external R&D, intermediate firms increase their demand for labor. The migration of labor force from intermediate firms to innovators that we observe in our baseline results, therefore, reverses course under a monopoly. The positive response of intermediate firms' input production, however, is small compared to the baseline response given the weaker spillover and the overall drop in labor efficiency. This, together with the lower amount of production by innovators, generates a more mitigated response of output.

3.5 R&D adjustment costs

So far we assumed that R&D adjustment costs apply similarly to innovators and intermediate goods producers. In this section, we investigate how the economy behaves when adjustment costs for innovators are smaller. To do so, we set the value of the adjustment cost parameter of innovators to one-fourth of the corresponding value for intermediate firms. The results displayed in Figure 5 indicate that the main mechanism in our baseline results is reinforced by the smaller obstacle that innovators face when adjusting R&D. Specifically, there is a larger shift of production and labor away from the intermediate goods producers to the innovators as intermediate goods producers rely more on the innovation and the input goods of innovators. The positive effect of this compositional change in overall output is amplified with smaller adjustment costs.

3.6 Other shocks, parameterizations and a welfare analysis

In this section, we first broaden the set of calibrations to obtain a more general inference from our model. We then consider 3 other shocks, a "standing on shoulders shock" to the intermediate firms' input production process, a government spending and a monetary policy shock. Finally, we investigate the welfare implications of R&D intensity and diffusion.

3.6.1 Other parameterizations

Table 2 shows, in the first 4 columns, the maximum/minimum responses of some key variables (in absolute value) to a one-standard deviation "standing on shoulders shock" to the innovators' R&D process. The last 4 columns show the standard deviations of the same variables.[9] Higher technology adoption costs suppresses the positive effects of the technology shock and causes higher economic volatility. This can also be said for relative adjustment costs and market power, albeit the contrast between the baseline scenario and high relative adjustment costs is less noticeable. Higher market power suppresses the responses and amplifies the volatility of not only output but also all other variables listed in the table, especially R&D labor. These results suggest that technology shocks have more adverse affects on an economy if they originate in a sector with high market power. The results corresponding to the different rates of inter-industry technology spillover show that while the positive response of the key variables become larger in magnitude when spillover is stronger, their volatilities remain roughly the same, implying that there is no significant downside

[9] Simulations that generate these standard deviations are the same as those used to compute model moments in Table 1.

to stronger inter-industry technology linkages. We should note that this result depends on whether one allows the growth rate of the economy to change with the higher spillover or not. In the exercise discussed here we keep the growth rate along the balanced growth path the same. Below, we explore the welfare and volatility implications when we allow the growth rate to change.

3.6.2 Other shocks

So far, we focused on a technology shock that originated in the innovators' R&D process. Here we investigate how our results change when the same shock originates instead in the intermediate firms' R&D process. We also consider two other shocks. These shocks, a government spending and monetary policy shock, change the overall demand in the economy unlike the supply shock we have considered so far.

The responses to these alternative shocks are reported in Figure 6. The corresponding baseline responses are reported in the first row for comparison. When the technology shock originates in the intermediate goods sector, there is a shift in R&D activity away from the innovators to the intermediate firms. Despite the lack of spillover from intermediate firms to the innovators, intermediate firms, faced with higher marginal returns to R&D, increase R&D activity and thus the efficiency of their labor force working in input production. The resulting decline in the demand for input goods from innovators decreases innovators' production and R&D activity. We also find that if the technology shock originates in the intermediate goods sector, the magnitude of the positive output response is higher. The reason is that input goods of intermediate firms have a much higher share (90%) than those purchased from innovators (10%). A technology shock of a similar size, therefore, has a much larger impact on overall intermediate good production and output.

The two demand shocks generate a symmetric response in the two sectors. In response to a one-standard-deviation government spending shock, there is a higher demand for inputs from both sectors, which boosts production and R&D activity in both sectors. Similarly, the decrease in consumption demand that is prompted by an exogenous increase in interest rates, generates the opposite result. Output and R&D activity in both sectors decline.

Notice also that setting the inter-industry innovation spillover rate to different levels generates the largest variation in the responses to the standing on shoulder shock that originates in the innovation industry. The sensitivity of the responses to spillover rate is much smaller for the other three shocks.

3.6.3 Welfare analysis

To gauge the welfare implications of R&D activity, we compare two economies. In the first economy, which we refer to as the R&D intense economy, we set the parameters related to R&D process to values that favor high levels of R&D. For example, we set the adoption costs to 0% , so that the two types of firms do not pay any cost of adopting each others' innovations. Similar in spirit, we set the inter-industry technology spillover rate to 90% and the adjustment costs to 25% of the costs in the benchmark calibration. Finally, we model innovators as perfectly competitive entities as this increases the amount of R&D activity. For the R&D averse economy we do the opposite and choose parameter values that restrict R&D activity. In doing so, we set the adoption costs to 95%, technology spillover to 5%, and adjustment costs to 5 times the costs in the benchmark calibration. We also model the innovator as a monopoly.

To measure welfare effects, we first second order approximate our model's utility function and optimality conditions. We then compute the share of steady state consumption that households require to sustain the volatility caused by the 4 shocks in our model. The second order approximation to the utility function can be derived as follows:

$$EU_t = E\left(c_t\right) - \tau E\left(l_t\right) - \frac{1}{2} var\left(c_t\right) - \frac{\tau\sigma_l}{2} var(c_t) - \tau\sigma_l cov(c_t, l_t) \tag{31}$$

where $E\left(c_t\right)$, $E\left(l_t\right)$, $var\left(c_t\right)$, $var\left(l_t\right)$ are the unconditional means and variances of consumption and labor, and $cov(c_t, l_t)$ is the covariance of consumption and labor covariance, respectively. The lower case letters represent the deviations of the corresponding variables from their steady state values.

Notice here that there are two potential channels through which welfare effects can feed through. First the volatility that shocks generate can affect the unconditional means of consumption and labor and/or it could directly feed through the two variables' unconditional variances and covariances. We refer to the welfare effects of these two separate channels as u^{mean} and u^{var} respectively, and derive them by using the following two conditions:

$$\ln[(1+u^{mean})C]-\tau=U+E\left(c_t\right)-\tau E\left(l_t\right) \tag{32}$$

$$\ln[(1+u^{var})C]-\tau=U-\frac{1}{2}var\left(c_t\right)-\frac{\tau\sigma_l}{2}var(l_t)-\tau\sigma_l cov(c_t,l_t) \tag{33}$$

where U and C are the steady state values of household utility and consumption. Using these conditions, u^{mean} and u^{var} can be obtained as,

$$u^{mean}=\exp\left[E\left(c_t\right)-\tau E\left(l_t\right)\right]-1 \tag{34}$$

$$u^{var}=\exp\left[-\frac{var\left(c_t\right)}{2}-\frac{\tau\sigma_l var(l_t)}{2}-\tau\sigma_l cov(c_t,l_t)\right]-1 \tag{35}$$

We also measure overall welfare costs, u^{total}, as follows:

$$u^{total}=u^{mean}+u^{var} \tag{36}$$

To compute these measures, we use the unconditional moments of the model variables (that are also consistent with the data). The results are displayed in Table 3. The value of 0.0778 in the first row implies that consumers are willing to give up 7.8% of their steady state consumption to avoid volatility. The results in the next two rows indicate that while welfare costs of economic shocks in a R&D averse economy are much larger than the baseline economy, they are not too different for the R&D intense economy. This suggests that there are no benefits to restricting R&D activity and that there is no substantial welfare loss associate attached to higher levels of R&D. Comparing the two channels, we observe that most of the negative welfare effects feed through the unconditional volatility of the two variables.

So far, we held the steady state growth rate constant when comparing the R&D averse and intense economies. It is, however, reasonable to postulate that an economy with high R&D activity would grow faster than the one in which R&D is restricted. To allow for this more realistic scenario, we adjust the steady state share of R&D labor so that the growth rate of the R&D intense and averse economies are 6% and nearly 0% (0.01%), respectively, as the economy becomes more R&D intense and averse (λ and F are set to different values to configure these calibrations).

The comparison of the two economies under this scenario are reported in the last two rows of the table. The inference here is similar. While higher R&D activity increases welfare costs by 2.2% (relative to the baseline case), these costs are small given that the quarterly growth rate of consumption is 3% higher. Similarly, while welfare losses decrease in the zero-growth economy, they are still large compared to the baseline case considering that consumption now does not grow at steady state.

4 Concluding remarks

This paper demonstrates that technology shocks have the largest impact on economies when industries adopt the innovations of other industries at a high rate, if costs of adopting these new technologies are low, if firms face lower costs of adjusting their R&D expenditures, and if the innovators face a higher degree of competition. The dynamic spillover of innovations across industries plays a key role in the overall output effects of technology shocks. The paper also finds that although R&D driven innovations can have a large impact under the conditions mentioned above, these conditions also make R&D expenditures along business cycle smoother. This inference from the paper matches the relatively low volatility of R&D in the data and at the same time corroborates the key role that R&D plays for business cycles in the literature that followed the 2008 crisis. These results are obtained from a dynamic stochastic general equilibrium framework of a real economy with endogenous growth.

The paper offers several testable predictions that could inform future empirical work. For example, do vertically-related industries with a large amount of open innovation experience larger expansion of output following a surge in innovations compare to other industries that conduct mostly internal R&D? Do these technology shocks generate the larger response in industries that face a higher level of competition?[10] Do positive technology shocks prompt a migration of labor from innovative to production activities? What is the significance of technology adoption and R&D adjustment costs on output volatility? The answers to these questions could be very insightful as they would reveal how business cycles vary across countries and across time as R&D intensity changes along these dimensions.

There are two extensions to our model that could be useful. First, one could embed our real economy into a New Keynesian DSGE framework to observe whether the propagation of technology shocks is different with nominal rigidities and how R&D spillover is affected by price shocks and a broader set of demand shocks. This methodology could also analyze/incorporate the well-documented financial constraints on R&D spending (e.g. Comin and Gertler, 2006; Rafferty and Funk, 2008; Aghion et al., 2012; Hall and Lerner, 2010). Second, it would be interesting to allow for firm entry/exit dynamics that we see in Schumpeterian models (Schumpeter, 1942) to observe how technology spillover is affected in economies with high rates of exit and entry in the innovation sector.

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Table 1. Model versus data moments

	Data	Model
Correlations with output		
R&D	0.405	0.347
Consumption	0.896	0.733
Labor	-0.001	-0.026
Real interest rates	-0.148	-0.196
Standard deviation relative to output		
R&D	1.820	1.838
Consumption	0.927	0.992
Labor	0.474	0.300
Real interest rates	0.507	0.398

Notes: The data moments are computed by using quarterly data (spanning 1990Q1 to 2018Q3) from the Federal Reserve

Table 2. Alternative calibrations and volatility

	Maximum/Minimum amplitudes				Standard deviations			
Technology adoption costs	Output	Labor	R&D	growth	Output	Labor	R&D	growth
baseline (0%)	0.387	0.019	7.804	0.425	0.2601	0.0933	9.5563	0.1890
25%	0.314	0.016	11.245	0.345	0.2665	0.0926	11.4717	0.1898
50%	0.236	0.012	17.630	0.260	0.2778	0.0916	14.3452	0.1937
75%	0.148	0.008	30.962	0.163	0.2997	0.0901	19.1491	0.2052
95%	0.051	0.003	58.110	0.056	0.3371	0.0881	26.3392	0.2310
Spillover rate								
baseline (33%)	0.387	0.019	7.804	0.425	0.2601	0.0933	9.5563	0.1890
5%	0.012	0.001	1.348	0.013	0.0267	0.0093	0.9641	0.0193
50%	0.532	0.026	5.879	0.583	0.2585	0.0936	9.5318	0.1901
75%	0.734	0.036	3.804	0.805	0.2589	0.0942	9.5233	0.1953
90%	0.849	0.041	3.879	0.930	0.2605	0.0946	9.5315	0.2001
# of innovators								
baseline (2)	0.387	0.019	7.804	0.425	0.2601	0.0933	9.5563	0.1890
1.001	0.009	0.001	35.109	0.009	1.1117	0.1228	64.8317	0.9811
2.2	0.381	0.018	5.318	0.417	0.2533	0.0943	7.3784	0.1905
4	0.374	0.018	0.585	0.409	0.2416	0.0961	1.6519	0.1936
Relative adjustment costs								
baseline (100%)	0.387	0.019	7.804	0.425	0.2601	0.0933	9.5563	0.1890
25%	0.523	0.027	56.503	0.576	0.2647	0.0899	30.3946	0.1610
50%	0.424	0.021	20.452	0.466	0.2596	0.0923	14.7038	0.1794
200%	0.371	0.018	2.834	0.407	0.2608	0.0937	7.6694	0.1936
500%	0.362	0.018	1.972	0.397	0.2612	0.0940	6.8097	0.1962

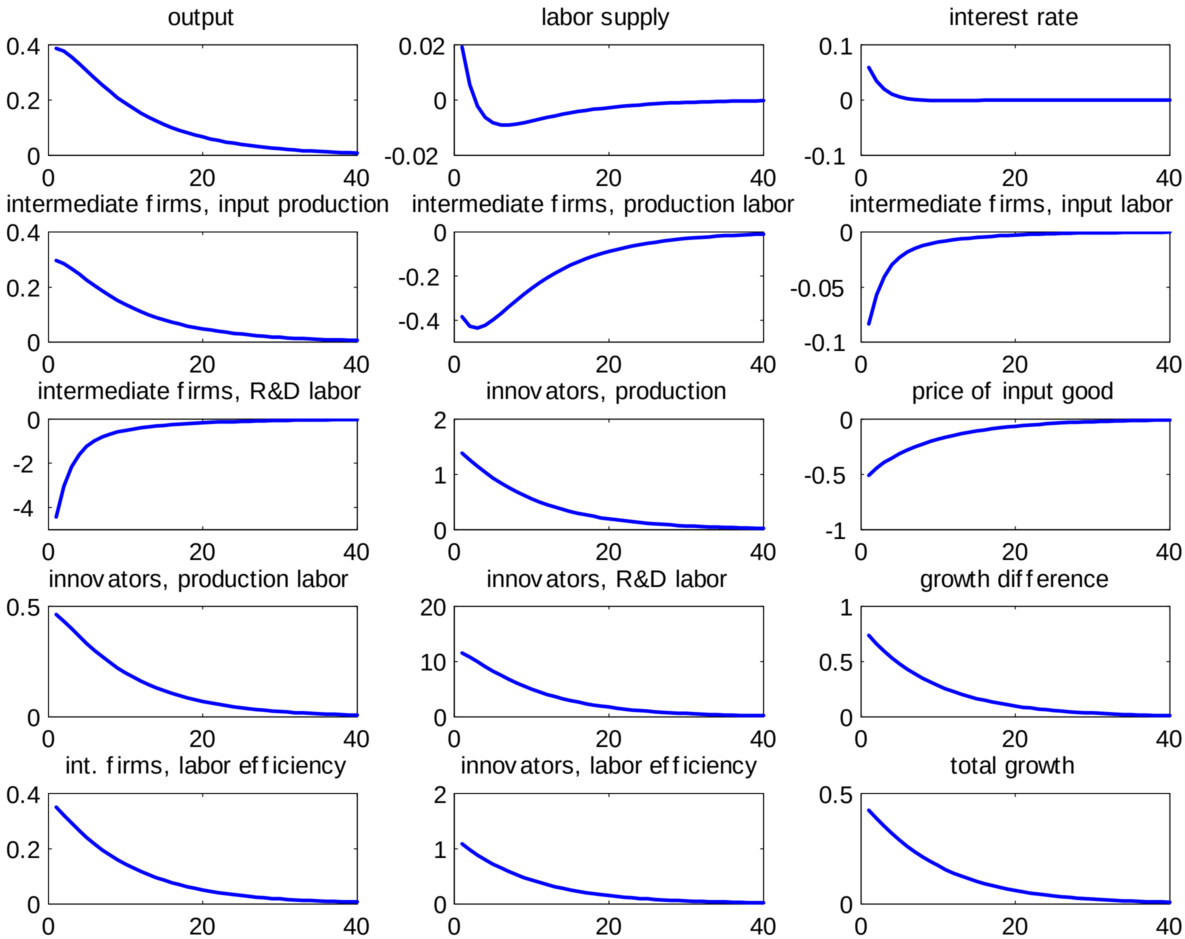
Note: The maximum amlitudes in the table are the absolute value of the percentage response of the variables to a one-standard-deviation shock to a_t^i. The standard deviations of the variables are also in percentages.

Table 3. Welfare

	u-mean	u-var	u-total
baseline	-0.0099	-0.0679	-0.0778
R&D averse economy	-0.0165	-0.2870	-0.3035
R&D intense economy	-0.0094	-0.0635	-0.0730
Zero growth, R&D averse economy	-0.0075	-0.0627	-0.0701
High growth, R&D intense economy	-0.0071	-0.0936	-0.1008

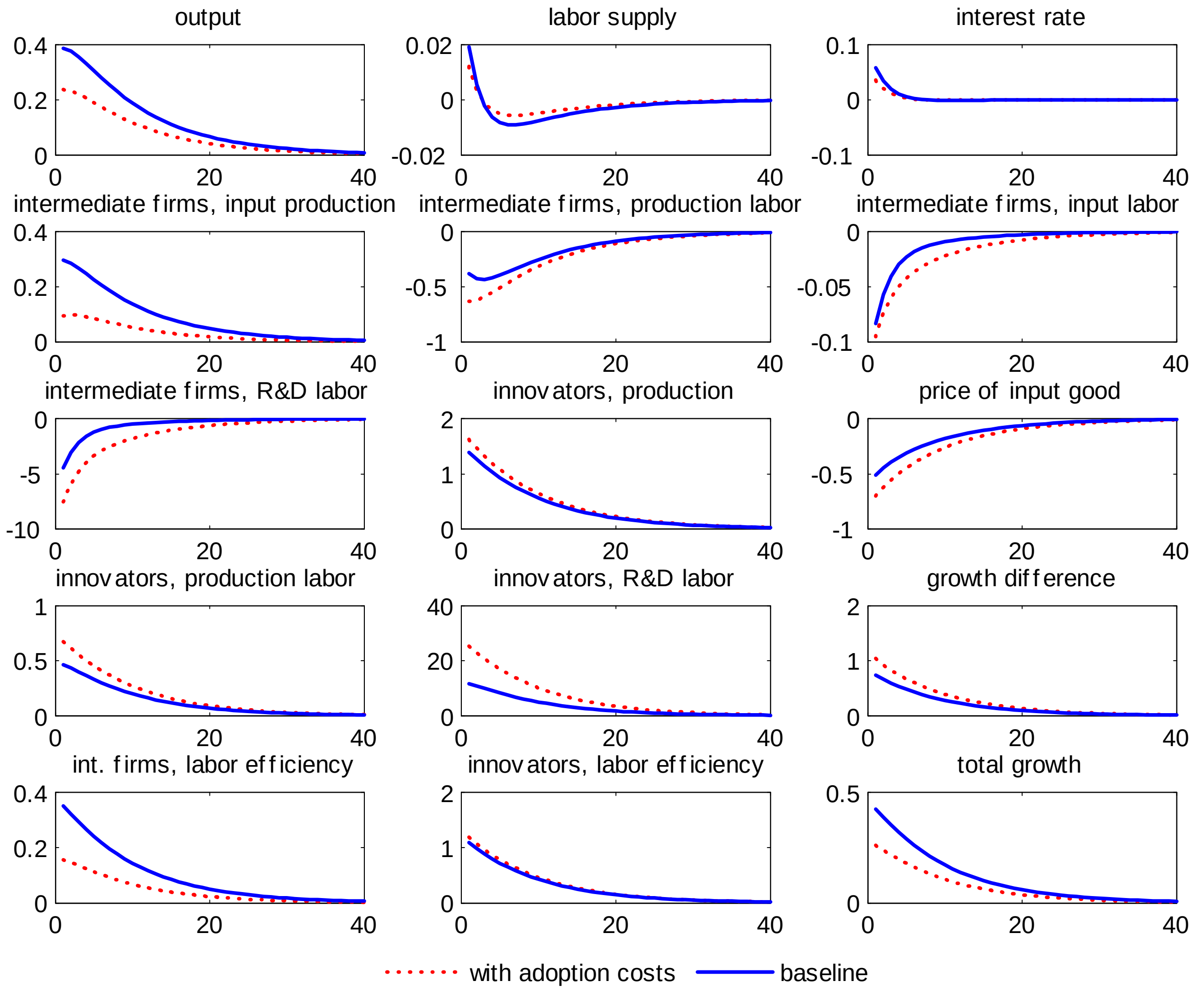
Note: This table shows the percentage of steady state consumption that households would require to sustain the volatility due to standing on shoulders, government spending and monetary policy shocks. In the R&D averse economy the innovator is a monopoly, adoption costs are 95%, innovators' adjustment costs are 500% of that of intermediate firms, and spillover rate parameter is 0.05. In the R&D intense economy, innovators are perfectly competitive and the adoption cost, relative adjustment cost and the spillover rate parameters are set equal to 1, 25% and 90%, respectively. In the zero and high growth rate economies share of R&D labor is set such that the growth rate is 0% and 6%, respectively.

Figure 1. "Standing on sholders" shock to the innovators' R&D process



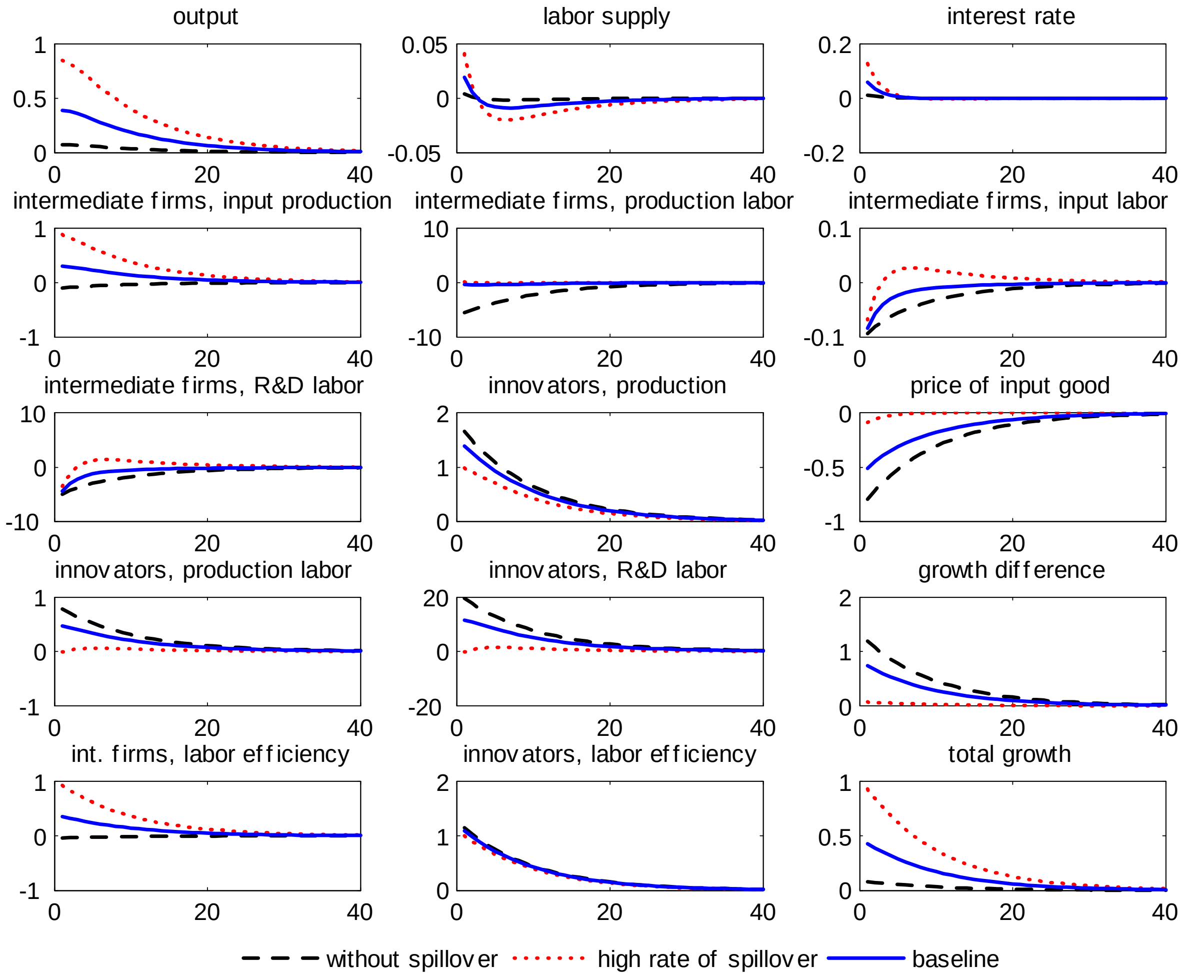
Note: The figure shows the impulse responses to a one-standard-deviation shock to a_t^i (efficiency of labor shock for innovators).

Figure 2. Technology adoption costs



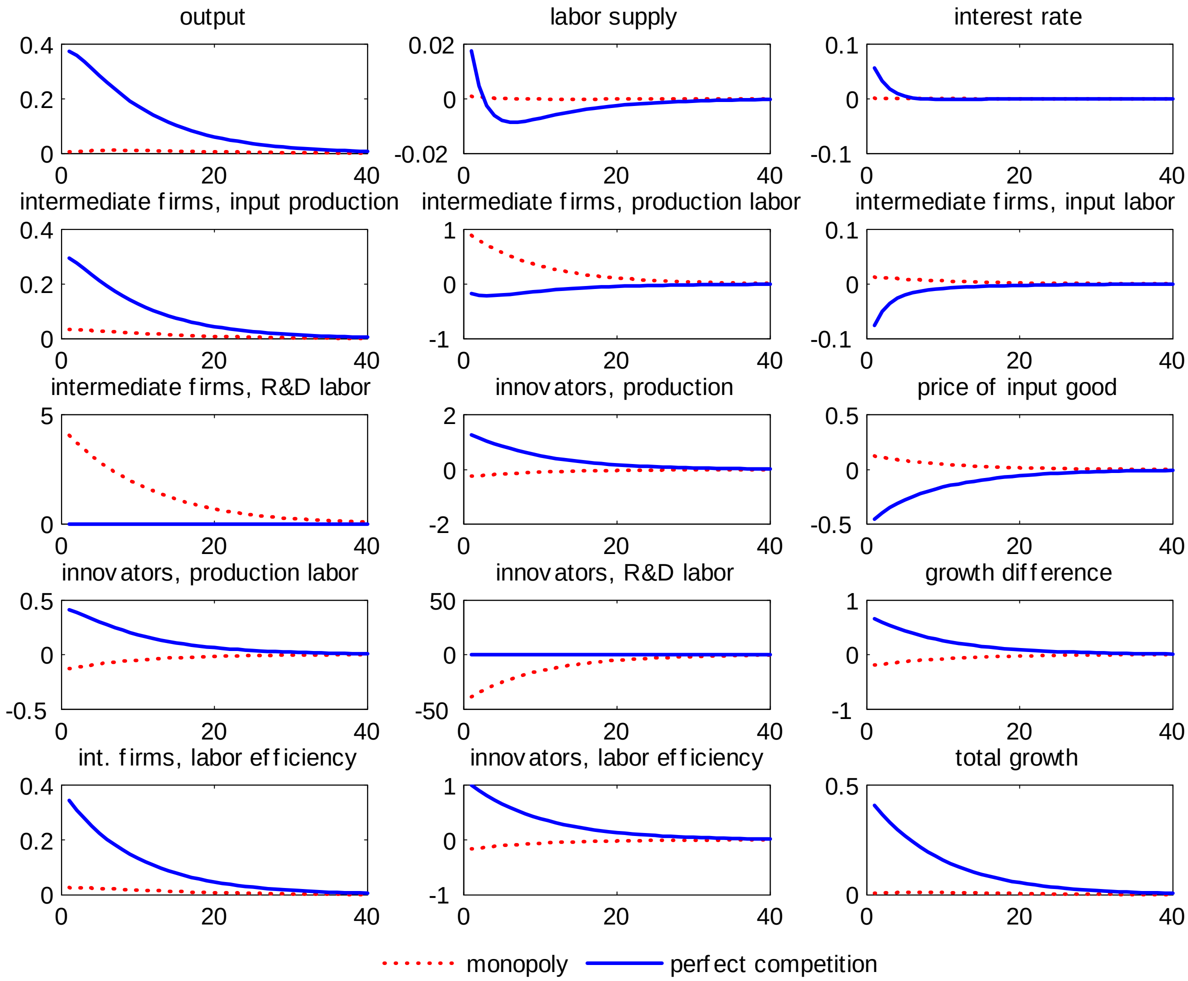
Note: The figure shows the impulse responses to a one-standard-deviation shock to a_t^i (efficiency of labor shock for innovators). In the model with technology adoption costs $u^I = u^M = u^s = u^m = 0.5$.

Figure 3. Spillover rate



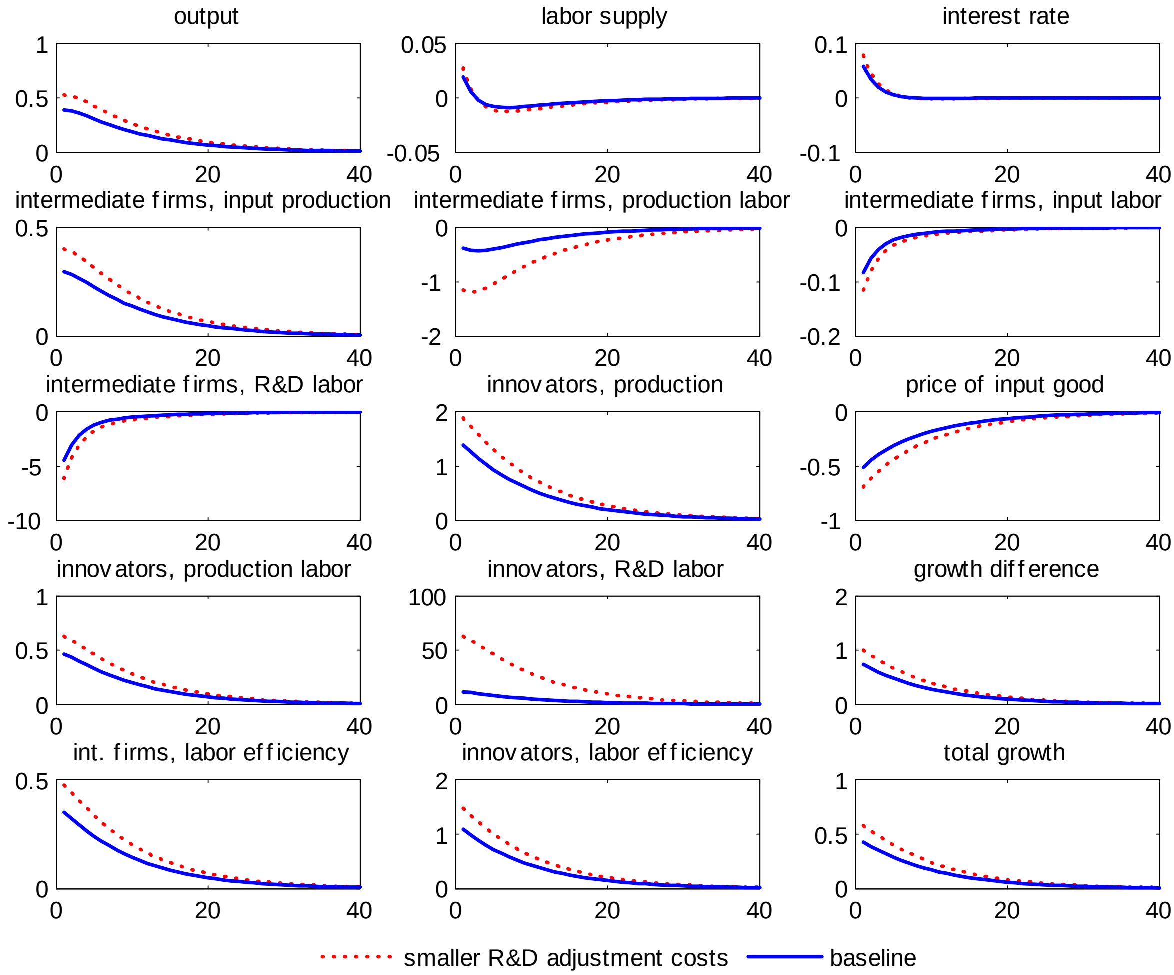
Note: The figure shows the impulse responses to a one-standard-deviation shock to a_t^i (efficiency of labor shock for innovators). In the model with a high rate of spillover $1-\eta^m-\eta^M=0.9$ and in the model with no spillover $1-\eta^m-\eta^M=0$.

Figure 4. Market power



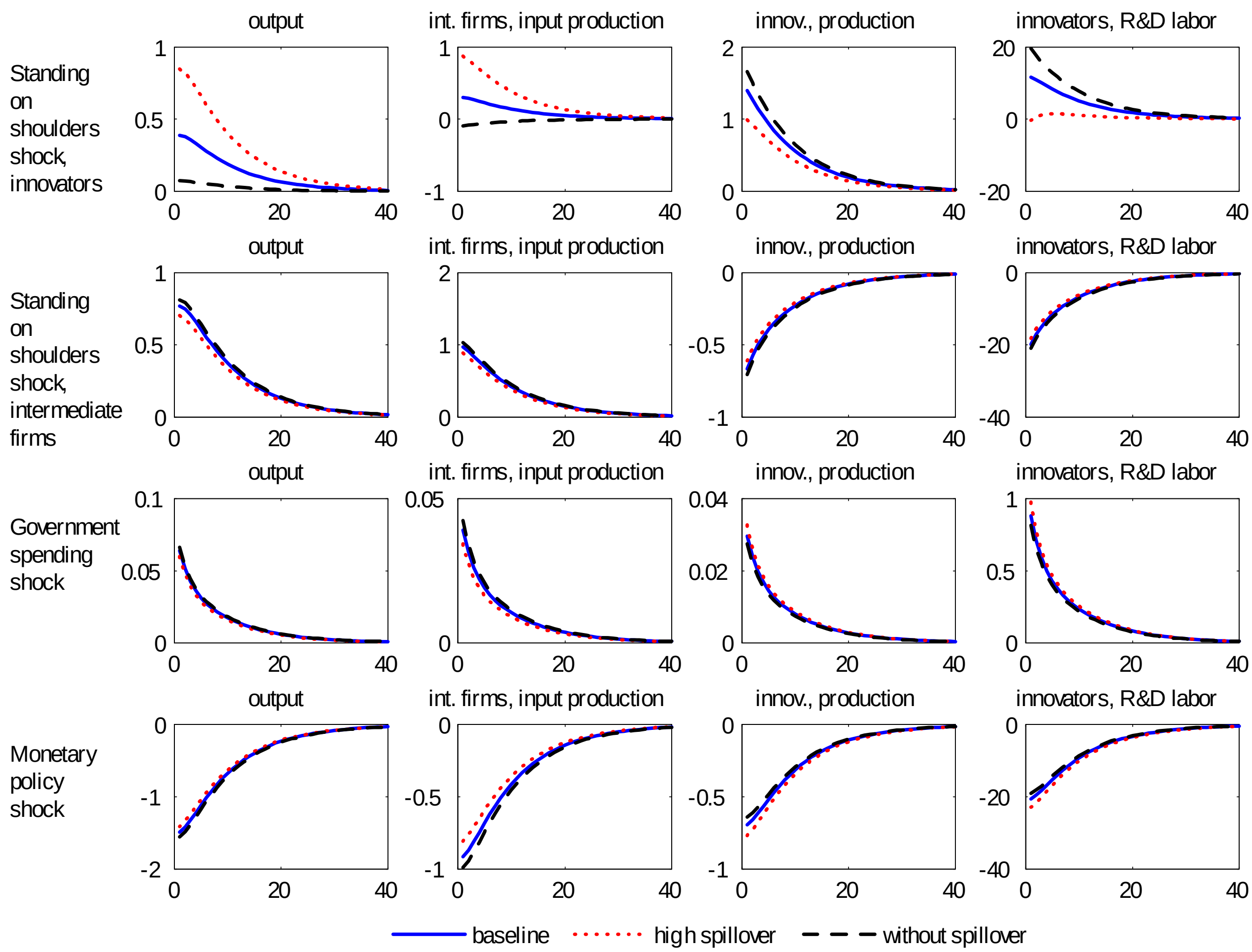
Note: The figure shows the impulse responses to a one-standard-deviation shock to a_t^i (efficiency of labor shock for innovators). N^I is set equal to 1.001 and 1,000 to approximate monopolistic and perfectly competitive structures.

Figure 5. Smaller R&D adjustment costs



Note: The figure shows the impulse responses to a one-standard-deviation shock to a_t^i (efficiency of labor shock for innovators). In the model with small R&D adjustment costs, the adjustment costs for innovators is one-fourth of the those for intermediate goods producers.

Figure 6. Other shocks



Note: The figure shows the impulse responses to a one-standard-deviation shock to innovators' and intermediate firms' R&D labor efficiency, a government spending shock, and a 100 basis (annualized) shock to the interest rate. In the model with a high rate of spillover $1-\eta^m-\eta^M=0.9$ and in the model with no spillover $1-\eta^m-\eta^M=0$.