

Heterogeneous Innovations, Firm Creation and Destruction, and Asset Prices*

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Abstract

We study the implications of the creative destruction lifecycle of innovation for asset prices. We develop a general equilibrium model of endogenous firm creation and destruction where “incremental” innovations by incumbents and “radical” innovations by entrants drive the volatility of growth prospects of the economy. Higher entry—bigger threat of displacement of incumbents by entrants—implies higher incumbent betas (cash flow channel) and lower market price of risk (discount rate channel). Furthermore, less market power implies higher incumbent betas and lower market price of risk. Economies with low barriers to entry in innovation and competitive product markets are thus less risky. The effect of competitive forces on incumbents’ cost of capital is ambiguous. Empirical evidence using data on patenting activity in the US supports the model’s predictions.

JEL Classification: E22; G12; O30; O41

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1 Introduction

Schumpeter (1934, 1942) emphasizes the importance of both creative destruction by new firms and innovations by large firms for economic growth. When describing the nature of the technological innovation process, Scherer (1984) and Freeman and Soete (1997) highlight the importance of new ventures for infrequent major advances in science and technology as well as the dominance of large firms in commercialization and continued development. Existing literature examines how the heterogeneity in R&D investments and innovation outcomes between incumbent firms and entrants affects economic growth,¹ but little is known about how are risks that stem from the creative destruction lifecycle of innovation priced in financial markets.

In this paper, we develop a dynamic stochastic general equilibrium model of endogenous firm creation and destruction to study how competition in innovation driven by market power affects asset prices. Existing firms (incumbents) enjoy monopoly profits, but face the threat of being displaced by new firms (entrants). Both incumbent firms and potential entrants invest in R&D, but their innovations are heterogenous. Incumbent firms' R&D results in incremental improvements of their existing products and higher profits. Potential entrants undertake R&D in order to create radically better products, displace incumbent firms, and capture their profits.

At the core of our model is the feedback effect between R&D decisions and the value of future monopoly profits. Incumbent firms' and potential entrants' R&D incentives depend on the value attained upon success in innovation. This value depends on R&D through two channels. First, a “cash flow channel”: higher potential entrants' R&D expenditure increase the probability of entrants displacing incumbent firms and lower their value. Second, a “discount rate channel”: the equilibrium stochastic discount factor of the economy depends on the expectation of future growth and hence on the structure of R&D expenditure in the economy. We solve for the competitive equilibrium in this economy and analyze the implications of heterogeneous innovations by incumbent firms and entrants—and the implied entry and exit firm dynamics—for aggregate asset prices.

Our main result is that, when responding to aggregate shocks, the incremental and radical margins of innovation interact and jointly alter the volatility of growth prospects of the econ-

¹See seminal contributions of Grossman and Helpman (1991) and Aghion and Howitt (1992) to endogenous growth theory. Aghion and Howitt (1998, 2009) and Acemoglu (2010) provide a summary of the literature. Akgic and Kerr (2010) show that large firms engage more in exploitative R&D, while small firms pursue exploratory R&D.

omy. Specifically, keeping the long-term economic growth constant, economies with higher entry threat exhibit lower volatility of expected consumption growth. This obtains because R&D expenditure of potential entrants and incumbent firms are jointly determined in equilibrium, and higher entry threat thus obtains when potential entrants are more efficient in converting their R&D into innovation success compared to incumbent firms. This also means that, in economies with higher entry threat, potential entrants account for a bigger share of aggregate R&D expenditure. Therefore, for a given long-term growth rate of the economy, higher innovative efficiency of potential entrants leads to lower volatility of aggregate R&D expenditure and expected consumption growth. If the representative household prefers early resolution of uncertainty, the market price of risk is declining with entry threat.

Next, we show that incumbent firms' betas are positive and, in calibrations that are in line with US innovation data, increasing in the level of entry threat they face. This is because higher entry threat is eroding incumbent firms' effective monopoly power by exposing them to a bigger probability of displacement, in other words, to a bigger probability of default. Incumbent firms that are exposed to a high entry threat can thus be thought of as firms with a high leverage. The result that firms that are more exposed to entry threat have bigger betas is consistent with what a partial equilibrium model—where the price of risk does not change across entry levels—would predict about the risk premia of such firms. This conclusion, however, can be misleading. As our previous result shows, higher entry threat is associated with a lower market price of risk, making the overall effect on incumbent firms' risk premia ambiguous.

These two main predictions are consistent with empirical evidence. To measure entry threat in innovation, we compute the ratio of the number of US patents applied for, in a given quarter, by firms that did not patent prior to this quarter to the total number of US patents applied for by all firms in the same quarter. The entry threat ranges from 8 to 16 percent and is mostly declining over the 1985-2008 period (see Figure 1). Figure 2 Panel A shows that, after removing the linear time trend, the correlation between our measure of entry threat and the quarterly conditional Sharpe ratio of the market portfolio computed as in Lettau and Ludvigson (2010) is negative. In contrast, Figure 2 Panel B shows that the correlation between our detrended entry threat measure and the market beta of the portfolio of US firms that repeatedly patent is positive. Regression analysis leads to analogous results.

Finally, we find that, for the same levels of entry threat, bigger market power of incumbent firms implies higher market price of risk and lower incumbent firms' betas. The former obtains because higher markups amplify the effect of aggregate productivity shocks on incumbent firms' profits and hence induce larger equilibrium R&D responses to these shocks. The market price of risk increases because higher volatility of R&D expenditure leads to more volatile expected consumption growth. The latter obtains because, with less market power, incumbent firms' profits and values are smaller due to high degree of product substitutability. More substitutability acts as a form of "economic distress" for incumbent firms. We also find that, when incumbent firms enjoy relatively bigger market power, the same increase in entry threat leads to a more significant increase in incumbent firms' betas. This suggests that the effect of displacement described above is stronger for firms with more market power.

Our findings have implications for empirical work that examines the effects of product market structure and competition in innovation on asset prices. We emphasize that, in order to understand how the degree of market power or entry/exit firm dynamics affects aggregate asset prices and the cross section of stock returns, it is important to account for both the cash flow and discount rate channels. In equilibrium, firms' returns are determined by the sensitivity of their value to aggregate shocks (betas) and the price of aggregate risk (the Sharpe ratio of a security perfectly correlated with the aggregate shocks). We show that different degrees of market power or different levels of entry/exit result in changes of both firms' betas and the market price of risk. Empirical studies that fail to account for the discount rate channel when studying the role of market power or competition in innovation provide only incomplete answers.

Our model builds on recent contributions to Schumpeterian growth theory, that capture micro-founded incentives of firms to innovate, preserve competitive aspects of innovation, as formalized by the industrial organization literature, and model firm dynamics (Acemoglu and Cao (2010) and Klette and Kortum (2004)). A growing body of work studies the asset pricing implications of technological innovation. Using an equilibrium model with heterogeneous firms, households, and imperfect risk sharing, Kogan, Papanikolaou, and Stoffman (2013) show that technological innovations embodied in new capital displace existing firms and thus benefit new cohorts of shareholders at the expense of existing ones. Gârleanu, Kogan, and Panageas (2012) argue that innovation introduces an unhedgeable displacement risk due to lack of intergenerational risk sharing. Gârleanu, Panageas, and Yu (2012) examine the link between infrequent

technological shocks embodied in new capital vintages and excess return predictability and other stylized cross-sectional return patterns. Pástor and Veronesi (2009) show how technology adoption can explain the rise of stock price bubbles. Greenwood and Jovanovic (1999) and Hobijn and Jovanovic (2001) link the stock market drop in the 1970s and its rebound in the 1980s to the information technology revolution. We differ from these papers by endogenizing the arrival of new technologies, which leads to endogenous creation and destruction of firms in our economy.

Building on the long-run risk mechanism of Bansal and Yaron (2004), Ai and Kiku (2013) and Ai, Croce, and Li (2013) develop general equilibrium models with tangible and intangible capital to show that growth options are less risky than assets in place, providing a micro foundation for value premium. Our focus is to study aggregate implications of firm entry and exit driven by R&D expenditure. As in Kung and Schmid (2013), in our model, R&D creates a persistent component of expected consumption growth that allows us to jointly match macroeconomic and aggregate asset pricing quantities. Since our model is based on Schumpeterian growth and we allow for heterogeneous innovations by firms, we are able to study implications of entry threat for asset prices. Loualiche (2013) shows that differential exposure to shocks to entrants' productivity across sectors of incumbent firms explains differences in incumbent firms' expected returns. Our setting differs from Loualiche (2013) in two main aspects. First, in line with empirical evidence, and in contrast to Loualiche (2013), incumbent firms in our model innovate and their contribution to economic growth is large.² Second, our model is more parsimonious, because there is no shock to entrants' productivity, but only an aggregate productivity shock. Entry threat is not priced directly in our model, but we show that it is an important determinant of the price of risk in the economy. Finally, unlike expanding product variety models of Kung and Schmid (2013) and Loualiche (2013), the Schumpeterian nature of growth in our model allows for a more realistic relationship between competition and growth.³

The paper is structured as follows. In Section 2, we describe our model. In Section 3, we examine the asset pricing implications of entry threat and market power. Section 4 concludes.

²According to U.S. Manufacturing Census data in recent years, annual product creation, by existing firms and new firms, accounts for 9.3 percent of output, and the lost value from product destruction, by existing and exiting firms, accounts for 8.8 percent of output. About 70 percent of product creation and destruction occurs within existing firms (see Bilbiie, Ghironi, and Melitz (2012), Bernard, Redding, and Schott (2010), and Broda and Weinstein (2010)). Bartelsman and Doms (2000) and Foster, Haltiwanger, and Krizan (2001) show that most total factor productivity growth comes from existing as opposed to new establishments.

³Compared to expanding product variety models (Romer (1990)), where more intense product market competition always leads to a lower economic growth, Schumpeterian growth models allow for a positive relation between competition and growth (Aghion, Harris, Howitt, and Vickers (2001)). See empirical evidence by Nickell (1996) and Blundell, Griffith, and Reenen (1995, 1999).

2 Model

We develop a Schumpeterian model of growth in which R&D activities are carried out by both existing firms (incumbents) and new firms (entrants). The economy admits a representative final good sector firm producing the unique good consumed by an infinitely-lived representative household with recursive preferences. The production of the consumption good requires labor, physical capital, and a continuum of intermediate goods (inputs). The model features a single aggregate shock affecting the productivity of the final good sector firm.

Each incumbent firm is a monopolist in the production of its own input and has access to an innovation technology that stochastically improves its input's quality. For each input, there is an infinite supply of atomistic potential entrants deploying R&D to radically increase the input's quality. Upon success, the entrant displaces the incumbent firm in the production of the input and captures its monopoly position.

Economic growth arises endogenously and is driven by the speed of quality improvements of inputs, i.e., by the rate of growth of technology capital. The relative contributions of incumbent firms and entrants to growth are determined in equilibrium through their decisions to invest in R&D. We show that the equilibrium R&D investments by incumbent firms and potential entrants play a key role in determining asset prices. The rest of this section lays out the model in more details.

2.1 Representative household

The representative household has Epstein-Zin-Weil preferences over the final consumption good

$$U_t = \left\{ (1 - \beta)C_t^{1-\frac{1}{\psi}} + \beta \left(\mathbb{E}_t \left[U_{t+1}^{1-\gamma} \right]^{\frac{1}{1-\gamma}} \right)^{1-\frac{1}{\psi}} \right\}^{\frac{1}{1-\frac{1}{\psi}}}, \quad (1)$$

where β is the subjective time preference parameter, γ is the coefficient of relative risk aversion and ψ is the elasticity of intertemporal substitution. The household chooses consumption C_t to maximize (1) taking the wage and aggregate dividends distributed by all firms in the economy as given

$$\max_{\{C_s\}_{s=t}^{\infty}} U_t \quad \text{s.t.} \quad C_t \leq w_t L_t + D_t^A - S_t^E. \quad (2)$$

In problem (2), w_t is wage, L_t is labor, D_t^A is the aggregate dividend defined in (34) below, i.e., the dividend distributed by the final good firm plus the sum of dividends distributed by all incumbent firms and S_t^E is potential entrants' R&D expenditure. Since we do not model the consumption-leisure tradeoff, labor is supplied inelastically, and we thus normalize it to be $L_t = 1$ for all t . In the household budget constraint, potential entrants' R&D expenditures reduce the amount of available consumption goods.

We obtain the stochastic discount factor (SDF) from the household problem (2). The one-period SDF at time t , implied by the preferences, can be expressed as

$$\mathbb{M}_{t,t+1} = \beta^\theta \left(\frac{C_{t+1}}{C_t} \right)^{-\theta/\psi} R_{C,t+1}^{-(1-\theta)}, \quad (3)$$

where $\theta \equiv \frac{1-\gamma}{1-\frac{1}{\psi}}$ and $R_{C,t+1}$ is the return on the consumption claim.⁴

2.2 Final good sector

The production of the unique final good requires labor, capital, and a continuum of measure one of intermediate goods denoted “inputs” $i \in [0, 1]$. The production function is

$$Y_t = (K_t^\alpha (A_t L_t)^{1-\alpha})^{1-\xi} G_t^\xi, \quad \text{with} \quad G_t = \left[\int_0^1 q(i, t)^{1-\frac{1}{\nu}} x(i, t|q)^{\frac{1}{\nu}} di \right]^\nu. \quad (4)$$

In (4), K_t and L_t denote capital and labor, respectively, $\alpha \in (0, 1)$ is the capital share, $\xi \in (0, 1)$ is the share of inputs in the final output. Quantity G_t defines a composite intermediate good obtained by weighting the quantity $x(i, t|q)$ of each input i by its quality $q(i, t)$ through a constant elasticity aggregator. Parameter ν captures the elasticity of substitution between any two inputs.⁵ The production process (4) implies that, for each input $i \in [0, 1]$, only the highest quality type is used. In the next section, we discuss the dynamics of the quality of inputs. Aggregate risk originates from an exogenous shock $A_t = e^{a_t}$, where a_t is a stationary AR(1)

⁴Formally, $R_{C,t+1} = \frac{W_{t+1}}{W_t - C_t}$ is the return on household's wealth W_t , defined as the present value of future aggregate dividends and labor income, $W_t = \mathbb{E}_t[\sum_{s=1}^{\infty} \mathbb{M}_{t,t+s} C_{t+s}]$.

⁵The elasticity of substitution between inputs i and j is

$$\frac{\frac{\Delta(x_i/x_j)}{x_i/x_j}}{\frac{\Delta(G_{x_i}/G_{x_j})}{G_{x_i}/G_{x_j}}} = \frac{d \log(x_i/x_j)}{d \log(G_{x_i}/G_{x_j})} = \frac{\nu}{\nu - 1}, \quad \text{where} \quad G_x = \frac{\partial G}{\partial x}.$$

process

$$a_t = \rho a_{t-1} + \varepsilon_t, \quad \varepsilon_t \sim \mathcal{N}(0, \sigma^2). \quad (5)$$

The final good firm takes wage w_t , the prices $p(i, t|q)$ of each input i and the SDF $\mathbb{M}_{t,t+1}$ as given, and chooses labor L_t , investment I_t , and the quantity $x(i, t|q)$ of each input to maximize its value

$$\max_{\{I_s, K_{s+1}, L_s, x(i, s|q)\}_{s=t}^{\infty}} \mathbb{E}_t \left[\sum_{s=t}^{\infty} \mathbb{M}_{t,s} D_s \right]. \quad (6)$$

In problem (6), the firm's dividend D_s is

$$D_s = Y_s - I_s - w_s L_s - \int_0^1 p(i, s|q) x(i, s|q) di, \quad (7)$$

and the next period capital stock K_{s+1} is

$$K_{s+1} = (1 - \delta)K_s + \Lambda \left(\frac{I_s}{K_s} \right) K_s, \quad (8)$$

where δ is the capital depreciation rate and $\Lambda(\cdot)$ is a convex adjustment cost function.⁶

2.3 Intermediate good sector

The intermediate good sector is composed of a continuum of firms each producing a single input $i \in [0, 1]$. At each time t , input i is characterized by quality $q(i, t)$. Economic growth arises due to the growth of inputs' quality achieved by incremental innovations by incumbents and by more radical innovations by entrants.

2.3.1 Incumbent firms

At each time t , each input belongs to an incumbent firm who holds a fully enforced patent on the input's current quality. Incumbents are thus monopolists in the production of the input with current quality. Taking the demand schedule $x(i, t|q)$ for input i of quality $q(i, t)$ determined by the final good sector firm as given, incumbent i sets price $p(i, t|q)$ by maximizing its profits at

⁶We follow Jermann (1998) and define $\Lambda \left(\frac{I_s}{K_s} \right) = \frac{\alpha_1}{1-\frac{1}{\zeta}} \left(\frac{I_s}{K_s} \right)^{1-\frac{1}{\zeta}} + \alpha_2$, where $\alpha_1 = (\bar{\alpha} + \delta - 1)^{\frac{1}{\zeta}}$, $\alpha_2 = \frac{1}{1-\frac{1}{\zeta}} (\bar{\alpha} + \delta - 1)$. We choose constant $\bar{\alpha}$ such that there are no adjustment costs in the deterministic steady state. Parameter ζ is the elasticity of the investment rate. The limiting cases $\zeta \rightarrow 0$ and $\zeta \rightarrow \infty$ represent infinitely costly adjustment and frictionless adjustment, respectively.

each time t

$$\pi(i, t|q) = \max_{p(i, t|q)} p(i, t|q) x(i, t|q) - \mu x(i, t|q), \quad (9)$$

where μ is the marginal cost of production of input i with quality $q(i, t)$.

Each incumbent has access to a stochastic quality-improving innovation technology for its own input. If the incumbent spends $s^I(i, t) q(i, t)$ units of the consumption good on R&D towards its input with current quality $q(i, t)$, over a time interval Δt , the quality increases to $q(i, t + \Delta t) = \kappa_I q(i, t)$, $\kappa_I > 1$, with probability $\phi_I(s^I(i, t))\Delta t$, where $\phi_I(\cdot)$ is a strictly increasing and concave function satisfying the Inada-type conditions $\phi_I(0) = 0$ and $\phi_I'(0) = \infty$.⁷ If R&D does not result in innovation, we assume that quality “depreciates” by a factor $\kappa_D < 1$, i.e., $q(i, t + \Delta t) = \kappa_D q(i, t)$. Parameter κ_D captures patent expiration and general obsolescence of products over time.

For an incumbent, investing in R&D is an intertemporal decision that affects the accumulation of the technology capital $q(i, t)$ and hence future profits. Patent protection of the input with quality $q(i, t)$, however, does not prevent potential entrants to invest in R&D to invent a higher-quality input. If successful, incumbent’s input with quality $q(i, t)$ becomes obsolete and the entrant “displaces” the incumbent in the production of input i . Since incumbent’s innovation success is uncertain and because of the likelihood that the incumbent is displaced by an entrant, the evolution of quality is stochastic. Value $V(i, t|q)$ of incumbent i producing input of quality $q(i, t)$ is the discounted value of the profits it earns until it is displaced by an entrant. We describe the optimal choice of R&D expenditure and determine $V(i, t|q)$ in Section 2.4.

2.3.2 Entrants

For each input i and at each time t , there is an infinite supply of atomistic entrants who deploy R&D in order to increase the input’s quality and steal the right to produce the input from the current incumbent firm. If all input- i entrants spend in total $\hat{s}^E(i, t) q(i, t)$ units of the consumption good on R&D, over a time interval Δt , the quality increases to $q(i, t + \Delta t) = \kappa_E q(i, t)$, $\kappa_E > \kappa_I$, with probability $\hat{s}^E(i, t) \phi_E(\hat{s}^E(i, t))\Delta t$, where $\phi_E(\cdot)$ is a strictly decreasing function satisfying the same Inada-type conditions as $\phi_I(\cdot)$. The condition $\kappa_E > \kappa_I$ means that potential entrants’ innovation technology is more “radical” than that of incumbents. Upon

⁷The conditions ensure that, for any interval $\Delta t > 0$, the probability of one innovation is $\phi_I(s^I(i, t))\Delta t$, while the probability of more than one innovation is $o(\Delta t)$ with $o(\Delta t)/\Delta t \rightarrow 0$ as $\Delta t \rightarrow 0$.

innovation success, the entrant acquires a fully enforceable patent on the quality $\kappa_E q(i, t)$ of input i and becomes a new incumbent firm producing the input. Following Acemoglu and Cao (2010), we assume that the function $\phi_E(\cdot)$ is strictly decreasing to capture the fact that, if many entrants attempt to replace the same input, they are likely to try out similar ideas resulting in diminishing returns. We further assume that $\hat{s}^E \phi_E(\hat{s}^E)$ is increasing in \hat{s}^E to insure that a bigger aggregate R&D toward a particular input increases the overall probability of discovery for this input.

Since there is an infinite supply of potential entrants and each potential entrant is atomistic, their R&D expenditure $\hat{s}^E(i, t)$ is determined by a zero profit, or free-entry, condition.⁸ We formalize the equilibrium determination of potential entrants' R&D expenditure in the next section.

2.4 Equilibrium

We denote by X_t the total amount of expenditure on the production of the intermediate goods

$$X_t = \mu \int_0^1 x(i, t) di, \quad (10)$$

by S_t^I the total amount of R&D expenditure by incumbent firms

$$S_t^I = \int_0^1 s^I(i, t) q(i, t) di, \quad (11)$$

and by S_t^E the total amount of R&D expenditure by potential entrants

$$S_t^E = \int_0^1 \hat{s}^E(i, t) q(i, t) di. \quad (12)$$

Aggregate R&D expenditure in the economy is $S_t = S_t^I + S_t^E$. Since the labor market is competitive, the wage satisfies

$$w_t = \frac{\partial Y_t}{\partial L_t} = (1 - \alpha)(1 - \xi)Y_t. \quad (13)$$

An equilibrium allocation in this economy consists of (i) time paths of consumption levels, physical capital, investment, aggregate spending on inputs and aggregate R&D expenditure

⁸Although the technology for radical innovation is also available to incumbents, they have no incentive to use it. This is a consequence of the ‘‘Arrow’s replacement effect’’: Because potential entrants earn zero profits, an incumbent who invests to replace its own product via radical innovation would earn negative profits.

$\{C_t, K_t, I_t, X_t, S_t\}_{t=0}^{\infty}$, (ii) time paths of R&D expenditures by incumbents and potential entrants $\{s^I(i, t), \hat{s}^E(i, t)\}_{i \in [0,1] t=0}^{\infty}$, (iii) time paths of prices and quantities for each input, and values of each incumbent $\{p(i, t|q), x(i, t), V(i, t|q)\}_{i \in [0,1] t=0}^{\infty}$, and (iv) time paths for wages and SDF $\{w_t, M_{t,t+1}\}_{t=0}^{\infty}$ such that (a) the representative household maximizes lifetime utility (2), (b) the final good firm maximizes the present value of future dividends (6)–(8), (c) incumbents and entrants maximize present values of their future net profits (see equations (29), (30) and (32) below), (d) the labor market clears (i.e., $L_t = 1$), and (e) the final good market clears (i.e., the resource constraint (35) holds).

We now determine the equilibrium quantity $x(i, t|q)$ and price $p(i, t|q)$ of inputs, the optimal level of R&D expenditure by incumbents $s^I(i, t)$ and potential entrants $\hat{s}^E(i, t)$, and the value of incumbent firms $V(i, t|q)$. Given $x(i, t)$ and $p(i, t|q)$, the solution of the final good firm's maximization problem (6)–(8) is standard and is described in Appendix A.

2.4.1 Quantity and price of intermediate goods

The final good firm's demand $x(i, t|q)$ for input i arises from an intra-temporal decision where the final good firm maximizes its dividend D_t defined in (7) at each time t . Using the definition of Y_t in (4), this maximization yields the following demand for input

$$x(i, t|q) = \xi^{\frac{\nu}{\nu-1}} (K_t^\alpha (A_t L_t)^{1-\alpha})^{\frac{(1-\xi)\nu}{\nu-1}} G_t^{\frac{\xi\nu-1}{\nu-1}} (p(i, t|q))^{\frac{\nu}{1-\nu}} q(i, t). \quad (14)$$

Using (14) in incumbent's problem (9) leads to markup pricing

$$p(i, t|q) = \nu \mu. \quad (15)$$

The profit maximizing price is a markup over marginal cost because demand (14) is isoelastic. Higher degree of substitutability across inputs (i.e., lower ν) leads to a smaller markup. Using the markup price (15), incumbent's profit is

$$\pi(i, t|q) = (\nu - 1) \mu x(i, t|q). \quad (16)$$

Substituting (14) and (15) into (4) gives the following expression for the composite input

$$G_t = \left(\frac{\xi}{\nu \mu} \right)^{\frac{1}{1-\xi}} K_t^\alpha (A_t L_t)^{1-\alpha} Q_t^{\frac{\nu-1}{1-\xi}}, \quad (17)$$

where

$$Q_t = \int_0^1 q(i, t) di \quad (18)$$

is the aggregate quality of inputs. As we discuss in Section 2.4.3, Q_t is the key state variable that captures the endogenous growth of technology capital in the economy.

Expressions (15) and (17) allow us to rewrite the equilibrium quantity of input $x(i, t|q)$ in (14) as a linear function of quality

$$x(i, t|q) = \left(\frac{\xi}{\nu\mu} \right)^{\frac{1}{1-\xi}} K_t^\alpha (A_t L_t)^{1-\alpha} Q_t^{\frac{\xi\nu-1}{1-\xi}} q(i, t). \quad (19)$$

Linearity of $x(i, t|q)$ in $q(i, t)$ is convenient because it allows us to easily obtain aggregate quantities. Specifically, using (10), (16) and (17), we obtain that the equilibrium aggregate spending on inputs X_t , aggregate incumbents' profits Π_t and output Y_t are

$$X_t = \mu \int_0^1 x(i, t) di = \mu \left(\frac{\xi}{\nu\mu} \right)^{\frac{1}{1-\xi}} K_t^\alpha (A_t L_t)^{1-\alpha} Q_t^{\frac{(\nu-1)\xi}{1-\xi}}, \quad (20)$$

$$\Pi_t = \int_0^1 \pi(i, t|q) di = (\nu - 1) X_t, \quad (21)$$

$$Y_t = \left(\frac{\xi}{\nu\mu} \right)^{\frac{\xi}{1-\xi}} K_t^\alpha (A_t L_t)^{1-\alpha} Q_t^{\frac{(\nu-1)\xi}{1-\xi}}. \quad (22)$$

As the technology capital Q_t is a growing process driven by R&D expenditures by incumbents and entrants, to insure balanced growth, we impose the following parametric restriction

$$\frac{(\nu - 1)\xi}{1 - \xi} = 1 - \alpha. \quad (23)$$

Under this condition, output and aggregate expenditures on inputs can be written as

$$Y_t = \left(\frac{\xi}{\nu\mu} \right)^{\frac{\xi}{1-\xi}} K_t^\alpha (A_t Q_t L_t)^{1-\alpha}, \quad (24)$$

$$X_t = \frac{\xi}{\nu} Y_t. \quad (25)$$

Technology capital acts as an endogenous “labor augmenting” productivity factor. The presence of the stochastic process A_t implies that the productivity growth is stochastic. Variables A_t , K_t and Q_t are the state variables describing the evolution of the economy.

2.4.2 R&D expenditure by incumbent firms and entrants

Value $V(i, t|q)$ of incumbent i at time t is the present value of its future net profits. Due to the possibility that the incumbent will be replaced by an entrant, the time at which the incumbent’s stream of net profits ends is a random variable $\mathcal{T}(i, t) > t$. Incumbent’s value is

$$V(i, t|q) = \max_{\{s^I(i, \tau)\}_{\tau=t}^{\mathcal{T}(i, \tau)}} \mathbb{E}_t \left[\sum_{\tau=t}^{\mathcal{T}(i, \tau)} \mathbb{M}_{t, \tau} (\pi(i, \tau|q) - s^I(i, \tau)q(i, \tau)) \right]. \quad (26)$$

Innovation technologies of incumbents and entrants described in Sections 2.3.1 and 2.3.2 imply that, over the next Δt time period, the incumbent is displaced with probability $\hat{s}^E(i, t)\phi_E(\hat{s}^E(i, t)) \Delta t$ and survives otherwise. The incumbent takes potential entrants’ R&D expenditure $\hat{s}^E(i, t)$ and the SDF process (3) as given. In case of displacement, incumbent’s value drops to zero. In case of survival, its value depends on whether or not incumbent’s R&D expenditure $s^I(i, t)$ result in a quality improvement. With probability $\phi_I(s^I(i, t)) \Delta t$, quality increases to $q(i, t + \Delta t) = \kappa_I q(i, t)$, while with probability $1 - \phi_I(s^I(i, t)) \Delta t - \hat{s}^E(i, t)\phi_E(\hat{s}^E(i, t)) \Delta t$, quality depreciates to $q(i, t + \Delta t) = \kappa_D q(i, t)$. Assuming that Δt is sufficiently small, the future incumbent’s value $V(i, t + \Delta t|q')$ can be written as a random variable with the following distribution

$$V(i, t + \Delta t|q') = \begin{cases} 0 & \text{with probability } \hat{s}^E(i, t)\phi_E(\hat{s}^E(i, t)) \Delta t, \\ V(i, t + \Delta t|\kappa_I q) & \text{with probability } \phi_I(s^I(i, t)) \Delta t, \\ V(i, t + \Delta t|\kappa_D q) & \text{otherwise.} \end{cases} \quad (27)$$

For simplicity of notation, in the sequel, we refer to time “ $t + \Delta t$ ” as “ $t + 1$ ”, with the understanding that the time lapse between two adjacent periods is close enough for the above approximation to be valid. Using (27), the stopping time problem (26) can then be rewritten as the following Bellman equation

$$V(i, t|q) = \max_{s^I(i, t)} \{ \pi(i, t|q) - s^I(i, t)q(i, t) + \mathbb{E}_t [\mathbb{M}_{t, t+1} \{ \phi_I(s^I(i, t)) \times V(i, t + 1|\kappa_I q) + (1 - \phi_I(s^I(i, t)) - \hat{s}^E(i, t)\phi_E(\hat{s}^E(i, t))) \times V(i, t + 1|\kappa_D q) \}] \}. \quad (28)$$

We interpret $\pi(i, t|q) - s^I(i, t)q(i, t)$ as the dividend distributed by the incumbent firm, term $\hat{s}^E(i, t)\phi_E(\hat{s}^E(i, t))$ as the (per period) probability with which a radical innovation by an entrant occurs in input i , and term $\phi_I(s^I(i, t))$ as the (per period) probability with which incumbent i innovates improving its input.

From (19), input quantities $x(i, t)$ are linear in quality $q(i, t)$. By (16), profits $\pi(i, t|q)$ and thus incumbents' dividends are also linear in quality. This homogeneity property and the balanced growth path condition imply that $\pi(i, t|q) = \pi_t q(i, t)$, $s^I(i, t)q(i, t) = s_t^I q(i, t)$, and $\hat{s}^E(i, t)q(i, t) = \hat{s}_t^E q(i, t)$. Therefore, incumbent's value is $V(i, t|q) = v_t q(i, t)$ for all t and $i \in [0, 1]$, where v_t and s_t^I solve the following Bellman equation

$$v_t = \max_{s_t^I} \{ \pi_t - s_t^I + \mathbb{E}_t [M_{t,t+1} v_{t+1} (\phi_I(s_t^I) \kappa_I + (1 - \phi_I(s_t^I) - \hat{s}_t^E \phi_E(\hat{s}_t^E)) \kappa_D)] \}. \quad (29)$$

Quantities π_t , s_t^I , \hat{s}_t^E , and v_t are functions of the state variables K_t and A_t , which we omit to ease notation. The aggregate value of all incumbents is $V_t = \int_0^1 V(i, t|q) di = v_t Q_t$. The optimal choice of incumbents' R&D expenditure s_t^I is determined by the first order condition for problem (29)

$$1 = \phi_I'(s_t^I) (\kappa_I - \kappa_D) \mathbb{E}_t [M_{t,t+1} v_{t+1}]. \quad (30)$$

Potential entrants maximize the present value of future net profits achieved if they become incumbents

$$\max_{\hat{s}_t^E} \hat{s}_t^E \phi_E(\hat{s}_t^E) \kappa_E \mathbb{E}_t [M_{t,t+1} v_{t+1}] - \hat{s}_t^E. \quad (31)$$

Since entrants are atomistic, each entrant takes $\phi_E(\hat{s}_t^E)$ as given. Solving (31) under this assumption leads to the following free entry condition that implicitly determines the optimal level of potential entrants' R&D expenditure

$$1 = \phi_E(\hat{s}_t^E) \kappa_E \mathbb{E}_t [M_{t,t+1} v_{t+1}]. \quad (32)$$

Equations (30) and (32) show that R&D investment decisions of incumbents and potential entrants depend on the same equilibrium value v_t given in (29). Specifically, in equilibrium, both incumbents' and potential entrants' R&D expenditures are such that marginal benefit of R&D equals marginal cost. In Section 3, we show how the interaction between incumbents' and potential entrants' R&D expenditures implied by these conditions affect asset prices.

2.4.3 Aggregation

Due to the homogeneity property that allows solving incumbents' value using equation (29) and the balanced growth assumption (23), to describe the problem, we do not need to know the distribution of qualities $q(i, t)$ across incumbent firms. Furthermore, since incumbents' and potential entrants' R&D expenditures are not functions of product specific quality, the aggregate quality Q_t defined in (18) evolves according to

$$\frac{Q_{t+1}}{Q_t} = \phi_I(s_t^I) \kappa_I + \hat{s}_t^E \phi_E(\hat{s}_t^E) \kappa_E + (1 - \phi_I(s_t^I) - \hat{s}_t^E \phi_E(\hat{s}_t^E)) \kappa_D. \quad (33)$$

Equation (33) describes the growth of technology capital in our economy. The growth of technology capital depends on the level of R&D expenditures by incumbents and potential entrants. Over a period of time, $\phi_I(s_t^I)$ input sectors experience an innovation by incumbents who increase quality by factor κ_I , $\hat{s}_t^E \phi_E(\hat{s}_t^E)$ sectors experience displacement by entrants who increase quality by factor κ_E , and the remaining sectors see their quality depreciate by factor κ_D . The growth of technology capital is thus due to a combination of heterogenous innovations by incumbents and entrants.

From (11) and (12), the aggregate R&D expenditures of incumbents and potential entrants are, respectively, $S_t^I = s_t^I Q_t$ and $S_t^E = \hat{s}_t^E Q_t$. The aggregate dividend D_t^A distributed by the final good firm and all incumbent firms is

$$\begin{aligned} D_t^A &= D_t + \int_0^1 (\pi(i, t|q) - s_t^I q(i, t)) di \\ &= Y_t - I_t - w_t L_t - X_t - S_t^I, \end{aligned} \quad (34)$$

where we use the definition of dividend of the final good firm D_t given in (7), equilibrium price $p(i, t|q)$ given in (15), equilibrium incumbent profits $\pi(i, t|q)$ given in (16), and the definition of the aggregate spending on inputs X_t given in (10). Using the resource constraint

$$Y_t = C_t + I_t + X_t + S_t^I + S_t^E, \quad (35)$$

we can express the aggregate dividend as $D_t^A = C_t + S_t^E - w_t L_t$.

To summarize, the economy is described by two endogenous state variables: physical capital K_t evolving according to (8) and technology capital Q_t evolving according to (33); and the

exogenous state variable $A_t = e^{a_t}$, where a_t evolves according to (5). Due to the balanced growth assumption (23), we can rescale all aggregate variables in the economy by Q_t . This makes the problem stationary and allows solving for a deterministic steady state growth. Details of the rescaled problem and of the steady state conditions are in Appendix A.

2.5 Asset prices

To study asset pricing implications of our model, in this section, we first define the market price of risk for the shock to the exogenous component of aggregate productivity. Next, we define securities that are exposed to this shock and derive risk premia demanded in equilibrium for holding those securities.

2.5.1 Market price of risk

The only source of risk in the economy is shock ε_{t+1} to the exogenous component of aggregate productivity A_t defined in (5). Projecting the log of the SDF process (3) on the space spanned by these shocks gives

$$\mathfrak{m}_{t,t+1} = \log(\mathbb{M}_{t,t+1}) = \mathbb{E}_t[\mathfrak{m}_{t,t+1}] - \gamma_{t+1}^\varepsilon \frac{\varepsilon_{t+1}}{\sigma}. \quad (36)$$

The quantity γ_{t+1}^ε is the market prices of risk for shock ε_{t+1} . To see this, consider a projection of the log return $r_{j,t+1}$ of a generic asset j on the space spanned by the shocks

$$r_{j,t+1} = \mathbb{E}_t[r_{j,t+1}] + \beta_{j,t+1}^\varepsilon \varepsilon_{t+1}, \quad (37)$$

where $\beta_{j,t+1}^\varepsilon = \text{Cov}(\varepsilon_{t+1}, r_{j,t+1})/\sigma^2$. With the Jensen's inequality adjustment, the log risk premium on asset j can be written as

$$\mathbb{E}_t[r_{j,t+1} - r_{f,t+1} + \sigma_j^2/2] = -\text{Cov}(\mathfrak{m}_{t,t+1}, r_{j,t+1}) = \beta_{j,t+1}^\varepsilon \sigma \gamma_{t+1}^\varepsilon, \quad (38)$$

where $r_{f,t+1}$ is the log risk-free rate from t to $t+1$, σ_j is the volatility of asset j 's log returns and the second equality follows from (36) and (37). If asset j is perfectly correlated with shock ε_{t+1} , $\beta_{j,t+1}^\varepsilon = \sigma_j/\sigma$. Hence, from (38) the Sharpe ratio of this asset is

$$\frac{\mathbb{E}_t[r_{j,t+1} - r_{f,t+1} + \sigma_j^2/2]}{\sigma_j} = \frac{\beta_{j,t+1}^\varepsilon \sigma \gamma_{t+1}^\varepsilon}{\beta_{j,t+1}^\varepsilon \sigma} = \gamma_{t+1}^\varepsilon, \quad (39)$$

proving that γ_{t+1}^ε in parameterization (36) is the market price of risk for shock ε_{t+1} , i.e., the risk premium per unit volatility of the shock. From the SDF equation (36), the market price of risk is

$$\gamma_{t+1}^\varepsilon = -\sigma \frac{\partial m_{t,t+1}}{\partial \varepsilon_{t+1}}. \quad (40)$$

The market price of risk is positive (negative) if a positive shock $\varepsilon_{t+1} > 0$ causes a decrease (increase) in the marginal utility of consumption of the representative household.

2.5.2 Risk premia

To analyze risk premia of securities exposed to ε_{t+1} shocks, let $R_{j,t+1}$, be the return of a claim on a dividend stream $D_{j,t}$ and let $V_{j,t}$ be the corresponding value. The log return $r_{j,t+1}$ of asset j is

$$r_{j,t+1} = \log(R_{j,t+1}) = \log\left(\frac{V_{j,t+1}}{V_{j,t} - D_{j,t}}\right). \quad (41)$$

From equation (37), the loading of the returns of asset j on shock ε_{t+1} is

$$\beta_{j,t+1}^\varepsilon = \frac{\partial r_{j,t+1}}{\partial \varepsilon_{t+1}} = \frac{\partial \log(V_{j,t+1})}{\partial \varepsilon_{t+1}}. \quad (42)$$

Using the risk premium definition (38), we see that the risk premium of asset j is

$$\lambda_{j,t+1}^\varepsilon = \beta_{j,t+1}^\varepsilon \sigma \gamma_{t+1}^\varepsilon, \quad (43)$$

where the loading $\beta_{j,t+1}^\varepsilon$ is given in (42) and the market price of risk γ_{t+1}^ε is given in (40).

We consider four securities: (i) the consumption claim asset, defined as a claim on aggregate consumption C_t whose value we denote by $V_{c,t}$; (ii) the market, defined as a claim on aggregate dividend D_t^A given in (34) whose value we denote $V_{m,t}$; (iii) the stock of the final good firm, defined as a claim on dividend D_t given in (7) whose value we denote $V_{d,t}$; and (iv) the portfolio that holds all incumbent firms, defined as a claim on the aggregate dividend of incumbent firms $D_{I,t} = \Pi_t - S_t^I$ (see equations (20) and (21)) whose value we denote $V_{I,t} = v_t Q_t$, where v_t is a solution to equation (29). The loadings of the returns of these assets on shock ε_{t+1} and their risk premia are given in (42) and (43), respectively, with $j = \{c, m, d, I\}$.

3 Results

3.1 Calibration

We calibrate the model to different probabilities of success of incumbents and entrants in innovation. Specifically, we set the probability of entrants succeeding in innovation, conditional on an innovation occurring, i.e., $\frac{\hat{s}_t^E \phi_E(\hat{s}_t^E)}{\phi_I(s_t^I) + \hat{s}_t^E \phi_E(\hat{s}_t^E)}$, in the deterministic steady state to be 2, 5, 12.2, 20, and 98 percent. Below, we refer to these conditional probabilities as the “levels of entry”. Different levels of entry represent different intensities of the threat with which entrants displace incumbents. The entry level of 12.2 percent represents the benchmark calibration of our model as it matches the average entry threat computed using US patent data over the 1985-2008 period. Entry levels 5 and 20 percent correspond to the minimum and maximum values of the empirical measure of entry threat in this period.

We model the innovation technologies of incumbents and potential entrants using the following constant elasticity functions:⁹

$$\phi_I(s_t^I) = \eta_I (s_t^I)^{\omega_I} \quad \text{and} \quad \phi_E(\hat{s}_t^E) = \eta_E (\hat{s}_t^E)^{\omega_E - 1}, \quad \text{where } 0 < \omega_I, \omega_E < 1 \quad \text{and} \quad \eta_I, \eta_E > 0. \quad (44)$$

In the model, $\phi_I(s_t^I)$ is the intensity of the Poisson process that drives the arrival of incumbents’ innovations, and $\hat{s}_t^E \phi_E(\hat{s}_t^E)$ is the intensity of the Poisson process that drives the arrival of potential entrants’ innovations. Given the functional form of ϕ_E in (44), the arrival intensity of potential entrants’ innovations has the same form as that of incumbents’ innovations, i.e., $\hat{s}_t^E \phi_E(\hat{s}_t^E) = \eta_E (\hat{s}_t^E)^{\omega_E}$. In (44), η_I and η_E represent productivity shift parameters, and ω_I and ω_E represent the (constant) elasticity of the innovation intensity with respect to R&D expenditure. Figure 3 illustrates the effect of changing the shift and elasticity parameters on the intensity of incumbents’ and potential entrants’ innovations. Bigger shift parameter η_I increases the intensity of incumbents’ innovations. Bigger elasticity parameter ω_I increases the intensity of incumbents’ innovations for $s^I > 1$, but decreases the intensity for $s^I < 1$. The comparative statics of potential entrants’ innovation technology is the same.

In our numerical analysis, we fix shift parameters η_I and η_E and vary elasticity parameters ω_I and ω_E in order to achieve different levels of entry and a common annual consumption growth

⁹The functional form is similar to that adopted in several other studies, for example, Comin, Gertler, and Santacreu (2009).

of 1.9 percent across economies with different levels of entry. All other parameters are kept constant across entry levels. We solve the model using third-order perturbation around the steady state. Model statistics are computed based on 1,000 paths of quarterly simulated data. Each path is 220 quarters long after excluding the initial 50 quarters. All reported statistics are annualized. The details of the calibration and parameter choices are discussed in Appendix B.

3.2 Sources of long-run risk

The source of endogenous growth in our model can be seen from the expression for total output (24), where the productivity of labor is

$$Z_t = \left(\frac{\xi}{\nu\mu} \right)^{\frac{\xi}{(1-\xi)(1-\alpha)}} A_t Q_t. \quad (45)$$

The evolution of the forcing process A_t is exogenously given in (5), but the evolution of the technology capital Q_t is endogenously determined by R&D expenditure of incumbents and potential entrants according to (33). Technology capital induces a stochastic trend in the evolution of Z_t . Specifically, from (45), productivity growth is $\Delta Z_t = \Delta A_t \Delta Q_t$. Since A_t is a persistent process, $\Delta A_t \approx e^{\varepsilon_t}$ and hence, from (33), the expected productivity growth is approximately

$$\mathbb{E}_t[\Delta Z_{t+1}] \approx \phi_I(s_t^I) \kappa_I + \hat{s}_t^E \phi_E(\hat{s}_t^E) \kappa_E + (1 - \phi_I(s_t^I) - \hat{s}_t^E \phi_E(\hat{s}_t^E)) \kappa_D. \quad (46)$$

In the model, as in the data, R&D expenditures are persistent and volatile. Therefore, from (46), we conclude that, in our model, expected productivity growth exhibits low-frequency variation. This mechanism, studied by Kung and Schmid (2013), is the source of long-run risk. Different from Kung and Schmid (2013), our model features two sources of low-frequency variation in productivity growth: incumbents' and potential entrants' R&D.

To illustrate how the endogenous long-run risk mechanism operates, Figure 4 plots impulse response functions of selected model quantities to a positive shock ε_{t+1} for the benchmark calibration of our model. In response to the shock, a_t raises persistently (Panel A). This increases the final good firm's demand for inputs x_t , leading to a persistent increase in incumbents' profits π_t (Panel B). The increase in profits results in a persistent increase in incumbents' values v_t , which in turn induces a persistent increase in R&D expenditure of both incumbents and potential entrants (Panels C, D, and E). The equilibrium incumbents' values and the levels

of R&D expenditure are jointly determined by conditions (29), (30) and (32). Incumbents invest in R&D to “escape” the threat of being displaced. Potential entrants invest in R&D in order to displace incumbents and capture their profits. Persistent responses of R&D expenditure result in a persistent increase of the expected growth of technology capital (Panel F) and thus of the expected productivity growth (46). This generates low-frequency fluctuations in expected economic growth and provides a foundation for the long-run risk channel in our model.

3.3 Heterogeneous innovations and entry threat: Inspecting the mechanism

In this section, we study the mechanism that drives incumbents’ and potential entrants’ R&D investments in our model. Table 1 presents statistics of consumption and technology capital for different levels of entry in the economy. To help assess the economic magnitude of different entry levels, we report the probabilities of success in innovation by incumbents and potential entrants. Since entrants’ innovations are more radical, $\kappa_E > \kappa_I$, and long-term economic growth is constant across columns, the overall probability of success in innovation declines with entry. As we move from low to high entry levels, the probability with which incumbents innovate decreases while the probability with which potential entrants innovate increases.

The growth of technology capital is a very persistent process irrespective of the level of entry. This leads to a high autocorrelation of expected consumption growth that underlies the long-run risk mechanism described above. Consistent with Kung and Schmid (2013), both the short-run business cycle risk, measured by the volatility of consumption growth $\sigma_{\Delta C}$, and the long-run risk, measured by the volatility of the expected consumption growth $\sigma_{\mathbb{E}_t[\Delta C_{t+1}]}$, are higher compared to analogous quantities obtained using real business cycle models. The volatility of the growth of technology capital $\sigma_{\Delta Q}$ is declining with entry, causing the volatility of the expected consumption growth to decline as well. This suggests that, when there is more entry, the intensity with which the long-run risk mechanism operates in our model is lower. We show later that risk premia and asset returns vary with different levels of entry and explain how endogenously determined decisions of incumbents and potential entrants to invest in R&D lead to this result.

While the magnitude of long-run risk is inversely related to entry, there are two ways in which entry can be thought of as more risky. First, the representative household’s intertemporal problem involves a trade-off between changes in the realized consumption and the expected

changes in future consumption. Specifically, because of the constant-elasticity nature of the time aggregator in her recursive utility, the household tries to smooth the contribution to total utility coming from current consumption $\sigma_{\Delta C_t}$ and from future utility $\sigma_{\mathbb{E}_t[\Delta C_{t+1}]}$. Due to this trade-off, the volatility of realized consumption growth increases as the volatility of the expected consumption growth declines. More entry is thus associated with bigger short-run business cycle risk. Second, the growth of technology capital stems from incremental innovations by incumbents and radical innovations by entrants. In economies with high entry, in relative terms, more goods are experiencing radical innovations and less goods are experiencing incremental innovations. Since we keep the same long-term economic growth for all entry levels, more entry means higher cross-sectional volatility of the growth of technology capital (labeled “Cross sectional $\sigma_{\Delta Q}$ ” in Table 1).

Table 2 presents statistics of aggregate, incumbents’, and potential entrants’ R&D expenditure for different levels of entry. Our key predictions about aggregate asset prices stem from the economic mechanism by which volatilities of the growth of R&D expenditure of incumbents and potential entrants are determined in our model. Both incumbents and potential entrants invest in R&D so that the marginal benefit of R&D equals marginal cost, as shown in first-order conditions (30) and (32). In equilibrium, marginal benefits of R&D expenditures of incumbents s_t^I and potential entrants \hat{s}_t^E are equal, i.e.,

$$\phi'_I(s_t^I)(\kappa_I - \kappa_D) = \phi'_E(\hat{s}_t^E)\kappa_E. \quad (47)$$

Using the functional forms for the innovation intensities given in (44), we can solve for the equilibrium relationship between R&D expenditures of potential entrants and incumbents

$$\eta_I(s_t^I)^{\omega_I-1}(\kappa_I - \kappa_D) = \eta_E(\hat{s}_t^E)^{\omega_E-1}\kappa_E, \quad 0 < \omega_I, \omega_E < 1. \quad (48)$$

This equilibrium relationship allows for an intuitive interpretation of the effect of productivity shocks on the dynamics of incumbents’ and potential entrants’ R&D expenditures.

Both s_t^I and \hat{s}_t^E respond to shocks ε_{t+1} by adjusting in the direction of the shock (see Figure 4, Panels D and E). A high entry level is achieved when potential entrants’ R&D investments are relatively more productive compared to R&D investments of incumbents. Note that \hat{s}_t^E and s_t^I are quantities less than one since they represent R&D expenditure scaled by technology

capital Q_t . From Figure 3, we see that when s_t^I and \hat{s}_t^E are less than one, lower ω_I and ω_E imply higher innovation intensities $\phi_I(s_t^I)$ and $\hat{s}_t^E \phi_E(\hat{s}_t^E)$, respectively. Therefore, potential entrants are relatively more (less) productive than incumbents when $\omega_E < \omega_I$ ($\omega_E > \omega_I$).

To see the effect of R&D elasticity ω_I and ω_E on the volatility of R&D expenditures, $\sigma_{\Delta \hat{s}^E}$ and $\sigma_{\Delta s^I}$, consider the limiting case in which entrants are infinitely more productive than incumbents, i.e., $\omega_I \rightarrow 1$. In this case, the equilibrium condition (48) implies that \hat{s}_t^E is a constant, i.e., $\sigma_{\Delta \hat{s}^E} \rightarrow 0$. Similarly, for the case in which incumbents are infinitely more productive than potential entrants, the equilibrium condition implies a constant R&D expenditure s_t^I , i.e., $\sigma_{\Delta s^I} \rightarrow 0$. In general, the equilibrium condition (48) implies that \hat{s}_t^E responds less (more) strongly to shocks when potential entrants' (incumbent) R&D technology is more (less) productive. Because high (low) entry obtains when entrants are more (less) productive, we have that the volatility of potential entrants' R&D is smaller (larger) than that of incumbents' when there is high (low) entry in the economy. In Table 2, we observe that, in fact, $\sigma_{\Delta \hat{s}^E} < \sigma_{\Delta s^I}$ for high entry levels while the opposite is true for low entry levels.

With higher entry, the relative share of potential entrants' R&D increases, while the share of incumbents' R&D decreases. Since the volatility of potential entrants' R&D $\sigma_{\Delta \hat{s}^E}$ decreases with entry and that of incumbents' R&D $\sigma_{\Delta s^I}$ increases with entry, the volatility of aggregate R&D expenditure $\sigma_{\Delta s}$ declines with entry. Since the growth of technology capital ΔQ depends on the levels of R&D expenditures of incumbents and potential entrants, the volatility of ΔQ is driven by the volatility of these two R&D expenditures. Therefore, the volatility of the growth of technology capital $\sigma_{\Delta Q}$ and thus the volatility of expected consumption growth $\sigma_{\mathbb{E}_t[\Delta C_{t+1}]}$ is declining with entry.

To illustrate this reasoning, Figure 5 plots impulse response functions of expected consumption growth to a positive shock ε_{t+1} for different levels of entry in the economy. We show that the magnitude of the response declines with entry. Figure 6 plots impulse response functions of incumbents' (Panel A) and potential entrants' (Panel B) R&D expenditures to a positive shock ε_{t+1} for different levels of entry in the economy. For incumbents' R&D expenditure, the magnitude of the response increases with entry, while it decreases with entry for potential entrants' R&D expenditure.

In summary, the mechanism by which shocks to the exogenous component of aggregate productivity propagate through R&D investments to create variations in expected consumption

growth operates with different intensities depending on the level of entry. When entry is higher, the economy features lower long-run risk. In the next section, we show how risk premia and asset returns vary with different levels of entry.

3.4 Asset prices

Table 3 presents statistics of the risk-free rate, the market price of risk γ_{t+1}^ε defined in (40), and risk premia $\lambda_{j,t+1}^\varepsilon$ defined in (43), where j is either the consumption claim asset or the market, as defined in Section 2.5.2.

The table shows that the risk-free rate increases with entry. To understand this result, from the Euler equation and the SDF in (3), the risk-free rate is

$$r_{f,t} = \log(R_{f,t}) = -\log(\mathbb{E}_t[\mathbb{M}_{t+1}]) = -\log\left(\mathbb{E}_t\left[\beta^\theta e^{-(\theta/\psi)\Delta c_{t+1} - (1-\theta)r_{C,t+1}}\right]\right), \quad (49)$$

where $\Delta c_{t+1} = \log(C_{t+1}/C_t)$ and $r_{C,t+1} = \log(R_{C,t+1})$. To provide intuition, suppose that consumption growth and the return on the consumption claim are jointly lognormally distributed. Under this assumption, (49) can be rewritten as¹⁰

$$r_{f,t} = -\log(\beta) + \frac{1}{\psi}\mathbb{E}_t[\Delta c_{t+1}] - \frac{\theta}{2\psi^2}\sigma_{\Delta c}^2 + \frac{\theta}{2}\sigma_{r_C}^2. \quad (50)$$

In our calibrations, $\theta = \frac{1-\gamma}{1-1/\psi} < 0$, because $\gamma, \psi > 1$ and $\mathbb{E}_t[\Delta c_{t+1}] = 1.9$ percent for all levels of entry. According to (50), the variation in the risk-free rate across different entry levels arises due to differences in the volatility of consumption growth $\sigma_{\Delta c}$ and the volatility of returns on the consumption claim σ_{r_C} . From Table 1, as discussed above, $\sigma_{\Delta c}$ increases with entry, while, from Table 3, σ_{r_C} decreases with entry. Combining these patterns with (50) leads to the result that the risk-free rate increases with entry. The effect of higher entry in the economy on the risk-free rate is similar to the effect of reducing the intertemporal substitution; more entry generates precautionary savings motives that induce an increase in the risk-free rate.

Table 4 reports statistics of the returns on the final good firm r_d and incumbents r_I . We refer to r_d as the return on *physical capital* and to r_I as the return on *technology capital*. Since productivity shocks ε_{t+1} directly affect output, the major component of the final good firm's dividend D_t given in (7), and, as discussed above, the market price of risk for ε_{t+1} declines with

¹⁰To derive (50), we use the fact that $\mathbb{E}_t[\mathbb{M}_{t,t+1}R_{C,t+1}] = 1$.

entry, the risk premium $\mathbb{E}_t[r_d - r_f]$ demanded in equilibrium for holding the final good firm's stock declines with entry. Table 4 also shows that the final good firm's beta β_d^ε defined in (42) is close to one and declines with entry. This happens because, for high entry levels, incumbents' R&D expenditure reacts more strongly to shocks (see Figure 6), and since incumbents have market power, they are able to pass increased R&D cost to the final good firm. As a consequence, more procyclical R&D expenditure of incumbents partially "hedges" any increase in the final good firm's output, making the final good firm's dividends less risky. Overall, more entry makes the final good firm less risky not only because the market price of risk declines with entry, but also because the final good firm's exposure to the productivity shocks declines with entry.

The return on technology capital $R_{t,t+1}^I$ can be computed from the Bellman equation (29), which defines the value of incumbents. Under optimal R&D investment policies of incumbents and potential entrants, we can rewrite equation (29) as

$$1 = \mathbb{E}_t [\mathbb{M}_{t,t+1} R_{t,t+1}^I], \quad \text{where } R_{t,t+1}^I = \frac{g_t^I v_{t+1}}{v_t - (\pi_t - s_t^I)}, \quad (51)$$

and

$$g_t^I = \phi_I(s_t^I) \kappa_I + (1 - \phi_I(s_t^I) - \hat{s}_t^E \phi_E(\hat{s}_t^E)) \kappa_D. \quad (52)$$

Quantity g_t^I can be interpreted as the expected value of the following random variable

$$\tilde{g}_{t+1}^I = \begin{cases} \kappa_I & \text{with probability } \phi_I(s_t^I), \\ 0 & \text{with probability } \hat{s}_t^E \phi_E(\hat{s}_t^E), \\ \kappa_D & \text{with probability } 1 - \phi_I(s_t^I) - \hat{s}_t^E \phi_E(\hat{s}_t^E). \end{cases} \quad (53)$$

Since there is a continuum of incumbents, at each time t , a fraction $\phi_I(s_t^I)$ of them experience an increase in technology capital by factor $\kappa_I > 1$, a fraction $\hat{s}_t^E \phi_E(\hat{s}_t^E)$ get displaced by entrants, and the remaining incumbents experience a decline of their technology capital by factor $\kappa_D < 1$. Using this interpretation, quantity $g_t^I v_{t+1}$ in the definition of incumbents' return (51) is the incumbents' *expected* value, where the expectation is taken with respect to the endogenous innovation intensities $\phi_I(s_t^I)$ and $\hat{s}_t^E \phi_E(\hat{s}_t^E)$ of incumbents and entrants. Return $R_{t,t+1}^I$ can thus be thought of as the return on the portfolio strategy that buys every new incumbent upon entry and assigns return -1 on every incumbent that gets displaced.

Table 4 shows that the expected value g_t^I decreases with entry and it becomes negative for high enough entry levels, which means that incumbents are losing value on average. The standard deviation of random variable \tilde{g}_{t+1}^I , which captures the cross-sectional volatility of incumbent returns, decreases with entry. This obtains because, when entry is high, incumbents innovate less often. This reduces the probability of κ_I outcome occurring in (53) and thus reduces its volatility.

Table 4 shows that incumbents' beta β_I^ε is positive, lower than one, and has a U-shape pattern in the level of entry. Low incumbents' beta obtains because, in response to shocks, incumbents can costlessly adjust their R&D expenditure. This implies that changes in incumbents' profits are largely offset by changes in their R&D expenditure and the procyclicality of R&D expenditure thus acts as a hedge against procyclical profits.

To understand the U-shape pattern of β_I^ε , consider the definition of beta (42) as the elasticity of incumbents' value to productivity shocks ε_{t+1}

$$\beta_I^\varepsilon = \frac{\partial v}{\partial \varepsilon} \times \frac{\varepsilon}{v}, \quad (54)$$

where $\partial v / \partial \varepsilon$ is the impulse response function of incumbents' value to ε_{t+1} . From Figure 7, we see that the response of incumbents' value to ε_{t+1} decreases with entry: a productivity shock has a bigger impact on the value of incumbents when they contribute more to the growth of the economy. The second term in (54), ε / v , increases with entry because incumbents' value decreases with entry. The combination of these two effects generates the U-shape pattern of incumbents' beta. Table 4 shows that, for low entry levels, more entry acts mainly as a "hedge" that reduces incumbents' beta, while for high entry levels, more entry acts mainly as "leverage" that increases incumbents' beta.

It is important to emphasize that this analysis ignores the general equilibrium effect that entry has on the price of risk (discount rate channel) and focuses only on the partial equilibrium effect on incumbents' beta (cash flow channel). In a partial equilibrium setting, bigger beta would suggest that incumbents are generally riskier when they are exposed to more entry and thus to bigger displacement risk. However, as we show in Table 3, since the market price of risk decreases with entry, there is no clear relationship between equilibrium risk premia of incumbents and the level of entry. These results highlight the importance of using a general equilibrium model to study the effects of entry and displacement on firms' returns. More broadly, our

results underline the importance of the joint equilibrium determination of R&D investments of incumbents and potential entrants for the propagation of shocks through the economy and thus for asset prices.

3.5 Market power

In this section, we study how changes in the product market power affect our conclusions about the role of entry in asset prices. This is important since the degree of market power, captured by parameter ν in our model, is the key source of profits and value of incumbents. Market power is therefore the ultimate driver of incentives to invest in R&D of both incumbents and potential entrants.

Our baseline results presented above are based on $\nu = 1.25$, which means that incumbents enjoy 25% markups. Since ν captures the elasticity of substitution between any two goods, we can think of ν to be the breadth of patent protection in the economy. Enforcement of patents with broad scope leads to low elasticity of substitution between goods and high markups. If only patents with narrow scope are enforced, the elasticity of substitution between goods is high and markups are low. We perform the analysis as a comparative statics exercise, i.e., ν changes for an exogenous reason. We can think of this comparative static exercise as a way to assess the asset pricing consequences of a patent reform in which policymakers alter the breadth of patent protection.

Table 5 presents key statistics of real quantities and asset prices for the case of high markups in Panel A (based on $\nu = 1.65$) and low markups in Panel B (based on $\nu = 1.05$). The volatility of expected consumption growth and thus the market price of risk are declining with entry in both cases. The weakening effect of entry on long-run risk documented in section 3.3 is present at any level of market power.

Larger markups ν correspond to larger incumbents' profits π_t (see equations (21), (24), and (25)) and higher R&D expenditure s_t^I . In Table 5, we show that s_t^I , as the fraction of total output as well as the fraction of total R&D expenditure, increases with ν for any given entry level. All else equal, market power amplifies the effect of productivity shocks on R&D expenditure, and the volatility of the growth of incumbents' R&D expenditure $\sigma_{\Delta s^I}$ thus increases with market power. Since s_t^I accounts for a bigger share of total R&D expenditure, the growth of technology capital (33) and thus the expected consumption growth are more volatile when market power

is high. This means that, for any given entry level, the market price of risk increases with incumbents' market power. Figure 8 Panel A illustrates this result.

When incumbents have large market power, they can extract more rents from the competitive final good sector. Specifically, an increase in incumbents' market power leads to an increase in the expenditure on inputs relative to total final good firm's expenditure and thus to a higher final goods firm's operating leverage. This affects the final good firm's beta β_d^ε , which increases in incumbents' market power (see Figure 9 Panel B). A higher β_d^ε , together with higher market price of risk, leads to a higher risk premium λ_d^ε of the final good firm for any given entry level in the economy (see Figure 9 Panel A). Since the aggregate risk primarily affects the final good firm, the market risk premium is higher in economies in which incumbents have larger market power (see Figure 8 Panel B).

Figure 10 Panel B plots incumbents' beta β_I^ε for different levels of market power and entry. Incumbents' beta is lower when market power is higher for any level of entry, suggesting that, based on this metric, monopoly in product market leads to lower risk. The U-shape pattern of β_I^ε discussed in the previous section obtains in all cases, but is less strong when incumbents' market power is high. Generally, β_I^ε increases with the level of entry, suggesting that more intense competition in innovation, i.e., higher displacement risk, is eroding incumbents' "effective" monopoly power by reducing their profits and value. This mechanism operates more strongly when market power is high: when incumbents enjoy, in relative terms, larger market power, an increase in entry leads to a more significant increase in incumbents' beta. Overall, since the market price of risk increases with market power, the risk premium on technology capital can increase as well as decrease with a change in product market power as shown in Figure 10 Panel A.

In summary, in our model, a patent reform aimed at reducing the breadth of patent protection and thus increasing the substitutability between intermediate goods results in a lower market risk premium. The risk premium demanded on physical capital also decreases. The effect on risk premium of technology capital, i.e., on the firms that undertake R&D and innovate, is ambiguous. The possible increase in the cost of capital of innovative firms might be an unintended consequence of a policy reform intended to increase competition in the product market.

4 Conclusion

In this paper, we study the implications of competition in innovation and market power for asset prices. To this end, we develop a dynamic stochastic general equilibrium model of endogenous firm creation and destruction. Incumbents and entrants in our model differ in their innovation technologies: incumbents pursue incremental innovations while potential entrants pursue radical innovations.

The key to our results is the interdependence between firms' R&D decisions and the valuation of future monopoly rents. Due to this interdependence, in equilibrium, the incremental and radical margins of innovation interact when responding to aggregate shocks. We show that the amount of long-run risk in the economy depends on the level of entry threat faced by incumbent firms. Higher entry threat implies higher incumbent firms' betas, but lower market price of risk. Stronger protection of monopoly rents implies lower incumbent firms' betas, but higher market price of risk. The overall effect of competition in innovation and the degree of market power on risk premia is ambiguous. Our findings highlight the need to empirically capture both the cash flow and discount rate channels through which competitive forces affect equilibrium returns.

Figure 1: Empirical measure of entry threat

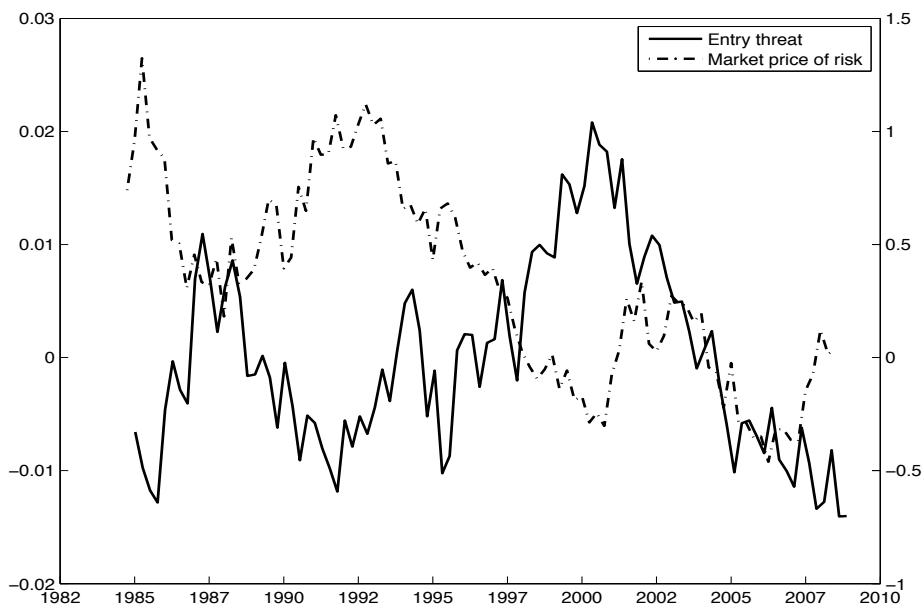
This figure plots the quarterly time series of the empirical measure of entry threat in innovation over the 1985-2008 period. Entry threat is the ratio of the number of US patents applied for, in a given quarter, by firms that did not patent prior to the beginning of this quarter to the total number of US patents applied for by all firms in the same quarter. In the benchmark calibration of our model, we set the probability of potential entrants succeeding in innovation, conditional on an innovation occurring, i.e., $\frac{\hat{s}_t^E \phi_E(\hat{s}_t^E)}{\phi_I(\hat{s}_t^I) + \hat{s}_t^E \phi_E(\hat{s}_t^E)}$, to be 12.2 percent, which corresponds to the time-average of our quarterly entry threat measure. See Appendix B for details.



Figure 2: Empirical measure of entry threat and asset prices

This figure plots the quarterly time series of the empirical measure of entry threat in innovation (left axis), the market price of risk (Panel A), and the beta of the portfolio of incumbent firms (Panel B). We remove the linear time trend from the entry threat measure. The market price of risk is measured as the conditional Share ratio of the market portfolio computed according to Lettau and Ludvigson (2010). The portfolio of incumbent firms in innovation consists of the CRSP/Compustat firms that applied for at least 3 US patents in each year over the 3-year moving window period. We use the NBER Patent Data Project to match Compustat firms to patents. The beta of the portfolio is computed using the Market model fitted using monthly returns over the 3-year moving window period. Excess returns are computed using the value-weighted market returns and the 1-month Treasury Bill rates.

Panel A: Market price of risk



Panel B: Beta of incumbent firms

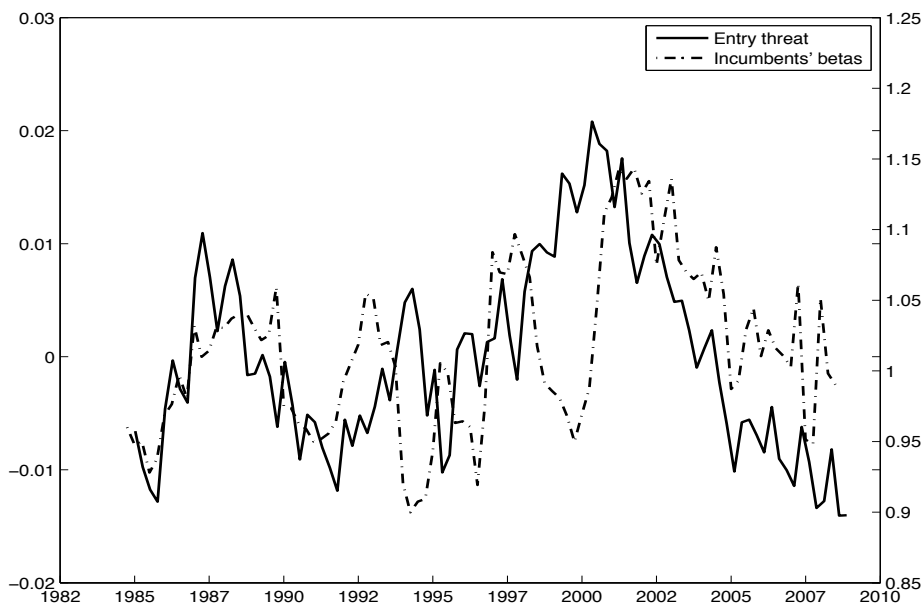
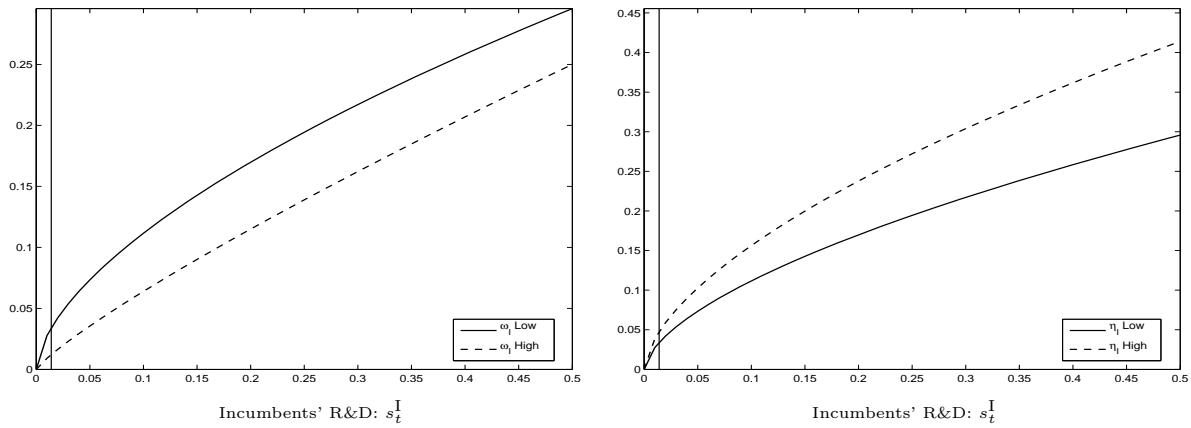


Figure 3: Innovation technology of incumbents and potential entrants

This figure plots the innovation intensities of incumbents and potential entrants, $\phi_I(s_t^I)$ and $\hat{s}_t^E \phi_E(\hat{s}_t^E)$, respectively, used in the numerical solution of the model (see equation (44)). Panel A reports incumbents' intensity $\phi_I(s_t^I)$ for different levels of elasticity ω_I (left graph) and shift η_I (right graph) parameters. Panel B reports potential entrants' intensity $\hat{s}_t^E \phi_E(\hat{s}_t^E)$ for different levels of elasticity ω_E (left graph) and shift η_E (right graph) parameters. The vertical line in all graphs represents the steady state level of R&D expenditures s_t^I and \hat{s}_t^E in our benchmark calibration. The solid lines in all the graphs refer to the benchmark parameter values described in Table B-1 of Appendix B.

Panel A: Incumbents' innovation intensity: $\phi_I(s_t^I)$



Panel B: Potential entrants' innovation intensity: $\hat{s}_t^E \phi_I(\hat{s}_t^E)$

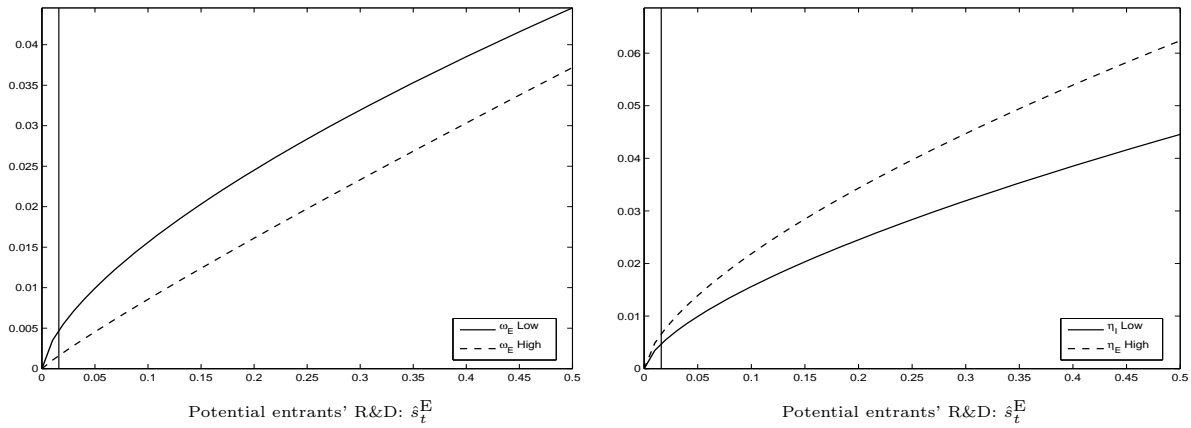


Figure 4: Sources of long-run risk

This figure plots impulse response functions of process a_t given in (5), incumbents' profits π_t and value v_t , incumbents' R&D expenditure s_t^I , potential entrants' R&D expenditure \hat{s}_t^E , and the expected growth of technology capital $\mathbb{E}_t[\Delta Q_{t+1}]$ to a positive one standard deviation shock to the exogenous component of aggregate productivity A_t ($\varepsilon_t > 0$). We use the benchmark parameter values described in Table B-1 of Appendix B.

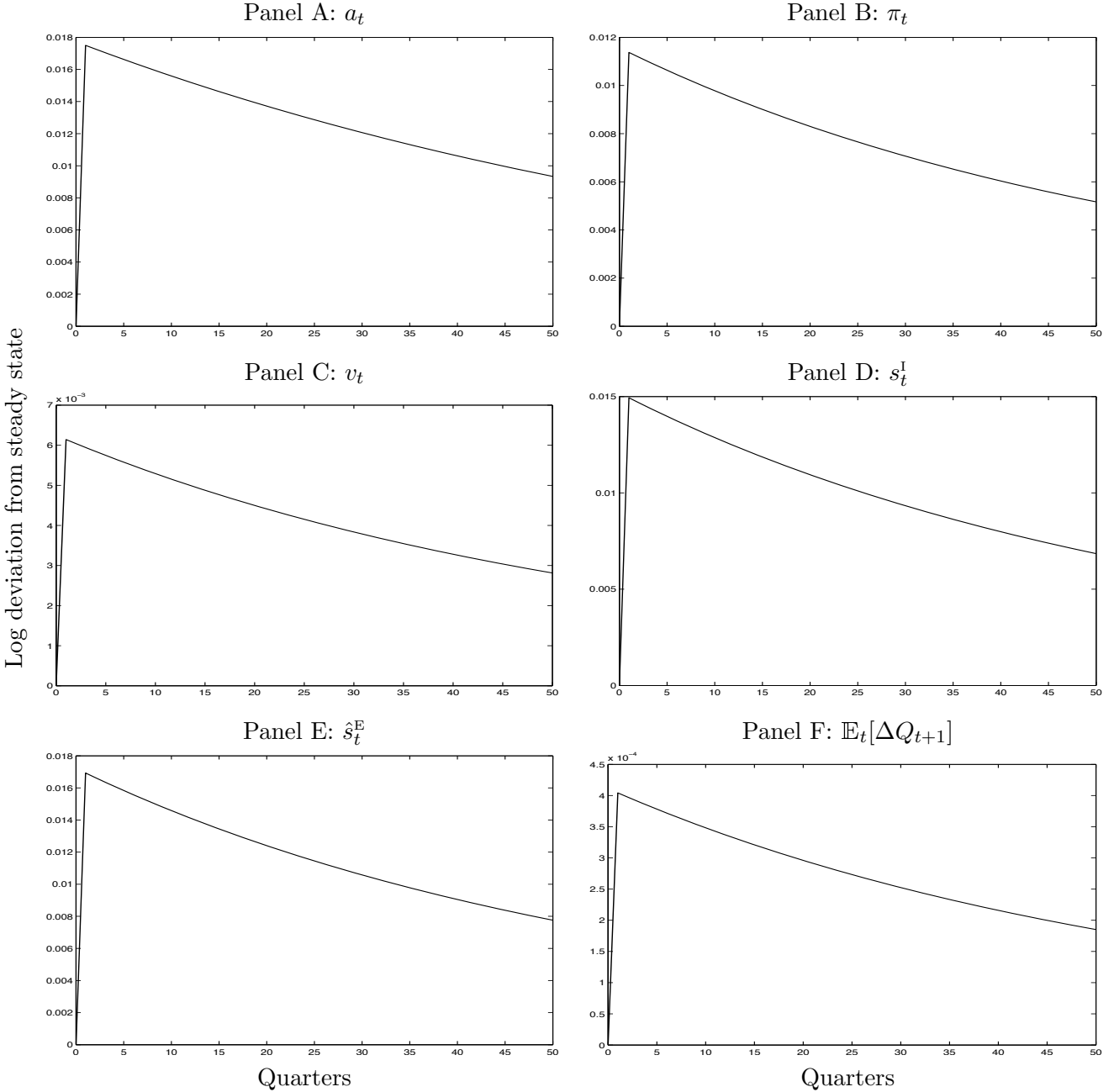


Figure 5: Entry threat and consumption dynamics

This figure plots impulse response functions of expected consumption growth $\mathbb{E}_t[\Delta C_{t+1}]$ to a positive one standard deviation shock to the exogenous component of aggregate productivity A_t ($\varepsilon_t > 0$) for different levels of entry in the economy. The levels of entry are the probabilities of entrants succeeding in innovation conditional on an innovation occurring in the deterministic steady state. Appendix B describes how we calibrate the model and what parameters we use.

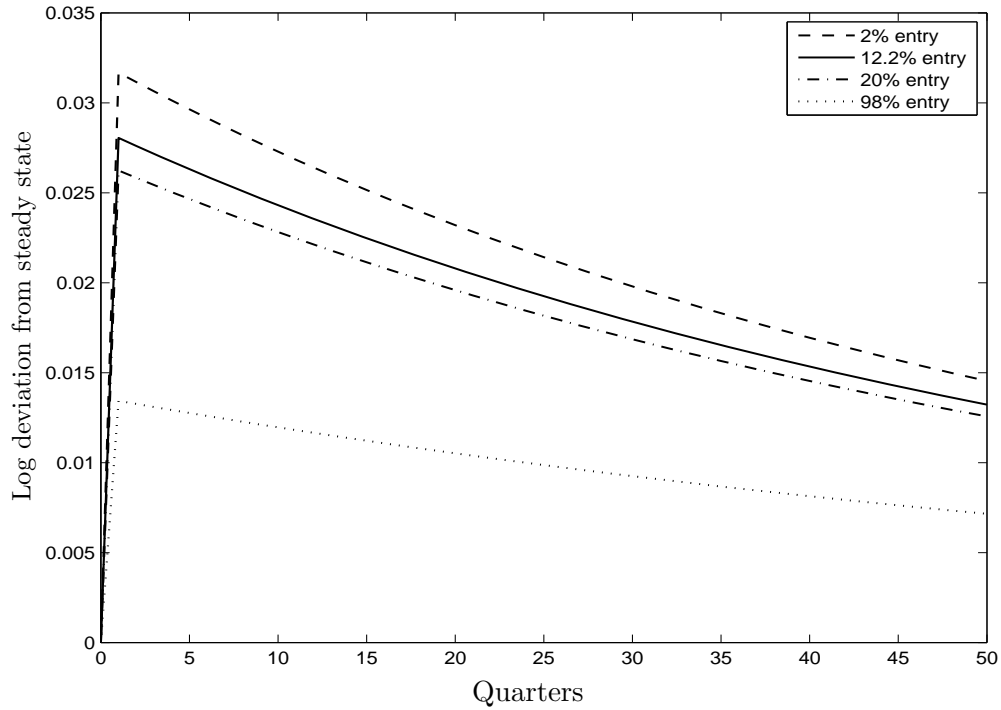


Figure 6: Entry threat and R&D expenditure

This figure plots impulse response functions of incumbent firms' and potential entrants' R&D expenditure s_t^I and \hat{s}_t^E , respectively, to a positive one standard deviation shock to the exogenous component of aggregate productivity A_t ($\varepsilon_t > 0$) for different levels of entry in the economy. The levels of entry are the probabilities of entrants succeeding in innovation conditional on an innovation occurring in the deterministic steady state. Appendix B describes how we calibrate the model and what parameters we use.

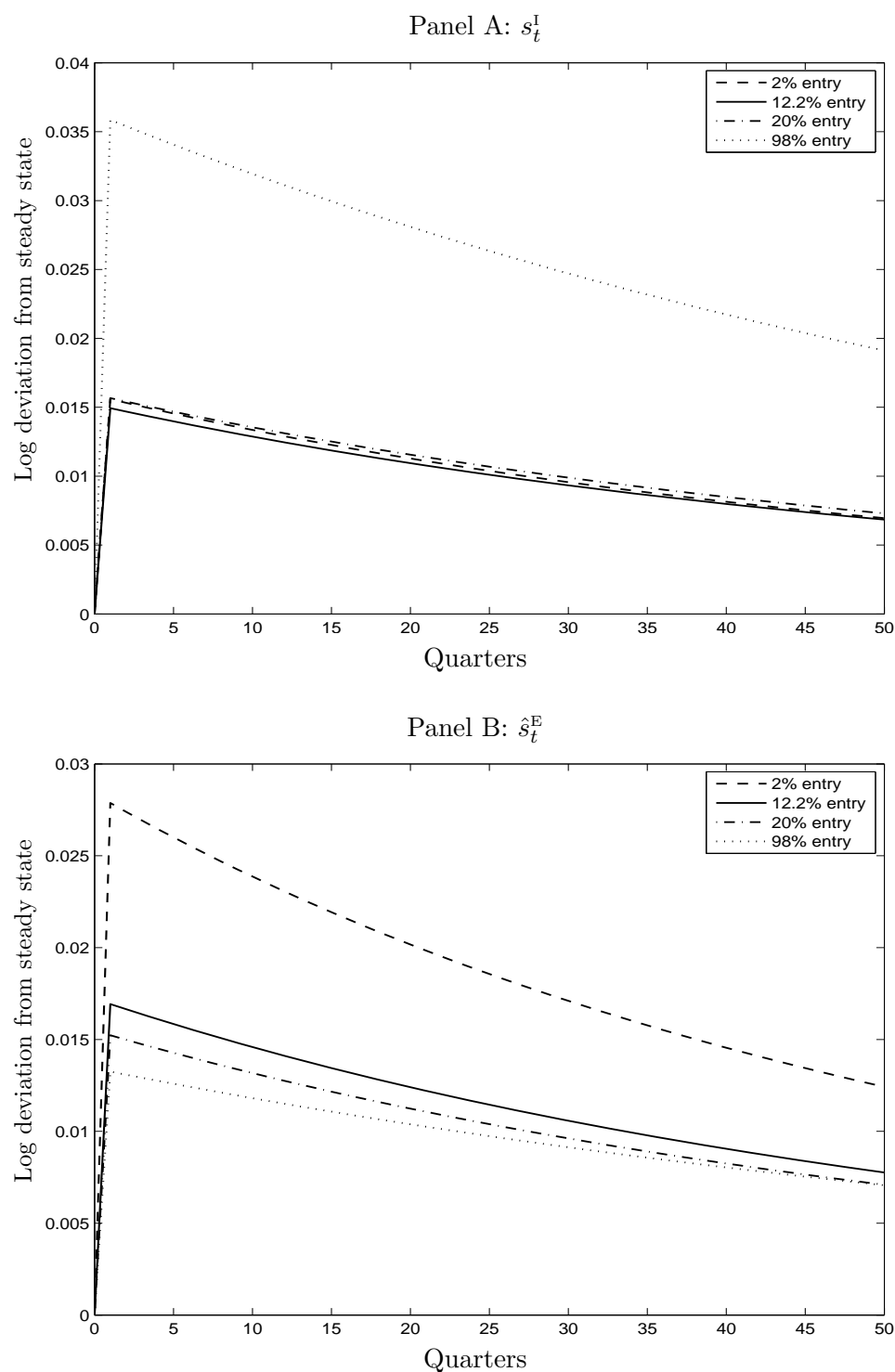


Figure 7: Entry threat and incumbent value

This figure plots impulse response functions of incumbents' value v_t to a positive one standard deviation shock to the exogenous component of aggregate productivity A_t ($\varepsilon_t > 0$) for different levels of entry in the economy. The levels of entry are the probabilities of entrants succeeding in innovation conditional on an innovation occurring in the deterministic steady state. Appendix B describes how we calibrate the model and what parameters we use.

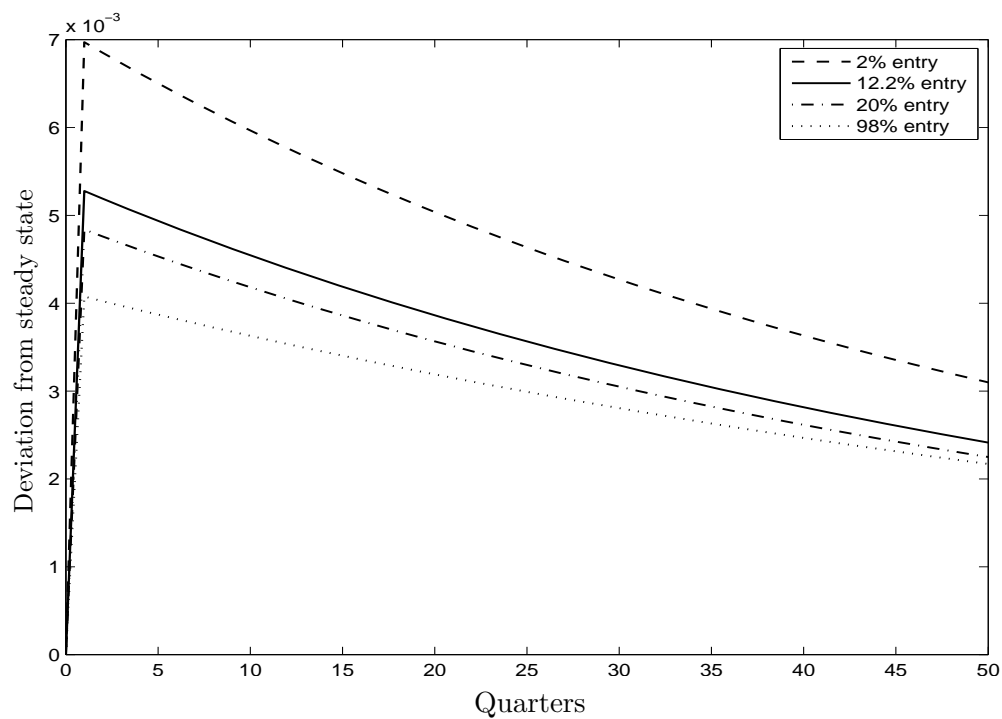


Figure 8: Market power and aggregate returns

This figure plots the market price of risk and risk premium obtained by simulating the model of Section 2 for three different values of incumbent firms' product market power: $\nu = 1.05, 1.25$ and 1.65 . Market return is the return on a claim that pays aggregate dividend D_t^A given in (34) in Section 2.4.3. Market price of risk (see Section 2.5) is the market prices of risk for shock ε_{t+1} to the exogenous component of aggregate productivity A_t defined in (5). It is computed as the 1st period impulse response of $-1 \times \text{SDF}$ to a positive one standard deviation shock to the exogenous component of aggregate productivity A_t ($\varepsilon_t > 0$). The risk premium is levered following Boldrin, Christiano, and Fisher (2001). The levels of entry are the probabilities of entrants succeeding in innovation conditional on an innovation occurring in the deterministic steady state. Appendix B describes how we calibrate the model and what parameters we use. The model statistics correspond to annualized population moments.

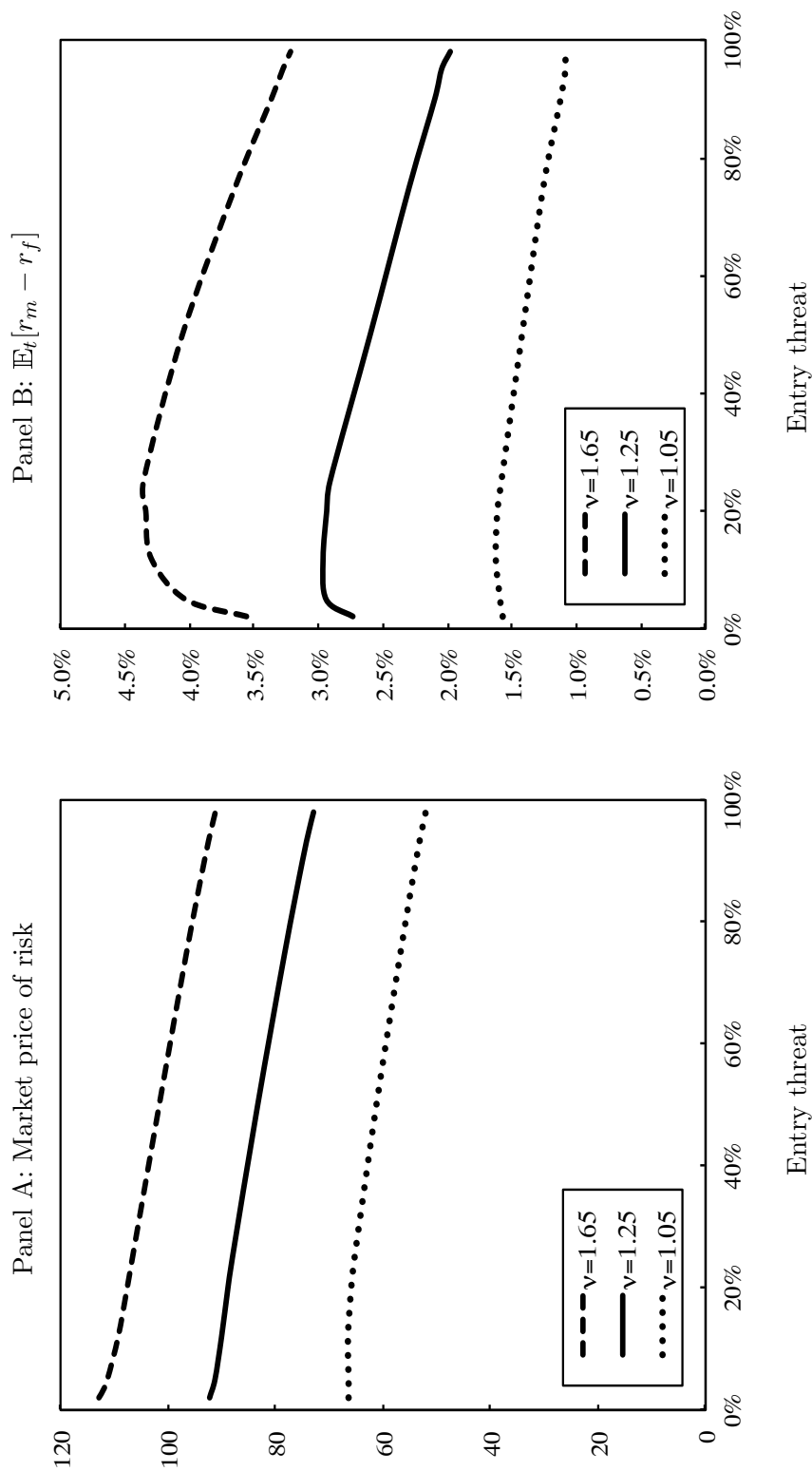


Figure 9: Market power and return on physical capital

This figure plots risk premium and beta of returns on physical capital obtained by simulating the model of Section 2 for three different values of incumbent firms' product market power: $\nu = 1.05, 1.25$ and 1.65 . Return on physical capital is the return on a claim that pays final good firm's dividend D_t given in (7). β_d^ε is computed as the 1st period impulse response of the value of the final good firm to a positive one standard deviation shock to the exogenous component of aggregate productivity A_t ($\varepsilon_t > 0$) scaled by the shock's volatility. The risk premium is levered following Boldrin, Christiano, and Fisher (2001). The levels of entry are the probabilities of entrants succeeding in innovation conditional on an innovation occurring in the deterministic steady state. Appendix B describes how we calibrate the model and what parameters we use. The model statistics correspond to annualized population moments.

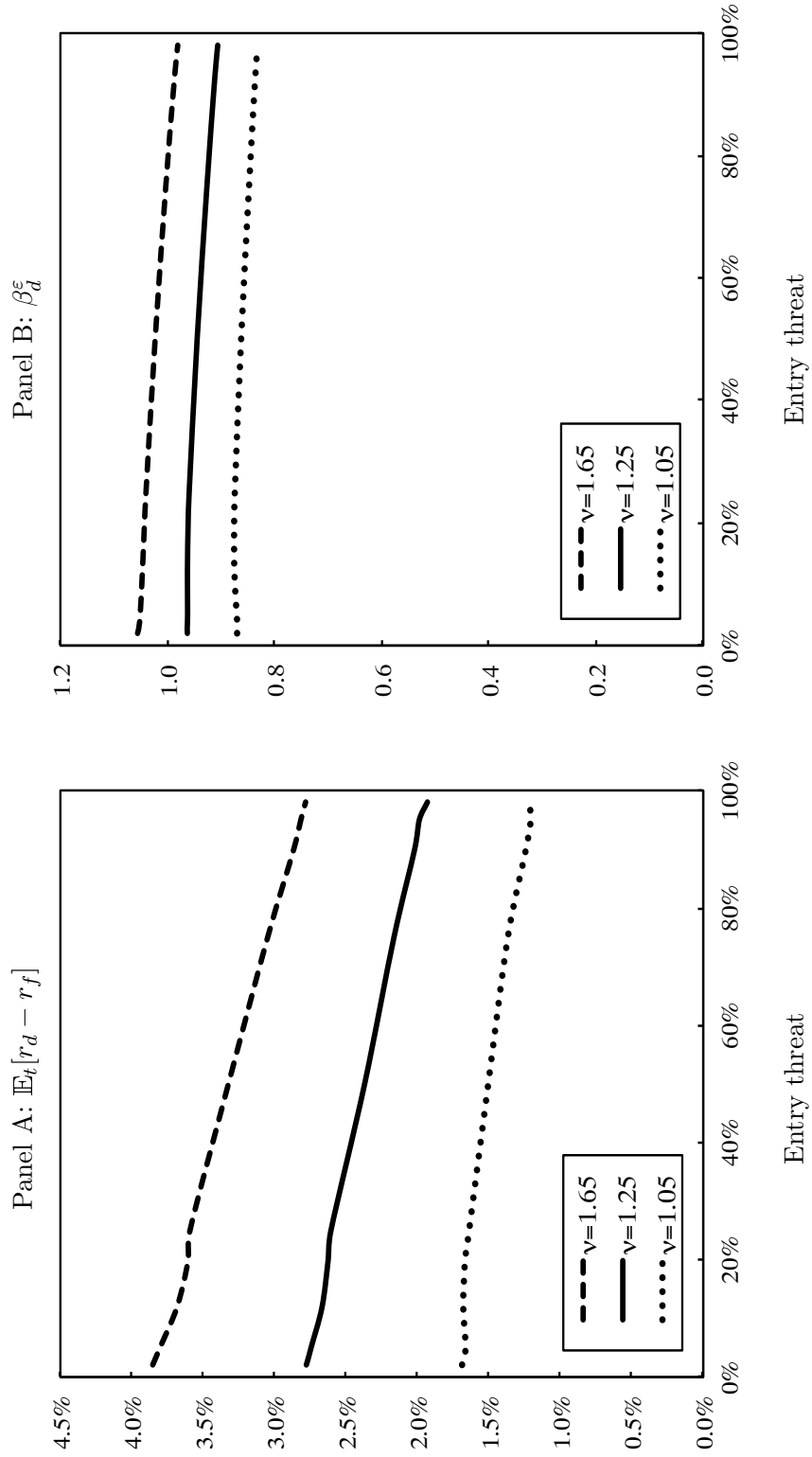


Figure 10: Market power and return on technology capital

This figure plots risk premium and beta of returns on technology capital obtained by simulating the model of Section 2 for three different values of incumbent firms' product market power: $\nu = 1.05, 1.25$ and 1.65 . Return on technology capital is the return on a claim that pays aggregate dividend of incumbent firms $D_{T,t} = \Pi_t - S_t^I$ (see equations (20) and (21)) adjusted for displacement of incumbent firms by entrants. β_T is computed as the 1st period impulse response of the incumbent firm's value (given in (29)) to a positive one standard deviation shock to the exogenous component of aggregate productivity A_t ($\varepsilon_t > 0$) scaled by the shock's volatility. The risk premium is levered following Boldrin, Christiano, and Fisher (2001). The levels of entry are the probabilities of entrants succeeding in innovation conditional on an innovation occurring in the deterministic steady state. Appendix B describes how we calibrate the model and what parameters we use. The model statistics correspond to annualized population moments.

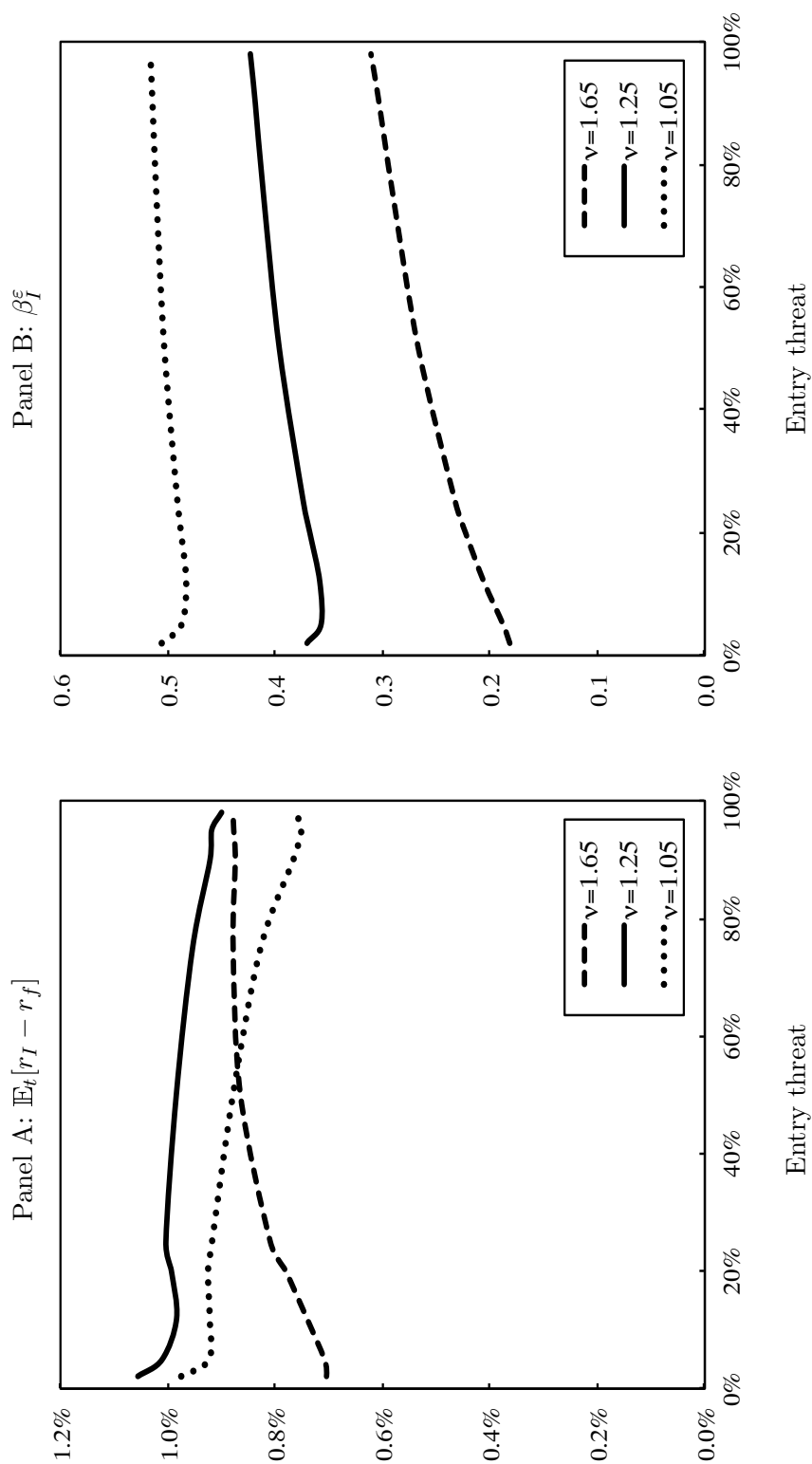


Table 1: Consumption and technology capital

This table reports statistics for consumption growth dynamics, the evolution of technology capital and the probabilities of success in innovation obtained by simulating the model of Section 2. The evolution of technology capital ΔQ_t is given in (33) in Section 2.4.3. The levels of entry threat are the probabilities of entrants succeeding in innovation conditional on an innovation occurring in the deterministic steady state. Appendix B describes how we calibrate the model and what parameters we use. The model statistics correspond to annualized population moments.

	2%	5%	12.2%	20%	98%
	<i>Consumption</i>				
Long-term growth	1.9%	1.9%	1.9%	1.9%	1.9%
$\sigma_{\Delta C}$	1.57%	1.62%	1.72%	1.80%	2.08%
$\sigma_{\mathbb{E}_t[\Delta C_{t+1}]}$	0.26%	0.25%	0.23%	0.22%	0.12%
$AC1(\Delta C)$	0.17	0.15	0.12	0.10	0.02
	<i>Technology capital</i>				
$\sigma_{\Delta Q}$	0.73%	0.72%	0.69%	0.67%	0.48%
Cross-sectional $\sigma_{\Delta Q}$	39.5%	43.8%	50.9%	55.9%	71.0%
$AC1(\Delta Q)$	0.92	0.92	0.92	0.92	0.93
	<i>Probability of success in innovation</i>				
Incumbents	19.47%	17.50%	13.76%	10.79%	0.11%
Potential entrants	0.40%	0.92%	1.91%	2.70%	5.54%
	<i>Elasticity of innovation technology to R&D expenditure</i>				
ω_I	0.61	0.61	0.61	0.61	0.80
ω_E	0.78	0.73	0.65	0.60	0.47

Table 2: R&D expenditure

This table reports statistics for variables capturing R&D expenditure obtained by simulating the model of Section 2. Aggregate R&D expenditure is the sum of the incumbents' and potential entrants' R&D expenditures. The levels of entry threat are the probabilities of entrants succeeding in innovation conditional on an innovation occurring in the deterministic steady state. Appendix B describes how we calibrate the model and what parameters we use. The model statistics correspond to annualized population moments.

	Entry threat				
	2%	5%	12.2%	20%	98%
<i>Aggregate R&D expenditure</i>					
$\sigma_{\Delta s}$	3.5%	3.4%	3.2%	3.1%	2.7%
AC1(<i>s</i>)	0.97	0.97	0.97	0.97	0.98
<i>R&D expenditure of incumbents</i>					
$\sigma_{\Delta s^I}$	3.2%	3.0%	3.0%	3.2%	7.1%
AC1(<i>s</i> ^I)	0.97	0.97	0.97	0.97	0.98
<i>R&D expenditure of potential entrants</i>					
$\sigma_{\Delta s^E}$	5.6%	4.3%	3.4%	3.1%	2.7%
AC1(<i>s</i> ^E)	0.97	0.97	0.97	0.97	0.98
<i>Share of R&D expenditure in total output</i>					
Incumbents	11.9%	9.8%	6.6%	4.7%	0.0%
Potential entrants	2.0%	4.2%	7.5%	9.4%	14.1%

Table 3: Aggregate returns

This table reports statistics for the risk-free rate, returns on consumption, and market returns obtained by simulating the model of Section 2. Market return is the return on a claim that pays aggregate dividend D_t^A given in (34) in Section 2.4.3. Market price of risk (see Section 2.5) is the market prices of risk for shock ε_{t+1} to the exogenous component of aggregate productivity A_t defined in (5). It is computed as the 1st period impulse response of $-1 \times \text{SDF}$ to a positive one standard deviation shock to the exogenous component of aggregate productivity A_t ($\varepsilon_t > 0$). The risk premiums are levered following Boldrin, Christiano, and Fisher (2001). The levels of entry threat are the probabilities of entrants succeeding in innovation conditional on an innovation occurring in the deterministic steady state. Appendix B describes how we calibrate the model and what parameters we use. The model statistics correspond to annualized population moments.

	Entry threat				
	2%	5%	12.2%	20%	98%
$\mathbb{E}_t[r_f]$	1.67%	1.67%	1.67%	1.68%	1.90%
σ_{r_f}	0.3%	0.3%	0.3%	0.2%	0.1%
	<i>Market price of risk</i>				
γ_{t+1}^ε	0.92%	0.91%	0.90%	0.89%	0.73%
	<i>Return on consumption claim</i>				
$\mathbb{E}[r_c - r_f]$	3.06%	2.98%	2.94%	2.91%	1.95%
$\sigma_{r_c - r_f}$	4.9%	4.9%	5.0%	5.0%	4.7%
	<i>Market return</i>				
$\mathbb{E}_t[r_m - r_f]$	2.73%	2.91%	2.96%	2.95%	1.98%
$\sigma_{r_m - r_f}$	4.4%	4.9%	5.1%	5.1%	4.8%

Table 4: Cross-section of returns

This table reports statistics for the returns on physical and technology capital obtained by simulating the model of Section 2. Return on physical capital is the return on a claim that pays final good firm's dividend D_t given in (7). Return on technology capital is the return on a claim that pays aggregate dividend of incumbent firms $D_{I,t} = \Pi_t - S_t^I$ (see equations (20) and (21)) adjusted for displacement of incumbent firms by entrants. β_d^ε and β_I^ε are computed as the 1st period impulse responses of the value of the final good firm and the incumbent firm's value (given in (29)), respectively, to a positive one standard deviation shock to the exogenous component of aggregate productivity A_t ($\varepsilon_t > 0$) scaled by the shock's volatility. The risk premiums are levered following Boldrin, Christiano, and Fisher (2001). The levels of entry threat are the probabilities of entrants succeeding in innovation conditional on an innovation occurring in the deterministic steady state. Appendix B describes how we calibrate the model and what parameters we use. The model statistics correspond to annualized populations moments.

	Entry threat				
	2%	5%	12.2%	20%	98%
<i>Return on physical capital</i>					
$\mathbb{E}_t[r_d - r_f]$	2.77%	2.72%	2.66%	2.64%	1.93%
$\sigma_{r_d - r_f}$	5.5%	5.5%	5.5%	5.5%	5.1%
β_d^ε	0.965	0.964	0.964	0.963	0.906
<i>Return on technology capital</i>					
$\mathbb{E}_t[r_I - r_f]$	1.06%	1.00%	0.98%	1.00%	0.90%
$\sigma_{r_I - r_f}$	2.1%	2.0%	2.0%	2.1%	2.4%
β_I^ε	0.372	0.361	0.359	0.368	0.423
<i>Technology shock to incumbents' value</i>					
$\mathbb{E}_t[\tilde{g}_{t+1}^I] - 1$	11.6%	9.5%	5.5%	2.4%	-9.0%
σ_{g^I}	32.7%	32.4%	31.4%	30.2%	22.2%

Table 5: Monopoly power

This table reports selected statistics introduced in Tables 1-4 obtained by simulating the model of Section 2 with different levels of product market power of incumbent firms. Panel A uses $\nu = 1.65$ and Panel B uses $\nu = 1.05$. Other parameters remain unchanged.

Panel A: High markup: $\nu = 1.65$

	Entry threat				
	2%	5%	12.2%	20%	98%
$\sigma_{\mathbb{E}_t[\Delta C_{t+1}]}$	0.42%	0.40%	0.38%	0.36%	0.21%
$\sigma_{\Delta Q}$	1.1%	1.0%	1.0%	1.0%	0.7%
$\sigma_{\Delta s^I}$	3.9%	3.8%	3.9%	4.1%	11.8%
$\sigma_{\Delta s^E}$	5.4%	4.4%	3.6%	3.3%	3.0%
Incumbents	17.8%	15.2%	10.9%	7.9%	0.1%
Potential entrants	2.1%	4.7%	9.0%	11.9%	19.4%
$\gamma_{t+1}^{\varepsilon}$	1.13%	1.11%	1.09%	1.08%	0.91%
$\mathbb{E}_t[r_m - r_f]$	3.54%	4.01%	4.31%	4.35%	3.22%
$\mathbb{E}_t[r_d - r_f]$	3.84%	3.78%	3.69%	3.62%	2.78%
β_d^{ε}	1.056	1.052	1.048	1.044	0.981
$\mathbb{E}_t[r_I - r_f]$	0.70%	0.71%	0.74%	0.78%	0.88%
β_I^{ε}	0.182	0.188	0.206	0.223	0.311

Table 5 (cont.): Monopoly power

Panel B: Low markup: $\nu = 1.05$

	Entry threat		
	2%	5%	12.2%
$\sigma_{\mathbb{E}_t[\Delta C_{t+1}]}$	0.11%	0.10%	0.10%
$\sigma_{\Delta Q}$	0.4%	0.4%	0.4%
$\sigma_{\Delta s^I}$	2.7%	2.6%	2.7%
$\sigma_{\Delta s^E}$	4.1%	3.4%	2.9%
Incumbents	3.2%	2.4%	1.5%
Potential entrants	0.9%	1.7%	2.7%
$\gamma_{t+1}^{\varepsilon}$	0.66%	0.66%	0.67%
$\mathbb{E}_t[r_m - r_f]$	1.55%	1.60%	1.61%
$\mathbb{E}_t[r_d - r_f]$	1.66%	1.68%	1.66%
β_d^{ε}	0.870	0.872	0.876
$\mathbb{E}_t[r_I - r_f]$	0.95%	0.93%	0.91%
β_I^{ε}	0.507	0.488	0.484

	2%	5%	12.2%	20%	98%
<i>Consumption</i>	0.11%	0.10%	0.10%	0.09%	0.03%
<i>Technology capital</i>	0.4%	0.4%	0.4%	0.4%	0.3%
<i>R&D expenditure of incumbents</i>	2.7%	2.6%	2.6%	2.7%	4.8%
<i>R&D expenditure of potential entrants</i>	4.1%	3.4%	2.9%	2.7%	2.5%
<i>Share of R&D expenditure in total output</i>	3.2%	2.4%	1.5%	1.0%	0.0%
<i>Market price of risk</i>	0.9%	1.7%	2.7%	3.2%	4.3%
<i>Market return</i>	0.66%	0.66%	0.67%	0.66%	0.52%
<i>Return on physical capital</i>	1.55%	1.60%	1.61%	1.61%	1.09%
<i>Return on technology capital</i>	1.66%	1.68%	1.66%	1.67%	1.22%
<i>Return on technology capital</i>	0.870	0.872	0.876	0.876	0.832
<i>Return on technology capital</i>	0.95%	0.93%	0.91%	0.93%	0.76%
<i>Return on technology capital</i>	0.507	0.488	0.484	0.488	0.516

A Appendix. Model solution

In this Appendix, we provide conditions that characterize the solution of the model described in Section 2. In Appendix A.1, we state the first order conditions for the original, non-stationary, formulation of the model. Appendix A.2 presents the equivalent conditions for the rescaled stationary version of the model. Appendix A.3 describes how to solve for the deterministic steady state. In this Appendix, variable λ_t refers to the lagrangian multiplier with respect to the capital accumulation constraint (8), i.e., Tobin's marginal Q.

A.1 Original problem

$$(DEF_U) \quad U_t = \left\{ (1 - \beta)C_t^{1-\rho} + \beta \left(\mathbb{E}_t \left[U_{t+1}^{1-\gamma} \right]^{\frac{1}{1-\gamma}} \right)^{1-\rho} \right\}^{\frac{1}{1-\rho}}, \quad \rho = 1/EIS \quad (A1)$$

$$(FOC_I) \quad \lambda_t = \frac{1}{\Lambda'_t(I_t/K_t)}, \quad \text{where } \Lambda_t(\cdot) = \frac{a_1}{1-\zeta^{-1}} (\cdot)^{1-\zeta^{-1}} + a_2 \quad (A2)$$

$$(FOC_L) \quad w_t = (1 - \alpha)(1 - \xi) \frac{Y_t}{L_t} \quad (A3)$$

$$(FOC_K) \quad \lambda_t = \mathbb{E}_t \left[\mathbb{M}_{t,t+1} \left\{ \alpha(1 - \xi) \frac{Y_{t+1}}{K_{t+1}} + \lambda_{t+1} \left((1 - \delta) - \Lambda'_{t+1} \frac{I_{t+1}}{K_{t+1}} + \Lambda_{t+1} \right) \right\} \right] \quad (A4)$$

$$(FOC_X) \quad p_t = \nu \mu \quad (A5)$$

$$(FOC_K) \quad K_{t+1} = K_t(1 - \delta) + \Lambda_t K_t \quad (A6)$$

$$(DEF_Y) \quad Y_t = \left(\frac{\xi}{\nu \mu} \right)^{\frac{\xi}{1-\xi}} K_t^\alpha (A_t L_t)^{1-\alpha} Q_t^{1-\alpha} \quad (A7)$$

$$(DEF_X) \quad X_t = \frac{\xi}{\nu} Y_t \quad (A8)$$

$$(DEF_II) \quad \Pi_t = (\nu - 1)X_t \quad (A9)$$

$$(DEF_v) \quad v_t = \pi_t - s_t^I + (\phi_I(s_t^I) \kappa_I + (1 - \phi_I(s_t^I) - \hat{s}_t^E \phi_E(\hat{s}_t^E)) \kappa_D) \mathbb{E}_t [\mathbb{M}_{t,t+1} v_{t+1}],$$

where $\phi_I(\cdot) = \eta_I(\cdot)^{\omega_I}$, $\phi_E(\cdot) = \eta_E(\cdot)^{\omega_E - 1}$, $\omega_I, \omega_E < 1$. (A10)

$$(FOC_s^I) \quad 1 = \phi'_I(s_t^I) (\kappa_I - \kappa_D) \mathbb{E}_t [\mathbb{M}_{t,t+1} v_{t+1}] \quad (A11)$$

$$(FOC_s^E) \quad 1 = \phi'_E(\hat{s}_t^E) \kappa_E \mathbb{E}_t [\mathbb{M}_{t,t+1} v_{t+1}] \quad (A12)$$

$$(DEF_Q) \quad Q_{t+1} = Q_t (\kappa_D + (\kappa_I - \kappa_D) \phi_I(s_t^I) + (\kappa_E - \kappa_D) \hat{s}_t^E \phi_E(\hat{s}_t^E)) \quad (A13)$$

$$(MCC_C) \quad C_t = Y_t - I_t - X_t - S_t^I - S_t^E \quad (A14)$$

$$(DEF_SDF) \quad \mathbb{M}_{t,t+1} = \beta \left(\frac{C_{t+1}}{C_t} \right)^{-\rho} \left(\frac{U_{t+1}^{1-\gamma}}{\mathbb{E}_t [U_{t+1}^{1-\gamma}]} \right)^{\frac{\rho-\gamma}{1-\gamma}} = \beta^{\frac{1-\gamma}{1-\rho}} \left(\frac{C_{t+1}}{C_t} \right)^{-\rho \frac{1-\gamma}{1-\rho}} (R_{t+1}^W)^{\frac{\rho-\gamma}{1-\rho}} \quad (A15)$$

A.2 Rescaled problem

We scale all aggregate growing variables by Q_t , and denote the rescaled variables using lower-case letters, e.g., $k_t = \frac{K_t}{Q_t}$, etc. We define $g_{q,t+1} = \frac{Q_{t+1}}{Q_t}$. With some abuse of notation, we define $u_t = \frac{U_t}{C_t} = \frac{u_t Q_t}{c_t Q_t}$.

$$(DEF_U) \quad u_t = \left\{ 1 - \beta + \beta \left(\mathbb{E}_t \left[\left(u_{t+1} \frac{c_{t+1}}{c_t} g_{q,t+1} \right)^{1-\gamma} \right]^{\frac{1}{1-\gamma}} \right)^{1-\rho} \right\}^{\frac{1}{1-\rho}} \quad (A16)$$

$$(FOC_I) \quad \lambda_t = \frac{1}{\Lambda'_t(i_t/k_t)}, \quad \text{where } \Lambda_t(\cdot) = \frac{a_1}{1-\zeta^{-1}} (\cdot)^{1-\zeta^{-1}} + a_2 \quad (A17)$$

$$(FOC_L) \quad w_t = (1-\alpha)(1-\xi) \frac{y_t}{L_t} \quad (A18)$$

$$(FOC_K) \quad \lambda_t = \mathbb{E}_t \left[\mathfrak{m}_{t,t+1} \left\{ \alpha(1-\xi) \frac{y_{t+1}}{k_{t+1}} + \lambda_{t+1} \left((1-\delta) - \Lambda'_{t+1} \frac{i_{t+1}}{k_{t+1}} + \Lambda_{t+1} \right) \right\} \right] \quad (A19)$$

$$(FOC_X) \quad p_t = \nu \mu \quad (A20)$$

$$(FOC_K) \quad k_{t+1} g_{q,t+1} = k_t(1-\delta) + \Lambda_t k_t \quad (A21)$$

$$(DEF_Y) \quad y_t = \left(\frac{\xi}{\nu \mu} \right)^{\frac{\xi}{1-\xi}} k_t^\alpha (A_t L_t)^{1-\alpha} \quad (A22)$$

$$(DEF_X) \quad x_t = \frac{\xi}{\nu} y_t \quad (A23)$$

$$(DEF_PI) \quad \pi_t = (\nu - 1)x_t \quad (A24)$$

$$(DEF_v) \quad v_t = \pi_t - s_t^I + [(\kappa_I - \kappa_D) \phi_I(s_t^I) + \kappa_D (1 - \hat{s}_t^E \phi_E(\hat{s}_t^E))] \mathbb{E}_t[\mathfrak{m}_{t,t+1} v_{t+1}],$$

where $\phi_I(\cdot) = \eta_I(\cdot)^{\omega_I}$, $\phi_E(\cdot) = \eta_E(\cdot)^{\omega_E - 1}$, $\omega_I, \omega_E < 1$. (A25)

$$(FOC_S^I) \quad 1 = \phi'_I(s_t^I) (\kappa_I - \kappa_D) \mathbb{E}_t[\mathfrak{m}_{t,t+1} v_{t+1}] \quad (A26)$$

$$(FOC_S^E) \quad 1 = \phi_E(\hat{s}_t^E) \kappa_E \mathbb{E}_t[\mathfrak{m}_{t,t+1} v_{t+1}] \quad (A27)$$

$$(DEF_Q) \quad g_{q,t+1} = \kappa_D + (\kappa_I - \kappa_D) \phi_I(s_t^I) + (\kappa_E - \kappa_D) \hat{s}_t^E \phi_E(\hat{s}_t^E) \quad (A28)$$

$$(MCC_C) \quad c_t = y_t - i_t - x_t - s_t^I - \hat{s}_t^E \quad (A29)$$

$$(DEF_SDF) \quad \mathfrak{m}_{t,t+1} = \beta \left(\frac{c_{t+1}}{c_t} g_{q,t+1} \right)^{-\rho} \left(\frac{(u_{t+1} c_{t+1})^{1-\gamma}}{\mathbb{E}_t[(u_{t+1} c_{t+1})^{1-\gamma}]} \right)^{\frac{\rho-\gamma}{1-\gamma}} \quad (A30)$$

A.3 Steady state

$$(DEF_U) \quad u^{1-\rho} = 1 - \beta + \beta(u g_q)^{1-\rho} \Rightarrow u^{1-\rho} = \frac{1 - \beta}{1 - \beta g_q^{1-\rho}} \quad (A31)$$

$$(FOC_I) \quad \lambda = 1 \quad (A32)$$

$$(FOC_L) \quad w = (1 - \alpha)(1 - \xi)y \quad (A33)$$

$$(FOC_K) \quad \lambda = \mathfrak{m} \left\{ \alpha(1 - \xi) \frac{y}{k} + \lambda(1 - \delta) \right\} \quad (A34)$$

$$(FOC_X) \quad p = \nu \mu \quad (A35)$$

$$(FOC_λ) \quad k g_q = k(1 - \delta) + i \quad (A36)$$

$$(DEF_Y) \quad y = \left(\frac{\xi}{\nu \mu} \right)^{\frac{\xi}{1-\xi}} k^\alpha \quad (A37)$$

$$(DEF_X) \quad x = \frac{\xi}{\nu} y \quad (A38)$$

$$(DEF_π) \quad \pi = (\nu - 1)x \quad (A39)$$

$$(DEF_v) \quad v = \frac{\pi - s^I}{1 - \mathfrak{m}((\kappa_I - \kappa_D)\phi_I(s^I) + \kappa_D(1 - \hat{s}^E\phi_E(\hat{s}^E)))} \quad (A40)$$

$$(FOC_S^I) \quad 1 = \phi_I'(s^I) (\kappa_I - \kappa_D) \mathfrak{m} v \quad (A41)$$

$$(FOC_S^E) \quad 1 = \phi_E(\hat{s}^E) \kappa_E \mathfrak{m} v \quad (A42)$$

$$(DEF_Q) \quad g_q = \kappa_D + (\kappa_I - \kappa_D) \phi_I(s^I) + (\kappa_E - \kappa_D) \hat{s}^E \phi_E(\hat{s}^E) \quad (A43)$$

$$(MCC_C) \quad c = y - i - \mu x - s^I - \hat{s}^E \quad (A44)$$

$$(DEF_SDF) \quad \mathfrak{m} = \beta g_q^{-\rho} \quad (A45)$$

Using (A32), (A34), (A37) and (A45), we can express k as a function of s^I and \hat{s}^E

$$k(s^I, \hat{s}^E) = \left[\frac{1}{(1 - \xi)\alpha} \left(\frac{\xi}{\nu \mu} \right)^{\frac{\xi}{\xi-1}} \left(\delta - 1 + \frac{1}{\beta} g_q(s^I, \hat{s}^E)^\rho \right) \right]^{\frac{1}{\alpha-1}}, \quad (A46)$$

where $g_q(s^I, \hat{s}^E)$ is given by (A43). Using (A38) and (A46) in (A39) we have that $\pi = \pi(s^I, \hat{s}^E)$. Hence, solving the steady state involves solving for v , s^I and \hat{s}^E from the equations (A40), (A41) and (A42). Once v , s^I and \hat{s}^E are determined, all the other quantities can be obtained directly.

B Appendix. Calibration

The model is solved via third-order perturbation around the stochastic steady state. Statistics we report in the tables and figures are computed based on 1,000 paths of quarterly simulated data. Each path is 220 quarters long after excluding the initial 50 quarters. Growth rates and returns are in logs. All moments are annualized. Growth rates and returns are annualized by summing up 4 consecutive quarterly observations. Standard deviations of quantities in levels are annualized by multiplying quarterly standard deviation by $\sqrt{4}$.

Parameter values we use in simulations of our model are summarized in Table B-1. We set the preference parameters to standard values used in the finance literature that employs recursive preferences (Bansal and Yaron (2004) and Bansal, Kiku, and Yaron (2010)). In particular, we closely follow Kung and Schmid (2013) who show that augmenting a standard endogenous growth model with aggregate risk and applying recursive preferences can jointly capture the dynamics of aggregate quantities and asset markets.

Following Acemoglu and Cao (2010), the size of potential entrants' innovations is $\kappa_E = 4$, while the size of incumbent firms' innovations is $\kappa_I = 1.7693$. Potential entrants' innovations increase the technology capital by significantly more compared to incumbent firms' innovations consistent with empirical evidence that entrants are pursuing more radical innovations. We check that the limit-pricing condition $\kappa_E \geq \nu^{\frac{1}{\nu-1}}$ is satisfied in all our calibrations. The intermediate goods share is chosen to satisfy the balanced growth condition (23), hence $\xi = \frac{1-\alpha}{\nu-\alpha}$ for given parameters α and ν .

We calibrate the model with different probabilities of success of incumbents and entrants in innovation. Specifically, we set the probability of potential entrants succeeding in innovation, conditional on an innovation occurring, i.e., $\frac{\hat{s}_t^E \phi_E(\hat{s}_t^E)}{\phi_I(\hat{s}_t^I) + \hat{s}_t^E \phi_E(\hat{s}_t^E)}$, in the deterministic steady state to be 2, 5, 12.2, 20, and 98 percent. We refer to these fractions as entry levels.

The benchmark calibration uses entry level 12.2 percent, which corresponds to the empirical measure of entry threat we compute using the universe of patents awarded by the The United States Patent and Trademark Office (USPTO) over the 1976-2012 period. Specifically, to measure the entry threat in innovation, we compute the ratio of the number of US patents applied for, in a given quarter, by firms that did not patent prior to the beginning of this quarter (i.e., by “successful entrants” in innovation as of the beginning of this quarter) to the total number

of US patents applied for by all firms in the same quarter. The resulting quarterly time series of entry threat starts with the first quarter of 1985 and ends with the last quarter of 2008. We start in 1985 because data on awarded patents are available since 1976 and, for the first quarter of 1985, we define the successful entrants in innovation based on at least 10 years of data prior to this quarter. For all consecutive quarters, we gradually expand the window over which we define successful entrants till the beginning of the respective quarter. We stop in 2008, because many patents applied in 2009 and later are still in the patent prosecution process and it is not clear whether they will be awarded. The time-average of our quarterly entry threat measure is 12.2 percent over the 1985-2008 period. Further, in the benchmark calibration, we set $\phi_I(s_t^I)$ in the deterministic steady state to be 3.45 percent quarterly. This corresponds to the empirical success rate of incumbents in innovation measured as the fraction of the number of firms that patented prior to a given quarter (i.e., incumbents in innovation) that also patented in this quarter. To define incumbents in innovation, we use the analogous expanding window as described above.

To achieve different entry levels, we change parameters ω_E and ω_I so that the consumption growth is equal to 0.475 percent quarterly (i.e., annual growth rate of 1.9 percent) for all entry levels. All other parameters do not change across entry levels. Specifically, we use the following two conditions to restrict parameter values in the deterministic steady state system A.3

$$1 + 0.00475 = \kappa_I \phi_I(s_t^I) + \kappa_E \hat{s}_t^E \phi_E(\hat{s}_t^E) + \kappa_D (1 - \phi_I(s_t^I) - \hat{s}_t^E \phi_E(\hat{s}_t^E)),$$

$$\text{entry level} = \frac{\hat{s}_t^E \phi_E(\hat{s}_t^E)}{\phi_I(s_t^I) + \hat{s}_t^E \phi_E(\hat{s}_t^E)},$$

where $\phi_I(s_t^I)$ and $\phi_E(\hat{s}_t^E)$ are given in (44).

Table B-1: Calibration parameters

This table reports the parameters used in the quarterly calibration of the model of Section 2 with 12.2 percent entry level and the success rate of incumbents in innovation equal to 3.45 percent quarterly.

Parameter	Description	Value
β	Subjective discount factor	$\sqrt[4]{0.984}$
γ	Risk aversion	10
ψ	Elasticity of intertemporal substitution	1.85
α	Capital share	0.35
ξ	Intermediate goods share	0.7222
ν	Elasticity of substitution between intermediate goods	1.25
μ	Marginal cost of producing an intermediate good	1
δ	Depreciation rate of physical capital	0.02
ζ	Investment adjustment costs parameter	0.7
ρ	Autocorrelation of exogenous shock ε_{t+1}	$\sqrt[4]{0.95}$
σ	Volatility of exogenous shock ε_{t+1}	1.75%
κ_I	Size of incumbent firms' innovation upon success	1.7693
κ_E	Size of potential entrants' innovation upon success	4
κ_D	Depreciation rate of technology capital	0.9625
η_I	Incumbent firms' R&D innovation productivity shift parameter	0.45
η_E	Potential entrants' R&D innovation productivity shift parameter	0.07
ω_I	Incumbent firms' elasticity of the innovation intensity w.r.t. R&D	0.6055
ω_E	Potential entrants' elasticity of the innovation intensity w.r.t. R&D	0.6519

References

- ACEMOGLU, D. (2010): *Introduction to Modern Economic Growth*. Princeton University Press.
- ACEMOGLU, D., AND D. V. CAO (2010): “Innovation by Entrants and Incumbents,” Working Paper.
- AGHION, P., C. HARRIS, P. HOWITT, AND J. VICKERS (2001): “Competition, Imitation and Growth with Step-by-Step Innovation,” *Review of Economic Studies*, 68, 467–492.
- AGHION, P., AND P. HOWITT (1992): “A Model of Growth Through Creative Destruction,” *Econometrica*, 60(2), 323–351.
- (1998): *Endogenous Growth Theory*. MIT Press.
- (2009): *The Economics of Growth*. MIT Press.
- AI, H., M. M. CROCE, AND K. LI (2013): “Toward a quantitative general equilibrium asset pricing model with intangible capital,” *Review of Financial Studies*, 26(2), 491–530.
- AI, H., AND D. KIKU (2013): “Growth to value: Option exercise and the cross section of equity returns,” *Journal of Financial Economics*, 107(2), 325–349.
- AKCIGIT, U., AND W. R. KERR (2010): “Growth through heterogeneous innovations,” Discussion paper, National Bureau of Economic Research.
- BANSAL, R., D. KIKU, AND A. YARON (2010): “Long run risks, the macroeconomy, and asset prices,” *American Economic Review*, 100(2), 542–546.
- BANSAL, R., AND A. YARON (2004): “Risks for the long run: A potential resolution of asset pricing puzzles,” *Journal of Finance*, 59, 1481–1509.
- BARTELSMAN, E. J., AND M. DOMS (2000): “Understanding Productivity: Lessons from Longitudinal Microdata,” *Journal of Economic Literature*, 38(3), 569–594.
- BERNARD, A. B., S. J. REDDING, AND P. K. SCHOTT (2010): “Multiple-Product Firms and Product Switching,” *American Economic Review*, 100(1), 70–97.
- BILBIE, F. O., F. GHIRONI, AND M. J. MELITZ (2012): “Endogenous Entry, Product Variety and Business Cycles,” *Journal of Political Economy*, 120(2), 304–345.

- BLUNDELL, R., R. GRIFFITH, AND J. V. REENEN (1995): “Dynamic Count Data Models of Technological Innovation,” *Economic Journal*, 105(429), 333–344.
- (1999): “Market Share, Market Value and Innovation in a Panel of British Manufacturing Firms,” *Review of Economic Studies*, 66(3), 529–554.
- BOLDRIN, M., L. J. CHRISTIANO, AND J. D. FISHER (2001): “Habit Persistence, Asset Returns and the Business Cycle,” *American Economic Review*, 91(1), 149–166.
- BRODA, C., AND D. E. WEINSTEIN (2010): “Product Creation and Destruction: Evidence and Price Implications,” *American Economic Review*, 100(3), 691–723.
- COMIN, D. A., M. GERTLER, AND A. M. SANTACREU (2009): “Technology innovation and diffusion as sources of output and asset price fluctuations,” Discussion paper, National Bureau of Economic Research.
- FOSTER, L., J. C. HALTIWANGER, AND C. J. KRIZAN (2001): “Aggregate productivity growth. Lessons from microeconomic evidence,” in *New developments in productivity analysis*, pp. 303–372. University of Chicago Press.
- FREEMAN, C., AND L. L. SOETE (1997): *The economics of industrial innovation*. Psychology Press.
- GÂRLEANU, N., L. KOGAN, AND S. PANAGEAS (2012): “Displacement risk and asset returns,” *Journal of Financial Economics*, 105(3), 491–510.
- GÂRLEANU, N., S. PANAGEAS, AND J. YU (2012): “Technological growth and asset pricing,” *Journal of Finance*, 67(4), 1265–1292.
- GREENWOOD, J., AND B. JOVANOVIĆ (1999): “The Information-Technology Revolution and the Stock Market,” *American Economic Review (Papers and Proceedings)*, 89(2).
- GROSSMAN, G. M., AND E. HELPMAN (1991): “Quality Ladders in the Theory of Growth,” *Review of Economic Studies*, 58(1), 43–61.
- HOBIIJN, B., AND B. JOVANOVIĆ (2001): “The Information-Technology Revolution and the Stock Market: Evidence,” *American Economic Review*, 91(5), 1203–1220.

- JERMANN, U. J. (1998): “Asset Pricing in production economies,” *Journal of Monetary Economics*, 41, 257–275.
- KLETTE, T. J., AND S. KORTUM (2004): “Innovating Firms and Aggregate Innovation,” *Journal of Political Economy*, 112(5), 986–1018.
- KOGAN, L., D. PAPANIKOLAOU, AND N. STOFFMAN (2013): “Technological innovation: Winners and losers,” Discussion paper, National Bureau of Economic Research.
- KUNG, H., AND L. SCHMID (2013): “Innovation, Growth, and Asset Prices,” Working Paper.
- LETTAU, M., AND S. C. LUDVIGSON (2010): “Measuring and Modeling Variation in the Risk-Return Trade-off,” *Handbook of Financial Econometrics*, vol.1, pp. 617–690.
- LOUALICHE, E. (2013): “Asset Pricing with Entry and Imperfect Competition,” Working Paper.
- NICKELL, S. J. (1996): “Competition and Corporate Performance,” *Journal of Political Economy*, 104(4), 724–746.
- PÁSTOR, L., AND P. VERONESI (2009): “Technological Revolutions and Stock Prices,” *American Economic Review*, 99(4), 1451–1483.
- ROMER, P. M. (1990): “Endogenous Technological Change,” *Journal of Political Economy*, 98(5), 71–102.
- SCHERER, F. M. (1984): *Innovation and growth: Schumpeterian perspectives*, vol. 1. The MIT Press.
- SCHUMPETER, J. (1942): “Creative destruction,” *Capitalism, socialism and democracy*.
- SCHUMPETER, J. A. (1934): *The Theory of Economic Development*. Harvard University Press.