

# On the link between volatility and growth

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**Abstract** A model of growth with endogenous innovation and distortionary taxes is presented. Since innovation is the only source of volatility, any variable that influences innovation directly affects volatility and growth. This joint endogeneity is illustrated by working out the effects through which economies with different tax *levels* differ in their volatility and growth process. We obtain analytical measures of macro volatility based on cyclical output and on output growth rates for plausible parametric restrictions. This analysis implies that controls for taxes should be included in the standard growth–volatility regressions. Our estimates show that the conventional Ramey–Ramey coefficient is affected sizeably. In addition, tax *levels* do indeed appear to affect volatility in our empirical application.

**Keywords** Tax effects · Volatility measures · Poisson uncertainty · Endogenous cycles and growth · Continuous-time DSGE models

**JEL Classification** E32 · E62 · H3 · C65

## 1 Introduction

### 1.1 Background

In a seminal paper, [Ramey and Ramey \(1995\)](#) find a strong empirical negative link between volatility and growth. Subsequent papers confirm this relationship for other datasets

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(Martin and Rogers 1997; Acemoglu et al. 2003; Aghion et al. 2010; Posch 2011a).<sup>1</sup> Complementary to Ramey and Ramey, these studies use additional controls such as exchange rate variability, financial development and measures of openness, institutions or monetary and fiscal policy.

## 1.2 The open question

The previous studies are primarily of an empirical nature. These papers do not, however, inquire into the exact structural channels through which macro volatility and growth interact. It therefore largely remains an open question what the determinants of the link between volatility and growth are.

## 1.3 Our message

This paper plays the devil's advocate and argues that, theoretically, any correlation pattern can emerge. The sign of the growth-volatility correlation depends—inter alia—on time-invariant economic policies of a country. We show that a link between volatility and growth may arise from endogenous innovations and their propagation. Volatility is endogenous for measures based on cyclical output and for measures based on output growth rates. Growth emerges endogenously from innovations of a research sector. In our theoretical framework the *level* of taxes jointly affects growth and volatility and thereby their link.

## 1.4 Our framework

Our analysis builds on dynamic stochastic equilibrium models in which cyclical growth emerges endogenously (Bental and Peled 1996; Matsuyama 1999; Francois and Lloyd-Ellis 2003, 2008; Wälde 2002, 2005).<sup>2</sup> We use a version of Wälde (2005), because it has analytical solutions for plausible parametric restrictions for non-trivial dynamics and comprises the continuous-time real business cycle (RBC) model as a special case.

Using a well-known parametric restriction, we obtain two types of analytical volatility measures (borrowing extensively from García and Griego 1994). The first type is based on stochastically detrended (henceforth cyclical) variables. The second type is based on growth rates of the original (non-stationary) series. While the first one is identical in spirit to empirical decompositions, where a time series is split into a growth trend and a stationary cyclical component, the second one is the common measure in the empirical literature.

## 1.5 Results

We illustrate how structural parameters affect our measures of volatility and growth directly by changing the variance and intensity of the shocks, and indirectly by affecting the shock propagation. In our model, we focus on taxes as an example for economic policy parameters. Any correlation between volatility and growth can be predicted if the growth and volatility

<sup>1</sup> There is work suggesting that the link is not as pronounced when using time series evidence (Beaumont et al. 2008). At different levels of aggregation either no significant relationship is found using state data (Dawson and Stephenson 1997), or an ambiguous empirical result—either a positive or negative link—is found at the sectoral level (Imbs 2007; Chong and Gradstein 2009).

<sup>2</sup> These papers in turn build on Aghion and Howitt (1992), Grossman and Helpman (1991) and Segerstrom et al. (1990). The present paper builds explicitly on the stochastic Aghion and Howitt model using the formulation for risk averse agents introduced by Wälde (1999).

measures in our model economy are considered for different tax levels. The volatility-growth link can even change sign if tax rates are altered.

We identify three channels through which macro volatility can be affected by policy parameters, i.e., the speed of convergence (to the non-stochastic steady state), the jump size and the arrival rate.

For empirical studies of the Ramey–Ramey type, the inclusion of control variables in the conditional variance equation is suggested. By including such controls, we find that 3 out of the 4 controls we suggest are significant at the 5% level. We also find that the conventional Ramey–Ramey coefficient which links volatility and growth is affected sizably.

## 1.6 Further related literature

Our theoretical and empirical results are complementary to the finding that volatility can have detrimental effects on growth (Chong and Gradstein 2009). The authors provide empirical evidence that unexpected changes in economic and fiscal policies is a channel through which the link between volatility and growth could materialize at the macro level. We show that even with constant policies the link materializes through the joint endogeneity. Jaimovic and Siu (2009) also provide evidence for controlling for additional variables in Ramey–Ramey regressions. While they do stress the effect of the age composition of the labor force on volatility, they do not estimate the link between volatility and growth. Aghion et al. (2010) argue that tighter credit constraints can lead to both lower and more volatile growth rates. While this is complementary to our channel, they do not study the implications for the conventional Ramey–Ramey coefficient.

## 1.7 Table of contents

The paper proceeds as follows. Section 2 introduces the model of endogenous innovation and distortionary taxes. Section 3 presents the equilibrium dynamics and illustrates the notion of cyclical growth. Section 4 contains our theoretical contribution, the derivation of closed-form volatility measures. Section 5 comprises our main economic insights and Sect. 6 provides our empirical results. The final section concludes.

## 2 The model

### 2.1 Production possibilities

Technological progress is labor augmenting and embodied in capital. All capital goods can be identified by a number denoting their date of manufacture and therefore their vintage. A capital good  $K_j$  of vintage  $j$  allows workers to produce with labor productivity  $A^j$ , where  $A > 1$  is a constant parameter. Hence, a more modern vintage  $j + 1$  implies a labor productivity that is  $A$  times higher than that of vintage  $j$ . The corresponding production function reads  $Y_j = K_j^\alpha (A^j L_j)^{1-\alpha}$ , where the amount of labor allocated to that vintage is  $L_j$  and  $0 < \alpha < 1$  denotes the output elasticity of capital.

There is a very large number of research firms which operate under perfect competition. Research costs are recovered by returns of a prototype which is the outcome of a successful project. This differs from standard modeling of R&D where successful research only leads to a blueprint. The prototype is a production unit—a machine—of size  $\kappa_t$ . This new prototype is owned by the individuals who financed the successful R&D project (as reflected in the

budget constraint below). The currently most advanced vintage is denoted by  $q$  and implies a labor productivity of  $A^q$ .<sup>3</sup> The new prototype yields a labor productivity of  $A^{q+1}$  for workers having access to this new technology.

Research is a risky activity. Uncertainty in research is captured by a Poisson process  $q_t$  where the arrival rate of success is denoted by  $\lambda_t$ . Resources employed for research are denoted by  $R_t$ . An exogenous function  $D_t$  captures the difficulty to make an invention (as in Segerstrom 1998). This function captures the idea that an economy needs to put more effort into research for the next generation of capital goods if new technologies are to appear at a constant rate. There are constant returns to scale at the firm level. On the sectorial level, however, an externality  $h(\cdot)$  implies decreasing returns to scale,

$$\lambda_t = (R_t/D_t)h(R_t/D_t) \equiv (R_t/D_t)^{1-\gamma}, \quad 0 < \gamma < 1, \tag{1}$$

where the difficulty function  $D_t$  and the externality  $h(\cdot)$  are taken as given by the firm.<sup>4</sup>

Given this research process, the capital stock of the next vintage follows

$$dK_{q+1} = \kappa_t dq_t, \tag{2}$$

which is a simple stochastic differential equation (SDE). The increment  $dq_t$  of the Poisson process  $q_t$  can either be 0 or 1. As successful research means  $dq_t = 1$ , this equation states that the capital stock increases from 0 to  $\kappa_t$  in the good outcome. When research is not successful,  $dK_{q+1} = 0$  because  $dq_t = 0$ .

Capital accumulation of existing vintages 1 to  $q$  is riskless. When resources are used to accumulate existing capital, the capital stock of vintage  $j$  increases if investment in vintage  $j$  exceeds depreciation  $\delta$ ,

$$dK_j = (I_j - \delta K_j) dt, \quad j \leq q. \tag{3}$$

Given that value marginal productivity is highest for the most advanced vintage, investment only takes place in vintage  $q$ . As R&D takes place under perfect competition, there is no monopolist owning the new vintage and there is no patent protection. Thus, we observe  $I_j = 0 \forall j < q$ , and  $I_q = I_t$  for the most advanced vintage. As soon as a new capital good is discovered through R&D, it is replicated by a large number of competing firms. In contrast to R&D, this is a deterministic process because capital accumulation simply means replicating existing machines. The process of capital accumulation is also—as in the standard Solow growth model—perfectly competitive.

Before we continue with the description of the model, we present a few equilibrium properties, some of them related to the vintage capital structure used here. They are useful as they simplify the presentation of the government, preferences and the assumptions about the difficulty function as well as the size of the prototype. Each vintage of capital allows a single output good to be produced, which is used for producing consumption goods,  $C_t$ , investment goods,  $I_t$ , as an input for research,  $R_t$ , and for government expenditures,  $G_t$ ,

$$\sum_{j=0}^q Y_j = Y_t = C_t + I_t + R_t + G_t, \tag{4}$$

<sup>3</sup> More precisely,  $q_t$  denotes the Poisson process whereas  $q$  denotes the label of the most recent vintage (number of jumps up to time  $t$ ). Though in principle interchangeable, after successful research,  $q_t$  increases by 1 while the label of older vintages remains like a stamp on the capital goods.

<sup>4</sup> Remember that arrival rates of Poisson processes can be added. Economically speaking, this means that there are many “small” arrival rates  $\lambda_t^f = (R_t^f/D_t)h(R_t^f/D_t)$  where  $R_t^f$  stands for R&D investment in research firm  $f$ . Aggregating over all research firms leads to the economy wide arrival rate  $\lambda_t$ .

where the quantities denote *net* resources used for these activities, i.e., after taxation. All activities in the economy take place under perfect competition. Hence, the producer price of the production good, the consumption good, and both investment goods used for capital accumulation and research will therefore be identical,

$$p_t^Y = p_t^C = p_t^K = p_t^R. \tag{5}$$

Aggregate constant labor supply in this economy is  $L$ . Allowing labor to be mobile across all vintages such that wage rates equalize and assuming market clearing,  $\sum_{j=0}^q L_j = L$ , total output of the economy can be represented by a simple Cobb-Douglas production function,

$$Y_t = K_t^\alpha L^{1-\alpha}, \tag{6}$$

in which vintage-specific capital has been combined to an aggregate capital index  $K_t$ ,

$$K_t = K_0 + B K_1 + \dots + B^q K_q = \sum_{j=0}^q B^j K_j, \quad B \equiv A^{\frac{1-\alpha}{\alpha}}. \tag{7}$$

This index can be thought of as counting the ‘number of machines’ of the first vintage,  $j = 0$ , that would be required to produce the same output  $Y_t$  as with the current mix of vintages.

Applying Itô’s formula (or change of variable formula, cf. [Sennewald \(2007\)](#) for a rigorous analysis and [Sennewald and Wälde \(2006\)](#) for an introduction) to (7) using (2) and (3), the capital index  $K_t$  follows the SDE,

$$dK_t = (B^q I_t - \delta K_t) dt + B^{q+1} \kappa_t dq_t. \tag{8}$$

Because the capital index,  $K_t$ , is measured in units of the first vintage, it increases as a function of effective investment,  $B^q I_t$ , minus depreciation,  $\delta K_t$ . When an innovation occurs, the capital index increases by the effective size of the new prototype,  $B^{q+1} \kappa_t$ .

### 2.2 Government

The government levies taxes on income,  $\tau_i$ , on wealth,  $\tau_a$ , on consumption expenditures,  $\tau_c$ , on investment expenditures,  $\tau_k$ , and on research expenditures,  $\tau_r$ . In our study, a positive tax either implies a real decrease in income or an increase in the effective price (consumer price), whereas a negative tax denotes a subsidy. The government uses all tax income (and does not save or run a debt) to provide basic government services  $G_t$ ,

$$G_t = \tau_i(Y_t - \delta B^{-q} K_t) + \tau_k(I_t - \delta B^{-q} K_t) + \tau_r R_t + \tau_c C_t + \tau_a (1 + \tau_k) B^{-q} K_t \geq 0. \tag{9}$$

In order to focus on the effects of taxation from government expenditures, we assume that government expenditure does not affect household utility or the production possibilities of the economy. A myopic government simply provides basic government services without having any interest in stabilization policy or optimal taxation. The tax structure thus is exogenously given to the model. Additional effects through the channel of fiscal debt might be interesting but beyond the scope of this paper.

Producer prices from (5) are identical for all three production processes. When goods are sold, they are taxed differently such that consumer prices are  $(1 + \tau_c) p_t^C$ ,  $(1 + \tau_k) p_t^K$ ,  $(1 + \tau_r) p_t^R$ , respectively. To rule out arbitrage between different types of goods, we assume that a unit of production is useless for other purposes once it is assigned for a special purpose: once a consumption good is acquired, it cannot be used for, e.g., capital accumulation.

Sales taxes have no theoretical upper bound. A 300% tax on the consumption good would imply that 3/4 of the price are taxes going to the government and 1/4 goes to the producer. Their lower bound is clearly  $-100%$ , when the good would be gratis. Similarly, the upper bound for taxes on income is 100% (instant confiscation of income), while there is no lower bound. Hence, we obtain  $-1 < \tau_c, \tau_k, \tau_r$  and  $\tau_i, \tau_a < 1$ .

### 2.3 Preferences

The economy has a large number of representative households. Households maximize expected utility given by the integral over instantaneous utility,  $u = u(c_t)$ , resulting from consumption flows,  $c_t$ , and discounted at the subjective rate of time preference,  $\rho$ ,

$$U_0 = E_0 \int_0^\infty e^{-\rho t} u(c_t) dt. \tag{10}$$

We assume that instantaneous utility is characterized by constant relative risk aversion,

$$u(c_t) = \frac{c_t^{1-\sigma}}{1-\sigma}, \quad \sigma > 0. \tag{11}$$

The budget constraint reflects investment possibilities in this economy, the impact of taxes and shows how real wealth,  $a_t$ , evolves over time. Households can invest in a risky asset by financing research,  $i_t$ , and in an (instantaneously) riskless asset by replicating capital. We measure wealth in units of the consumption good, priced at consumer prices. The household’s budget constraint can best be illustrated by looking at

$$\begin{aligned} da_t = & \left( \frac{1-\tau_i}{1+\tau_c} \sum_{j=0}^{q+1} w_j^K k_j + \frac{1-\tau_i}{1+\tau_c} w_t - c_t - \frac{1+\tau_r}{1+\tau_c} i_t \right) dt - \left( \frac{1-\tau_i}{1+\tau_k} \delta + \tau_a \right) a_t dt \\ & + \left( \frac{1+\tau_k}{1+\tau_c} \kappa_t \frac{i_t}{R_t} - \frac{B-1}{B} a_{t-} \right) dq_t, \end{aligned} \tag{12}$$

where  $a_{t-} \equiv \lim_{s \rightarrow t} a_s, s < t$ , denotes individual wealth an instant before a jump in  $t$ . The first sum in (12),  $\sum_{j=0}^{q+1} w_j^K k_j$ , captures capital income from all vintages. This is taxed at the income tax rate  $\tau_i$  and divided by the after-tax price of the consumption good,  $1+\tau_c$  (keeping in mind that the consumption good is the numeraire). Hence, the entire term  $\frac{1-\tau_i}{1+\tau_c} \sum_{j=0}^{q+1} w_j^K k_j$  captures after-tax capital income in units of the consumption good. The same reasoning applies to labor income  $w_t$ , consumption expenditures  $c_t$ , and investment into research  $i_t$ . Thus, the first bracket captures the increase in wealth  $a_t$  measured in units of the consumption good at after-tax consumer prices. The second term captures the deterministic wealth-reducing effect due to depreciation and the tax on wealth, where the tax rates in front of the depreciation rate ensure that only net capital rewards (after depreciation) are taxed. The third term is a stochastic component which increases the individual’s wealth in case of successful research by the ‘dividend payments’ less ‘economic depreciation’. Here, ‘dividend payments’ at the household level are given by the share  $i_t/R_t$  of a successful research project financed by the household times total payoffs determined by the size  $\kappa_t$  of the prototype times its value in units of the consumption good, i.e.,  $\frac{1+\tau_k}{1+\tau_c}$ . The term  $1+\tau_k$  points out that a successful research project yields an installed capital good (and not an investment good). Moreover, ‘economic depreciation’ of  $s \equiv \frac{B-1}{B} > 0$  percent emerges from the vintage capital structure as the most advanced vintage from (5) has a relative price of unity and all other vintages lose in value relative to the consumption good.

After some algebra, the budget constraint can be written as follows (cf. app. A.2),<sup>5</sup>

$$\begin{aligned}
 da_t = & \left( \left( \frac{1 - \tau_i}{1 + \tau_k} (r_t - \delta) - \tau_a \right) a_t + \frac{1 - \tau_i}{1 + \tau_c} w_t - c_t - \frac{1 + \tau_r}{1 + \tau_c} i_t \right) dt \\
 & + \left( \frac{1 + \tau_k}{1 + \tau_c} \kappa_t \frac{i_t}{R_t} - sa_{t-} \right) dq_t,
 \end{aligned}
 \tag{13}$$

where factor rewards

$$r_t = B^q \frac{\partial Y_t}{\partial K_t} \equiv B^q Y_K, \quad w_t = \frac{\partial Y_t}{\partial L} \equiv Y_L,
 \tag{14}$$

are defined by the rental rate of capital and the wage rate respectively.

### 2.4 Assumptions

For the problem to be well defined, we need assumptions on the functional forms of the ‘difficulty function’ as well as on the ‘size’ of the new prototype. We capture the innovations of the past by the current (tax-independent) size of total wealth,  $K_t^{obs} = La_t$ ,

$$D_t \equiv D \frac{1 + \tau_c}{1 + \tau_k} K_t^{obs} = DB^{-q} K_t, \quad D > 0.
 \tag{15}$$

Measuring wealth in consumer prices, the price of the capital good increases by the tax  $\tau_k$  and the price to be paid for one unit of the consumption good increases by  $\tau_c$ . Through these channels taxes directly affect individual’s real wealth, however, it seems plausible that taxes do *not* directly affect the difficulty level.

The size of the prototype is argued to increase in the amount of time and resources  $R_t$  spent on developing  $\kappa_t$ . Longer research could imply a larger prototype. We capture these aspects in a simple and tractable way by keeping  $\kappa_t$  proportional to the (tax-independent) size of total wealth an instant before a jump,  $K_{t-}^{obs} = La_{t-}$ ,

$$\kappa_t \equiv \kappa \frac{1 + \tau_c}{1 + \tau_k} K_{t-}^{obs} = \kappa B^{-q} K_{t-}, \quad 0 < \kappa \ll 1.
 \tag{16}$$

While it may be debatable whether or not the payoffs of the risky research project, as a kind of income, could be subject to taxation, it seems a plausible assumption that the payoff itself, that is the size of the prototype, does not directly depend on tax rates.

### 3 Equilibrium dynamics

Solving the model requires conditions for optimal consumption and research expenditure. These two conditions, together with the capital accumulation constraint (8), market clearing, and optimality conditions of competitive firms provide a system consisting of six equations that determines the time paths of variables of interest  $K_t, C_t, R_t, Y_t, w_t$  and  $r_t$ .

This type of system can best be understood by introducing auxiliary variables: In the classical Solow growth model, capital per effective worker (or efficiency unit) is shown to converge to a non-stochastic steady state and transitional dynamics can be separated from the analysis of long-run growth. In the present context, we define  $\hat{K}_t$  and  $\hat{C}_t$  as

$$\hat{K}_t \equiv K_t/A^{q/\alpha} = B^{-qt} K_t/A_t^q, \quad \hat{C}_t \equiv C_t/A^q,
 \tag{17}$$

<sup>5</sup> All references starting with characters refer to the web appendix of this paper available from the authors.

which is almost identical to capital and consumption per effective worker as labor supply is constant here. These variables allow us to separate the analysis of cyclical properties of the model from long-run growth. In what follows, we denote  $\hat{K}_t$  and  $\hat{C}_t$  as ‘cyclical components’ of  $K_t$  and  $C_t$  since  $A^{q/\alpha}$  and  $A^q$  turn out to be the stochastic trends for the capital index in units of vintage 0 and in units of the most recent vintage  $q$ , respectively. All variables expressed in units of the consumption good (including the capital stock in units of the most recent vintage) share the same trend,  $A^q$ , as from (17). Thus dividing non-stationary variables such as  $Y_t, C_t, R_t, I_t, w_t$  and  $G_t$  by the common stochastic trend  $A^q$ , these ‘cyclical variables’ turn out to be stationary and within a bounded range ( $r_t$  is stationary by construction).

### 3.1 An explicit solution

It would be interesting to analyze such a system in all generality. However, one would run the risk of losing the big picture and instead be overwhelmed by many small results. As the main objective of this paper is closed-form measures of volatility, we restrict ourselves to a particular parameter set of the model that allows very sharp analytical results.

**Theorem 1** *If relative risk aversion equals the output elasticity of the capital stock,  $\sigma = \alpha$ , we obtain an equilibrium with optimal policy functions*

$$\hat{C}_t = \Psi \hat{K}_t, \quad \hat{R}_t = \Gamma \hat{K}_t, \tag{18}$$

where we define constants

$$\Psi \equiv \frac{1 + \tau_k}{1 + \tau_c} \left( \frac{1 - \sigma}{\sigma} \left( \frac{1 - \tau_i}{1 + \tau_k} \delta + \tau_a \right) + \frac{\rho + \lambda - (1 - s) \lambda \xi^{-\sigma}}{\sigma} - \frac{1 + \tau_r}{1 + \tau_k} \lambda^{1-\gamma} D \right), \tag{19}$$

$$\Gamma \equiv \lambda^{1-\gamma} D, \tag{20}$$

$$\xi \equiv 1 + \kappa - s, \tag{21}$$

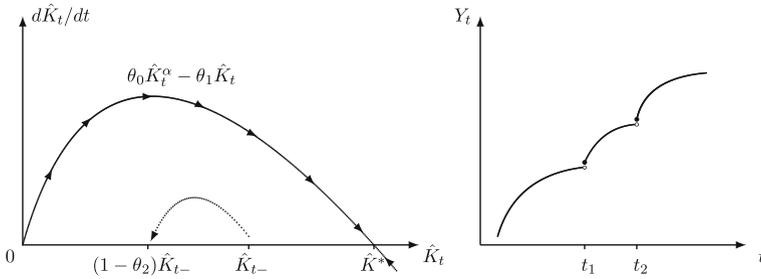
and the arrival rate becomes

$$\lambda = \left( \frac{1 + \tau_k}{1 + \tau_r} \frac{\kappa}{D} \xi^{-\sigma} \right)^{\frac{1-\gamma}{\gamma}}. \tag{22}$$

*Proof* see app. B.3 □

Suppose the technological improvement (or economic depreciation  $s$ ) of an innovation is sufficiently large relative to the size of the new prototype  $\kappa \ll 1$  such that  $\xi \leq 1$ , or  $\kappa \leq s$ . Intuitively this assumption ensures that cyclical variables are accumulated and not reduced over the cycle which seems the only empirically plausible assumption (cf. [Wälde 2005](#)). It follows from (13) and (16) that wealth,  $a_t/a_{t-}$ , and thus consumption,  $C_t/C_{t-}$  or research  $R_t/R_{t-}$  jump by the factor  $\xi$  or equivalently by  $\kappa - s$  percent, whereas output  $Y_t/Y_{t-}$  from (6), (8), and (16) increases by  $(1 + B\kappa)^\alpha$  immediately after successful research.

The parametric restriction  $\sigma = \alpha$  implies a relatively high intertemporal elasticity of substitution above unity (or risk aversion below unity). While there is supporting empirical evidence (as in [Vissing-Jørgensen 2002](#); [Gruber 2006](#)), our fundamental insights about the presence of tax effects on volatility, as well as the channels through which taxes affect volatility, will not depend on this restriction. Further, it has proven very useful in the macro literature to study equilibrium dynamics (e.g. [Chang 1988](#); [Xie 1991, 1994](#); [Boucekkine and Tamarit 2004](#); [Smith 2007](#); [Posch 2009b](#)).



**Fig. 1** Dynamics of cyclical capital and growth cycles: This figure illustrates equilibrium dynamics of cyclical capital stock (intensive form) (left panel), and the resulting endogenous growth cycles for output (right panel), where jumps occur at  $t_1$  and  $t_2$ , each starting a new growth cycle

### 3.2 Cyclical growth

Exploiting the implications of Theorem 1, we can obtain the general-equilibrium behavior of agents in a way as simple as in the deterministic Solow growth model with a constant saving rate, even though we have forward-looking agents and an uncertain environment.

In terms of cyclical components, using Itô’s formula (change of variables) together with capital accumulation in (8), the market clearing condition in (4) and the detrending rule (17), our capital index follows (cf. app. B.3)

$$d\hat{K}_t = (\hat{Y}_t - \hat{C}_t - \hat{R}_t - \hat{G}_t - \delta\hat{K}_t)dt + (A^{-1}\xi - 1)\hat{K}_{t-}dq_t.$$

Inserting optimal consumption and research expenditure from (18) of Theorem 1, as well as government revenues using  $\hat{G}_t = A^{-q}G_t$  and government revenues yields

$$\begin{aligned} d\hat{K}_t &= \left( \frac{1 - \tau_i}{1 + \tau_k} \hat{Y}_t - \left( \frac{1 + \tau_c}{1 + \tau_k} \Psi + \frac{1 + \tau_r}{1 + \tau_k} \Gamma + \frac{1 - \tau_i}{1 + \tau_k} \delta + \tau_a \right) \hat{K}_t \right) dt + (A^{-1}\xi - 1)\hat{K}_{t-}dq_t \\ &\equiv (\theta_0 \hat{K}_t^\alpha - \theta_1 \hat{K}_t)dt - \theta_2 \hat{K}_{t-}dq_t, \end{aligned} \tag{23}$$

where we inserted  $\hat{Y}_t = A^{-q}Y_t = \hat{K}_t^\alpha L^{1-\alpha}$  from (6) and defined parameters

$$\theta_0 \equiv \frac{1 - \tau_i}{1 + \tau_k} L^{1-\alpha}, \quad \theta_1 \equiv \frac{1}{\sigma} \left( \rho + \lambda - (1 - s) \lambda \xi^{-\sigma} + \frac{1 - \tau_i}{1 + \tau_k} \delta + \tau_a \right), \quad \theta_2 \equiv 1 - A^{-1}\xi.$$

As a result, similar to Solow’s growth model our model implies a one-dimensional SDE with non-linear drift in (23), but satisfying utility-maximizing behavior of agents for  $\alpha = \sigma$ . Note that  $\theta_1$  is obtained when inserting  $\Psi$  and  $\Gamma$  from (19) and (20) respectively.

The terms in (23) containing parameters  $\theta_0$  through  $\theta_2$  have an economic interpretation:  $\theta_0 \hat{K}_t^\alpha$  represents cyclical output of this economy reduced by taxation,  $\theta_1 \hat{K}_t$  denotes effective resource allocation to research, private and government consumption, as well as physical depreciation. As from (23), the term  $\theta_1 - \alpha\theta_0 \hat{K}_t^{\alpha-1}$  denotes the speed of convergence towards the non-stochastic steady state,  $\hat{K}^* = (\theta_0/\theta_1)^{\frac{1}{1-\alpha}}$ . When an innovation occurs, the parameter  $\theta_2$  denotes the size of the jump in the cyclical capital index. For illustration, Fig. 1 plots  $\hat{K}_t$  against the deterministic part of cyclical capital (left panel). Note that the non-linear deterministic part in equation (23) implies that the speed of convergence (the slope in Fig. 1) depends on the level of  $\hat{K}_t$ , thus changes as  $\hat{K}_t$  moves towards  $(1 - \alpha)\theta_1$ .

We can now start our analysis as in the neoclassical growth model. Suppose  $\hat{K}_0$  is the initial capital stock,  $0 < \hat{K}_0 < \hat{K}^*$ .<sup>6</sup> Households optimally allocate their savings to either research or capital accumulation. Assuming a certain length of time without jumps, i.e., without successful innovation, the economy grows due to capital accumulation and converges to the non-stochastic steady state,  $\hat{K}^*$ . As in the Solow model, growth rates are initially high and approach zero. Once a jump occurs,  $q_t = q_{t-} + 1$ , the capital stock of the new vintage  $q + 1$  increases by  $\kappa_t$  as in (2). This leads to a discrete increase of the capital index by the effective size,  $B^{q+1}\kappa_t$ . Although the capital stock increases by the size of the new prototype, our assumption about  $\kappa$  being sufficiently small ensures  $\xi \leq 1$  in (21), and cyclical capital  $\hat{K}_t$  unambiguously decreases because the frontier technology shifts outwards (cf. Fig. 1). Due to higher marginal products, capital accumulation becomes more profitable, growth rates jump to a higher level approaching zero again until the next innovation occurs.

The discrete increases of labor productivity by  $A$  imply a step function in *vintage-specific* total factor productivity (TFP), in contrast to the smooth evolution in traditional balanced growth models à la Romer (1990). As a result, output in this economy is growing through cycles as illustrated in Fig. 1 and fluctuations are a natural phenomenon in a growing economy. However, this step function of vintage-specific TFP does *not* imply that there are discrete jumps in aggregate TFP. As we show in (6), vintages of capital goods can easily be aggregated to an index (7) which weights them such that prices fully reflect differences in productivity and the *aggregate* TFP is constant and equal to unity.

#### 4 Volatility measures

Volatility can be measured in many ways. The empirical literature focuses on either the standard deviation of detrended variables or output growth rates. In this study, we derive and employ three closed-form measures for volatility. Our first two measures are based on the cyclical component of output and the second one is based on output growth rates.

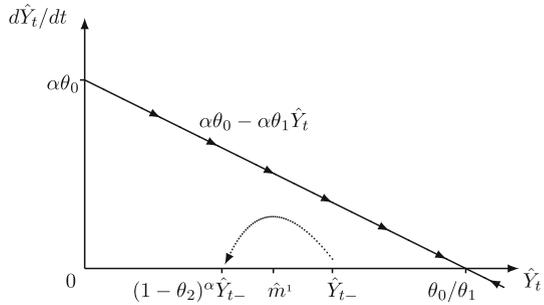
##### 4.1 Cyclical component

There are many techniques to obtain stationary variables. Given their complexity, virtually none of these filters allow us to derive tractable cyclical variables which imply closed-form measures of volatility. Any deterministic filter would give no meaningful cyclical variables in our model as the second moment would not be bounded. We therefore use a very simple stochastic filter, a Solow-type detrending rule used in (17), to compute the cyclical component of output. It captures our stochastic trend by a step function  $A^q$  caused by the discrete increases of  $q_t$ . In fact, we decompose the output series  $Y_t$  into a stochastic trend  $A^q$  and a stationary cyclical component  $\hat{Y}_t$ . Using (6) and (17), they are related according to  $\hat{Y}_t \equiv A^{-q}Y_t = \hat{K}_t^\alpha L^{1-\alpha}$ .

In order to obtain an analytical measure now suppose that  $\alpha = 0.5$  and normalize  $L = 1$ . We restrict our focus to this parametric restriction for the following two reasons. First, we are able to compute all moments of cyclical output explicitly as they are given by the solution to an ordinary differential equation. Second, we can show that it is reasonable to assume that the

<sup>6</sup> Without loss of generality, we abstract from the case where  $\hat{K}_0 > \hat{K}^*$ . Given that  $\theta_2 < 1$ , at some point in time cyclical capital stock will be below its non-stochastic steady state with probability one.

**Fig. 2** The cyclical component of output: This figure illustrates the dynamics of cyclical output with constant speed of convergence (the slope of  $d\hat{Y}_t/dt$ ). Otherwise the dynamics are similar to those of cyclical capital stock (compare with Fig. 1)



qualitative effects of taxation on other empirically identifiable measures such as consumption are equivalent because the channels are the same.<sup>7</sup>

Using Itô’s formula and (23), cyclical output follows (cf. app. A.1 for a discussion)

$$\begin{aligned}
 d\hat{Y}_t &= \alpha \hat{K}_t^{\alpha-1} (\theta_0 \hat{K}_t^\alpha - \theta_1 \hat{K}_t) dt + ((1 - \theta_2)^\alpha \hat{K}_{t-}^\alpha L^{1-\alpha} - \hat{K}_{t-}^\alpha L^{1-\alpha}) dq_t \\
 &= (\alpha\theta_0 - \alpha\theta_1 \hat{Y}_t) dt - (1 - (1 - \theta_2)^\alpha) \hat{Y}_{t-} dq_t, \quad \text{where } \alpha = 0.5, L = 1. \quad (24)
 \end{aligned}$$

In fact, the dynamics of (24) are similar to the evolution of cyclical capital (23). The speed of convergence,  $\alpha\theta_1$  is constant (the slope in Fig. 2). For our parametric restriction  $\alpha = 0.5$  the SDE in (24) has a linear drift. Again, we can gain insights from plotting  $\alpha\theta_0 - \alpha\theta_1 \hat{Y}_t$  on the vertical axis, while  $\hat{Y}_t$  is depicted on the horizontal axis (Fig. 2). Obviously, cyclical output has support between 0 and its non-stochastic steady state,  $0 < \hat{Y}_0 < \hat{Y}^*$ , which from (24) is given by  $\theta_0/\theta_1$ . Starting from  $\hat{Y}_0$ , as long as no innovation takes place, the cyclical component approaches its upper bound. Each successful research project reduces cyclical output by  $(1 - (1 - \theta_2)^\alpha) \hat{Y}_{t-}$ , or  $1 - (1 - \theta_2)^\alpha$  percent of cyclical output an instant before the innovation (which ensures that cyclical output always remains positive).

Exploiting the methods in García and Griego (1994), we can compute analytical moments of the cyclical component and a closed-form measure of volatility. We use the coefficient of variation ( $cv$ ) as a scale-independent measure for volatility (see app. A.3 for details),

$$cv(\hat{Y}_t)^2 \equiv \lim_{t \rightarrow \infty} \frac{Var_0(\hat{Y}_t)}{(E_0(\hat{Y}_t))^2} = \frac{1 - (1 - \theta_2)^\alpha - \alpha\theta_2}{\alpha\theta_1/\lambda + \alpha\theta_2}, \quad \text{where } \alpha = 0.5. \quad (25)$$

Looking at the  $cv$  shows that it is independent of  $\theta_0$ . This is not surprising as  $\theta_0$  is a scaling parameter and the  $cv$  is scale-independent. This can intuitively be understood from Fig. 2 where the effect of  $\theta_0$  on the cyclical component could be removed by scaling both axes with  $1/\theta_0$ . A lower speed of convergence,  $\alpha\theta_1$ , implies a higher measure of relative dispersion,  $cv$ . Clearly, the slower the economy approaches its non-stochastic steady state, the higher the overall variability of cyclical components is. The jump term  $\theta_2$  and the arrival rate,  $\lambda$  (note that  $\theta_1/\lambda$  decreases in  $\lambda$ ), have a positive effect on  $cv$ , meaning that larger and more frequent jumps imply a higher measure of relative dispersion.

We can also derive a measure of volatility based on growth rates of cyclical components of output,  $\Delta \hat{y}_t \equiv \ln \hat{Y}_t - \ln \hat{Y}_{t-\Delta}$ . Since this measure involves computing the variance of an integral over capital rewards, an analytical derivation—as for our measure based on the

<sup>7</sup> A similar analysis could be undertaken for  $\alpha = \sigma$ . The analytical measure would then describe the volatility of instantaneous utility. As the empirical counterpart for utility is not as obvious as for output, we prefer to work with  $\alpha = 0.5$ .

coefficient of variation—is not possible. Thus we use a deterministic Taylor expansion and neglect third-order terms in order to obtain (see app. A.3 for a full derivation)

$$\begin{aligned}
 Var(\Delta \hat{y}_t) &\equiv \lim_{t \rightarrow \infty} Var_0 \left( \frac{1 - \tau_i}{1 + \tau_k} \int_{t-\Delta}^t r_s ds \right) + (\alpha \ln(1 - \theta_2))^2 \lambda \Delta \\
 &\approx \lim_{t \rightarrow \infty} Var_0 \left( \frac{1 - \tau_i}{1 + \tau_k} r_t \right) \Delta^2 + (\alpha \ln(1 - \theta_2))^2 \lambda \Delta \\
 &= \frac{\alpha^2}{1 - \alpha} \left( \frac{1 - (1 - \theta_2)^{1 - \alpha}}{(1 - \theta_2)^{1 - \alpha}} + (1 - \alpha) \ln(1 - \theta_2) \right) (\theta_1 - \ln(1 - \theta_2) \lambda) \lambda \Delta^2 \\
 &\quad + (\alpha \ln(1 - \theta_2))^2 \lambda \Delta.
 \end{aligned}
 \tag{26}$$

Obviously, this measure shares the property of scale independence with the *cv* because we consider growth rates, which by construction are scale independent. It can be interpreted as an approximation for the variance of growth rates of cyclical output.

### 4.2 Output growth rates

An empirically more obvious measure is based on output growth rates,  $\Delta y_t \equiv \ln Y_t - \ln Y_{t-\Delta}$ . Using the detrending rule (17) it can be shown that

$$\begin{aligned}
 Var(\Delta y_t) &\approx \frac{\alpha^2}{1 - \alpha} \left( \frac{1 - (1 - \theta_2)^{1 - \alpha}}{(1 - \theta_2)^{1 - \alpha}} + (1 - \alpha) \ln(1 - \theta_2) \right) (\theta_1 - \ln(1 - \theta_2) \lambda) \lambda \Delta^2 \\
 &\quad + (\alpha \ln(1 - \theta_2) + \ln A)^2 \lambda \Delta,
 \end{aligned}
 \tag{27}$$

which again is only an approximation since we neglect third-order terms.

We can also derive an explicit expression for mean growth,

$$E(\Delta y_t) \equiv \lim_{t \rightarrow \infty} E_0(\Delta y_t) = E(\Delta \hat{y}_t) + E(\Delta q_t) \ln A = \lambda \ln A \Delta.
 \tag{28}$$

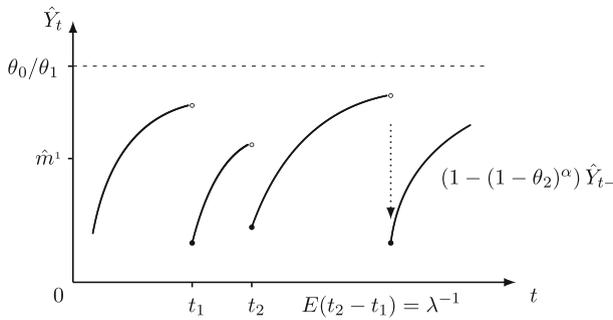
This long-run expected growth rate of the common stochastic trend is determined by the arrival rate of new technologies. From (22),  $\lambda$  increases in the investment tax,  $\tau_k$ , and decreases in the tax on research,  $\tau_r$ . We study the effects of taxes on volatility below.

Note that this measure comes closest to output growth residuals used in Ramey–Ramey type regressions. As our model does not contain exogenous disturbances, a regression analysis of data produced by a simulated version of our model would not have to control for any disturbances. In other words,  $\Delta y_t$  in our theoretical model corresponds to the output growth residuals in the Ramey–Ramey regression. The next section will analyze, inter alia, how taxes affect our theoretical ‘output growth residual’  $\Delta y_t$ .

## 5 Volatility and taxation

### 5.1 Theoretical findings

Our measure of volatility in (25) is affected through three channels, the speed of convergence  $\alpha\theta_1$ , the jump size  $1 - (1 - \theta_2)^\alpha$ , and the arrival rate  $\lambda$ . As shown, these determinants appear in the measures based on growth rates in (26) and (27). For illustration, the interpretation of these channels is based on cyclical output in (24). Consider an arbitrary realization of the cyclical component in Fig. 3. In line with our previous results, the speed of convergence,  $\alpha\theta_1$ , determines the range of cyclical output  $(0, \theta_0/\theta_1)$ . The upper limit corresponds



**Fig. 3** The cyclical component of output and its determinants: This figure illustrates the determinants of the cyclical component of output and thus the coefficient of variation (*cv*) using an arbitrary realization of the SDE in (24). Our measure in (25) is determined by the speed of convergence,  $\alpha\theta$ , the arrival rate,  $\lambda$ , and the jump size,  $1 - (1 - \theta_2)^\alpha$

to the non-stochastic steady state for cyclical capital,  $\hat{K}^* = (\theta_0/\theta_1)^{\frac{1}{1-\alpha}}$ . However, the only parameter which is relevant for the relative dispersion of cyclical output is  $\theta_1$  ( $\theta_0$  is a scaling parameter). From its definition in (24) and the discussion of (23), it is clear that  $\alpha\theta_1$  denotes the effective resource allocation to both research expenditures and total consumption. The arrival rate  $\lambda$  measures the frequency of jumps (the inverse measures the expected length of growth cycles). Finally, the size of the jump is measured by  $1 - (1 - \theta_2)^\alpha$ . Hence we find that output volatility depends on the *level* of taxes if at least one of the following three channels, (i) the speed of convergence, (ii) the jump size or (iii) the arrival rate depends on taxes.<sup>8</sup>

To understand the effects of taxation on macro volatility, we may restrict attention to the speed of convergence and the arrival rate (or jump probability), because the jump size does not depend on taxes. The independence of  $\theta_2$  follows from the fact that the jump in consumption,  $\xi = 1 - s + \kappa$ , from (24) is not affected by taxes. Economically, this result is obtained because payoffs  $\kappa$  are not taxed and economic depreciation,  $s$ , does not imply tax-exemption as does physical depreciation,  $\delta$ . The tax effects on the arrival rate  $\lambda$  are obtained from (22). The parameter  $\theta_1$  in (24) depends on taxes both directly and indirectly through the arrival rate. The direct effect reflects the effective rate of physical depreciation,  $\frac{1-\tau_i}{1+\tau_k} \delta + \tau_a$ , whereas the indirect effect reflects tax effects on the arrival rate,  $\lambda$ , which in turn are due to changes in private consumption,  $\hat{C}_t$ , research expenditures,  $\hat{R}_t$ , and government consumption,  $\hat{G}_t$ . Inserting  $\lambda$  into  $\theta_1$  gives unambiguous results (cf. app. D.1 for details). For reading convenience, the qualitative results are summarized in tab. 1.

### 5.2 Comparative statics

Let us now combine the effects of our three channels on output volatility measured by (25) in a comparative static analysis. As we have only two tax-dependent channels, the speed of convergence,  $\alpha\theta_1$ , and the arrival rate,  $\lambda$ , taxes affect the variance of the limiting distribution of stationary output by either changing the speed of convergence (without affecting  $\lambda$  in  $\theta_1$ ), the arrival rate, or both. Clearly, a tax which has no effect on  $\theta_1$  and  $\lambda$ , does not affect our measures either. The tax on consumption expenditures,  $\tau_c$ , is such a tax because government consumption completely offsets changes in private consumption.

<sup>8</sup> If growth and cycles are exogenous, i.e., if there is an exogenous arrival rate  $\lambda$  without research, the model describes a continuous-time RBC model with vintage-specific capital. In this case, macro volatility is partly endogenous and affected by taxation through the speed of convergence,  $\alpha\theta_1$ .

**Table 1** Qualitative effects of taxes on composite parameters, volatility and growth

		Taxes				
		$\tau_i$ (income)	$\tau_c$ (consumption)	$\tau_r$ (research)	$\tau_k$ (investment)	$\tau_a$ (wealth)
$\alpha\theta_1$	(speed of convergence)	–	0	–	+ <sup>a</sup>	+
$1 - (1 - \theta_2)^\alpha$	(jump size)	0	0	0	0	0
$\lambda$	(arrival rate)	0	0	–	+	0
$E(\Delta y_t)$	(mean growth rate)	0	0	–	+	0
$Var(\Delta y_t)$	(variance of growth rates)	–	0	–	+ <sup>a</sup>	+
$cv(\hat{Y}_t)$	(coefficient of variation)	+	0	–	+	–

*Note:* This table shows the qualitative tax effects of the level of tax rates on output volatility and growth and their components. Our measures include the speed of convergence of cyclical output,  $\alpha\theta_1$ , the jump size,  $1 - (1 - \theta_2)^\alpha$ , and the arrival rate,  $\lambda$ ,  $\Delta y_t$ , and the coefficient of variation of cyclical output,  $cv(\hat{Y}_t)$

<sup>a</sup> For  $\delta$  sufficiently small

When taxing wealth,  $\tau_a$ , the arrival rate  $\lambda$  is not affected. The speed of convergence,  $\alpha\theta_1$ , increases which causes  $cv$  in (25) to decline. Economically,  $\tau_a$  decreases the households’ return on savings, or equivalently, increases the effective rate of depreciation. This in turn implies a lower non-stochastic steady-state,  $\hat{K}^*$ , and more resources are used for consumption and research. Holding constant the length of a cycle but ‘squeezing’ cyclical output in Fig. 3, the relative dispersion of cyclical output must be lower.

An increase in the income tax,  $\tau_i$ , reduces the speed of convergence  $\alpha\theta_1$  but does not affect the jump probability,  $\lambda$ . As a consequence, volatility unambiguously increases in this tax. How can this result be understood? The parameter  $\theta_1$  in (24) decreases for the following reason: only net investment is taxed (as discussed above). This means that a higher tax on income increases the positive effect of the refunding policy and reduces the impact of the depreciation rate,  $\delta$ . A lower effective depreciation rate increases incentives for capital accumulation, and the non-stochastic steady-state capital stock,  $\hat{K}^*$ , increases.

For the taxes on research,  $\tau_r$ , and investment,  $\tau_k$ , the results are less clear-cut. With these taxes the arrival rate  $\lambda$  is affected which in turn changes  $cv$  directly and indirectly through  $\theta_1$ . The direct effect of  $\lambda$  on  $cv$  is unambiguously positive. Computing the derivatives, however, we obtain the results for our measures of volatility as in tab. 1. A higher tax on research depresses the arrival rate and the ratio  $\theta_1/\lambda$  increases, which in turn decreases  $cv$  in (25). Intuitively, higher rates  $\tau_r$  make investment in research less profitable and the arrival rate falls. Less frequent jumps imply a lower relative dispersion of cyclical output. A lower  $\lambda$  also decreases  $\theta_1$ , thus less resources are used for consumption and research. This implies a larger range  $1/\theta_1$  in Fig. 2 and higher volatility. The indirect effect through the lower speed of convergence does not compensate the direct effect of a lower arrival rate. Hence, the ratio  $\theta_1/\lambda$  increases and  $cv$  in (25) decreases. A similar interpretation can be given for  $\tau_k$ .

Given the discussion above, we can now understand why measures based on output growth rates may also depend on taxes. Consider the speed of convergence  $\alpha\theta_1$ . As shown above, an increase in  $\theta_1$  decreases the range of the cyclical component. Obviously, this decreases the  $cv$  and variables in efficiency units, but increases the variance of capital rewards. This in turn implies a higher variance of output growth rates. Hence, the tax effects implied through the propagation of shocks is reversed for measures based on growth rates. However, the qualitative effects on the arrival rate are identical to our measures of relative dispersion.

### 5.3 The link between volatility and growth

We are now prepared to make our main point. For a given tax policy, our economy follows a certain cyclical growth path. Now imagine a second economy with a different tax policy and a third one with yet another tax policy and so on. Given our comparative static results, it is straightforward to understand why growth and volatility are correlated and that this correlation can take any sign—depending on cross-country differences in tax levels and which measure we use for volatility.

Suppose two countries differ only in the level of the investment tax (value added tax on physical investment goods). Tab. 1 shows that both growth and volatility increase in the investment tax (independently of which measure is used), as resources are shifted to R&D. In a cross-section of countries, we expect a positive correlation between volatility and growth. The same positive correlation would exist if countries differ only in their tax on research. Our model predicts a negative correlation between volatility and growth for various combinations of tax rates. An example of this is when countries with a high tax on investment also have a high tax on income. The investment tax increases volatility and growth, the income tax decreases volatility (focusing on the measure based on growth rates in tab. 1). If the negative effect is stronger than the volatility-increasing effect of the investment tax, we expect a negative correlation between investment and growth.

The reader may want to discuss our examples on tax policy structures as well as the generality of our parametric restrictions  $\alpha = \sigma$  (the sign of tax effects may be ambiguous in the general case). Yet, our general point remains: differences in economic policies across countries may imply differences in output growth rates and output volatility. Depending on cross-country differences, correlations of any magnitude and sign can occur.

## 6 Empirical implications and findings

### 6.1 Implications for empirical research

Given our theoretical findings on the effects of tax levels on both volatility and growth, our message for empirical work is that a volatility-growth regression in the spirit of Ramey and Ramey (1995) should include controls of this type. To elaborate on this point, consider the following extension of Ramey and Ramey,

$$\Delta y_{it} = \nu\sigma_{it} + \theta X_{it} + \varepsilon_{it}, \quad \text{where } \varepsilon_{it} \sim N(0, \sigma_{it}^2), \tag{29a}$$

$$\log(\sigma_{it}^2) = \alpha_i + \mu_t + \beta Z_{it}. \tag{29b}$$

$\Delta y_{it}$  is the growth rate of output for country  $i$  in year  $t$  computed as log difference;  $\sigma_{it}$  is the standard deviation of residuals;  $X_{it}$  is a vector of control variables such as the Levine-Renelt variables and/or taxes;  $Z_{it}$  is a vector of control variables (could be a subset of  $X_{it}$ );  $\alpha_i$  and  $\lambda_t$  are country and time fixed effects;  $\theta$  and  $\beta$  are vectors of coefficients. The key parameter of interest in a volatility-growth analysis is  $\nu$ , which links growth to volatility.

For  $Z_{it} = 0$ , this specification coincides with the basic Ramey–Ramey setup.<sup>9</sup> Given our theoretical arguments, the conditional variance equation needs to include additional controls  $Z_{it}$ . As we have seen that the level of taxes can have an effect on volatility, we would expect  $\beta$  to be significant if  $Z_{it}$  measures the level of taxes. If those measures were constant

<sup>9</sup> The authors extend their basic framework where government-spending volatility replace the fixed-effects in the conditional variance equation. Proceeding in this direction does not change our results (not shown).

over time,  $Z_{it} = Z_i$ , our proposed extension would be equivalent to country-specific fixed effects—as already included in the basic Ramey–Ramey setup. New empirical insights from our arguments therefore require sufficient variation in taxes over time. It is well-known from Mendoza-Razin-Tesar tax rates that such variation is present in the data.

We admit that, though it illustrates our argument, the absence of uncertainty other than endogenous innovations makes it difficult to relate our theoretical measure of output volatility in (27) to the conditional variance of residuals (29b). In a stylized Ramey–Ramey framework, however, a regression of growth rates on a constant,  $\Delta y_{it} = \mu + \varepsilon_{it}$  in which  $\mu$  is the mean output growth rate shows that the conditional residual variance, by construction, coincides with our theoretical measure. This suggests that the variance of output growth rates and the variance of the error term may indeed share some important properties. We therefore feel justified in letting our empirical approach be guided by our theoretical model.<sup>10</sup>

## 6.2 Empirical findings

Our empirical sample consists of 20 countries for which we have data for the period from 1970 to 2009.<sup>11</sup> To measure the tax burden of a representative household on the macro level we follow Mendoza et al. (1994). We employ data from the OECD Revenue Statistics 2010 (OECD-iLibrary, <http://dx.doi.org/10.1787/data-00262-en>) and OECD Aggregate National Accounts 2010 (<http://dx.doi.org/10.1787/na-ana-data-en>) to obtain updated tax ratios and annual growth rates of real GDP per capita respectively (cf. Mendoza et al. 1994; Posch 2011a). We also compute the relative price of investment from the Penn World Table 6.3 as in Restuccia and Urrutia (2001). This variable measures barriers to capital accumulation and growth. It turned out to be to be important for accounting for cross-country differences in investment rates.<sup>12</sup>

In tab. 2 we present the results from a joint estimation of equations (29a) and (29b). The first column is a specification with  $Z_{it} = 0$ , i.e., with no variables in the conditional variance equation apart from fixed effects. The only explanatory variable  $X_{it}$  in the growth equation is the price of aggregate investment over consumption (*RPRICE*). This specification extends the basic Ramey–Ramey setup by allowing for variations in the relative price of investment. The column ‘Ramey–Ramey’ contains our benchmark results for understanding the effects of adding further controls to the conditional variance equation.

The column ‘our claim’ adds control variables to both the growth equation (29a) and the conditional variance equation (29b). We include four different taxes: the tax induced cost of dependent labor (*LABOR*), the tax induced cost of capital (*CAPITAL*), the consumption tax (*CONS*) and the corporate income tax (*CORP*). We find that 3 out of 4 tax measures are significant at the 5% level. Hence, the *level* of taxes indeed appears to affect volatility. For example, if *LABOR* is increased by one percentage point, the variance of output growth rates decreases by 8.85 percent. We also find that the conventional Ramey–Ramey coefficient  $\nu$  is affected sizably. Accounting for taxes in the conditional residual variance equation strengthens the previous findings of a statistically significant negative correlation between growth and volatility. Compared to our benchmark specification, the link remains

<sup>10</sup> Empirical work by Posch (2011a) has shown that the impact of taxes on volatility is very similar for a specification as in (29b) and a specification where the variance of the error term is replaced by observed output variances (estimated e.g. through rolling windows).

<sup>11</sup> Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Italy, Japan, Korea, Netherlands, New Zealand, Norway, Spain, Sweden, Switzerland, United Kingdom, United States.

<sup>12</sup> We would like to thank a referee for drawing our attention to this work.

**Table 2** The link between volatility and growth

OECD		Ramey–Ramey	Our claim
$LABOR_{i,t-1}$	$\theta_1$		-0.15 (0.08)
$CAPITAL_{i,t-1}$	$\theta_2$		0.06 (0.07)
$CONSi_{i,t-1}$	$\theta_3$		0.12 (0.08)
$CORP_{i,t-1}$	$\theta_4$		-0.02 (0.05)
$RPRICE_{i,t-1}$	$\theta_5$	-0.06 (0.01)***	-0.07 (0.01)***
$LABOR_{i,t-1}$	$\beta_1$		-8.84 (2.37)***
$CAPITAL_{i,t-1}$	$\beta_2$		8.55 (2.22)***
$CONSi_{i,t-1}$	$\beta_3$		4.81 (3.17)
$CORP_{i,t-1}$	$\beta_4$		-4.19 (1.70)*
$\sigma_{i,t}$	$\nu$	-1.61 (0.51)**	-2.46 (0.83)**
Degrees of freedom		672	664
Log-likelihood		-1894.8	-1918.1
Country fixed effects	$\theta_i$	Yes	Yes
Country fixed effects	$\alpha_i$	Yes	Yes
Time fixed effects	$\mu_t$	Yes	Yes

Notes: This table reports the semi-elasticities on output growth innovations treating variances as parameters using MLE. Similar to Ramey and Ramey (1995) all specifications include two lags of log real GDP per capita and a trend variable in the growth equation. Standard errors in parentheses. Including government spending volatility does not change our results, whereas its estimated parameter is not different from zero for any conventional significance level (not shown)

Signif. codes: ‘\*\*\*’ 0.001 ‘\*\*’ 0.01 ‘\*’ 0.05 ‘.’ 0.1

negative and increases in absolute terms. It appears that previous estimates have been much too modest and the (negative) correlation is stronger than found so far.

As one caveat, it is well-known that although the Mendoza–Razin–Tesar tax rates are very useful on the one hand, it is difficult to link them closely to theoretical (marginal) tax rates on the other. For example, the income tax in our model is a composite of *LABOR* and *CAPITAL* in the estimation. This makes it difficult to conclude whether the empirical finding of a negative effect (*LABOR*) and a positive effect (*CAPITAL*) confirms or contradicts our theoretical prediction in tab. 1 that an income tax reduces volatility.

We conclude this short empirical application by stressing that our fundamental point made in the theoretical model—a *level* variable affects volatility and growth—is confirmed. Future work should construct theoretical models which closely replicate the construction of the empirical tax ratios. With such one-to-one correspondence between theoretical and empirical taxes, more insights can be gained into the volatility effect of taxes.

## 7 Conclusion

There is a growing literature studying the link between volatility and growth. This paper theoretically shows that the correlation between volatility and growth can be positive or negative. The sign of the correlation is determined inter alia by the economic policy implemented by the country under consideration.

We illustrate our main point by identifying taxes as the truly fundamental parameters which determine the growth rate and the degree of volatility of a country. Our theoretical contribution is that our measures of volatility are obtained analytically. This allows us to follow an analytical approach in understanding the channels through which the *level* of taxes affects both the volatility and the growth processes. We find that taxes determine the sign of the correlation between volatility and growth. For example, if taxes on wealth are used to facilitate R&D investment, growth and volatility are positively correlated. In contrast, if taxes on wealth are used to promote physical capital investment, a negative link may occur.

In an empirical application of the Ramey–Ramey type, we add levels of taxes to the growth and the conditional variance equation. We find that the growth-volatility link is much more negative than in regressions where taxes are not taken into account. In addition, taxes do indeed appear to affect volatility.

This paper opens up interesting future research avenues. Our theoretical model does not allow for any exogenous source of volatility. In an extended framework with both endogenous and exogenous shocks, one can identify which share of volatility is due to endogenous sources. This would provide a framework that allows to split the growth-volatility link into a correlation-component and into a causation-component.

## Appendix

### A.1 Cyclical components

Using (23) and Itô’s formula,  $d\hat{Y}_t = L^{1-\alpha} d\hat{K}_t^\alpha$ , we compute

$$d\hat{K}_t^\alpha = \alpha(\theta_0 \hat{K}_t^{\alpha-1} - \theta_1) \hat{K}_t^\alpha dt - (1 - (1 - \theta_2)^\alpha) \hat{K}_t^\alpha dq_t,$$

which is an SDE with a non-linear drift component. The non-stochastic steady state is  $\hat{K}^{\alpha*} = (\theta_0/\theta_1)^{\frac{\alpha}{1-\alpha}}$ , the speed of convergence is  $\alpha\theta_1 - (2\alpha - 1)\theta_0 \hat{K}_t^{\alpha-1}$  is *not* constant unless  $\alpha = 0.5$ , and the jump term  $1 - (1 - \theta_2)^\alpha$ , increases (decreases) relative to  $\hat{K}_t^{1-\alpha}$  for  $\alpha > 0.5$  ( $\alpha < 0.5$ ) and is the same for  $\alpha = 0.5$ .

### A.2 Properties of the Poisson process

We use the martingale property of various expressions. These expressions are special cases of  $\int_0^t f(q_s, s) dq_s - \lambda \int_0^t f(q_s, s) ds$ , which is a martingale (cf. García and Griego 1994), i.e.,

$$E_0 \left( \int_0^t f(q_s, s) dq_s - \lambda \int_0^t f(q_s, s) ds \right) = 0, \tag{30}$$

where  $\lambda$  is the (constant) arrival rate of  $q_t$ .

### A.3 Appendix for (25) and (26)

Use the integral version of (24),  $\hat{Y}_t = \hat{Y}_0 + \int_0^t (\alpha\theta_0 - \alpha\theta_1 \hat{Y}_s) ds - \int_0^{t-} (1 - (1 - \theta_2)^\alpha) \hat{Y}_s dq_s$ , and the martingale property (cf. app. A.2), we obtain

$$E_0(\hat{Y}_t) = \hat{Y}_0 + \int_0^t (\alpha\theta_0 - \alpha\theta_1 E_0(\hat{Y}_s)) ds - \lambda \int_0^{t-} (1 - (1 - \theta_2)^\alpha) E_0(\hat{Y}_s) ds, \tag{31}$$

which gives the evolution of the first moment of  $\hat{Y}_t$  as a linear ordinary differential equation (ODE) which can be solved and is shown to converge to a constant. Using a similar approach, higher-order moments can be computed easily.<sup>13</sup> In fact, denoting the  $n$ th moment by

$$\hat{m}_t^n \equiv E_0(\hat{Y}_t^n), \tag{32}$$

the first and second moment of the stationary distribution are given by

$$\hat{m}^1 \equiv \lim_{t \rightarrow \infty} \hat{m}_t^1 = \frac{\alpha\theta_0}{\alpha\theta_1 + \lambda(1 - (1 - \theta_2)^\alpha)}, \tag{33}$$

$$\hat{m}^2 \equiv \lim_{t \rightarrow \infty} \hat{m}_t^2 = \frac{\theta_0}{\theta_1 + \lambda\theta_2} \hat{m}^1. \tag{34}$$

A scale-independent measure is the coefficient of variation ( $cv$ ). Given that the variance of a random variable is the difference between its second moment and the square of its mean, it is defined by

$$cv^2 \equiv \lim_{t \rightarrow \infty} \frac{Var_0(\hat{Y}_t)}{(E_0(\hat{Y}_t))^2} = \frac{1 - (1 - \theta_2)^\alpha - \alpha\theta_2}{\alpha\theta_1/\lambda + \alpha\theta_2}, \tag{35}$$

where for the second equality we inserted the moments from (33) and (34), respectively.

In order to obtain moments based on growth rates, we use integral equations for the log-variables and exploit the martingale property (cf. app. A.2). For cyclical capital it reads

$$\begin{aligned} d \ln \hat{K}_t &= (\theta_0 \hat{K}_t^{\alpha-1} - \theta_1)dt + (\ln \hat{K}_t - \ln \hat{K}_{t-\Delta})dq_t \\ &= (\theta_0 \hat{K}_t^{\alpha-1} - \theta_1)dt + \ln(1 - \theta_2)dq_t. \end{aligned} \tag{36}$$

Integrating gives the growth rate of cyclical capital per unit of time  $\Delta$  as

$$\ln \hat{K}_t - \ln \hat{K}_{t-\Delta} = \int_{t-\Delta}^t \frac{1 - \tau_i}{1 + \tau_k} r_s / \alpha ds - \theta_1 \Delta + \ln(1 - \theta_2)(q_t - q_{t-\Delta}), \tag{37}$$

where we relate growth rates to the integrated process of capital rewards,  $r_t = \alpha \hat{K}_t^{\alpha-1} L^{1-\alpha}$ . Similarly, the growth rate of cyclical output is  $\Delta \hat{y}_t \equiv \ln \hat{Y}_t - \ln \hat{Y}_{t-\Delta} = \alpha (\ln \hat{K}_t - \ln \hat{K}_{t-\Delta})$ .<sup>14</sup> In order to calculate the variance of growth rates the following lemma is very useful.

**Lemma 1** *Suppose that  $\ln \hat{K}_t$  follows (36), then*

$$\lim_{t \rightarrow \infty} Cov_0 \left( \ln \hat{K}_t - \ln \hat{K}_{t-\Delta}, q_t - q_{t-\Delta} \right) = \ln(1 - \theta_2)\lambda\Delta.$$

See web app. C.3 □

After some algebra, we obtain the asymptotic variance as (cf. app. A.7)

$$\lim_{t \rightarrow \infty} Var_0(\Delta \hat{y}_t) = \lim_{t \rightarrow \infty} Var_0 \left( \frac{1 - \tau_i}{1 + \tau_k} \int_{t-\Delta}^t r_s ds \right) + (\alpha \ln(1 - \theta_2))^2 \lambda \Delta. \tag{38}$$

<sup>13</sup> The structure of the moments is remarkable as it shows that the distribution of  $\hat{Y}_t$  exists, is unique and represents a generalization of the  $\beta$ -distribution (thanks to Christian Kleiber for pointing this out). As shown in Appendix A.4, fairly complex expressions appear for state dependent moments.

<sup>14</sup> Obviously the expected growth rate of cyclical variables per unit of time is zero. This result is intuitive because  $\hat{K}_t$  is bounded between 0 and  $\hat{K}$ , which implies a stationary distribution (as illustrated in Fig. 1).

This result is remarkable because it shows that the variance of growth rates depends on the variance of the (integrated) process of capital rewards, which in turn follows

$$dr_t = c_1 r_t (c_2 - r_t) dt + c_3 r_t - dq_t, \tag{39}$$

where  $c_1 \equiv \frac{1-\alpha}{\alpha} \frac{1-\tau_i}{1+\tau_k}$ ,  $c_2 \equiv (1 - \alpha)\theta_1/c_1$ , and  $c_3 \equiv (1 - (1 - \theta_2)^{1-\alpha})/(1 - \theta_2)^{1-\alpha}$ . In fact, this SDE describes the (transitional) equilibrium dynamics of capital rewards, often referred to as the stochastic Verhulst equation. It is shown that  $r$  has a unique limiting distribution, and the moments of the limiting distribution are available in closed-form (cf. app. A.6)

$$E(r) = \frac{c_1 c_2 + \ln(1 + c_3)\lambda}{c_1}, \quad Var(r) = \frac{c_3 \lambda - \ln(1 + c_3)\lambda}{c_1} E(r). \tag{40}$$

We use the deterministic Taylor expansion to approximate the asymptotic variance of the integrated process by (neglecting third order terms, cf. Posch 2011a)<sup>15</sup>

$$\lim_{t \rightarrow \infty} Var_0 \left( \int_{t-\Delta}^t r_s ds \right) \approx \lim_{t \rightarrow \infty} Var_0 (r_t \Delta) = Var(r) \Delta^2. \tag{41}$$

Starting from (38) and inserting (41),

$$Var(\Delta \hat{y}_t) \equiv \lim_{t \rightarrow \infty} Var_0(\Delta \hat{y}_t) \approx \lim_{t \rightarrow \infty} Var_0 \left( \frac{1 - \tau_i}{1 + \tau_k} r_t \right) \Delta^2 + (\alpha \ln(1 - \theta_2))^2 \lambda \Delta,$$

which is (26) in the main text.

#### A.4 Computing moments

Express (31) as a differential equation and use (32) to obtain  $d\hat{m}_t^1 = (\alpha\theta_0 - (\alpha\theta_1 + \lambda\vartheta_2)\hat{m}_t^1) dt$ , where  $\vartheta_2 \equiv 1 - (1 - \theta_2)^\alpha$ . Hence, the first moment follows a linear ODE with solution

$$\hat{m}_t^1 = e^{-(\alpha\theta_1 + \lambda\vartheta_2)t} \left( \hat{m}_0^1 + \int_0^t e^{(\alpha\theta_1 + \lambda\vartheta_2)s} \alpha\theta_0 ds \right) = e^{-(\alpha\theta_1 + \lambda\vartheta_2)t} \left( \hat{m}_0^1 + \alpha\theta_0 \frac{e^{(\alpha\theta_1 + \lambda\vartheta_2)t} - 1}{\alpha\theta_1 + \lambda\vartheta_2} \right).$$

It can be simplified to

$$\hat{m}_t^1 = e^{-(\alpha\theta_1 + \lambda\vartheta_2)t} \left( \hat{m}_0^1 - \frac{\alpha\theta_0}{\alpha\theta_1 + \lambda\vartheta_2} \right) + \frac{\alpha\theta_0}{\alpha\theta_1 + \lambda\vartheta_2}. \tag{42}$$

As  $\alpha\theta_1 + \lambda\vartheta_2 > 0$ , the first moment of  $\hat{Y}_t$  is in the long run given by (33). Similarly, for higher moments, the basic ODE determining the evolution of  $\hat{Y}_t^n$  is from (24)

$$\begin{aligned} d\hat{Y}_t^n &= n\hat{Y}_t^{n-1}(\alpha\theta_0 - \alpha\theta_1\hat{Y}_t)dt - (1 - (1 - \theta_2)^{\alpha n})\hat{Y}_t^n dq_t \\ &= n(\alpha\theta_0\hat{Y}_t^{n-1} - \alpha\theta_1\hat{Y}_t^n)dt - (1 - (1 - \theta_2)^{\alpha n})\hat{Y}_t^n dq_t. \end{aligned} \tag{43}$$

Using the integral version, applying expectations and the martingale result (30), we obtain  $dE_0\hat{Y}_t^n = (n\alpha\theta_0 E_0\hat{Y}_t^{n-1} - (n\alpha\theta_1 + \lambda(1 - (1 - \theta_2)^{\alpha n})) E_0\hat{Y}_t^n) dt$ . Using (32) we get

$$d\hat{m}_t^n = (n\alpha\theta_0\hat{m}_t^{n-1} - (n\alpha\theta_1 + \lambda(1 - (1 - \theta_2)^{\alpha n}))\hat{m}_t^n) dt. \tag{44}$$

<sup>15</sup> A precise measure would take into account the auto-covariance function based on asymptotic moments  $\lim_{t \rightarrow \infty} E_0(r_s r_u)$  which turn out to be negligible in simulations. Joint moments depend on higher-order moments and because of the non-linear dynamics in (39) are not available analytically.

It shows that all moments converge to finite limits for  $t \rightarrow \infty$ . For the first moment, this follows from (42). The proofs for higher moments follow an identical approach. In short, for asymptotic moments where  $d\hat{m}_t^n/dt = 0$ , we obtain from (44)

$$\hat{m}^n = \frac{n\alpha\theta_0}{n\alpha\theta_1 + \lambda(1 - (1 - \theta_2)^{\alpha n})} \hat{m}^{n-1}. \tag{45}$$

Thus  $n = 2$  implies (34), with  $n = 1$  it becomes (33), and by definition  $\hat{m}^0 = 1$ .

### A.5 Limiting distribution

If the  $n$ th moment  $\hat{m}_t^n \equiv E_0(\hat{Y}_t^n)$  has bounded support, then  $\hat{m}^j \equiv \lim_{t \rightarrow \infty} E_0(\hat{Y}_t^j)$  is the  $j$ th moment of the limiting distribution for any  $j < n$ , and the moments in (33) and (34) converge to the moments of the limiting distribution. Moreover,  $\hat{Y}_t$  has a unique limiting distribution (Rao 1973, p.121; Casella and Berger 2001, Theorem 2.3.11.). In other words, the sequence  $\{\hat{Y}_t\}_{t=t_0}^\infty$  converges in distribution to a random variable  $\hat{Y}$ ,

$$\hat{Y}_t \xrightarrow{\mathcal{D}} \hat{Y} \text{ where } 0 < \hat{Y}_t < \hat{Y}^*. \tag{46}$$

In fact, the limiting density of any smooth transformation of  $\hat{Y}_t$  is determined by the change of variable formula for densities (cf. Merton 1975).

By inspection of moments in (45),  $\hat{Y}$  has a generalized  $\beta$ -distribution. For  $\theta_2 = 1$ , the moments in (45) are  $\hat{m}^n = \frac{n\alpha\theta_0}{n\alpha\theta_1 + \lambda} \hat{m}^{n-1}$ . Starting from  $\hat{m}^0 = 1$ , repeated inserting yields

$$\hat{m}^n = \frac{(\alpha\theta_0)^n n!}{\prod_{i=1}^n (i\alpha\theta_1 + \lambda)} = \left(\frac{\theta_0}{\theta_1}\right)^n \frac{\Gamma(n + 1)}{\prod_{i=1}^n (i + \lambda/(\alpha\theta_1))} = \left(\frac{\theta_0}{\theta_1}\right)^n \frac{\Gamma(n + 1)\Gamma(1 + \lambda/(\alpha\theta_1))}{\Gamma(n + 1 + \lambda/(\alpha\theta_1))},$$

where  $\Gamma$  is the gamma function. Apart from the scaling factor  $(\theta_0/\theta_1)^n$ , the last expression denotes the  $n$ th moment of a  $\beta$ -distribution with parameters 1 and  $\lambda/(\alpha\theta_1)$ . Hence,  $\hat{Y}$  has the asymptotic representation  $\hat{Y} = (\theta_0/\theta_1)^n X$ , where  $X \sim \text{Beta}(1, \lambda/(\alpha\theta_1))$ . For  $\theta_2 \neq 1$ , we obtain a generalized  $\beta$ -distribution which, to the best of our knowledge, has not been encountered before. Analyzing its properties in detail should be done in future research.

### A.6 Moments of the rental rate of capital

Along the lines of our derivations for (46) it can be shown that  $r_t$  is a smooth transformation of a cyclical variable for the more general case  $\alpha = \sigma$ . Hence, the sequence  $\{r_t\}_{t=t_0}^\infty$  converges in distribution to a random variable  $r$  (compare also to Posch 2009b),

$$r_t \xrightarrow{\mathcal{D}} r \text{ where } r^* < r_t < \infty. \tag{47}$$

Using (23) and  $r_t = B^q \alpha K_t^{\alpha-1} L^{1-\alpha} = \alpha \hat{K}_t^{\alpha-1} L^{1-\alpha}$  we obtain

$$\begin{aligned} d\hat{K}_t^{\alpha-1} &= (\alpha - 1)K_t^{\alpha-2}(\theta_0 \hat{K}_t^\alpha - \theta_1 \hat{K}_t)dt + (\hat{K}_t^{\alpha-1} - \hat{K}_{t-1}^{\alpha-1})dq_t \\ &= (\alpha - 1)(\theta_0 \hat{K}_t^{2\alpha-2} - \theta_1 \hat{K}_t^{\alpha-1})dt - (1 - (1 - \theta_2)^{\alpha-1})\hat{K}_{t-1}^{\alpha-1}dq_t, \end{aligned}$$

which implies defining  $c_1$  to  $c_3$  as in (39),

$$\begin{aligned} dr_t &= (\alpha - 1)r \left( \frac{1 - \tau_i}{1 + \tau_k} r_t/\alpha - \theta_1 \right) dt + ((1 - \theta_2)^{\alpha-1} - 1) r_{t-1} dq_t \\ &= c_1 r_t (c_2 - r_t) dt + c_3 r_{t-1} dq_t. \end{aligned}$$

We use the smooth transformation  $\ln r_t$ ,

$$\ln r_t \xrightarrow{\mathcal{D}} \ln r \quad \text{where} \quad \ln r^* < \ln r_t < \infty, \tag{48}$$

to obtain  $d \ln r_t = c_1(c_2 - r_t)dt + \ln(1 + c_3)dq_t$ , which has the solution

$$\ln r_t - \ln r_{t-\Delta} = \int_{t-\Delta}^t c_1(c_2 - r_s)ds + \ln(1 + c_3)(q_t - q_{t-\Delta}).$$

Employing the property that  $\ln r_t$  and  $\ln r_{t-\Delta}$  share the same asymptotic mean as from (48),

$$\begin{aligned} \lim_{t \rightarrow \infty} E_0(\ln r_t) - \lim_{t \rightarrow \infty} E_0(\ln r_{t-\Delta}) &= c_1c_2\Delta - c_1 \lim_{t \rightarrow \infty} \int_{t-\Delta}^t E_0(r_s)ds + \ln(1 + c_3) \lim_{t \rightarrow \infty} E_0(q_\Delta) \\ \Rightarrow E(r) &\equiv \lim_{t \rightarrow \infty} E_0(r_t) = \frac{c_1c_2 + \ln(1 + c_3)\lambda}{c_1}. \end{aligned}$$

For the second moment, we use the integral equation applying the expectation operator,

$$dE_0(r_t) = c_1(c_2E_0(r_t) - E_0(r_t^2))dt + c_3E_0(r_{t-})\lambda dt.$$

Letting  $t \rightarrow \infty$  we obtain for the integral equation

$$\begin{aligned} \lim_{t \rightarrow \infty} E_0(r_t) - \lim_{t \rightarrow \infty} E_0(r_{t-\Delta}) &= \lim_{t \rightarrow \infty} \int_{t-\Delta}^t (c_1c_2 + c_3\lambda)E_0(r_s)ds - \lim_{t \rightarrow \infty} \int_{t-\Delta}^t c_1E_0(r_s^2)ds \\ \Leftrightarrow 0 &= \lim_{t \rightarrow \infty} E_0(r_t)(c_1c_2 + c_3\lambda)\Delta - \lim_{t \rightarrow \infty} E_0(r_t^2)c_1\Delta \\ \Rightarrow E(r^2) &\equiv \lim_{t \rightarrow \infty} E_0(r_t^2) = E(r) \frac{c_1c_2 + c_3\lambda}{c_1}. \end{aligned}$$

Hence the asymptotic variance, i.e., the variance of the limiting distribution for  $r_t$  is

$$Var(r) \equiv \lim_{t \rightarrow \infty} Var_0(r_t) = E(r^2) - (E(r))^2 = \frac{c_3\lambda - \ln(1 + c_3)\lambda}{c_1} E(r).$$

Note that the variance is proportional to the mean, which seems plausible given the geometric structure of the stochastic differential in (39).

### A.7 Moments of growth rates

Because  $\ln \hat{K}_t$  is a smooth transformation of a the rental rate of capital,  $r_t = \alpha \hat{K}_t^{\alpha-1} L^{1-\alpha}$ , the sequence  $\{\ln \hat{K}_t\}_{t=t_0}^\infty$  converges in distribution to a random variable  $\ln \hat{K}$ ,

$$\ln \hat{K}_t \xrightarrow{\mathcal{D}} \ln \hat{K} \quad \text{where} \quad -\infty < \ln \hat{K}_t < \ln \hat{K}^*.$$

Intuitively, cyclical variables  $\ln \hat{K}_t$  and  $\ln \hat{K}_{t-\Delta}$  share the same asymptotic mean, which is the mean of the limiting distribution,  $E(\ln \hat{K})$ . Therefore, defining

$$\begin{aligned} E(\Delta y_t) &\equiv \lim_{t \rightarrow \infty} E_0(\Delta y_t) = \lim_{t \rightarrow \infty} E_0(\ln \hat{K}_t - \ln \hat{K}_{t-\Delta})\alpha + \lim_{t \rightarrow \infty} E_0(q_t - q_{t-\Delta}) \ln A \\ &= E_0(q_\Delta) \ln A = \lambda \Delta \ln A \end{aligned}$$

for any  $t_0 > 0$ , gives the asymptotic mean of output growth rates. Economically, it employs a large sequence of growth rates of length  $\Delta$ .

**Lemma 2** Given capital rewards as in (39), then

$$\lim_{t \rightarrow \infty} Cov \left( \int_{t-\Delta}^t \left( \frac{1 - \tau_i}{1 + \tau_k} r_s / \alpha \right) ds, q_t - q_{t-\Delta} \right) = 0$$

is asymptotically uncorrelated.

*Proof* Observe that from  $Cov(aX + bY, Z) = aCov(X, Z) + bCov(Y, Z)$  we have

$$Cov \left( \ln \hat{K}_t - \ln \hat{K}_{t-\Delta}, q_t - q_{t-\Delta} \right) = Cov \left( \int_{t-\Delta}^t \left( \frac{1 - \tau_i}{1 + \tau_k} r_s / \alpha \right) ds, q_t - q_{t-\Delta} \right) + \ln(1 - \theta_2) Cov(q_t - q_{t-\Delta}, q_t - q_{t-\Delta}).$$

Employing Lemma 1 and the property  $Var(q_\Delta) = \lambda\Delta$  gives the asymptotic result. □

Observe that using growth rates of cyclical capital stock in (37) and Lemma 2,

$$Var(\hat{y}_t) = \lim_{t \rightarrow \infty} Var_0 \left( \frac{1 - \tau_i}{1 + \tau_k} \int_{t-\Delta}^t r_s ds \right) + \alpha^2 (\ln(1 - \theta_2))^2 \lim_{t \rightarrow \infty} Var_0(q_\Delta) + \alpha^2 \ln(1 - \theta_2) \lim_{t \rightarrow \infty} Cov_0 \left( \frac{1 - \tau_i}{1 + \tau_k} \int_{t-\Delta}^t r_s / \alpha ds, q_t - q_{t-\Delta} \right).$$

Using Lemma 2 we obtain the measure in (38). A similar approach computes the variance of observed output growth rates (cf. web app. C.2 for details).

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