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Public education, technological change and economic prosperity

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Abstract

We introduce publicly funded education in R&D-based economic growth theory. The framework allows us to i) incorporate a realistic process of human capital accumulation for industrialized countries, ii) reconcile R&D-based growth theory with the empirical evidence on the relationship between economic prosperity and population growth, iii) revise the policy invariance result of semi-endogenous growth frameworks, and iv) show that the transitional effects of an education reform tend to be qualitatively different from its long-run impact.

JEL classification: I25, J24, O11, O31, O41

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1 Introduction

The role of education in the process of economic development has been analyzed extensively in the empirical literature. Most of the studies[1] find a positive association between economic growth and measures for overall educational attainment and Lutz et al. (2008) even conclude that

> "...better education does not only lead to higher individual income but also is a necessary (although not always sufficient) precondition for long-term economic growth [...] Education is a long-term investment associated with near-term costs, but, in the long run, it is one of the best investments societies can make in their futures." (Lutz et al., 2008, p. 1048).

Fortunately, in this context, the data shows tremendous improvements of education indicators in industrialized countries over the last decades. Table 1 displays the mean years of schooling of the population aged 15+ for the G-8 countries in 1960 and 2010. There has been an increase over time with annualized growth rates between 0.5% and 2%. The table also contains pupil-teacher ratios in primary education, the substantial declines of which indicate that education investments per child and per year have also been steadily rising. These observations and the fact that the G-8 countries featured substantial increases in living standards over the corresponding time-frame are consistent with the results of the empirical studies mentioned above.

Despite these findings and the seminal theoretical contributions of Nelson and Phelps (1966), Lucas (1988) and Galor and Weil (2000) — showing different mechanisms by which education exerts a positive influence on economic prosperity — the main focus of R&D-based growth theory has long been on technological progress as being determined by the R&D effort of an *uneducated* workforce. In one of the first models of this type, Romer (1990) acknowledges that the aggregate human capital stock of an economy and not raw, uneducated, labor is the driving force behind technological progress, but he does not model this idea explicitly. Within these frameworks, therefore, the aggregate human capital stock exhibits the same properties as raw labor does. Consequently, these frameworks would have to be modified to analyze changes in education investments and their impact upon

[1] See for example Barro (1991), Sachs and Warner (1995), Bils and Klenow (2000), Krueger and Lindahl (2001) and the survey of Durlauf et al. (2005).

Table 1: Mean years of schooling and pupil-teacher ratios in primary education for the G-8 countries

Country	Mean years of schooling 1960	Mean years of schooling 2010	Pupil-teacher ratios 1971	Pupil-teacher ratios 2009
Canada	8.31	11.37	23.00*	17.42*
France	4.20	10.53	22.79	18.73
Germany	5.15	11.82	17.46*	13.00
Italy	4.86	9.88	21.62	10.33*
Japan	8.02	11.59	26.39	18.05
Russia	5.16	8.84	27.95*	18.06
U.K.	7.04	9.75	24.86*	17.96
USA	9.25	12.20	14.05	13.87

The data has been obtained from Barro and Lee (2010) and the World Bank (2012) “Education Statistics”. Note that the indicated year differs for the entries marked with an asterisk because of missing data. The base years for pupil-teacher ratios are 1972 for Canada, 1995 for Germany, 1981 for Russia and 1985 for the USA. The end years for the same data series are 2000 for Canada and 2007 for Italy.

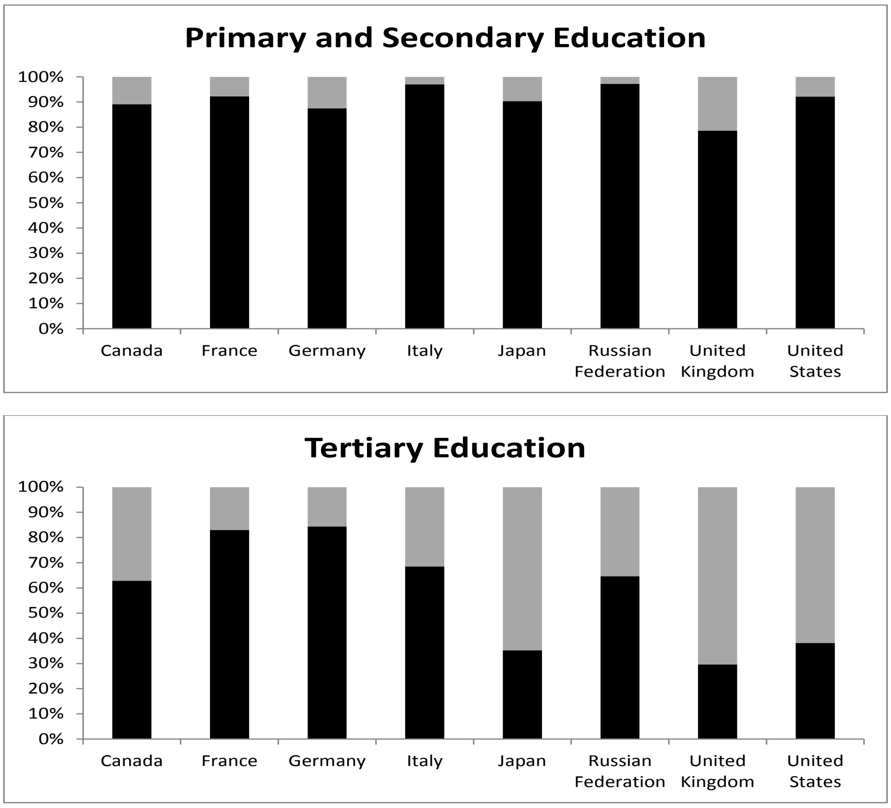
technological progress and economic prosperity.

Early R&D-based growth models in the vein of Romer (1990) have also been criticized for their support of a strong scale effect in the sense that the size of a countries' population determines its long-run economic growth prospects. While Kremer (1993) shows that the scale effect was indeed important in economic history prior to the twentieth century for the world as a whole, Jones (1995a) and Jones (1995b) refute it for individual countries and their growth experiences over the second half of the twentieth century. As a consequence, Jones (1995a) modifies the Romer (1990) framework and thereby removes the strong scale effect such that the long-run economic growth rate positively depends on population *growth* but not anymore on its *size*. However, even this implication has been criticized on the basis of empirical evidence that rather supports a *negative* association between economic growth and population growth in the twentieth century (see for example Brander and Dowrick, 1994; Kelley and Schmidt, 1995; Ahituv, 2001; Bernanke and Gürkaynak, 2001; Herzer et al., 2012). Furthermore, the removal of the strong scale effect came at the price that the long-run economic growth rate within early semi-endogenous growth models is invariant to economic policy. Dinopoulos and Thompson (1998), Peretto (1998), Young (1998) and Howitt (1999) were the first to criticize this implication and to build frameworks that leave scope for policymakers to intervene, even in the long run. Jones (1999) in turn is concerned that the complexity of these frameworks substantially reduces their generality.

In light of this short discussion, our aim is to design one single framework that is able to simultaneously deal with the mentioned shortcomings of earlier R&D-based growth models. At this point we want to stress explicitly that doing so should not be misunderstood as an attempt to devalue some of the earlier work. The contrary is the case and we greatly acknowledge all the seminal contributions that have been made in order to improve the understanding of long-run economic growth. However, we hope that our framework is able to shed additional light on the process of economic development along the following three lines.

First, we want to implement the notion of *publicly* financed education into R&D-based economic growth frameworks. According to the available data for the G-8 countries, the assumption of *privately* financed education is hard to justify because in continental European countries education systems are almost entirely financed by the state and the same holds true for primary and secondary education in Canada, Japan, the United States and the United Kingdom. Only in case of tertiary education are private expenditures playing a substantial role in these countries (cf. Docampo, 2007; OECD, 2012, and Figure 1). Altogether, the average share of governmental education expenditures in all OECD countries for primary, secondary and tertiary education amounts to 84% (cf. OECD, 2012, p. 248). As another important aspect of public education, we want to introduce a realistic production process for human capital by relaxing the implicit assumption often made in the literature that the sole input in human capital accumulation is time and effort by those to be educated (or by their parents). In contrast, our model features an education sector that employs teachers to build up the human capital stock of the next generation. Consequently, an increase in education investments has the realistic effect that the additional labor required in the education sector needs to be drawn away from other sectors of the economy.

Second, we attempt to reconcile theory and evidence by showing that our model allows for both a negative and a positive relationship between economic growth and population growth. The negative relationship is more likely to prevail for countries in which the education sector is well developed and population growth is slow, that is, typically for modern industrialized countries. This implication is consistent with the empirical findings of Brander and Dowrick (1994), Kelley and Schmidt (1995), Ahituv (2001), Bernanke and



The black areas of the histograms represent the fraction of governmental education expenditures and the gray areas the share of private (household and firm) education expenditures. Data source: OECD (2012) and own calculations.

Figure 1: Share of public education investments in the G-8 countries

Gürkaynak (2001) and Herzer et al. (2012) for the twentieth century. The positive relationship, on the other hand, is more likely to prevail for countries in which the education sector is badly developed and population growth is fast. Since this is primarily the case for countries in an early stage of development, our results are also consistent with the empirical findings of Kremer (1993) on the positive association between population growth and economic growth prior to the twentieth century.[2]

Third, we aim to reintroduce scope for policymakers to influence long-run economic development which would be consistent with the implications of Dinopoulos and Thompson (1998), Peretto (1998), Young (1998) and Howitt (1999). In so doing we show that public education investments are important drivers of long-run growth. This result is in turn consistent with the empirical literature on the interrelation between education and

[2]However, we do not want to overstretch the R&D-based growth framework and acknowledge that it is only suited for a description of countries that have already established sound property rights and a certain industrial base.

economic prosperity cited above.

The basic mechanism of our model is the following. Human capital is used as an input in three sectors that compete for it on the labor market: workers produce goods in the final goods sector, scientists produce blueprints in the R&D sector and teachers produce human capital for the next generation in the education sector. The government collects taxes and uses the proceeds to pay the wages of the teachers. Consequently, an increase in taxes raises the number of teachers and thereby draws labor away from the other sectors. This harms economic growth in the *short*- to *medium* run. However, the increase in the number of teachers fosters human capital accumulation and thereby increases productivity of the next generations. This in turn raises the *long*-run growth perspectives of the economy.

Our model is related to other recent developments in the literature that try to address the shortcomings of standard R&D-based growth theory. However, we are not aware of any model that is able to cope with all the mentioned aspects within one single framework. Dalgaard and Kreiner (2001), Strulik (2005) and Strulik et al. (2011) implement *privately* financed education into R&D-based growth theory to develop models that support a negative association between economic growth and population growth. While Dalgaard and Kreiner (2001) and Strulik (2005) emphasize that newborns do not have any education and consequently a larger birth rate slows down growth of average human capital and thereby hampers economic development, Strulik et al. (2011) rely on a child quality-quantity trade-off in the vein of Becker (1993) to show that a shift toward having fewer but better educated children can lead to a larger human capital stock on the aggregate level and therefore to faster economic growth.

Some aspects of human capital accumulation in the context of R&D-based growth theory have also been analyzed in the articles by Eicher (1996), Arnold (1998) and Funke and Strulik (2000). In these contributions, however, the growth rate of the population is assumed to be zero. This means that human capital accumulation fully adopts the role that population growth has had in standard R&D-based semi-endogenous growth models and that the interrelations between population growth and human capital accumulation — as well as their joint impact upon technological progress — cannot be addressed.

One contribution that analyzes publicly financed education (in the form of subsidies for private education) in the context of R&D-based growth is made by Grossmann (2007).

Similar to the models of the previous paragraph, population growth is not considered, which rules out the possibility to study the interrelations between demographic change and human capital accumulation. In addition, the framework does not explicitly take into account an education production sector and the associated trade-off between education and goods production. However, one of our central results, the long-run growth promoting effect of public education investments, supports the main implication of Grossmann (2007).

This paper proceeds as follows: Section 2 contains the theoretical model and the derivation of the dynamic system that fully describes the model economy. In Section 3 we derive the growth rates of endogenous variables along the balanced growth path and analytically assess the dependence of these growth rates on the underlying parameters. We then proceed to a numerical illustration of the effects of an increase in public education expenditures during the transition to the new balanced growth path and along the new balanced growth path itself. Finally, Section 4 summarizes, draws conclusions for economic policy and highlights scope for further research.

2 The model

This section describes the discrete time overlapping generations version of the R&D-based economic growth framework of Romer (1990) and Jones (1995a).[3] We introduce a governmentally funded education sector that employs teachers to educate the young and analyze its implications for long-run economic growth perspectives.

2.1 Basic assumptions

The basic structure of our overlapping generations economy follows Diamond (1965). There are three phases of an individual's life cycle: childhood, adulthood and retirement. Children do not face economic decisions but they receive publicly funded education, the intensity of which determines their human capital level as an adult. Adults, whose cohort size at time t is given by L_t, inelastically supply their skills on the labor market, consume, and save for retirement. The retirees in turn finance their consumption expenditures out

[3] Due to the isomorphism between R&D-based growth models with horizontal and vertical innovations (cf. Grossman and Helpman, 1991; Aghion and Howitt, 1992; Segerström, 1998, for the latter), the growth effects of education investments would not be different when using a model of vertical innovation as baseline framework.

of savings carried over from adulthood. We treat population growth as exogenous and assume that adults give birth to $n > 0$ children such that the population grows at rate $n-1$. Note that this includes the possibility of negative population growth which is ruled out by the model setup in Jones (1995a). Endogenizing population growth and private education investments along the lines of Strulik et al. (2011) would mainly obscure the basic mechanism we aim to highlight and is therefore left for further research.

There are four sectors: final goods production, intermediate goods production, R&D and education. Two production factors can be used in these sectors: physical capital and labor. The latter is available in three different forms: i) workers in the final goods sector denoted by $L_{t,Y}$, ii) scientists in the R&D sector denoted by $L_{t,A}$, and iii), teachers in the education sector denoted by $L_{t,E}$. The final goods sector employs workers and machines supplied by the intermediate goods sector to produce for a perfectly competitive consumption good market. The Dixit and Stiglitz (1977) monopolistically competitive intermediate goods sector produces the machines used in the final goods sector with physical capital as variable production factor and one machine-specific blueprint as fixed input. The blueprints are in turn supplied by the R&D sector, which employs scientists to produce them. Finally, the education sector employs teachers to produce individual human capital for the next generation denoted by h_{t+1}. The expenditures for the education sector are financed by taxing wages of adult workers. Following Mankiw et al. (1992) by assuming that human capital and raw labor are perfect substitutes allows us to write aggregate human capital employment as $H_t = h_t L_t$.

2.2 Consumption side

Suppose that adults maximize their discounted lifetime utility determined by consumption in adulthood and after retirement in the vein of Diamond (1965):

$$\max_{c_t, s_t} u_t = \log c_t + \beta \log(R_{t+1}\ s_t), \tag{1}$$

where c_t denotes consumption, s_t represents savings carried over to retirement, $\beta = 1/(1+\rho)$ refers to the discount factor with ρ being the discount rate, and R_{t+1} denotes the gross interest rate paid on assets between generations t and $t+1$. Note that each time period corresponds to one generation and therefore lasts for around 25 years. Assuming full depreciation of physical capital over the course of one generation, the gross interest rate corresponds to the capital rental rate and is given by $1 + r_{t+1}$ with r_{t+1} being the net interest rate. The budget constraint of a young adult reads

$$(1-\tau)w_t h_t + l_t = c_t + s_t, \tag{2}$$

where τ denotes the income tax rate, w_t represents the wage per efficiency unit of labor and l_t are lump-sum redistributions of the monopolistic rents accruing in the intermediate goods sector after a patent has expired (see section 2.3.3 for details). Consequently, the left hand side of the budget constraint refers to total lifetime income of an individual, which can be spent on consumption during adulthood or consumption after retirement. The results of the maximization problem are expressions for optimal consumption and savings

$$c_t = \frac{l_t + (1-\tau)h_t w_t}{1+\beta}, \tag{3}$$

$$s_t = \frac{\beta\left[l_t + (1-\tau)h_t w_t\right]}{1+\beta}, \tag{4}$$

exhibiting the standard properties for logarithmic utility, that is, they are increasing in wage income and lump-sum governmental transfers and decreasing in tax rates and the discount factor because the latter reduces savings and thereby lifetime interest income.

2.3 Production side

This subsection describes the production structure in the four sectors: final goods production, intermediate goods production, R&D and education. The treatment of the former two sectors is fairly standard (cf. Romer, 1990; Jones, 1995a; Strulik et al., 2011) and the description can be brief. Since we augment the standard framework to account for an income tax financed public education sector that employs labor to produce human capital of individuals (and thereby increases the productivity of subsequent generations), the education sector and the R&D sector compete for talents on the labor market. To our knowledge, this trade-off has not been analyzed in the literature and we will therefore describe it in more detail.

2.3.1 Final goods sector

Final output Y_t, being consumed by the individuals in the economy and representing the gross domestic product (GDP), is produced according to the production function

$$Y_t = H_{t,Y}^{1-\alpha} \int_0^{A_t} x_{t,i}^{\alpha} \, di, \tag{5}$$

where $H_{t,Y}$ is human capital employed in the final goods sector, A_t is the technological frontier, that is, it represents the most modern blueprint that has been developed in the R&D sector, $x_{t,i}$ is the amount of the blueprint-specific machine i used in final goods production and α is the elasticity of final output with respect to machines. Due to perfect competition in the final goods market, production factors are paid their marginal products. This means that the wage rate per unit of human capital and prices of blueprints are given by, respectively,

$$w_{t,Y} = (1-\alpha) H_{t,Y}^{-\alpha} \int_0^{A_t} x_{t,i}^{\alpha} \, di = (1-\alpha)\frac{Y_t}{H_{t,Y}}, \tag{6}$$

$$p_{t,i} = \alpha H_{t,Y}^{1-\alpha} x_t^{\alpha-1}. \tag{7}$$

Note that the derived prices for machines rely on the property that the contribution of an intermediate goods producing firm to the output of the whole sector can be neglected.

2.3.2 Intermediate goods sector

We assume that a single intermediate goods producer is able to convert physical capital $k_{t,i}$ one for one into machines $x_{t,i}$ after it has purchased the corresponding blueprint from the R&D sector. Therefore, its operating profit reads

$$\pi_{t,i} = p_{t,i} k_{t,i} - R_t k_{t,i} \tag{8}$$

and profit maximization leads to the familiar outcome of Dixit and Stiglitz (1977) that firms charge prices for machines that are a markup $1/\alpha$ over marginal cost. Hence, we have

$$p_{t,i} = \frac{R_t}{\alpha} \tag{9}$$

and there is symmetry between firms such that the index i can be dropped. As another consequence of symmetry, we know that each firm employs $k_t = K_t/A_t$ units of physical capital, where K_t denotes the aggregate physical capital stock. The aggregate production function can therefore be written as

$$Y_t = (A_t H_{t,Y})^{1-\alpha} K_t^{\alpha}, \tag{10}$$

where technology appears as human capital augmenting.

2.3.3 R&D sector

The R&D sector employs scientists with a human capital level $H_{t,A}$ and with productivity $\delta > 0$ in order to develop new blueprints. The production function of a representative firm in the research sector can be written as

$$A_{t+1} - A_t = \delta A_t^{\phi} H_{t,A}, \tag{11}$$

where ϕ measures the extent of intertemporal knowledge spillovers. In case that $\phi = 1$ we would be in the Romer (1990) environment and sustaining an exponential growth rate of technology would not become ever more difficult as the technological frontier expands. We see from Equation (11) that a constant amount of human capital in research would then suffice to have perpetual technological progress and therefore positive long-run economic growth. In contrast, if $\phi < 1$, we would be in the Jones (1995a) environment and a constant long-run growth rate of technology would either require a constant inflow of additional scientists into R&D, or a continuous increase in education of the scientists already employed, or both. Since our framework features positive population growth and individual human capital accumulation, no balanced growth path would exist in the Romer (1990) environment, that is, for $\phi = 1$. Instead, such a specification would lead to hyper-exponential growth, an implication that is at odds with the stylized facts of economic development over the long run (cf. Kaldor, 1957). We therefore restrict our attention to the case of $\phi < 1$ from now on.

The representative firm in the R&D sector maximizes its profits

$$\pi_{t,A} = p_{t,A}\delta A^{\phi} H_{t,A} - w_{t,A} H_{t,A}, \tag{12}$$

with $p_{t,A}$ being the price of a blueprint and $w_{t,A}$ being the wage rate of scientists. This leads to the optimality condition

$$w_{t,A} = p_{t,A}\delta A_t^{\phi}, \tag{13}$$

where wages of scientists increase in the price of blueprints. The reason is that if an R&D firm can charge a higher price for the blueprints it develops, it would strive to increase the pace of innovation. This would require the firm to attract workers from the other two labor-using sectors of the economy: final goods production and education. To be able doing so, the R&D firm would have to pay higher wages.

Following Aghion and Howitt (2005), it is assumed that patent protection for a newly discovered blueprint lasts for one generation, that is, for around 25 years. While this assumption keeps the profit motive for R&D intact, it simplifies the simulation of transitional dynamics, and it is also more realistic than the assumption of infinitely lived patents. For example, patent protection in the United States expires after 20 years and in Germany after 25 years latest (cf. The United States Patent and Trademark Office, 2012; The German Patent and Trade Mark Office, 2012). After a patent has expired, the proceeds of selling it are assumed to be redistributed to the consumers in a lump-sum manner. An R&D firm will then charge a price for a blueprint that is equal to the operating profit of an intermediate goods producer in period t (when patent protection is valid) because there is always a potential entrant in the intermediate goods sector willing to pay that price due to free entry. To put it differently, in case that blueprints were less (more) expensive, firms would have an incentive to enter (exit) the market for intermediate goods and consequently the only stable equilibrium involves zero overall profits. Therefore, we can write the price for blueprints as

$$p_{t,A} = (\alpha - \alpha^2)\frac{Y_t}{A_t}, \tag{14}$$

which follows from Equations (7) and (9) and the fact that $x_i = k_i$ holds for all i.

2.3.4 Education sector

The education sector employs teachers financed by the proceeds of income taxes in order to produce human capital (cf. Gersbach et al., 2009, who use a comparable financing scheme for basic research in a hierarchical growth model). We assume a balanced governmental budget such that

$$\tau w_t h_t L_t = w_t h_t L_{t,E}, \tag{15}$$

where the left hand side represents governmental revenues, that is, the proceeds of taxing the total wage bill $w_t h_t L_t$, and the right hand side represents governmental expenditures, that is, the wages paid for teachers in the education sector. This implies that the number of employed teachers is $L_{t,E} = \tau L_t$. The output of the education sector is schooling intensity denoted by e_t

$$e_t = \xi \frac{L_{t,E}}{n L_t} = \xi \frac{\tau}{n}, \tag{16}$$

where ξ measures the productivity of teachers and τ/n denotes the teacher-pupil ratio. This formulation implies that the intensity of schooling increases in the productivity of teachers and in public education investments per child. Recall that n is the gross population growth rate meaning that schooling intensity is also defined in case of zero population growth ($n = 1$). Note that, ceteris paribus, faster population growth lowers the teacher-pupil ratio and thereby the schooling intensity. Building upon Mincer (1974) and following Hall and Jones (1999), Bils and Klenow (2000), Jones (2002) and Caselli (2005), schooling intensity translates into individual human capital according to $h_{t+1} = \exp\left[\tilde{\psi}\left(\xi\tau/n\right)\right] h_t$, where $\tilde{\psi}(\cdot)$ measures the extent to which it does. To put it differently, $\tilde{\psi}(\cdot)$ represents the semi-elasticity of individual labor productivity with respect to increases in schooling intensity. Note that this formulation assumes that schooling intensity plays a comparable role to "years of schooling" in the empirical literature. In the context of an overlapping generations model with fixed period length, an increase in years of schooling would indeed be tantamount to an increase in schooling intensity. As regards the particular specification of the human capital accumulation function, Jones (2002) and Bloom and Canning (2005) use a linear relationship that can be justified upon evidence by Psacharopoulos (1994). We follow their approaches and therefore we have

$$h_{t+1} = \exp\left[\psi\left(\xi\frac{\tau}{n}\right)\right] h_t \tag{17}$$

with $\psi = const$. Altogether, Equation (17) implies that if the government does not invest in education at all, the human capital of the successive generation would be the same as those of their parents. This can be justified by the notion that, without formal education, people are observing and learning from their parents and peers (cf. Strulik et al., 2011, p. 8). Furthermore, if people would not observe and learn from others at all, the model would lack positive economic growth in equilibrium, which would again be at odds with stylized facts of economic development for modern societies (cf. Kaldor, 1957; Acemoglu, 2009; Galor, 2011).[4]

2.4 Market clearing and the balanced growth path of the economy

Labor market clearing implies that the total amount of available human capital is either employed in the final goods sector, in the education sector, or in the R&D sector, that is, we have $h_t L_t = h_t (L_{t,E} + L_{t,A} + L_{t,Y}) \Rightarrow H_t = H_{t,E} + H_{t,A} + H_{t,Y}$. Furthermore, we know that wages in all sectors have to equalize such that $w_{t,E} = w_{t,A} = w_{t,Y}$, otherwise one or more sectors would not be able to attract any workers and the economy ended up in a corner solution. Equalizing expressions (6) and (13), using Equation (14), and noting that employment in the education sector is τL_t, yields demand for workers in the final

[4] Of course it can be questioned whether a positive economic growth rate can be sustained indefinitely facing scarce resources, a limited carrying capacity of the environment and bounded space on earth. However, we do not insist that our model holds for $t \to \infty$, but that it represents a reasonable approximation for a certain period of time.

goods sector and in the R&D sector as, respectively,

$$H_{t,Y} = \frac{A_t^{1-\phi}}{\alpha\delta}, \tag{18}$$

$$H_{t,A} = (1-\tau)H_t - \frac{A_t^{1-\phi}}{\alpha\delta}. \tag{19}$$

Recalling that $H_t = h_t L_t$ and $H_{t,E} = h_t L_{t,E}$, we see that an increase in the population size or in individual human capital immediately leads to more employment of aggregate human capital in education and in science. The latter fosters technological progress such that A_{t+1} rises by more than it would have otherwise. This in turn increases human capital employment in the final goods sector in generation $t+1$. Altogether the development of new blueprints can then be described by

$$A_{t+1} = \delta(1-\tau)A_t^{\phi} h_t L_t - \frac{1-\alpha}{\alpha} A_t, \tag{20}$$

where the dynamic trade-off that public education investments imply is the following: while increasing taxes pulls labor from the R&D sector into the education sector, it also increases human capital accumulation and therefore the productivity of the next generation's scientists. In the short- to medium run, the negative effect of the decrease in the number of scientists on the development of new blueprints will dominate, whereas in the long run, the positive effect of better education on the productivity of scientists will prevail.

Full depreciation of physical capital and capital market clearing imply that the aggregate physical capital stock of an economy in generation $t+1$ is equal to aggregate savings. Furthermore, goods market clearing ensures that aggregate consumption together with aggregate savings is equal to total output such that

$$K_{t+1} = s_t L_t = Y_t - c_t L_t. \tag{21}$$

These identities can then be used to eliminate the lump-sum redistributions of the government to the households. After doing so, the equation governing the accumulation of aggregate physical capital reads

$$K_{t+1} = \frac{\beta}{1+\beta}\left(\frac{A_t^{2-\phi}}{\alpha\delta}\right)^{1-\alpha} K_t^{\alpha}. \tag{22}$$

Putting all information together, the system fully describing the equilibrium dynamics of our model economy is therefore given by

$$A_{t+1} = \delta(1-\tau)A_t^{\phi}h_tL_t - \frac{1-\alpha}{\alpha}A_t, \tag{23}$$

$$h_{t+1} = \exp\left(\frac{\psi\xi\tau}{n}\right)h_t, \tag{24}$$

$$L_{t+1} = nL_t, \tag{25}$$

$$K_{t+1} = \frac{\beta}{1+\beta}\left(\frac{A_t^{2-\phi}}{\alpha\delta}\right)^{1-\alpha} K_t^{\alpha}, \tag{26}$$

describing the evolution of the number of blueprints, individual human capital accumulation, population growth and physical capital accumulation. Note that these equations hold during the transition to the balanced growth path *and* along the balanced growth path itself. We will now use this system to derive our central analytical and numerical results.

3 Results and discussion

We first derive our analytical results in subsection 3.1. Afterwards, we use a numerical simulation to illustrate the medium- and long-run growth effects of an increase in governmental education investments in subsection 3.2.

3.1 Analytical results

Making use of the definition of a balanced growth path, that is, that the growth rate of a variable does not change over time, we can derive the long-run rate of technological progress as

$$g_A = [(g_h+1)(g_L+1)]^{\frac{1}{1-\phi}} - 1 = \left[\exp\left(\frac{\psi\xi\tau}{n}\right)n\right]^{\frac{1}{1-\phi}} - 1, \tag{27}$$

where g_j denotes the growth rate of variable j. Technological progress is driven by growth in aggregate human capital, which is composed of individual human capital and the population size. At first sight it seems as if a decrease in either of these variables decreases the long-run growth rate of the economy. This, however, misses the point that human capital accumulation is inversely related to the population growth rate via the latter's negative influence on the teacher-pupil ratio. The question which of the two effects prevails when population growth declines will be discussed in Proposition 1.

For the aggregate physical capital stock it follows either from Equation (26) or from inspection of the aggregate production function that its long-run balanced accumulation rate is given by

$$\begin{aligned} g_K &= (g_h+1)(g_L+1)(g_A+1)-1 = \left[\exp\left(\frac{\psi\xi\tau}{n}\right)n\right]^{\frac{2-\phi}{1-\phi}} - 1 \\ &= (g_A+1)^{2-\phi}-1. \end{aligned} \tag{28}$$

Denoting per capita GDP by y_t and putting everything together, the growth rates of aggregate GDP and per capita GDP are, respectively,

$$g_Y = (g_h+1)(g_L+1)(g_A+1)-1 = \left[\exp\left(\frac{\psi\xi\tau}{n}\right)n\right]^{\frac{2-\phi}{1-\phi}} - 1, \tag{29}$$

$$g_y = (g_h+1)(g_A+1)-1 = \left[\exp\left(\frac{\psi\xi\tau}{n}\right)\right]^{\frac{2}{1-\phi}} n^{\frac{1}{1-\phi}} - 1. \tag{30}$$

Altogether, the balanced growth path of the economy described in Equations (28), (29) and (30) is consistent with the stylized facts of economic development expressed by Kaldor (1957). At this stage, we can discuss the three crucial differences to standard semi-endogenous growth models.

First, the long-run growth rate of per capita GDP [as given by Equation (30)] is different from the rate of technological progress [as given by Equation (27)]. The reason is that per capita GDP, the crucial measure for prosperity in growth theory, not only increases with the rate of technological progress, but, additionally, with the rate of individual human capital accumulation. Since human capital accumulation is complemented by physical capital accumulation, constant returns to both of these accumulable factors in the aggregate production function ensure that long-run growth of per capita GDP would persist, even in the absence of technological progress. This illustrates that human capital exerts its positive influence on economic growth via *two* channels in our framework. The first channel is the direct effect that follows the mechanism described in Lucas (1988): human capital and physical capital accumulation *together* lead to perpetual increases of individual labor productivity, which prevents the decreasing returns of physical capital from becoming a binding constraint for long-run development. The second channel is the indirect effect based upon the mechanism described in Romer (1990) and Jones (1995a): human capital accumulation fosters technological progress, which in turn increases labor productivity and economic growth.

Second, the long-run growth rates of per capita GDP and technology depend upon population growth in a non-monotonous way. This allows for the possibility of a negative and a positive relationship between long-run economic growth and population growth depending on the parameters of the model economy which are related to the stage of development of a country. We can summarize this finding in the following proposition.

Proposition 1. *The long-run growth rates of technology and per capita GDP decrease in response to faster population growth if the education sector of an economy is well-developed and the population growth rate is low. The converse holds true for an economy with fast population growth and a badly developed education sector.*

Proof. We take the derivatives of the growth rates of technology and per capita GDP with respect to population growth

$$\frac{\partial g_A}{\partial n} = \frac{\left[\exp\left(\frac{\psi\xi\tau}{n}\right)n\right]^{\frac{1}{1-\phi}}(n-\xi\tau\psi)}{n^2(1-\phi)}, \tag{31}$$

$$\frac{\partial g_y}{\partial n} = \frac{\left[\exp\left(\frac{\psi\xi\tau}{n}\right)n\right]^{\frac{2-\phi}{1-\phi}}(n-\xi\tau(2-\phi)\psi)}{n^3(1-\phi)}. \tag{32}$$

The first expression is negative if the state of the education sector — as measured by the product of public investments in education represented by taxes (τ), productivity of teachers (ξ), and the Mincerian coefficient governing the translation of the schooling intensity into human capital (ψ), — is sound, while the population growth rate (n) is low. Qualitatively the same result holds true for the growth rate of per capita GDP. □

The economic intuition behind this results is that growth of aggregate human capital is either due to growth of individual human capital or to growth of the population size. An increase in population growth, which — by itself — positively impacts upon aggregate human capital accumulation, simultaneously decreases the teacher-pupil ratio. This in turn has a negative impact on the evolution of aggregate human capital. If the education sector is well developed and the population growth rate is low, the negative effect dominates and population growth therefore negatively impacts economic growth. This is most likely to be the case for developed countries which would be consistent with the evidence found by Brander and Dowrick (1994), Kelley and Schmidt (1995), Ahituv (2001), Bernanke and Gürkaynak (2001) and Herzer et al. (2012) for the twentieth century. If, on the other hand, the education sector is badly developed and population growth is high, the positive effect dominates and population growth therefore positively impacts economic growth. This is most likely to be the case for countries in an early stage of industrialization which would be consistent with the evidence found by Kremer (1993) on long-run growth prior to the twentieth century.

The third crucial difference to standard semi-endogenous growth models is that governmental investments in education (τ) are still present in the expressions for long-run growth of per capita GDP and technology indicating that there is scope for policymakers to have an influence on long-run development. This implication can be summarized in Proposition 2.

Proposition 2. *The long-run growth rates of technology and per capita GDP unambiguously increase in public education investments.*

Proof. We take the derivatives of the growth rate of technology and per capita GDP with respect to the tax rate

$$\frac{\partial g_A}{\partial \tau} = \frac{\left[\exp\left(\frac{\psi\xi\tau}{n}\right)n\right]^{\frac{1}{1-\phi}}\xi\psi}{n(1-\phi)}, \tag{33}$$

$$\frac{\partial g_y}{\partial \tau} = \frac{\left[\exp\left(\frac{\psi\xi\tau}{n}\right)n\right]^{\frac{2-\phi}{1-\phi}}\xi(2-\phi)\psi}{n^2(1-\phi)}. \tag{34}$$

Since both of them are unambiguously positive, the proposition holds. □

This implication is in line with the second wave of scale-free economic growth models advocated by Dinopoulos and Thompson (1998), Peretto (1998), Young (1998), Howitt (1999) and Dalgaard and Kreiner (2001) that reintroduces a scope for governmental policies to affect long-run economic development. The policy measure to be taken is to increase investments in public education. In this regard, our model is consistent with the empirical literature suggesting a positive association between education and economic growth (cf. Barro, 1991; Sachs and Warner, 1995; Bils and Klenow, 2000; Krueger and Lindahl, 2001; Lutz et al., 2008). The reason for this effect to prevail is that — in the long-run and for a constant population growth rate n — there is only a positive effect of increasing education on aggregate human capital accumulation. Hence, in the long run, effective labor unambiguously grows faster in all sectors of the economy if the government raises education investments.

However, in the short- and medium run, that is, during the transition to the new balanced growth path, there could also be negative growth effects of increases in public education investments because the education sector draws labor away from the R&D sector. This represents the "near term costs" mentioned by Lutz et al. (2008) in the introductory quote. We turn to this issue in Subsection 3.2, where we simulate an increase in education expenditures and keep track of its short- and medium-term costs as well as of its long-term benefits.

3.2 Simulating an increase in public education expenditures

To address the question how the model economy is affected by an increase in public education expenditures in the short- and medium run, we simulate the dynamic system displayed in Equations (23) to (26). The parameter values were either taken from the literature or calibrated such that both the simulated population growth rate and the simulated economic growth rate were in line with the average demographic and economic experience of euro area countries from 1960-2010. The reason for focusing on the euro area is that there the vast majority of educational expenditures are undertaken by the governments. The parameter for educational expenditures (τ) was then inferred from data of the World Bank (2012) on the fraction of GDP that governments of euro area countries spent on education over the corresponding time frame.

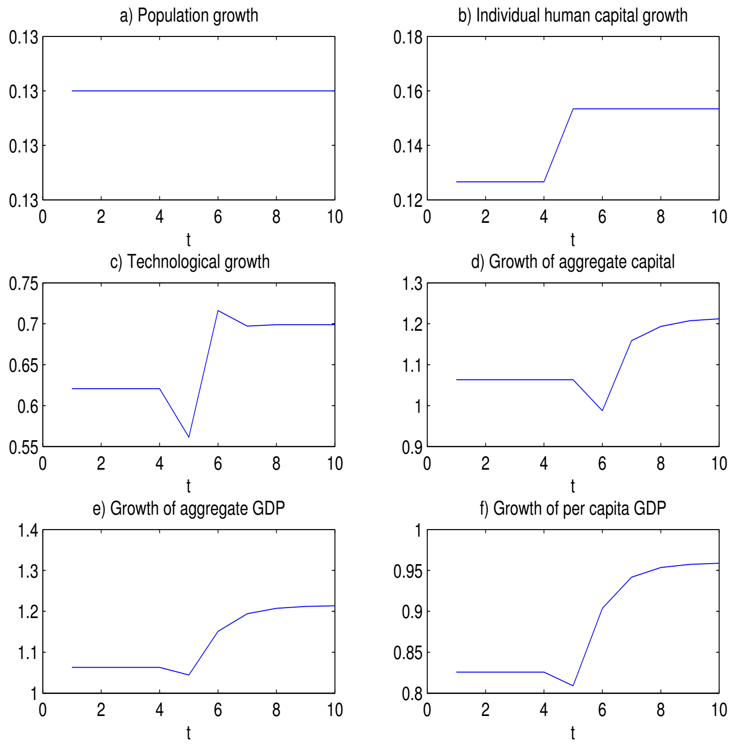
Table 2: Parameter values for simulation

Parameter	Value	Justification (growth rates appear as annualized)
β	0.28	Consistent with a discount rate of 5%
α	1/3	Common in the literature (cf. Jones, 1995a)
δ	1000	Parameter is free to choose
ξ	19.5	Parameter values for ξ and ϕ imply $g_y = 2.45\%$,
ϕ	0.5	which is consistent with data for the euro area
τ	0.0759	Implied by data for the euro area
ψ	0.091	Commonly used/inferred (cf. Psacharopoulos, 1994)
n	1.13	Implies population growth of 0.5%

The results of simulating an increase in education expenditures are depicted in Figure 2. We assume that the economy initially moves along the balanced growth path. At generation five a 1 percentage point increase in public education expenditures as a fraction of GDP occurs. Afterwards the behavior of the economy is traced for another five generations, that is, for 125 years. We see that an increase in public education investments at impact draws labor away from the R&D sector into the education sector. This leads to an increase in human capital accumulation as displayed in diagram b). However, since the better educated next generation does not yet supply its skills on the labor market, there is an initial slowdown in the growth rates of technology, aggregate GDP and per capita GDP, displayed in, respectively, diagrams c), e), and f). Furthermore, the decrease in the growth rate of GDP also leads to a subsequent slowdown in the rate of physical capital accumulation which is displayed in diagram d). Altogether, this initial decrease in the growth rates of technology, physical capital and GDP reflects the "near term costs" of education mentioned by Lutz et al. (2008).

In the generation after the increase in education investments, the better educated young enter the labor market. Since the human capital level of this generation is higher than it would have been without the increase in education investments and also the accumulation rate of human capital in the subsequent generations is faster, the growth rates of technology, GDP and — with a delay of one generation — aggregate physical capital, increase. Approximately three generations after the increase in education investments, the growth rates of technology, aggregate physical capital, aggregate GDP and per capita

Figure 2: Simulation of an increase in public education expenditures



Note: Time is displayed on the x-axis and growth (between two generations) is displayed on the y-axis. Initially, the economy moves along the balanced growth path. In the fifth generation, a 1 percentage point increase in public education expenditures as a fraction of GDP occurs. Afterwards the economy is traced for another five generations, that is, for 125 years.

GDP have reached their new balanced growth path levels.[5] These are higher than the balanced growth path levels before the increase in education investments which represents the long-term benefits of education according to Lutz et al. (2008). While the balanced growth rate of per capita GDP is 2.45% before the government increases education investments, it amounts to 2.73% afterwards, an increase of 0.28 percentage points. Note that this simulated long-run outcome is consistent with the claim expressed in Proposition 2.

4 Conclusions

We set up an R&D-based economic growth model with a *public* education sector as prevalent in most countries and being especially relevant for European economies (cf. Docampo, 2007; OECD, 2012). First, this allows us to generalize the R&D-based growth literature to

[5]For the transitional effects in standard semi-endogenous growth models see also Trimborn et al. (2008).

take education, which is an empirically important determinant of economic development, into account. We show that the long-run growth rate of the economy is not only affected by technological progress (being itself driven by population growth and human capital investments) but is further enhanced by sustained increases in the skills of the labor force together with faster physical capital accumulation. Consequently, the framework is able to bridge the gap between growth models relying solely on human capital accumulation like Lucas (1988) and the R&D-based growth literature of Romer (1990) and Jones (1995a).

Second, we show that the long-run growth rates of technology and per capita output are sensitive to changes in governmental education policies. Therefore we challenge a property of early semi-endogenous growth models in the vein of Jones (1995a) and Segerström (1998) in favor of later scale-free growth models in the spirit of Dinopoulos and Thompson (1998), Peretto (1998), Young (1998) and Howitt (1999). Our results suggest that education investments are very important to foster long-run economic development with an increase in the corresponding expenditures of 1% of GDP leading to an increase in the long-run growth rate of 0.28 percentage points. However, there is a short- and medium-term cost associated with the implementation of growth promoting education reforms because resources from other sectors have to be transfered to the education sector. Moreover, the benefits of education do not materialize immediately because it takes time until the next generation enters the labor market. Initially an increase in education expenditures therefore leads to a slowdown of economic growth. Consequently, the decision regarding the implementation of education reforms essentially pins down to the dynamic trade-off between benefiting future generations at the expense of currently tax paying adults. The presence of such a trade-off might be one reason why policy-makers are reluctant to implement costly education reforms (cf. Harris et al., 2001; Epple et al., 2012)

Third, our model framework suggests that increases in population growth might harm long-run economic growth perspectives in case that the education sector of an economy is well developed and population growth is low. This primarily applies to industrialized countries in the twentieth century and therefore has the potential to explain the negative correlation between economic growth and population growth found in empirical studies for this time frame (cf. Brander and Dowrick, 1994; Kelley and Schmidt, 1995; Ahituv, 2001; Bernanke and Gürkaynak, 2001; Herzer et al., 2012). Nevertheless, our model is also consistent with evidence for earlier stages of industrialization when public education sectors were typically less developed and population growth was still quite fast: In this case our framework supports a positive correlation between economic growth and population growth which is consistent with the empirical findings of Kremer (1993) for economic development prior to the twentieth century.

As already indicated, some aspects of the results in our paper have been shown within other frameworks. In particular, the notion that long-run economic growth is not solely driven by exogenously given population growth was the main reason for integrating horizontal and vertical innovations to remove the scale effect in otherwise endogenous growth models (cf. Dinopoulos and Thompson, 1998; Peretto, 1998; Young, 1998; Howitt, 1999). Moreover, *private* education investments represent a main driving force behind long-run economic development for example in Dalgaard and Kreiner (2001) and Strulik et al. (2011). However, we are confident that our paper i) represents a consistent framework for analyzing these issues and their interrelations simultaneously, ii) sheds some light on the notion and importance of public education and especially on the connection between education and population growth, and iii), allows for a fairly general dependence of economic prosperity on population growth that is consistent with the experience of modern economies as well as with the historical evidence on countries in an earlier stage of industrialization.

We also acknowledge that our framework is stylized and some important issues cannot be treated within its realms. Possible extensions might therefore reveal other aspects of the connection between economic growth, education and demography. For example, the population growth rate and private education investments could both be endogenized along the lines of Strulik et al. (2011) to analyze potential feedback effects between (public and privately financed) education, fertility and the teacher-pupil ratio. In particular, this could prove to be a useful framework for analyzing the extent to which public and private education complemented one another in the course of the industrial revolution (cf. Mokyr, 2005; Galor et al., 2009; Galor, 2011).

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