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Abstract

Using an endogenous growth model with non-renewable natural resources, the paper analyses the possibility of positive innovation and consumption growth under conditions, which are generally considered as most unfavourable. We assume poor substitution between primary input factors, positive population growth and a limited supply of materials in the static part of the framework as well as natural resources being an essential input into R&D and constant or decreasing returns to innovative activities in the dynamic part. It is shown that, even with this set-up, long-term growth is achieved under free market conditions. However, it is argued that adjustment costs and errors in long-term expectations might form serious obstacles for a permanent increase in living standards.

Keywords: endogenous technological change, environment, natural resources, sustainability

JEL-Classification: Q20, Q30, O41, O33

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1. Introduction

In developed economies, non-renewable resources such as fossil fuels play currently an important role. In the long run, the use of these resources will have to decrease because total stocks are limited. This brings about a major macroeconomic impact on consumption possibilities of future generations. When evaluating the probability of ongoing economic growth, several conditions are generally ranked as critical. The first issue is input substitution. In traditional resource economics, it has been argued that poor input substitution does not allow to sustain a constant per capita consumption level in the long run, as long as technical progress is weak or absent, see Solow (1974), Stiglitz (1974) and Dasgupta and Heal (1974). Second, many consider population growth as a major threat to economic development in the long run, see e.g. Meadows et al. (1972). In the standard neo-classical growth model, the effects of population growth consist of decreasing capital intensity and per capita income, which give rise to similar concerns. Third, the scope of physical capital substituting for non-renewable resources is limited because of material balance constraints, see Cleveland and Ruth (1997). When turning to knowledge accumulation, two additional points emerge. One is the use of natural resources in the innovation sector, or more generally, the “growth engine” of an economy. Groth and Schou (2002, p. 386) suggest that “non-renewable resources are clearly an important element in the technologies of present-day economies.” Finally, the intensity of knowledge spillovers is under debate; an ingredient of many endogenous growth models is proportional spillovers leading to constant returns to R&D, see Romer (1990) and Grossman and Helpman (1991).

Referring to these issues, the present paper asks whether it is possible to obtain positive long-term growth in an endogenous innovation model under conditions which seem to be very unfavourable. In particular, the framework assumes poor input substitution between inputs, positive population growth, limited supply of material and essential use of resources in R&D; decreasing returns to R&D are evaluated as well. We find that, quite surprisingly, economic growth is nevertheless possible under these conditions. This result is not based on a very complicated or specific model; the used framework can be seen as straightforward and quite general. But the issues, which have been described as critical before, turn out to be superable, neutral, or even positive under the used model assumptions, which explains the qualification “seemingly unfavourable” in the title of the paper. The study suggests that the debate on the substitution of non-renewable resources should favourably focus on additional issues, such as adjustment costs of structural change and formation of long-term expectations.
Specifically, the present contribution considers the substitution of a non-renewable natural resource and its effects on R&D-activities and economic growth in a simple endogenous innovation model. Labour and non-renewable natural resources are introduced as primary inputs. Physical capital appears in the form of differentiated capital services, knowledge capital is accumulated by endogenous R&D activities through positive spillovers. Innovations are embodied in new capital varieties. They increase the productivity of aggregate capital. The main mechanism driving the growth process is gradual labour reallocation from intermediate goods production to R&D.

The paper builds on various contribution in literature. The natural resource part builds on Dasgupta and Heal (1979) while the dynamic part incorporates the model elements of new growth theory, see Aghion and Howitt (1998), Romer (1990), Grossman and Helpman (1991) and Smulders (2000). Knowledge accumulation has been introduced into renewable and non-renewable resource models by Bovenberg and Smulders (1995) and Scholz and Ziemes (1999). Poor substitution between inputs and the consequences for economic dynamics have been studied in Bretschger (1998) and Bretschger and Smulders (2003). The assumption of positive population growth in a model with non-renewable resources is used by Groth and Schou (2002). These authors include the non-renewable resource as an essential input into R&D. They demonstrate that endogenous growth can be obtained assuming (slightly) increasing returns to capital. Most interestingly, in that paper it is also demonstrated that, to get constant growth, the questionable assumption of exactly proportional spillovers becomes redundant when including non-renewable resources in the model.

Taking these recent contributions into account, our results do not come as a complete surprise. That endogenous growth with non-renewable resources can be achieved with poor input substitution and limited material supply has recently been shown in Bretschger and Smulders (2003). Moreover, it is also known that, in new growth theory, population growth has a different meaning compared to the neo-classical approach. However, that these assumptions can be combined with essential non-renewable resources in R&D and possibly less than proportional spillovers in knowledge accumulation, without postulating increasing returns to capital, is a novelty. Thus, it is the combination of all five issues mentioned above and its long-term consequences, which adds to existing literature.

The remainder of the paper is organised as follows. Section 2 develops the model with natural resource use and endogenous innovations. Section 3 presents the results for long-term dynamics. In section 4, the quality of the results is discussed and the problems achieving long-term growth are reconsidered. Finally, section 5 concludes.
2. The model

The model consists of three different sectors, which are R&D, intermediate capital services and final goods, with a different type of firm in each sector. R&D firms use labour $L$ and non-renewable resources $R$ as rival and public knowledge $\kappa$ as non-rival inputs to produce the know-how for new intermediate goods in the form of designs. $n$ denotes the number of intermediate goods at each point in time. With proportional spillovers from R&D to public knowledge, we get $n = \kappa$. For the ease of exposition, we will use this assumption, which produces constant returns in R&D, and discuss the consequences of less than proportional spillovers at the end of the next section. With $\dot{n}$ denoting the derivative of $n$ with respect to time and $L_g$ and $R_g$ the labour and resource input into R&D, the production of new designs $\dot{n}$ and the growth rate of knowledge $g$ become:

\[
\dot{n} = L_g^\alpha \cdot R_g^{1-\alpha} \cdot n \\
\]

\[
g = \frac{\dot{n}}{n} = L_g^\alpha \cdot R_g^{1-\alpha} \\
\]

(0 < $\alpha$ < 1) (1a)

(1b)

With perfect competition in the research sector, the market value of an innovation $p_n$ equals the per-unit costs of designs, which depend on the labour wage $w$, the resource price $p_R$ and $n$:

\[
p_n = \left(\frac{w^\alpha \cdot p_R^{1-\alpha}}{n}\right) \\
\]

(2)

Labour and resources are also used for production in the intermediate sector, denoted by $X$, but not in the final goods sector, so that the labour market and resource market restrictions are:

\[
L = L_X + L_g \\
R = R_X + R_g \\
\]

(3)

(4)

_Ceteris paribus_, the less profitable is the intermediate sector, the lower are $w$ (which decreases $p_n$ and increases the profitability of R&D) and $L_X$, which raise $g$ by (3) and (1b). In a symmetric equilibrium, intermediate capital services $x_i$ are all of equal size $x$. The $x$s are
used by final goods firms to produce final output $Y$ under a CES-production function restriction:

$$Y = \left( \int_0^n x_i^{\beta} \, di \right)^{\frac{1}{\beta}} = (n \cdot x^\beta)^{\frac{1}{\beta}} = n^{1-\beta} X \quad (X = n \cdot x; \quad 0 < \beta < 1) \quad (5)$$

Intermediate goods firms use $L$ and $R$ as inputs to produce intermediate capital goods under the restriction of a CES-production function:

$$X = \left[ L \cdot X^{(\sigma-1)/\sigma} + (1 - L) \cdot R^{(\sigma-1)/\sigma} \right]^{\sigma/(\sigma-1)} \quad (0 < L < 1) \quad (6)$$

with $\sigma$ being the elasticity of substitution between $L$ and $R$, assumed to be lower than unity. It will turn out in the results below that the total quantity of capital services is limited; thus material balance restrictions are met. As no resources are used to assemble differentiated goods to final output, expenditures can be expressed in terms of $Y$ or $X$. For convenience, prices are normalised such that consumer expenditures are unity at every point in time:

$$p_Y \cdot Y = p_x \cdot X \equiv 1 \quad (7)$$

with $p_Y$ and $p_x$ standing for prices of $Y$ and $X$ (all xs have the same price). Households maximise a lifetime utility function subject to the usual budget constraint:

$$U(t) = \int_0^\infty e^{-(\rho - r)\tau} \log Y(\tau) \, d\tau \quad (8)$$

Intertemporal optimisation yields that the growth rate of consumer expenditures equals the difference between the nominal interest rate $r$ and the discount rate $\rho$ (Keynes-Ramsey rule), which means with (7) that $r = \rho$. The market form in the intermediate sector is monopolistic competition. According to (5), the mark-up over marginal costs for the optimal price of an intermediate good is $1/\beta$, so that, together with (7), we get for the per-period profit flow to each design holder:

$$\pi = (1 - \beta) / n \quad (9)$$
To calculate the full dynamics of the model, we additionally need factor shares and two intertemporal conditions. The share of labour in intermediate goods production $\lambda$ is, observing (5) and (7):

$$\lambda = \frac{w \cdot L_x}{\beta}$$  \hspace{1cm} (10)

and $1 - \lambda$ is the corresponding resource share. Calculating relative factor demands derived from (6) and assuming $\bar{\lambda} = 0.5$ for simplicity, we obtain for the relative share size:

$$\frac{\lambda}{1 - \lambda} = \left(\frac{w}{p_R}\right)^{-\sigma}$$  \hspace{1cm} (11)

On capital markets, the return on innovative investments (consisting of the direct profit flow $\pi$ and the value change of the design) is equalised to the return on riskless bond investment of size $p_n$ (with interest rate $r = \rho$):

$$\pi + \dot{p}_n = \rho \cdot p_n$$  \hspace{1cm} (12)

On resource markets, the return on resources (consisting of price increases) must also equalise the return on bonds (Hotelling rule), so that:

$$\dot{p}_R = \rho \cdot p_R; \quad \hat{p}_R = \rho$$  \hspace{1cm} (13)

where the hat denotes the growth rate. Due to (13), the use of $R$ decreases over time which poses a problem both for $X$-production and the innovative sector. Population is assumed to grow over time. Instead of exogenous geometric growth we use a relation between the change of $L$ and structural change expressed by a changing $\lambda$. According to the model results (see section 3), labour input in intermediates $L_x$ and wages $w$ are decreasing over time so that $\dot{\lambda} < 0$ and $L$ and $\lambda$ become negatively correlated. A general formulation is:

$$L = \mu \left[ (1 - \lambda)/\lambda \right]^\xi$$  \hspace{1cm} (14)

($\mu, \xi > 0$)
The purpose of (14) is to assure that $L$ grows over time; the chosen specification facilitates calculations below and does not influence the quality of the results. It can be seen from (14) that population grows without bound when $\lambda$ approaches zero.

3. Solving the model and results

To derive the dynamics of the model, note that (1b) can be rewritten as:

$$g = L_g \cdot \left( \frac{R_g}{L_g} \right)^{1-\alpha}$$  \hspace{1cm} (15)

According to (15), the innovation growth rate depends on the labour input in R&D $L_g$ and the relation of resource and labour input in the innovative sector. Cost minimisation in the R&D sector yields:

$$\frac{R_g}{L_g} = \frac{w \cdot (1-\alpha)}{p_R \cdot \alpha}$$  \hspace{1cm} (16)

From (15) and (16) we derive, using growth rates and (13):

$$\dot{g} = \hat{L}_g + (1-\alpha) \hat{w} - (1-\alpha) \rho$$  \hspace{1cm} (17)

Following (17), the percentage change of the innovation growth rate depends negatively on the discount rate and positively on the percentage change of the R&D-labour input and of the wage rate, to be determined next. Assume for simplicity that $\xi = (1-\alpha)/(1-\sigma)$. The percentage change of R&D-labour input $\hat{L}_g$ can then be calculated by using (3) and (10) as, see appendix:

$$\hat{L}_g = \frac{-\hat{w} + \left( 1 + \frac{(1-\alpha)/(1-\sigma)(1-\lambda)}{(\beta \lambda)/(w \cdot L)} \right) \lambda}{1 - (w \cdot L)/(\beta \lambda)}$$  \hspace{1cm} (18)
where $L$ is given by (14). The percentage change of the wage rate $\hat{w}$ is obtained by dividing (12) by $p_n$ and calculating $w$ as value marginal product from (1a), see appendix. Solve for $p_n$, replace $p_n$ in (12) and use (9) and (10) to get:

$$\hat{w} = \frac{g}{\alpha} + \rho - \frac{(1 - \beta)g}{wL - \lambda\beta}$$

(19)

Use (11) and (13) to derive the percentage change in the labour share according to:

$$\hat{\lambda} = (1 - \lambda)(1 - \sigma)(\hat{w} - \rho)$$

(20)

Finally, to calculate the wage rate $w$ appearing in (19), note that (15) can be rewritten, using (3) and (10), as:

$$g = (L - \lambda\beta / w)(R_g / L_g)^{1-\alpha}$$

(21)

Use (16) and (11) and solve (21) to get:

$$w = -\lambda\beta\left[\frac{g}{u - L}\right]^{-1} \quad \text{with} \quad u = \left(\frac{\lambda}{1 - \lambda}\right)^{1-\alpha}\left(\frac{1 - \alpha}{\alpha}\right)^{1-\alpha}$$

(22)

Equations (17)-(20) build together with (22) a system for the determination of $\hat{g}, \hat{L}_g, \hat{w}, \hat{\lambda}$, and $w$; $\hat{g}$ and $\hat{\lambda}$ lead to the expressions for the equations of motions, that is expressions for $\hat{g}$ and $\hat{\lambda}$, which are after rearranging:

$$\hat{g} = \frac{1}{\alpha^2 \beta \lambda} \left[ (\alpha - 1)^2 (\beta - 1) (\alpha / (1 - \alpha))^2 \mu^2 (-1 + \alpha (\lambda - 1)^2 + \sigma - \lambda (\lambda + \sigma - 3)) + \alpha g(-\alpha \beta \lambda \rho 
+ g(\alpha (\beta - 1) - \beta \lambda (-1 + \alpha + \lambda + \sigma - \lambda\sigma)) - \alpha \mu ((1 - \alpha) / \alpha)^{1-\alpha} (-\alpha \beta \lambda \rho + g(\alpha^2 (\beta - 1) 
+ (2 + (\lambda - 2) \lambda) + \beta \lambda (1 - \sigma + \lambda (-3 + \lambda + \sigma)) + \alpha (2 + \beta (\lambda (3 + \lambda - \lambda^2 - 2\sigma) + 2(\sigma - 1)) 
- 2\sigma + \lambda (-4 + \lambda + 2\sigma))) \right)$$

(23)
\[ \dot{\lambda} = \frac{(1 - \lambda)(1 - \sigma)}{\alpha \beta} \left\{ g [\alpha(1 - \beta) + \beta \lambda] - \left[ \frac{1 - \alpha}{\alpha} \right] (1 - \alpha)(1 - \beta) \mu \right\} \]  

(24)

(23) and (24) describe the full dynamics of the model depicted in figure 1. It applies for \( \sigma < 1 \) according to the assumption. It turns out that the rather complicated expressions for the dynamics of the economy can be neatly summarised in a phase diagram, which makes the interpretation of the lengthy algebra easy.

*** Figure 1 ****

about here

As can be seen from figure 1, the economy approaches on a unique saddle path, which lies between the two isoclines, a long-term equilibrium with positive innovation growth. The assumption of \( \sigma < 1 \) leads to crowding out of labour in the intermediate sector which fosters economic dynamics by lower wages. During convergence, labour gradually moves from the intermediate to the innovation sector which increases R&D activities. In the steady state, all labour is used in R&D, where the drag of decreasing resource input is exactly compensated by increasing labour input due to population growth.

The system approaches a long-term equilibrium value for the innovation growth rate, but the steady state is never entirely reached. Setting the rhs of (24) equal to zero and taking \( \lambda = 0 \), the asymptotic equilibrium innovation growth rate turns out to be:

\[ g^e = \frac{[\alpha/(1 - \alpha)]^\alpha (1 - \alpha)(1 - \beta) \cdot \mu}{\alpha(1 - \beta)} \]  

(25)

In the long run, \( g \) only depends on technological parameters like the production elasticity of labour in research and market power in differentiated goods and on the population growth parameter \( \mu \), but not on preferences, i.e. on \( \rho \). More specifically, a high \( \alpha \) is positive for innovation growth, which is not surprising, but also a high \( \mu \), which means that population growth
favours innovation activities. The stronger is the negative impact of $\lambda$ on $L$, the larger is the equilibrium innovation growth rate. Following (5), consumption growth is in the asymptotic equilibrium:

$$\dot{Y} = [(1-\beta)/\beta]g + \dot{X}$$

(26)

In the case of $\sigma < 1$, (asymptotically) all labour is in the research sector in the long run. $\dot{X}$ is negative because of the decreasing input of $R$ into intermediate goods production. In order to have positive consumption growth, the equilibrium innovation growth rate must be big enough to compensate for the drag of $R$ in the $X$-sector. In the long run, we have $\dot{R}_X = -\rho$ so that $\dot{X} = -\rho$. Inserting (25) in (26) we obtain aggregate consumption growth as:

$$\dot{Y} = \left[\frac{\alpha/(1-\alpha)}{\alpha\beta}\right] (1-\alpha)(1-\beta) \cdot \mu - \rho$$

(27)

Whether $\dot{Y}$ is positive in the long run depends on parameter values; positive consumption growth is a possible outcome, with realistic parameter values even the unambiguous result. According to (14), the population growth rate approaches a constant in the long run, which can only be calculated when linearising the system around the steady state. It is thus not possible to provide an exact solution for per-capita consumption growth in the long run. It can be positive but, when parameters are unfavourable, it might also be negative. The technical parameters from the production function must be big enough compared the discount rate and the parameters determining the growth rate of $L$ in order to get $\dot{Y} - \dot{L} > 0$ in the long run.

During convergence, labour gradually moves from the intermediate to the innovation sector. R&D benefits from increasing total population as well. During the whole convergence process, the innovation growth rate is increasing, which – among other things – depends on the assumption of proportional spillovers in the research sector. It can be inferred that spillovers, which are weaker than proportional, are sufficient to yield a constant innovation growth rate or a rate which increases at a slower pace compared to the standard model presented here. So even with less than proportional spillovers, sustainable development can be reached in this model with the used assumptions.
4. Discussion of the results

Introducing knowledge capital instead of physical capital as major substitute for non-renewable resources into the model removes the concerns about material balance restrictions. To conjecture whether there are any limits to total knowledge, which is potentially acquirable at all times, is difficult. The least we can say is that there are no indications of such limits so far. Comparing with earlier studies, the present analysis leads to reversed values regarding the issues of population growth and input substitution. An increasing labour force is positive in the long run, as knowledge – the decisive capital stock in the model – is produced by labour while the use of knowledge capital is a public good. In the same way, poor input substitution in the intermediate goods sector is advantageous because it supports structural change, that is labour moving from the intermediate goods sector to the innovative sector. R&D is not harmed, but supported by poor input substitution in the intermediate sector.

However, the fact that resources are an essential input into R&D, is a serious problem of course. Regarding the ratio of profit per innovation $\pi$ and market value of the innovation $p_n$, the latter is steadily raised by increasing resource prices (Hotelling rule). Ceteris paribus, this decreases the direct return on innovation. In many models, a countervailing force may not be found, unless increasing returns to capital are postulated. The present approach, however, introduces structural change and population growth as mechanisms which offset the drag of non-renewable resources. This seems to be a solution that is at least as appealing as assuming increasing returns to scale in $X$-production.

There are two issues, not mentioned yet, which could prevent the system from following the saddle path depicted in figure 1. First, as structural change is the main mechanism driving the result, any deviation from zero adjustment cost is critical for the outcome. Indeed, many causes for slow sectoral adjustments of labour, such as wage setting procedures and efficiency wages, can be found in reality. It becomes immediately clear from the results that, once we have a too slow inflow of labour in the R&D-sector, innovation growth rates will decrease. Specifically, equation (18) gives the percentage change of labour input into R&D as a function of the change of the labour wage and the labour share in $X$-production. Provided that wages do not fall as indicated on an equilibrium adjustment path, the percentage change of labour input in R&D becomes smaller, which entails a lower innovation growth rate according to (1b).

In addition, the Hotelling rule postulates perfect foresight of resource owners. Not only should they optimise for an infinitely long time-period, they must also have full information about demand in all sectors for all times. When deviating from this assumption, it might be
the case that price increases are too slow in the beginning, for instance due to myopia, and then, at a later stage, become too rapid compared to the Hotelling rule. As a consequence, too little knowledge is accumulated in the first phase and, combined with adjustment costs on labour markets, the increase of labour in the innovative sector becomes too sluggish compared to the solution with perfect foresight and no adjustment costs.

5. Conclusions

In resource economics, earlier theories have identified five issues that seem to be critical for the possibility of increasing living standards in the long run. This paper has demonstrated that even a combination of all these issues is not necessarily detrimental for economic growth. In particular, it is suggested that the effects of structural change and an increasing labour force can be strong enough to sustain knowledge accumulation and consumption growth in the future.

However, when analysing the mechanisms leading to this optimistic result, two issues emerge which may hamper economic development. When labour reallocation between sectors is not fast enough, due to adjustment cost or wrong expectations or both, the innovation and per-capita consumption growth rates decrease over time. As an extension of the model it would be possible to introduce adjustment cost, for example in the form of education cost, and analyse the effects for long-term growth. This is left for future research. Moreover, wrong price signals from the resource sector, due to wrong expectations, lead to a development which differs from the one predicted by the model.

Regarding policy, the results suggest that facilitating labour reallocation from knowledge-extensive to knowledge-intensive sectors is the best approach to support sustainable development. In a more realistic model, with different labour types, this might include education efforts. Concerning the long-term expectations on resource markets, a steady worldwide dissemination of all relevant knowledge about scarcities might be a possible way to avoid systematic errors of market participants.
References


Appendix

To derive $\hat{L}_g$, use (3) to get:

$$\hat{L}_g = \frac{L}{L-L_X} \hat{L} - \frac{L_X}{L-L_X} \hat{L}_X.$$ (A.1)

Observing (10) to calculate $L_X$ and $\hat{L}_X$ and (14) to obtain $\hat{L}$ yields (18) from the main text.

To derive (19), divide (12) by $p_n$:

$$\frac{\pi}{p_n} + \hat{p}_n = \rho,$$ (A.2)

calculate $w$ from (1a) and use (1b):

$$w = \alpha \cdot L_g^{a-1} \cdot R_g^{1-a} \cdot p_n \cdot n = \alpha \cdot p_n \cdot g \cdot n / L_g.$$ (A.3)

solve (A.3) for $p_n$ and replace $p_n$ in (A.2) and use (9) to have:

$$\frac{(1-\beta)\alpha g}{wL_g} + \hat{p}_n = \rho + g.$$ (A.4)

Then use (3) and (10) to eliminate $L_g$ and (2) to eliminate $\hat{p}_n$ in (A.4) to get expression (19)

of the main text.
Figures

Figure 1

The parameter values used to produce figure 1 are:
\( \alpha = 0.9; \sigma = 0.3; \rho = 0.01; \beta = 0.9; \mu = 0.2 \)