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Natural resource scarcity and long-run development: central mechanisms when conditions are seemingly unfavourable

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Abstract

Using a dynamic model with non-renewable natural resources and endogenous knowledge creation, the paper analyses economic development 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 there is an inverse relationship between input substitution and growth-enhancing sectoral change and that labour supply supports economic dynamics through the knowledge-creation effect. A permanent increase in living standards can be achieved under free market conditions. With a backstop technology, the system converges to a balanced growth path with classical properties.

Keywords: non-renewable resources, poor input substitution, technical change, sustainability

JEL-Classification: Q32, Q55, O41

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1. Introduction

In recent years, the limited supply of non-renewable natural resources has not generally been perceived as a major threat to long-term economic development. Many believe that supplies of the most important resources, such as oil, will be sufficient for several more decades so that the problem is not imminent. Moreover, in the eyes of many economists, the economic literature of the 1970s provides adequate answers to the scarcity problems by emphasising input substitution and capital build-up. Finally, some argue that other environmental issues, such as the greenhouse problem, are more important and the exhaustibility of resources does not need to receive particular attention.

However, these views are largely incomplete, even precarious. On the one hand, if we take the broad current debate on sustainable development seriously, we are by no means allowed to neglect the well-being of the generations following us. Already the next generation will be faced with much lower oil reserves and presumably much higher oil prices. On the other hand, resource economics of the 1970s, best represented by the famous 1974 *RES* symposium issue, was seminal in many respects, but did not result in an ultimate cure for natural resource scarcity. Too many of the assumptions used are inconsistent with empirical observations and technology remains unexplained. Finally, to get a comprehensive view of the various threats to sustainable development, all relevant issues have to be analysed. One problem cannot be played off against another, because they all appear to be too serious.

As total worldwide stocks of non-renewable resources are limited by assumption, the use of these resources will have to decrease in the future, which is a fundamental change compared to what has taken place during the last decades. Regarding fossil fuels, it is an open debate as to when the peak in the use of oil will occur, but several indications of tightening scarcity can be observed. Some oil companies have reported recently that their proven reserves are actually lower than they had previously estimated. Moreover, oil production in the North Sea will rapidly decrease in the coming years, and other oil-producing regions will experience a similar trend. Scarcity problems will also arise in the context of various other material inputs because worldwide supply is finite. Once a reversal of the trend in natural resource use has occurred, economic development is based on different fundamentals. A foretaste of the political consequences, at least in the short run, was the recent surge in oil prices. As an immediate consequence, finance ministers and central bank heads from the world's seven largest economies urged oil producers to increase supplies to bring down prices. The G7 officials said that the high prices were a threat to global prosperity.

To derive a consistent theory and appropriate predictions for economic development with exhaustible natural resources, several empirical facts have to be observed. First, the elasticity of substitution between energy, which is closely tied to non-renewable resources, and other inputs, specifically labour and capital, is estimated to be less than unity, see e.g. Christopoulos and Tsionas (2002) and Kemfert (1998). Second, the scope for physical capital build-up as a substitute for non-renewable resources is limited because of material balance constraints, as emphasised by Cleveland and Ruth (1997). Third, non-renewable resources are often an essential element in the technologies of present-day economies, so that knowledge creation as a substitute for natural resources becomes more expensive and thus difficult over time, see Groth and Schou (2002). Fourth, knowledge spillovers, supporting the knowledge build-up, may be weakening with increasing stocks, see Jones (1995) and (1999) and Eicher and Turnovsky (1999). In addition, world population is growing fast today and will grow further in the future, although at a decreasing pace. At the same time, economies are undergoing a substantial structural change during long-run development. Between 1979 and 2002, the share of total employment in manufacturing has decreased by 30 % in Europe and 34 % in the US, respectively, while employment in the research sector has risen by 28 % in Europe and 40 % in the US, see GGDC (2004). At least the first four empirical observations can be labelled as "unfavourable" conditions for development: they limit both the scope of input substitution and the scope for the accumulation of physical and knowledge capital as compensation for lower resource use. In addition, population growth often appears as a major threat to economic development, see e.g. Meadows et al. (1972) and Ehrlich and Ehrlich (1990); the neoclassical growth model gives rise to similar concerns.

Taking all these empirical findings into account, the present paper asks whether and how it is possible to obtain positive long-term growth under free market conditions. Notably, it seeks to model the main mechanisms driving development according to the empirical facts stated above. In particular, the framework assumes poor substitution between inputs, sectoral change, positive population growth, limited supply of material, and essential use of resources in R&D; constant and decreasing returns in R&D are evaluated. It also includes so-called backstop technologies which are suggested to be good substitutes for non-renewable resources when prices of resources become sufficiently high.

We find that issues, which have been described as critical (or even lethal) before, turn out to be superable, neutral, or even positive under the stated assumptions of the model, which explains the qualification "seemingly unfavourable" in the title of the paper. In particular, poor input substitution fosters sectoral change which turns out to be a central mechanism sustaining economic growth. The cited empirical trend in sectoral change, which impacts resource use, will be reproduced by the model economy. Moreover, labour supply has not only a capital-using but also a capital-producing effect. The positive effects can be strong enough to compensate for the essential use of natural resources in research, which constitutes a major hurdle for innovation activities in the long run. The results of the paper are not based on a very complicated or specific model; the presented framework can be seen as straightforward and general. Long-term economic growth is possible according to the model, although most model elements would suggest different conclusions. Ongoing growth is not guaranteed, however, which corresponds to the result that sustained growth may not be feasible in so-called endogenous growth models, see Eicher and Turnovsky (1999). The study does not advocate a laisser-faire policy; rather, by emphasising the central mechanisms, it suggests that the debate on the substitution of non-renewable resources should focus on the right issues, such as adjustment costs of structural change and formation of long-term expectations.

The paper is related to existing literature, but differs with respect to decisive points. In the seminal papers of Solow (1974), Stiglitz (1974) and Dasgupta and Heal (1974), elasticities of substitution are assumed to be unity, physical capital can be accumulated without bound and technical progress is exogenous; this paper assumes poor input substitution, bounded supply of material and endogenous technology. The natural resource part is based 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), Smulders (2000) and Xepapadeas (2003). Knowledge accumulation has been introduced into resource models by Bovenberg and Smulders (1995), Scholz and Ziemes (1999) and Grimaud and Rougé (2003), but – contrary to this paper – they all assume unit input elasticities, constant sector shares, inessential or no resource use in R&D, zero population growth, and non-decreasing learning spillovers. The essential use of resources in R&D is used in Groth and Schou (2002) but these authors again assume unit input substitution elasticities, do not model endogenous innovations and postulate increasing returns to capital to obtain endogenous per capita growth. Poor input substitution und structural change already appear in Bretschger (1998) but there, population is constant and resources are not an essential input into R&D, which leads to a different modelling. In newer growth theory, increasing returns in capital accumulation may revert the traditional view of population growth. The present paper shows how the capital-creation effect of labour can exceed the capital-using effect in an endogenous innovations model. Finally, backstop technologies are not included in the cited dynamic resource models but integrated in the present approach.

When including non-renewable resources in the model, we primarily think of fossil fuels and, in a somewhat broader sense, of energy supplies. But as the possibility of economic growth in the long run is essential for the general sustainability debate, one can interpret this input in a broader fashion. The world as a materially closed economy is not only confronted with fixed reserves of fossil fuels, but also with a fixed supply of raw materials needed for physical capital, housing etc. In addition, basic needs like food have an essential material component. The distinction between these different interpretations of the non-renewable resource are particularly important for the (very) long run. When considering the energy interpretation, so-called “backstop technologies” like solar or wind energy will be profitable after the price of the resource has reached a certain level. Regarding the material perspective, it is often assumed that a certain amount of material throughput is necessary to sustain economic activities in the long run. Recycling is the key to increasing the quantity of raw materials like metals etc. All these different aspects of natural resources can be addressed with the help of the present model.

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, first without a minimum resource requirement for production and backstop technology, then with both features. 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 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, which depict material inputs, are introduced as primary input factors, which seems to be a straightforward choice. Differentiated intermediate services are the produced inputs for final goods production and knowledge capital is accumulated by endogenous R&D-activities through positive spillovers. Innovations are embodied in new intermediate goods varieties. They increase the productivity of aggregate intermediate input. For the long run, a possible switch in technologies is evaluated to consider the effects of back-stop technologies and minimal material input requirements. Through this setting, the simplest case of a sectoral economy with endogenous innovations can be depicted. The text concentrates on the market solution to evaluate the probability of ongoing growth without policy intervention; optimality concerns are discussed in section 4.

The framework consists of three different sectors, namely R&D, intermediate services and final goods, with a different type of firm in each sector; see figure 1 for an overview.

*** Figure 1 ****
about here

R&D firms use labour *L* and non-renewable resources *R* as rival inputs and public knowledge κ as non-rival input 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 $\dot{n}$ denoting the derivative of *n* with respect to time and L_g and R_g the labour and resource inputs into R&D, the production of new designs $\dot{n}$ becomes:

$$\dot{n} = L_g^{\ \alpha} \cdot R_g^{\ 1-\alpha} \cdot \kappa \qquad (0 < \alpha < 1) \qquad (1a)$$

With positive spillovers from R&D to public knowledge, we get $\kappa = n^{\eta}$ where η denotes the intensity of the externalities; with proportional spillovers we have $\eta = 1$ so that $\kappa = n$. To simplify the explanation, we will use this assumption, which produces constant returns in R&D, and discuss the consequences of less than proportional spillovers $(\eta < 1)$ in section 4. Consequently, the growth rate of knowledge *g* is:

$$g = \frac{\dot{n}}{n} = L_g^{\ \alpha} \cdot R_g^{\ 1-\alpha} \qquad (1b)$$

According to (1a) and (1b), *R* is an essential input into research. This reflects the fact that research institutions use fossil fuels for heating and transportation or mineral products or other materials for machines and experiments. 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*:

$$p_n = \left(w/\alpha\right)^{\alpha} \cdot \left(p_R/(1-\alpha)\right)^{1-\alpha} / n \qquad (2)$$

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:

$$L = L_X + L_g \qquad (3)$$

$$R = R_X + R_g \qquad (4)$$

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

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

In (5), both the size of the gains from diversification, given by β, and the asymptotic properties of the production function for *Y* are important; they will be discussed in the next sections. Intermediate goods firms use *L* and *R* as inputs to produce intermediate goods under the restriction of an extended CES-production function:

$$X = [\bar{\lambda} \cdot L_X{}^{(\sigma-1)/\sigma} + (1-\bar{\lambda}) \cdot R_{X'}{}^{(\sigma-1)/\sigma}]^{\sigma/(\sigma-1)} - R_{\tilde{X}} \qquad (X \geq 0, 0 < \bar{\lambda}, \sigma < 1) \qquad (6)$$

with σ being the elasticity of substitution between *L* and *R*, assumed to be lower than unity. A positive $R_{\tilde{X}}$ means that a minimum resource input is necessary to get positive *X*-production, where $R_{X'} + R_{\tilde{X}} = R_X$ (as used in 4). In section 3, we will first solve the model for the case $R_{\tilde{X}} = 0$, then for $R_{\tilde{X}} > 0$. (6) indeed reflects the relevant input substitution process governing the dynamic behaviour of the economy, while the relationship between *n* and *X* in (5) does not reflect input substitution but the efficiency of final goods production according to past R&D. Again, the asymptotic properties of the production function, here for *X*, are important and will be considered in section 3. Intermediate services are modelled as flows, vanishing at the end of each period. It will turn out in the results below that the total quantity of intermediate services *X* decreases over time.

As no resources are used to assemble differentiated goods to final output, expenditures can be expressed in terms of *Y* or *X*. Nothing pins down the price level of the considered economy, so that the price path of one nominal variable can be freely chosen while, at any point in time, all prices are measured against the chosen numeraire. The choice of the numeraire has no effect on real magnitudes. For convenience, prices are normalised here such that aggregate consumer expenditures are constant and unity at every point in time:

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

with p_Y and p_x standing for prices of *Y* and *X* (all *x*s have the same price). Households maximise a lifetime utility function:

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

subject to the budget constraint: $\dot{V} = rN + wL + p_R R + p_R W_R - p_Y Y$, where *V* is household wealth, *r* the interest rate, $N = np_n$ asset holdings, and W_R the resource stock; for alternative utility assumptions in a similar context see Asheim and Withagen (1998). The transversality conditions requires that household wealth approaches a value of zero in the long run, that is we must have:

$$\lim_{t \to \infty} \left[n(t) \cdot p_n(t) + W_R(t) \cdot p_R(t) \right] \cdot e^{-\rho t} = 0$$

Using percentage changes one can also require that:

$$\lim_{t \to \infty} \hat{n}(t) + \hat{p}_n(t) - \rho \leq 0 \quad \text{and} \quad \lim_{t \to \infty} \hat{W}_R(t) + \hat{p}_R(t) - \rho \leq 0$$

which are stronger but equally useful conditions for this model. Intertemporal optimisation yields that the growth rate of aggregate consumer expenditures equals the difference between the nominal interest rate *r* and the discount rate ρ (Keynes-Ramsey rule), which means with (7) that $r = \rho$, that is the *nominal* interest rate always corresponds to the subjective discount rate. This holds true for any population growth rate. The evolution of the real interest rate, which is crucial for the development of the economy, is not predetermined by (7). As aggregate consumer expenditures are normalised to unity, the present value of consumption from any point in time onward is equal to $1/\rho$, so that the intertemporal budget constraint is well-defined in this economy.

The market form in the intermediate sector is monopolistic competition. The demand for an intermediate good can be derived from (5), see appendix. Accordingly, the mark-up over marginal costs for the optimal price of an intermediate good is $1/\beta$, so that, together with (7), we get the per-period profit flow to each design holder:

$$\pi = (1 - \beta) / n \qquad (9)$$

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 λ is, observing (5) and (7):

$$\lambda = \frac{w \cdot L_X}{\beta} \tag{10}$$

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

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

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

$$\pi + \dot{p}_n = \rho \cdot p_n \tag{12}$$

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

$$\dot{p}_R = \rho \cdot p_R; \quad \hat{p}_R = \rho \qquad \text{for} \qquad t < t^e \tag{13}$$

where the hat denotes the growth rate, *t* is the time index and t^e the point in time when a backstop technology becomes competitive, see section 3.3. If no such technology is ever available, t^e is infinity and (13) holds in all times. Due to (13), the use of *R* decreases over time which poses a problem both for *X*-production and the innovative sector. The total stock of resource *R* at time *t* is denoted by W_R; its depletion is effectuated according to:

$$\dot{W}_R = -R, \qquad \text{with } W_R(0) \text{ given and } W_R(t) \geq 0 \text{ for all } t.$$

To ensure that W_R is exactly depleted in the long run, total extraction must equal total resource stock in equilibrium. This can be achieved by setting the optimum price at the beginning of optimisation, which requires agents to form rational expectations. When a known backstop technology is available at some point in time, the initial resource price has to be adjusted, see 3.3. The population growth rate g_L is determined endogenously, according to:

$$g_L = -\xi \cdot \hat{\lambda}\left(\frac{1}{1-\lambda}\right) \qquad (0 < \xi < 1)$$

or, the same relation expressed in levels:

$$L = \mu\left[(1-\lambda)/\lambda\right]^{\xi} \qquad (\mu > 0) \quad . \tag{14}$$

Equation (14) links labour dynamics to the industry share λ of (10). Population growth is associated with a reallocation of labour from the intermediate sector to R&D, that is $\hat{\lambda} < 0$. In addition, population growth is small with a low industry share λ, meaning a small $1/(1-\lambda)$ in (14) and, at the same time, a large research sector. This reflects the empirical fact that fertility is negatively correlated with income and knowledge creation, see Tamura (2000) and de la Croix and Doepke (2003). In the model of this paper, the industry share and the population growth rate decrease in the course of time to approach either a constant positive value, $g_L = \left((1-\alpha)/\alpha\right)\cdot\rho$, or zero, in the long run, see section 3. This is consistent with predictions of demography. In the model, it is equally possible to use alternative assumptions instead of (14), like exogenous population growth, see section 4.

3. Solving the model and results

We solve the model in three steps. First, we combine the basic equations such that only the relevant variables are left. Then, results for the case of $R_{\tilde{X}} = 0$ and without backstop technology are derived. Finally, we discuss the effects of $R_{\tilde{X}} > 0$ and a backstop technology and/or recycling.

3.1 Obtaining the model solution

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

$$g = L_g \cdot \left(R_g / L_g\right)^{1-\alpha} \tag{15}$$

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:

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

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

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

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. The percentage change of R&D-labour input $\hat{L}_g$ can be calculated by using (3) and (10) as (see appendix):

$$\hat{L}_g = \left(1 - wL/\beta\lambda\right)^{-1}\left[-\hat{w} + \left(1 + \frac{\xi wL}{\beta\lambda(1-\lambda)}\right)\hat{\lambda}\right] \tag{18}$$

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:

$$\hat{w} = \frac{g}{\alpha} + \rho - \frac{(1-\beta)g}{wL - \lambda\beta} \tag{19}$$

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

$$\hat{\lambda} = (1-\lambda)(1-\sigma)(\hat{w} - \rho) \tag{20}$$

From this we can see that, with $\sigma < 1$ (which we assume), the labour share in the intermediate sector declines with $\hat{w} < \rho$. Finally, to calculate the wage rate w appearing in (19), note that (15) can be rewritten, using (3) and (10), as:

$$g = (L - \lambda\beta/w)\left(R_g/L_g\right)^{1-\alpha} \tag{21}$$

As can be seen from (21), with a given resource/labour input ratio in research, the innovation growth rate is high when labour supply is large, wages are low, the labour share in intermediates is low and monopoly power in intermediates (yielding profits for innovations) is high (low β). From (16) we know that the input ratio R_g/L_g in (21) depends on relative input prices, as usual. (11) says that relative input prices depend on $\lambda/(1-\lambda)$ representing relative sector shares. So we use (16) and (11) and solve (21) to get an equation for wages:

$$w = -\lambda\beta\left[\frac{g}{u} - L\right]^{-1} \quad \text{with} \quad u = \left(\frac{\lambda}{1-\lambda}\right)^{\frac{1-\alpha}{1-\sigma}} \cdot \left(\frac{1-\alpha}{\alpha}\right)^{1-\alpha} \tag{22}$$

(22) relates sector shares, given by $\left(\lambda/(1-\lambda)\right)^{\frac{1-\alpha}{1-\sigma}}$, to wages and, by this, to the incentives for research activities.

3.2 Results for $R_{\tilde{X}} = 0$

Equations (17)-(20) together with (22) and (14) build - with the appropriate endpoint conditions - a system for the determination of $\hat{g}$, $\hat{L}_g$, $\hat{w}$, $\hat{\lambda}$, L and w; $\hat{g}$ and $\hat{\lambda}$ lead to the expressions for the equations of motions in terms of $\dot{g}$ and $\dot{\lambda}$, which yields a convenient representation of the model. Specifically, by combining (14), (19), (20) and (22) we find, after rearranging, see appendix:

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

From (14), (17), (18), (19), (20) and (22) we similarly obtain:

$$\dot{g} = \frac{1}{\alpha^2\beta\lambda}\Big\{ \delta_1\left[\left(\lambda/(1-\lambda)\right)^{(1-\alpha)/(1-\sigma)-\xi}\left(\delta_2\right)^{\alpha}\right]^2 \mu^2(\lambda+\delta_3+\sigma(1-\lambda)) + \alpha g(-\alpha\beta\lambda\rho + g(\delta_4-\beta\lambda)$$

$$(-1+\alpha+\lambda+\sigma-\lambda\sigma)) - \alpha\mu\left(\lambda/(1-\lambda)\right)^{(1-\alpha)/(1-\sigma)-\xi}(\delta_2)^{\alpha-1}(-\alpha\beta\lambda\rho + g(\alpha\delta_4+\beta\lambda$$

$$(\xi+\lambda(\sigma-1)-\delta_5) - \delta_4(1+\xi+2\lambda(\sigma-1)-\delta_5-\sigma))) \Big\} \tag{24}$$

where: $\delta_1 = \left(\alpha-1\right)^2(\beta-1); \delta_2 = \alpha/(1-\alpha); \delta_3 = \xi(\sigma-1); \delta_4 = \alpha(\beta-1); \delta_5 = (1+\xi)\sigma.$

(23) and (24) describe the full dynamics of the model. It turns out that the rather complicated expressions can be neatly summarised in phase diagrams, which make the interpretation of the lengthy algebra convenient. The term $\left(\lambda/(1-\lambda)\right)^{(1-\alpha)/(1-\sigma)-\xi}$ is decisive for the dynamics of the system, especially in the long run. To see this more clearly, we set the rhs of (23) equal to zero and take $\lambda = 0$, which is the approximation for the (very) long run. This yields three possible solutions for the innovation growth rate in the long-term steady state g^e:

$$g^e = 0 \qquad \text{if } \xi < (1-\alpha)/(1-\sigma) \tag{25a}$$

$$g^e = \left(\frac{1}{1/\left[\xi(1-\sigma)\right]-1}\right)^{\xi(1-\sigma)} \cdot \mu \qquad \text{if } \xi = (1-\alpha)/(1-\sigma) \tag{25b}$$

$$g^e = \infty \qquad \text{if } \xi > (1-\alpha)/(1-\sigma) \tag{25c}$$

The clear separation of the different long run solutions according to (25) is surprisingly attractive, as it yields many insights to economic development with non-renewable resources. In the case of $\xi < (1-\alpha)/(1-\sigma)$ given by (25a), innovation ceases in the long run. This happens because in (23) the term $\left(\lambda/(1-\lambda)\right)^{(1-\alpha)/(1-\sigma)-\xi}$ approaches zero so that for $\dot{\lambda} = 0$ in the long run we must have *g* = 0. With given parameters for production technology (σ and α), weak population growth (a low ξ) will lead to this outcome. A constant population unambiguously falls into this category. This is an important result: in a knowledge-driven economy without backstop technology, positive population growth is not detrimental but needed to sustain economic growth. Without backstop technology, labour is indeed the ultimate resource, as it is highly productive for the accumulation of knowledge capital.

Let us next focus in detail on the inner solution given by (25b). The dynamics for the inner solution, with $\sigma < 1$ according to the assumption, are depicted in figure 2 in the λ-g-space.

*** Figure 2 ****
about here

The economy approaches a long-term equilibrium with constant positive innovation growth on a unique saddle path, which lies between the two isoclines for $\dot{\lambda} = 0$ and $\dot{g} = 0$. The equilibrium satisfies the transversality condition. By (13) we have $\hat{p}_R(t) = \rho$ and $\lim_{t\to\infty} W_R(t) \cdot e^{-\rho t} = 0$, that is $\hat{W}_R(t) < 0$ (because the resource is non-renewable), so that indeed we get $\lim_{t\to\infty} \hat{W}_R(t) + \hat{p}_R(t) - \rho \leq 0$. Moreover, by (2) it is that $\hat{p}_n(t) = \alpha \cdot w(t) + (1-\alpha) \cdot \rho - g$. Then, the part of the transversality condition reading $\lim_{t\to\infty} \hat{n}(t) + \hat{p}_n(t) - \rho \leq 0$ becomes:

$$\lim_{t\to\infty} g(t) + \alpha \cdot w(t) + (1-\alpha) \cdot \rho - g(t) - \rho \leq 0 .$$

After rearranging we are left with $\lim_{t\to\infty} \hat{w}(t) - \rho \leq 0$, which is satisfied with a growing (or a constant) population, taking into account (1), (7) and (9). Any path converging to $\lambda = 1$ must be ruled out since it violates the transversality condition: $\hat{\lambda} > 0$ would imply that $\rho - \hat{w} > 0$ according to (20) while the transversality condition requires $\lim_{t\to\infty} \rho - \hat{w}(t) < 0$. Any path converging to $g = \lambda = 0$ must also be ruled out as it violates (24). Thus, the economy jumps on the saddle path and asymptotically approaches the equilibrium given by (25b).

The assumption of poor substitution in the production of intermediate goods (σ < 1) entails a crowding-out of labour from the intermediate sector, which fosters economic dynamics through lower (nominal) wages. It has to be noted that goods prices might decrease as well while the number of varieties increases during adjustment; thus, decreasing *nominal* wages are by no means incompatible with constant or increasing well-being in this model. 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 (without backstop technology) the steady state is never entirely reached. Transitional dynamics for λ, g, L, and g_L are depicted in figures 3, 4, 5 and 6. From the figures one can infer that all these variables follow the predicted direction and that the adjustment process, in particular sectoral change, takes a very long time (time t is measured in years).

*** Figures 3,4, 5 and 6 ****
about here

For the inner solution, g only depends on technical parameters in the long run, that is on the elasticity of substitution in the intermediate goods sector σ and the population growth parameters ξ and μ, but not on preferences, i.e. on ρ. High values of ξ and μ are positive for innovation growth, which is characteristic for this model type. This clearly exhibits the importance of sufficient labour supply to support R&D-activities in the long run. A low σ means there is a strong intersectoral substitution effect, which leads to high innovation growth in the long-run. The discount rate has two opposing effects on innovation: on the one hand, a high discount rate discourages investments; but on the other, it accelerates the price increase of natural resources and therefore sectoral reallocation of labour. According to (25), the two effects are of the same size so that the impact of ρ is exactly cancelled.

Following (5), consumption growth is in the asymptotic equilibrium:

$$\hat{Y} = \left[(1-\beta)/\beta\right] g + \hat{X} \tag{26}$$

$\hat{X}$ 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 g must be big enough to compensate for the drag of R in the X-sector. In the (very) long run, labour is fully employed in research and we approximate $\hat{R}_X = -\rho$ so that $\hat{X} = -\rho$. Inserting (25b) in (26) we obtain aggregate consumption growth for the inner solution as:

$$\hat{Y} = \left(\frac{1}{1/\left[\xi(1-\sigma)\right]-1}\right)^{\xi(1-\sigma)} \frac{(1-\beta)}{\beta} \cdot \mu - \rho \tag{27}$$

Whether consumption growth is positive in the long run depends on the parameters; a positive $\hat{Y}$ is a possible outcome, with realistic parameter values it is even the unambiguous result. High innovation growth (from 25), large gains from diversification and monopoly power (low β) and a high response of population size on labour shares (high μ) favour positive (aggregate) consumption growth, whereas a high discount rate has a negative effect on consumption dynamics. Note that the negative effect of the discount rate stems from the negative effect of resource use on intermediates production and not from investment behaviour.

In order to get long-term sustainable consumption growth on a per capita basis, we need to calculate $\hat{Y} - g_L$. Differentiating (12) yields that a constant innovation growth rate requires the quotient π / p_n to be constant, which means using (2) and (13) that $\alpha\hat{w} + (1-\alpha)\hat{p}_n = \alpha\hat{w} + (1-\alpha)\rho = 0$. Without production of intermediates (in the limit), with a constant “output” of the research sector (a constant innovation growth rate), and a constant design price in the long run, factor incomes are fixed due to the Cobb-Douglas production technique in research (a share α of income goes to labour, 1-α to resources). Combining these results leads to asymptotic population growth as the negative wage change rate, which means:

$$g_L = \frac{1-\alpha}{\alpha}\rho \tag{28}$$

so that, for per capita consumption growth $\hat{y}$, one obtains:

$$\hat{y} = \left(\frac{1}{1/\left[\xi(1-\sigma)\right]-1}\right)^{\xi(1-\sigma)} \frac{(1-\beta)}{\beta}\cdot\mu - \frac{1}{\alpha}\rho \tag{29}$$

Again, high innovation growth, large gains from diversification and high labour force are the best means to compensate for a positive discount rate, which is now weighted with $1/\alpha$ due to positive population growth. For a positive (sustainable) outcome in the long run, the discount rate must be bounded from above according to:

$$\hat{y} \geq 0 \quad \Leftrightarrow \quad \left(\frac{1}{1/\left[\xi(1-\sigma)\right]-1}\right)^{\xi(1-\sigma)} \frac{\alpha(1-\beta)}{\beta}\cdot\mu \geq \rho \tag{30}$$

which can be met, assuming “realistic” parameter values.

Infinite long-run innovation growth, as given in (25c) when $\xi > (1-\alpha)/(1-\sigma)$ is comparable to the well-known scale models of economics growth, like Romer (1990), combined with population growth. This case is usually dismissed because it lacks empirical content. In technical terms, this case appears in the present model because the inflow of labour in the research sector, determined by the population growth parameter ξ, overcompensates the increasing scarcity of the resource input in the research sector. Combining (25c) with decreasing returns to knowledge (that is $\eta < 1$) is an interesting extension, however, see section 4.

3.3 Results for $R_{\tilde{X}} > 0$ and a backstop technology

Two issues emerge when looking at the results of section 3.2. First, resource use becomes very low and converges even to zero in the very long run. To think it is implausible that a small amount of the resource is sufficient to run a developed economy means to question the assumption of $R_{\tilde{X}} = 0$ in (6), which could be called a “free energy lunch”. Note that final goods production in (5) states that a sufficiently increasing knowledge stock can compensate for fading intermediate services, which is independent of material use, so that (5) remains to be valid in the long run. With a minimum resource input requirement for the production of intermediate goods, we have $R_{\tilde{X}} > 0$ in (6), restated for convenience:

$$X = [\bar{\lambda} \cdot L_X{}^{(\sigma-1)/\sigma} + (1-\bar{\lambda}) \cdot R_{X'}{}^{(\sigma-1)/\sigma}]^{\sigma/(\sigma-1)} - R_{\tilde{X}} \qquad (6)$$

Now, a fixed resource quantity is used to get positive *X*-production in every period, which has an effect on the intermediate goods and the resource price. As long as we have $R \geq R_{\tilde{X}}$ the economy has the same dynamics as described above, as resource markets take $R_{\tilde{X}}$ fully into account. But as soon as we have $R \leq R_{\tilde{X}}$, research and intermediates production have to stop. We reconsider this case together with the second feature, the backstop technology. Of course, if no such technology exists, a pessimistic outcome is unavoidable in this economy.

When interpreting *R* as fossil fuels, it is likely that a backstop technology becomes available. This new technology can build on resources like solar, wind, and/or tidal power or similar energies, all of them being renewable as long as the sun is shining. As soon as the price of the resource reaches unit production cost of the renewable energy, the new technology can take over the resource market so that the need for *R* vanishes and the resource price stops to increase. At this point in time t^e, the price of the resource is:

$$p_R = c_E \qquad \text{for} \qquad t \geq t^e \qquad (13')$$

where c_E is the unit production cost of the renewable energy *E*, which is assumed to be constant for simplicity. We also assume *E* to be a perfect substitute for *R* and perfect competition in *E*-production. In order to meet their first order conditions given by the original equation (13), resource owners have to choose the initial price of the exhaustible resource in such a way that all resources *R* are depleted before t^e. When the existence and the price of the backstop technology are not known from the beginning, this may cause a price jumps of the resource. Following (5) and (6), the energy share in intermediates production can be expressed as:

$$c_E \cdot E_X = \beta(1-\lambda) \qquad (31)$$

which shows that, for a given λ, the energy input in *X*-production becomes constant with given c_E. In the energy market restriction:

$$E_X + E_g = E \qquad (4')$$

we postulate a fixed supply *E* equal to the quantity demanded with given c_E. From the profit maximisation of the researchers we have:

$$\frac{E_g}{L_g} = \frac{w(1-\alpha)}{c_E \alpha} \tag{16'}$$

The labour share in intermediates production now evolves according to:

$$\hat{\lambda} = (1-\lambda)(1-\sigma)\hat{w} \tag{20'}$$

To find the equilibrium of the system with renewable energy, hypothetically suppose for a moment that wages decrease as in the previous section. With poor input substitution this would imply that, following (20'), λ falls so that $1-\lambda$ increases and E_X rises, following (31). With a given *E* in (4') this would decrease E_g which harms research and growth. Obviously, this is not an optimum. On the other hand, a constant wage implies a constant λ by (20'), a constant allocation of energy to the two sectors and a constant population, according to (14). The constant input of labour and energy in research yields constant innovation and consumption growth rate which is the optimum outcome in the case of a backstop technology. Individuals with rational expectation choose this development path. With a backstop technology, the model resembles the approach of Grossman and Helpman (1991, ch. 5) which provides constant growth rates due to constant returns to research. Summarising we thus find that for any point in time after t^e:

- (i) λ becomes constant, i.e. sectoral change stops,
- (ii) the innovation growth rate becomes constant, see also figure 2,
- (iii) the population growth rate becomes zero, and
- (iv) per-capita consumption is constantly increased in the long run.

Result (iii) corresponds to the prediction that world population will be stable in the distant future. Implication (iv) is the consequence of a constant aggregate *X*-production and a positive innovation growth rate, as is the case in basic endogenous growth models. If, however, knowledge spillovers were less than proportional, i.e. $\eta < 1$ in (1), per-capita consumption would converge to a constant value in the long run, as in semi-endogenous growth models.

We are now ready to discuss the combination of $R_{\tilde{X}} > 0$ and $E > 0$. Consider the three cases:

$$p_R\big|_{R=R_{\tilde{X}}} > c_E \qquad p_R\big|_{R=R_{\tilde{X}}} = c_E \qquad p_R\big|_{R=R_{\tilde{X}}} < c_E$$

In the first case, the renewable energy is introduced after it has become profitable, which contradicts profit maximisation of energy producers; this can be dismissed. In the second case, which is realised with profit maximising energy producers, the economy switches to the renewable energy without a jump in energy prices or a drop in output. This holds for both cases $\eta = 1$ and $\eta < 1$; the first leading to exponential growth, the second to arithmetic growth, once the discount rate is not too high, see (27). Balanced growth has then the classical properties known from recent endogenous and semi-endogenous growth literature. In the third case, the price of the renewable energy is higher than the resource price at the moment where all resources are needed to sustain intermediates production. Then, only a price jump (and a drop in real income) will lead to the use of *E* and the continuation of goods production.

Adopting a material interpretation of the resource *R*, recycling has a function which is similar to that of the backstop technology. Assuming that a recycling technology exists and that recycling starts to be profitable after the price of the natural resource has reached the level:

$$p_R = c_M \qquad \text{for} \qquad t \geq t^m \tag{13''}$$

where c_M is unit recycling cost of material *M*, assuming *M* to be a perfect substitute for *R* as well as constant returns to scale and perfect competition in the recycling activity. In our approach, similar to the reasoning above, this has the following consequences for any point in time after t^m:

(i) λ becomes constant, i.e. sectoral change stops,
(ii) the innovation growth rate becomes constant, and
(iii) the population growth rate becomes zero.

Regarding consumption, the analysis is similar to the energy case, if it is possible to completely recycle the required (constant) quantity of material at a constant speed. If, however, it is not possible to recycle one hundred percent of the material, the minimum material requirement will not be met at some point in time and production in the model has to stop. However, not all materials are non-renewable or predicted to be critical with regard to the minimum condition. For instance in food production, we primarily turn to the field of renewable natural resources. Here, limited regeneration and complementary inputs like land or water are possible bottlenecks for production. Regarding housing, natural supplies of materials seem to be (relatively) more abundant and partly renewable (e.g. timber).

4. Discussion of the results

In the present model, the progressive exhaustion of the resource stock decreases the labour income share in the intermediate goods sector, while the labour share in the research sector remains constant. As a consequence, the relative value of labour decreases and workers move from the intermediate goods to the R&D sector with a parallel increase in total labour force. Without a backstop technology, for the inner solution, the economy evolves toward a steady state where the knowledge stock grows to infinity, whereas natural resource use and the production of intermediate goods approach zero. The economy becomes "immaterial" in the long run because growth depends on increasing knowledge with an ever-decreasing input of intermediate goods and resources. In the long-run steady state, costs of innovations are (approximately) constant that is the decreasing wages compensate for increasing resource prices. With $R_{\tilde{X}} > 0$ only a backstop technology or complete recycling, respectively, guarantee constant growth in the long run. But also in this case, the mechanisms governing development before the switch to the backstop resource are crucial. Most importantly, they support incentives to do enough research raising welfare before the new technology is introduced.

Note that the pessimistic scenarios in section 3.3 are not the consequence of excessive growth during convergence. In the model, growth results from research which is less resource intensive than intermediates production in the longer run so that moderation in the growth rate does not help the economy in any way. (Sufficiently) Increasing resource prices are the best way to get a smooth transition to backstop technologies. Zero production in the long run emerges as the model outcome from the combination of a minimum resource requirement and a lack of a backstop technology and/or incomplete recycling.

The present analysis reveals specific development mechanisms with regard to population growth and input substitution. An increasing labour force is positive for growth, as knowledge creation is labour intensive while knowledge capital is a public good, favouring the whole research sector. The specific form of population growth is a convenient way to capture empirical regularities. If the growth rate of the labour force is larger than given in equation (14), the innovation growth rate becomes higher, and vice versa. Moreover, poor input substitution in the intermediate goods sector is advantageous because of structural change, that is, labour moving from the intermediate goods sector to the innovative sector. Thus R&D is not harmed, but rather supported by poor input substitution in the intermediate sector. It is even the case that an inverse relationship emerges: the lower the elasticity of substitution, the faster become structural change and growth. An elasticity of substitution of unity does not cause structural change in this approach and is therefore not a good presupposition for long-run development.

That resources are an essential input into R&D is a serious problem for development. Regarding the ratio of profit per innovation π and market value of the innovation p_n, the latter has a steady tendency to rise because of increasing resource prices (Hotelling rule). *Ceteris paribus*, rising resource prices decrease 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.

Of course, constant growth depends on a specific constellation of (production) parameters. But this is common to all endogenous growth models, which require (exactly) constant returns to capital. Even more to the point, the “knife-edge” character of (25) partly disappears when reconsidering the size of the knowledge spillovers. It is clear from (1) that the innovation growth rate positively depends on the intensity of spillovers expressed by η. On the other hand, $\xi > (1-\alpha)/(1-\sigma)$ causes ever increasing innovation growth. Thus, it can be inferred that a combination of less-than-proportional spillovers in research, i.e. $\eta < 1$, with ξ being “too large” can produce constant growth. The research output is with $\eta < 1$:

$$g = L_g{}^{\alpha} \cdot R_g{}^{1-\alpha} \cdot n^{\eta-1} \qquad \text{(1b')}$$

and the variable *u* in (22) is then given by:

$$u = \left(\frac{\lambda}{1-\lambda}\right)^{\frac{1-\alpha}{1-\sigma}} \cdot \left(\frac{1-\alpha}{\alpha}\right)^{1-\alpha} \cdot n^{\eta-1} \qquad \text{(22')}$$

So that for constant innovation growth we can use the system consisting of (1b'), (14), (17)-(21), (22') and (24) to solve for $\hat{L}_g$, $\hat{w}$, $\hat{\lambda}$, L , *w*, and *n*, given $\hat{g}=0$. To see the general mechanism it is more instructive to rewrite (17) as:

$$\hat{g} = \hat{L}_g + (1-\alpha)\hat{w} - (1-\alpha)\rho + (\eta-1)g \qquad , \qquad \text{(17')}$$

which means that the innovation growth rate *g* is diminished by the term $(1-\eta)g > 0$. Recalling that by (14) we have $g_L = -\xi \cdot \hat{\lambda}\left(1(1-\lambda)\right)$ reveals that in (17') $(\eta-1)g < 0$ can be compensated by a larger ξ fostering *L* and hence $\hat{L}_g$. Thus, for a whole array of combinations of values for ξ and η, with $\xi \geq (1-\alpha)/(1-\sigma)$ and $\eta < 1$, we find constant innovation growth rates in this model. We then indeed have the possibility to replicate results of the first strand of endogenous growth models - constant growth – without having to assume proportional spillovers. Population growth then leads to constant economic growth with decreasing returns in R&D, which corresponds to Jones (1995).

Introducing knowledge capital (instead of physical capital) as a major substitute for non-renewable resources requires a conjecture on whether there are limits to total knowledge κ, which is potentially acquirable at all times. An appropriate statement is difficult. The least we can say is that there are no indications of such limits so far. But what can be viewed as critical is the positive impact of the gains from diversification as given by (5). The positive productivity effect is assumed to be constant even when many varieties of intermediate inputs already exist. More importantly, the transformation of intermediates needs no additional resources; it could be assumed to require resources, as well. If the only required resource were labour, all results from above could be preserved. If natural resources were also necessary to assemble the intermediate input, a problem could arise when a minimum requirement exists as discussed for the production of intermediates themselves.

There are two issues, not mentioned yet, which could prevent the system from following the saddle path depicted in figure 2. First, as structural change is the main mechanism driving the result, any deviation from zero adjustment cost can become 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. Even more important, the research sector might require special skills which are not readily available in the economy. It becomes immediately clear from the results that, once we have too slow an inflow of labour into 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 adjust as indicated on an equilibrium convergence path, the percentage change of labour input in R&D becomes smaller, which entails a lower innovation growth rate according to (1b). The same holds true for the world economy, where sectoral shifts are associated with international changes in the division of labour.

Also, several equations postulate perfect foresight of the agents. In addition to the usual assumptions regarding capital markets and the intertemporal budget constraint, this model includes optimisation of resource owners. When deviating from perfect information in the resource sector, it might be that price levels are too low or price increases are too slow (at least in a first phase), for instance due to myopia. As a consequence, too little knowledge is accumulated and, combined with adjustment costs on labour markets, the increase of labour in the innovative sector becomes too sluggish compared to the model solution.

Turning to the issue of optimal economic growth, the market equilibrium reached in the present economy does not correspond to a first best-solution. Due to the positive spillovers in R&D, research efforts are too weak in equilibrium. Activities in the intermediate goods sector are also too low compared to the optimum because of monopolistic competition. This would lead to a static distortion in consumer expenditures if there were another consumer sector with goods priced at marginal costs. However, there is only one consumer sector in this economy. Regarding the intermediate goods sector, relative prices between goods reflect relative marginal cost, so that no static distortion arises. Thus, depending on the size of positive spillovers, policy could restore optimum sector size and provide optimal growth by subsidising research. According to the assumption, this would also have an impact on population growth.

5. Conclusions

In resource economics, earlier theories have identified several 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. The results establish an inverse relationship between input substitution and structural change: the lower the elasticity of substitution between inputs is, the faster the sectoral change - that is the labour inflow into R&D favouring growth - becomes. In addition, the labour force is not a problem for capital use in this model, because knowledge capital is a public good, while designs are labour intensive in production. As a consequence, per capita welfare can be increased with population growth, which is not the case when using physical capital as in the neo-classical growth model.

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 resource reallocation costs 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 resource reallocation costs, for example in the form of education costs, 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, optimum growth could be achieved by correcting for the distortion of positive externalities in R&D. The analysis of optimum growth in this set-up would also be an interesting issue for future research. When thinking of possible resource reallocation costs during sectoral change, the results suggest that facilitating labour reallocation from knowledge-extensive to knowledge-intensive sectors is the best approach to supporting sustainable development. In a more realistic model, with different labour types, this includes education efforts, which seems to be another important direction for future research. 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.

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Appendix

To obtain (9), use the price index of final goods *Y*, which is written as:

$$p_Y = \left[\int_0^n \left(p_{xj} \right)^{1-\varepsilon} dj \right]^{1/(1-\varepsilon)} \qquad \text{(A.1)}$$

With perfect competition in the *Y*-sector, this price equals the per-unit costs, so that differentiating (A.1) with respect to the price of intermediate good *i* yields, according to Shephard's Lemma, the per-unit input coefficient x_i / Y. Using this coefficient and (7), the demand for intermediate good *i* becomes:

$$x_i = \frac{\left(p_{xi} \right)^{-\varepsilon}}{\int_0^n \left(p_{xj} \right)^{1-\varepsilon} dj} \qquad \text{(A.2)}$$

For the case of many *x*-firms (large group case of Chamberlin), the denominator of (A.2) is given for the single firm so that the elasticity of demand for x_i is ε, and the optimum mark-up over marginal costs is indeed $1/\beta$, with $\beta = \left(\varepsilon - 1\right)/\varepsilon$. Hence, profits of *x*-firms used to compensate research are a share $1-\beta$ of total sales. Aggregate sales in the final goods sector are unity according to (7), so that we arrive at equation (9) for profits of a single *x*-firm.

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

$$\hat{L}_g = \frac{L}{L - L_X}\hat{L} - \frac{L_X}{L - L_X}\hat{L}_X \quad . \qquad \text{(A.3)}$$

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:

$$\frac{\pi}{p_n} + \hat{p}_n = \rho \quad , \qquad \text{(A.4)}$$

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

$$w = \alpha \cdot L_g^{\alpha-1} \cdot R_g^{1-\alpha} \cdot p_n \cdot n = \alpha \cdot p_n \cdot g \cdot n / L_g \qquad \text{(A.5)}$$

solve (A.5) for p_n and replace p_n in (A.4) and use (9) to have:

$$\frac{(1-\beta)\alpha g}{wL_g} + \hat{p}_n = \rho \quad . \tag{A.6}$$

Then use (3) and (10) to eliminate L_g and (2) to eliminate $\hat{p}_n$ in (A.6) to get expression (19) of the main text. To find (23), insert (19) into (20) to get:

$$\hat{\lambda} = (1-\lambda)(1-\sigma)g\left[\frac{1}{\alpha} - \frac{(1-\beta)}{wL-\lambda\beta}\right] \tag{A.7}$$

From (14) and (22) we get:

$$wL = -\lambda\beta\left[g/\left\{\left(\lambda/(1-\lambda)\right)^{\frac{1-\alpha}{1-\sigma}-\xi}\cdot\left((1-\alpha)/\alpha\right)^{1-\alpha}\right\}-1\right]^{-1} \tag{A.8}$$

This says that the labour income wL is directly associated to $\left(\lambda/(1-\lambda)\right)^{\frac{1-\alpha}{1-\sigma}-\xi}$ which provides intuition for (25). Inserting (A.8) in (A.7) yields (23). To confirm that (23) and (24) have the shape as shown in figure 2 it is easiest using the calibration method.

Figures

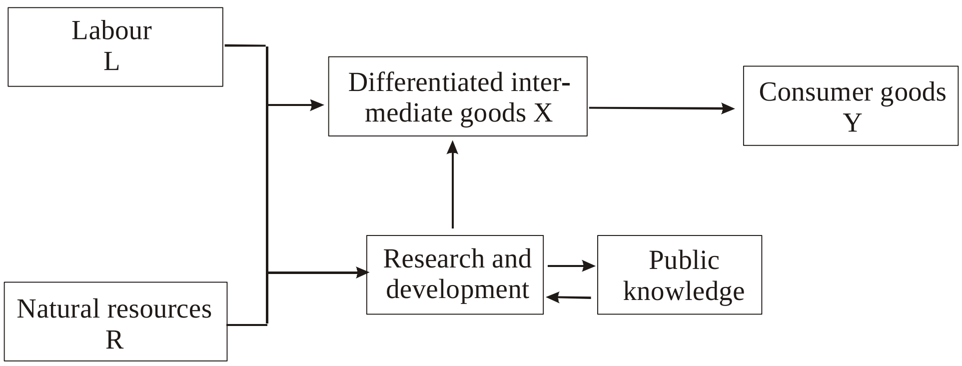

Figure 1

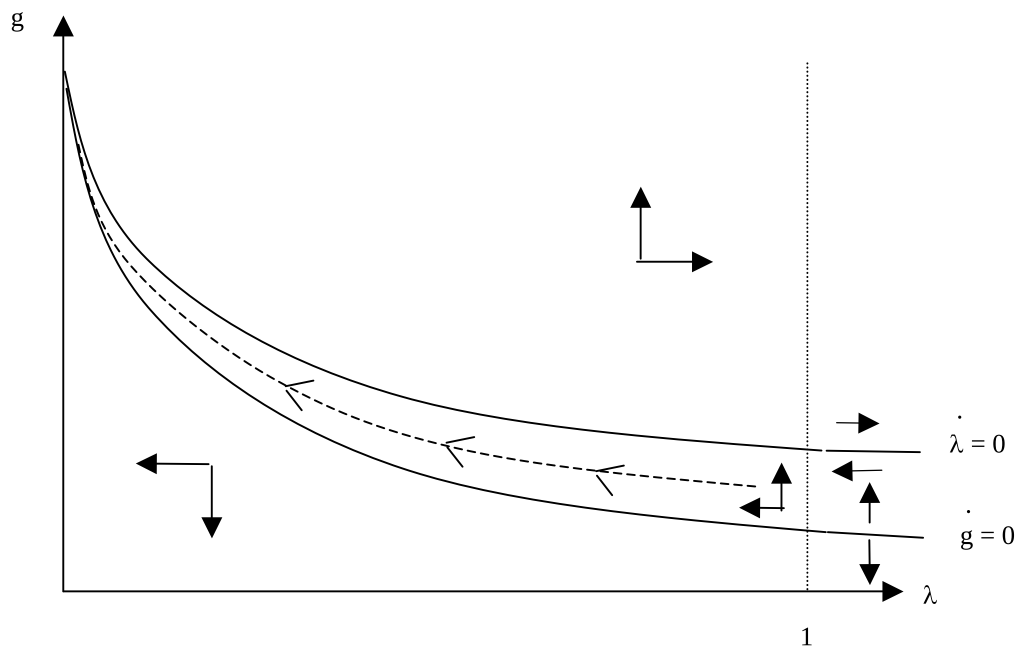

Figure 2

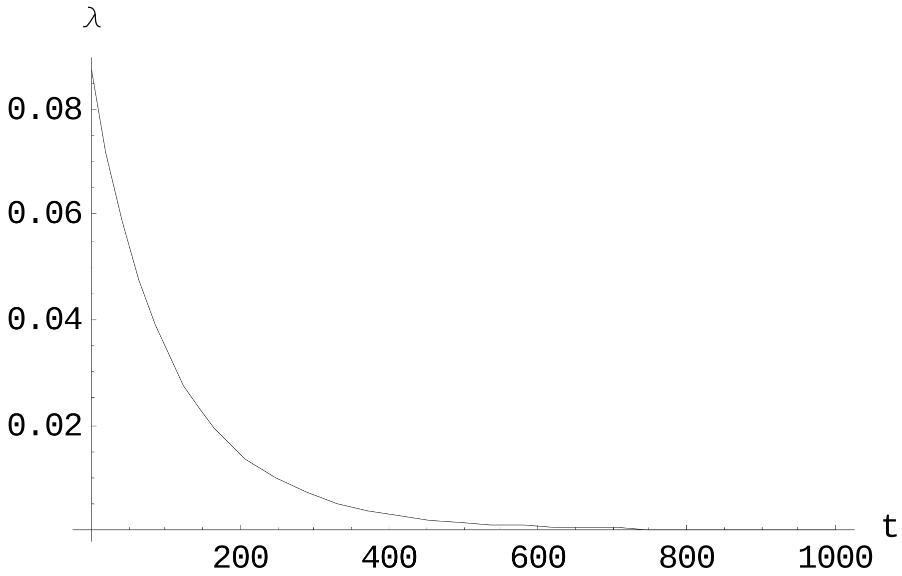

Figure 3

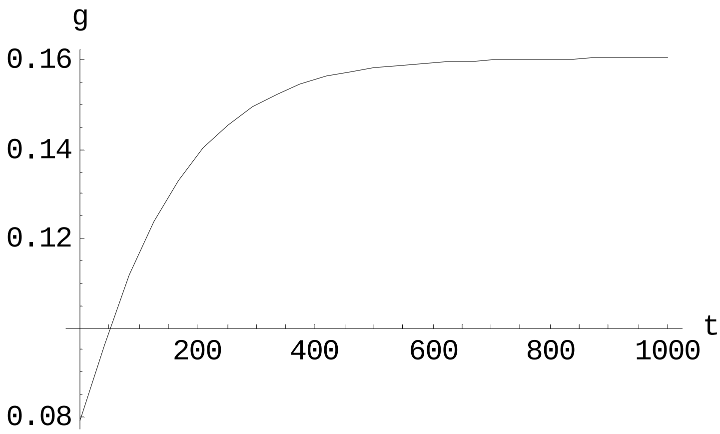

Figure 4

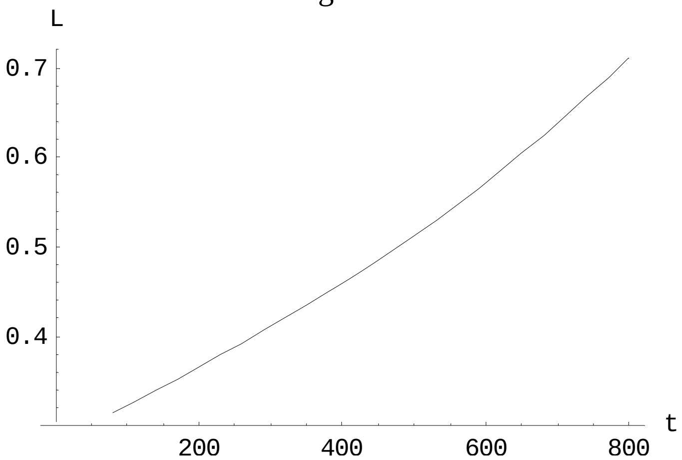

Figure 5

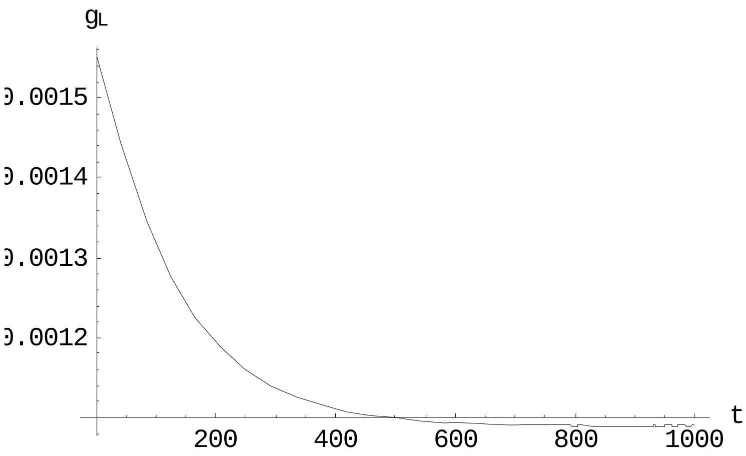

Figure 6

The parameter values used to produce figures 3-6 are:

α = **0.9;** σ = **0.3;** ρ = **0.01;** β = **0.9;** μ = **0.2**

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