Sustainability and Substitution of Exhaustible Natural Resources
How resource prices affect long-term R&D investments
Lucas Bretschger and Sjak Smulders
NOTA DI LAVORO 87.2003

SEPTEMBER 2003
SIEV – Sustainability Indicators and Environmental Valuation

Lucas Bretschger, WIF – Institute of Economic Research, ETH-Zentrum, Zurich, Switzerland and Sjak Smulders, Department of Economics, Tilburg University, The Netherlands

This paper can be downloaded without charge at:
The Fondazione Eni Enrico Mattei Note di Lavoro Series Index:
http://www.feem.it/web/activ/_wp.html
Social Science Research Network Electronic Paper Collection:
http://papers.ssrn.com/abstract_id=XXXXXX

The opinions expressed in this paper do not necessarily reflect the position of Fondazione Eni Enrico Mattei
Sustainability and Substitution of Exhaustible Natural Resources
How resource prices affect long-term R&D investments

Summary

Traditional resource economics has been criticised for assuming too high elasticities of substitution, not observing material balance principles and relying too much on planner solutions to obtain long-term growth. By analysing a multi-sector R&D-based endogenous growth model with exhaustible natural resources, labour, knowledge, and physical capital as inputs, the present paper addresses this critique. We study transitional dynamics and the long-term growth path and identify conditions under which firms keep spending on research and development. We demonstrate that long-run growth can be sustained under free market conditions even when elasticities of substitution between capital and resources are low and the supply of physical capital is limited, which seems to be crucial for today’s sustainability debate.

Keywords: Growth, Non-renewable resources, Substitution, Investment incentives, Endogenous technological change, Sustainability

JEL: Q20, Q30, O41, O33

The authors thank Christian Groth, Karl-Josef Koch, Peter Kort, Thomas Steger, Cees Withagen, and various seminar and session participants for valuable comments. Smulders' research is supported by the Royal Netherlands Academy of Arts and Sciences.

Address for correspondence:

Lucas Bretschger
WIF – Institute of Economic Research
ETH-Zentrum
WET D5
CH-8092 Zürich
Switzerland
E-mail: bretschger@wif.gess.ethz.ch
1. **Introduction**

Steady accumulation of man-made capital is the basic source of economic growth. Capital investments dropped substantially during the high-price period on markets for non-renewable resources in the 1970s. Since then, known stocks of resources have increased due to discoveries, prices have moderated, and investments have recovered. But given the finiteness of resources such as fossil fuels and precious minerals in the long run, will resource scarcity limit the future level of capital accumulation? This question is crucial in the context of sustainability, because, to maintain or increase consumption, capital has to substitute for resources in production. As soon as investments become critically low, future generations’ welfare levels fall behind those of today’s generations, which means that long-term development no longer satisfies the sustainability criterion.

Limited substitution of man-made capital for non-renewable natural resources may be the main obstacle to sustainable development. Most ecological economists argue that traditional economic theories are overly optimistic in this respect. Three major issues are under debate. First, to obtain unbounded growth in the standard neoclassical model, it has to be assumed that either the elasticity of substitution between natural resources and man-made capital is at least unity, or that exogenous resource-augmenting technological progress occurs at a constant rate, see the seminal papers of Dasgupta and Heal (1974) and Stiglitz (1974). Second, while many economic models rely on unlimited accumulation of man-made capital, ecological economists emphasise that material balances limit the use of physical capital in the long run, see Cleveland and Ruth (1997). Third, while sustained growth may be technically feasible, it is not necessarily reached under free market conditions. Low investment incentives and externalities may result in (too) little investment efforts in capital that substitutes for resources. Moreover, myopic behaviour may prevent the implementation by today’s generations of policy measures that are needed to obtain sustainability for future generations.

The present paper reconsiders investment incentives and the limits to growth in the presence of non-renewable resource scarcity in a multi-sector endogenous model. We rule out exogenous technological change that offsets resource depletion as “manna from heaven”, we bound the total supply of physical capital to take into account material balances, and we concentrate on market equilibria in which rates of return drive investment in physical capital and research and development. We show that growth can be sustained even if elasticities of substitution are small. The multi-sector structure of the model allows us to identify how substitution between sectors works as an additional mechanism for the substitution of natural resources. In particular, it will be shown that the effects on growth depend on which sector of the economy has poor or abundant substitution possibilities.

We focus on investment in knowledge capital through research and development (R&D) as the main engine of growth. R&D is often aimed at improving production techniques and thus at increasing capital productivity. For a large part of the economy, knowledge is only effective if it is embodied in certain types of physical capital. The decisive question, which is not answered yet in literature, reads: is it realistic to predict that knowledge accumulation is so powerful as to outweigh the physical limits of physical capital services and the limited substitution possibilities for natural resources? Only if the answer is positive the economy can provide a
constant or steadily increasing level of average individual utility in the long run, which is required for development to become sustainable. To eliminate hypothetical technical solutions for substitution, we focus on market outcomes to find out whether market incentives are strong enough to produce a sustainable level of investments in knowledge capital.

The present paper builds on various contributions in literature. The neoclassical literature on resource economics started with the seminal symposium issue of the Review of Economic Studies, 1974. This tradition stresses that the marginal returns on capital (and thus investment incentives) decrease when substitution possibilities between physical capital and exhaustible natural resources are low. In particular, Dasgupta and Heal (1974, 1979) show that, without technical progress and with an elasticity of substitution between natural resources and man-made capital being lower than unity, sustainable production is impossible. Indeed, if the elasticity of substitution is zero, which is implicitly assumed in the popular contribution of Meadows et al. (1972), the economic collapse is inevitable. Furthermore, Solow (1974) derives that sustainable production may be feasible without technical progress, whenever the elasticity equals unity. Provided that the production elasticity of capital exceeds the elasticity of natural resources, an appropriate constant share of income spent for savings leads to a constant flow of income, see Hartwick (1977). However, as soon as savings depend on interest rates, this result will not be obtained under free market conditions. Hence, an equilibrium with non-declining income is neither optimal nor does arise in a market equilibrium.

Taking into account technical change leads to less pessimistic results. In Stiglitz (1974), exogenous technical progress leads to sustained growth, which is feasible and optimal, provided that the elasticity is unity and the discount rate is not too high. Introducing exogenous resource-augmenting technical progress, sustained growth becomes feasible even when the elasticity is lower than unity; see Dasgupta and Heal (1979, p. 207). The optimistic view on technology in neoclassical models is criticised by Cleveland and Ruth (1997), who argue that in reality substitutability is low, that the continuity of technical progress is uncertain, and that the accumulation of physical capital is ultimately limited by biophysical constraints. Under these assumptions, sustainability indeed becomes a more demanding goal.

Long-run growth does not rely on exogenous technological change in the so-called new (or endogenous) growth theory developed in the 1990s. The endogenous accumulation of knowledge and human capital supplements the accumulation of physical capital as an engine of growth. The broadened view of man-made capital, the hypothesis of positive knowledge spillovers, and the assumed constant returns to aggregate capital inputs provide new perspectives on substitution of man-made capital for natural resources and sustained investment incentives.

For the case a unitary elasticity of substitution between capital and resource inputs, endogenous knowledge accumulation yields sustained optimal growth in the presence of non-renewable resources (Schou 1999, Scholz and Ziemes 1999, Aghion and Howitt 1998, Grimaud and Rougé 2003, Groth and Schou 2002). In the two-sector endogenous growth model with resource-augmenting knowledge production of Bovenberg and Smulders (1995), unbounded growth is feasible with elasticities of substitution between capital and resources that are smaller than unity. However, the model only applies to renewable resources. This is also true for Bretschger (1998),
who shows that lower resource use is compatible with sustained endogenous growth under free market conditions even when technical change is unbiased and the elasticity of substitution in production is smaller than unity.

The model of the present paper has the following special features.

First, we distinguish between two types of physical capital and knowledge capital. Physical capital stocks are a direct (but limited) substitute for natural resources whereas knowledge capital is directed at improving the efficiency of capital in one of the two consumer sectors. Accordingly, we call this consumer sector the “knowledge-using” sector. It is assumed that new ideas need to be embodied in a certain physical body before they can be used as a substitute for a natural resource. The heterogeneity of physical capital opens the possibilities of productivity gains in the knowledge-using sector by increasing division of labour. Applying the idea of expansion-in-varieties, this part of the model builds on Romer (1990) and Grossman and Helpman (1991). The increasing division of labour is assumed to have a similar effect on the efficiency of natural resource use, which is a scale effect that has to be distinguished from the basic substitution effect. In the other consumer sector, capital productivity depends on the input of skilled labour. As skilled labour is also an important input into R&D, which produces knowledge through positive spillovers, this sector is called “knowledge-competing” sector. Deviating from unitary elasticities, it will become evident that in the knowledge-using sector, a high elasticity of substitution fosters economic growth. In the knowledge-competing sector, however, a low elasticity is more favourable for long-term development.

Second, we introduce a non-renewable resource, which represents oil, precious metals, minerals etc. The resource is used in combination with physical capital to produce the two final outputs in the knowledge-using and the knowledge-competing sector. Natural resources are thus important for both sectors. Accordingly, a double-tracked input substitution process is modelled below.

Third, we emphasise the distinction between the market value and the production cost of additional designs. This alludes to Tobin’s q-theory of investment. Profit expectations in research are a variable that explicitly depends on the price of physical capital and, indirectly, on the price of the natural resource. On the other hand, costs of inventions are determined in a separate R&D sector, where skilled labour and knowledge are used as inputs. As skilled labour is also used in combination with the natural resource to produce final output, production cost in the research lab depend on resource prices.

Fourth, we do not exclusively focus on balanced growth paths but also look at adjustment paths leading to long-run equilibria. During adjustment, goods and factor prices as well as relative sectoral outputs are allowed to vary. It is shown how the size of the sectors and the growth rate converge to long-run values according to the assumed parameters for substitution.

The remainder of the paper is organized as follows. In section 2, the theoretical five-sector model of the economy with two consumer goods is presented in detail. Section 3 shows how the model can be solved. Section 4 provides results for transitional dynamics and long-run growth for different types of parameter and substitution conditions. Section 5 concludes.
2. The model

2.1 Overview

We introduce three primary input factors: a non-renewable natural resource $R$ as well as skilled labour $S$ and unskilled labour $L$, see figure 1. Unskilled labour produces differentiated physical capital components, which are assembled to an aggregate physical capital stock $K_Y$. Skilled labour is employed in two activities. First, the development of designs for new capital components requires skills. Second, skilled labour produces the physical capital good $K_T$. The natural resource is combined with the two capital stocks and produces “standard” $T$-goods in the knowledge-competing sector and “high-tech” $Y$-goods in the knowledge-using sector. The substitution of capital for the natural resource takes place in both sectors: in the high-tech sector, which determines the reward to research investments, and in the standard sector, which affects wages of skilled labour and therefore production costs of new designs. Knowledge capital is accumulated through positive spillovers in research and is an input into subsequent R&D; it is the driving force for long-run development.

The essential elements of our model set-up are, first, substitution across sectors between goods that differ in their knowledge intensity and, second, (poor) substitution between man-made inputs and resources within sectors. The degree of within-sector substitution may differ across sectors. By combining these different mechanisms, the model is suited to capture the basic substitution process in modern economies.

![Fig. 1](about here)

2.2 Production sector

Let us discuss the different productive sectors of the model in turn, beginning with high-tech goods, followed by standard goods, the two types of capital goods, and, finally, R&D.

**High-tech goods $Y$** are produced with different physical capital services $k$ and natural resources $R$ as inputs. We adopt a nested CES-function. The constant elasticity of substitution between aggregate capital and natural resources $\sigma$ in the $Y$-sector take any positive value. Aggregate capital input is a CES-index of a continuum of differentiated components of mass $n$; the constant elasticity of substitution between them equals $1/(1 - \beta)>0$. Each producer in the high-tech sector uses all types of components as well as natural resources, according to:

\[
Y = \left[ \bar{\theta} \left( \int_0^n k_j^\sigma \, dj \right)^{\frac{\sigma-1}{\beta \sigma}} + (1 - \bar{\theta}) \left( n^\delta \cdot R \right)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}},
\]  

(1)
where $0 < \beta, \bar{\sigma} < 1$, and $\delta, \sigma > 0$ are given parameters. In a symmetrical equilibrium, the quantities of capital services $k$ are equal for the different components, i.e. $k_1 = k_2 = \ldots = k_n = k$. With $n$ different components at a certain point of time, aggregate input of capital services is denoted by

$$K_Y = n \cdot k.$$  \hspace{1cm} (2)

Due to gains from specialization, an expansion-in-varieties of capital components leads to productivity gains of $Y$-producers. According to (1), holding aggregate capital input $K_Y$ constant, the production of the high-tech goods increases with the number of capital components, $n$. In a similar way, it is reasonable to argue that $Y$-producers are able to use natural resources more efficiently, the higher is the specialization of capital components a given amount of resources is combined with. We will come back to this point when discussing the general results at the end of section 4. The gains from specialization for both types of inputs can be seen more clearly when reformulating (1) by using (2) to get:

$$Y = \left[ \delta \left( \frac{1-\beta}{n^\sigma K_Y} \right)^{\frac{\sigma-1}{\sigma}} + (1-\delta)(n^\delta R_Y)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}}.$$

The specialization effect of an additional capital variety is given by $(1 - \beta)/\beta$ whereas the efficiency gain of resources $R$ used with additional varieties is expressed by the factor $\delta$. If $\delta = 0$, there is no efficiency gain from resource use. Rearranging the above equation, we find:

$$Y = n^{(1-\beta)/\beta} \cdot Q = n^{(1-\beta)/\beta} \left[ \delta \left( \frac{1-\beta}{n^\sigma K_Y} \right)^{\frac{\sigma-1}{\sigma}} + (1-\delta)(n^{-\nu} R_Y)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}}$$

with $\nu = (1 - \beta)/\beta - \delta$. The expression in brackets on the r.h.s. of (3) corresponds to the familiar CES-approach of resource economics, see Dasgupta/Heal (1979, p. 199). It aggregates capital inputs $K_Y$ and effective resource inputs $n^{-\nu} R_Y$ into a composite input $Q$. The total factor productivity term preceding brackets is the result of the expansion-in-varieties approach according to Romer (1990) and Grossman/Helpman (1991). Note that the degree of specialization (measured by $n$) affects productivity in two ways. First, it raises total factor productivity. Second, it introduces a bias in technological change: if $(1 - \sigma)\nu < 0$ technological change is capital-using; if $(1 - \sigma)\nu > 0$, it is resource-using.

The market for $Y$-goods is fully competitive. Producers take prices of output, resource inputs and capital components (denoted by $p_Y$, $p_R$, and $p_{kj}$, respectively) as given. They maximize total profits $p_Y Y - p_R R_Y - \int_0^n p_{kj} k_j dj$, subject to the production function (1). Under symmetry ($p_{kj} = p_{ki}$), see (2), relative demand for capital and energy is given by:
The production of standard goods $T$ requires homogenous capital $K_T$ and resources $R_T$ as inputs. We use again a CES-formulation:

$$
T = \left[ \eta \cdot K_T^{\omega-1} + \left( 1 - \eta \right) R_T^{\omega-1} \right]^{\omega} 
$$

with $\omega$ being the elasticity of substitution in the $T$-sector and $0 < \eta < 1$. Producers take prices as given and maximize profits $p_T T - p_{KT} K_T - p_R R_T$ subject to (5). This gives relative factor demand:

$$
\frac{K_T}{R_T} = \left( \frac{\eta}{1 - \eta} \right)^{\omega} \left( \frac{p_{KT}}{p_R} \right)^{-\omega} 
$$

The differentiated capital services $k$ are produced by monopolists. The production of one unit requires one unit of unskilled labour $L$. The profit maximizing monopolistic supplier faces a price elasticity of demand equal to $-1/(1 - \beta)$. As in the standard Dixit-Stiglitz approach, this follows from the $Y$-producers demand for $k$. Thus, the monopolist optimally sets a rental rate that is a mark-up $1/\beta$ times the labour costs $w_L$. All monopolistic suppliers set this same price:

$$
p_{kY} = w_L / \beta 
$$

Associated profits $\pi$ for each supplier of a capital components can be calculated as:

$$
\pi = (1 - \beta) \cdot p_{kY} \cdot K_Y n 
$$

Profits are used to cover the expenses for fixed costs in the production of $k$-goods, which consist of payments for the blueprint of the capital component. Each design contains the know-how for the production of one capital component $k$. Thus, each $k$-firm has to acquire one design as an up-front investment before it can start production.

New blueprints $n$ are produced in the R&D sector. Per blueprint, $a/n$ units of skilled labour are required. Here it is assumed that an increase in variety also increases the stock of public knowledge on which R&D builds so that research cost decline with $n$. Thus, the cost of a blueprint, $c_n$, equals:

$$
c_n = (a / n) \cdot w_s 
$$

The production of one unit of homogenous capital $K_T$ used in the $T$-sector requires skilled labour $S_T$ and materials inputs $M$ according to a Cobb-Douglas production
function \( K_T = S_T M^\mu \). We assume that materials are fully recyclable, such that each moment in time a fixed stock, of which we normalize the size to \( M = 1 \), is available. For simplicity, we disregard recycling costs, set \( \nu = 1 \), and assume perfect competition. The price of capital then equals the wage of skilled labour \( w_S \):

\[
p_{KT} = w_S.
\]  

(10)

### 2.3 Capital markets

There are three assets i.e. investment possibilities in the economy: riskless bonds, patents for the production of capital varieties \( k \), and natural resources \( R \). Let \( p_n \) denote the market price of a patent in time \( t \) and consider the brief time interval between \( t \) and \( t + dt \). In this time, the return for an investment of size \( p_n \) in a bond is \( r \cdot p_n \cdot dt \). A firm holding a patent for the production of an intermediate capital input earns an infinite stream of profits. Per-period profit \( \pi \) is given in (8). So in the same time interval, the total return on a patent is \( \pi \cdot dt + \hat{p}_n \cdot dt \) which yields the following no-arbitrage condition:

\[
\pi + \hat{p}_n = r \cdot p_n
\]  

(11)

Perfect capital markets affect the timing of R&D. Over a small period \( dt \) with positive investment in R&D, inventors should be indifferent between incurring the R&D cost \( c_n \) at the beginning or the end of the period. That is, the return to postponing investment, which amounts to interest payments on postponed costs \( r c_n dt \), should equal the cost of postponing, which amount to forgone dividends and change \( (\pi + \hat{c}_n) \cdot dt \). However, if over a small period the net benefits of postponing investment are positive, no investment will take place in this period. Hence, we may write the following no-arbitrage condition:

\[
\pi + \hat{c}_n \leq r \cdot c_n \quad \text{with equality (inequality) if } \dot{n} > 0 \ (\dot{n} = 0).
\]  

(12)

The final no-arbitrage condition concerns the comparison of returns between bonds and stocks of natural resources. Resource owners extract resources without costs and supply them at spot prices, which are denoted by \( p_R \) per unit of \( R \). The returns for investments of size \( p_R \) in bonds during the brief time interval between \( t \) and \( t + dt \) are \( r \cdot p_R \). In analogy to above, the return per unit of the stock of natural resource \( R \) can be expressed as \( \pi_R \cdot dt + \hat{p}_R \cdot dt \). However, it is a basic characteristic of natural resources to have no direct return like capital goods, i.e. it is that \( \pi_R = 0 \). So in equilibrium we are left with:

\[
\hat{p}_R = r \cdot p_R
\]  

(13)

The Hotelling-rule in (13) implies that resource owners are exactly indifferent between selling resources (and investing the profit with interest rate \( r \)) and preserving the stock of resources. The compensation for keeping the stock is the price rise of the resource.
2.4 Factor markets
The total stock of resource $R$ at time $t$ is denoted by $W_R$. It is depleted according to:

$$W_R = -R_t - R_y, \quad W_R(0) \text{ given, } W_R(t) \geq 0,$$

(14)

$$\int_0^\infty (R_t(t) + R_y(t)) dt = W_R(0),$$

(15)

which says that any flow of resource use depletes the total resource stock proportionally, that the resource stock is predetermined, and that the stock can never become negative. Profit maximization by resource owners implies that the price of natural resources increases at a rate equal to the interest rate, see (13). Resource owners do not have an incentive to conserve a part of the stock so that total extraction must be equal to the total resource stock in equilibrium, see (15). Total extraction can be ensured by setting the optimum price at the beginning of optimisation. Initial price level and price increase of natural resources do not deviate from the optimum path, provided that agents form rational expectations. This will be assumed in the following.

The market for skilled labour is in equilibrium if the fixed supply $S$ equals demand for production of capital and for research labour:

$$S = K_r + (a/n) \cdot n$$

(16)

The market for unskilled labour clears, which requires that demand for unskilled labour from the differentiated capital goods sector equals the fixed supply $L$:

$$L = K_y.$$

(17)

2.5 Consumer sector
The representative household maximizes a lifetime utility function subject to the usual intertemporal budget constraint; the function is additively separable in time and contains logarithmic intratemporal utility of the Cobb-Douglas type:

$$U(t) = \int_0^\infty e^{-\rho(t-\tau)} \log C(\tau)d\tau \quad \to \text{max}$$

(18)

with $C = Y^\phi \cdot T^{1-\phi}$

(19)

The Cobb-Douglas specification in (19) implies constant expenditure shares for $T$- and $Y$-goods. Accordingly, relative demand for final goods is given by:

$$\frac{p_y \cdot Y}{p_T \cdot T} = \frac{\phi}{1-\phi}.$$

(20)
where $p_T(p_Y)$ is the price of T-goods (Y-goods). Intertemporal optimisation gives the well-known Keynes-Ramsey rule stating that the growth rate of consumer expenditures is equal to the difference between the nominal interest rate $r$ and the discount rate $\rho$, that is:

$$\hat{p}_T + \hat{T} = r - \rho. \quad (21)$$

where hats denote growth rates.

Finally, intertemporal utility maximization requires that the value of household wealth, $np_n$, discounted by the interest rate, $r$, approaches zero if time goes to infinity. This transversality condition can be written as:

$$\lim_{t \to \infty} \hat{n}(t) + \hat{p}_n(t) - r(t) < 0. \quad (22)$$

### 3. Solving the model

To facilitate the analysis, we reduce the model to three differential equations, which characterize the dynamics of the system. Our three key variables will be the capital shares in the knowledge-using and knowledge competing sectors, to be denoted by $\theta$ and $\eta$ respectively, and the growth rate of product variety, also to be interpreted as the rate of innovation or the growth rate of the (public) knowledge stock, to be denoted by $g$. Hence, we define:

$$\theta = \frac{p_{K_Y} K_Y}{p_Y Y} \quad (23)$$

$$\eta = \frac{p_{K_T} K_T}{p_T T} \quad (24)$$

$$g = \hat{n}. \quad (25)$$

Note that the initial knowledge stock, $n(0)$, is given. Because total revenue equals total cost for energy and capital inputs, the energy shares in the two sectors are given by $1 - \eta = p_R R / p_T T$ and $1 - \theta = p_K K / p_Y Y$, respectively. Inserting the definitions (23) and (24) into the firms demand functions (4) and (6), differentiating (4) and (7) with respect to time and using (7), (10) and (13) to eliminate capital and resource prices, we find:

$$\hat{\theta} = -(1 - \theta)(1 - \sigma)(r - \hat{\omega}_L + \nu g), \quad (26)$$

$$\hat{\eta} = -(1 - \eta)(1 - \omega)(r - \hat{\omega}_S). \quad (27)$$
The equations show how interest cost, wage changes, and technical change (only in the Y-sector) drive factor substitution.

Substituting (23) and (24) into (19) to eliminate $p_T Y$ and $p_T T$ and inserting (7) and (17), we find:

$$\frac{w_L}{w_S} = \frac{\theta}{\eta} \frac{\beta \phi K_T}{1 - \phi L} . \quad (28)$$

This equation reflects that in final-goods market equilibrium the relative wage of unskilled labour increases with the share of capital in the unskilled-labour-intensive Y-sector ($\theta$), increases with the share of the Y-good in total demand for final goods ($\phi$), and falls with the relative abundance of unskilled labour.

Substituting $\hat{p}_T + \hat{T} = \hat{w}_S + \hat{K}_T - \hat{\eta}$, which follows from (24) and (10), into (21), we find:

$$r - \hat{w}_S = \rho + \hat{K}_T - \hat{\eta} . \quad (29)$$

Substituting (25) into (16), we express $K_T$ in terms of the innovation rate:

$$K_T = S - ag . \quad (30)$$

From (28), (29) and (26) and from (29), (30) and (27), we derive the following equations of motion for the cost shares, respectively:

$$\dot{\theta} = -\theta \left( \frac{(1-\sigma)(1-\theta)}{1-(1-\sigma)(1-\theta)} \right) (\rho + v_g) \quad (31)$$

$$\dot{\eta} = -\eta \left( \frac{(1-\omega)(1-\eta)}{1-(1-\omega)(1-\eta)} \right) \left( \rho - \frac{\dot{g}}{S / a - g} \right) \quad (32)$$

Dividing the capital market equilibrium (12) by the R&D cost $c_n$, inserting (7), (8), (9), (17) and (25), we find:

$$r - \hat{w}_S \geq \frac{1 - \beta}{\beta} \frac{L}{a} \frac{w_L}{w_S} - g . \quad \text{with equality for } g > 0 \quad (33)$$

This right-hand side of (33) represents the rate of return to R&D. It increases with the mark-up rate $1/\beta$ and with the size of the market as captured by $L$, which is the labour supply that produces the stock of physical capital in which innovations are embodied. The rate of return falls with the cost of R&D, which is proportional to $aw_S$.

Substituting (30), (28), (27) and (32) into (33), we find:
\[
\dot{g} = \left( \frac{S}{a} - g \right) \left[ 1 - (1 - \omega)(1 - \eta) \left( g - \Phi \frac{\theta S}{\eta a} + \rho \right) \right], \quad \text{for } g > 0, \quad (34)
\]

\[
\frac{\rho}{1 - (1 - \omega)(1 - \eta)} > \Phi \frac{\theta S}{\eta a}, \quad \text{for } g = \dot{g} = 0, \quad (35)
\]

with \( \Phi = \frac{(1 - \beta)\phi}{1 - \phi} \).

Equations (34), (32) and (31) now form a dynamic system in three variables, which are the rate of innovation \( g \), the share of capital in \( Y \)-goods production \( \theta \), and the share of capital in \( T \)-goods production \( \eta \). None of these three variables is predetermined, so we need to formulate the conditions that restrict initial values and end values of them. Crucial is that cumulative extraction cannot exceed the available resource stock, see (13) and (14). We therefore need to focus on extraction and express it in terms of our key variables \( g \), \( \eta \) and \( \theta \). Eliminating prices between (4) and (23) and between (6) and (24), and combining (23), (24) and (20), we find, respectively:

\[
R_Y = \left( \frac{\theta}{1 - \theta} \right)^{\sigma/(1 - \sigma)} \left( \frac{\bar{\theta}}{1 - \bar{\theta}} \right) Ln^a \quad (36)
\]

\[
R_T = \left( \frac{\eta}{1 - \eta} \right)^{\sigma/(1 - \sigma)} \left( \frac{\bar{\eta}}{1 - \bar{\eta}} \right) (S - ag) \quad (37)
\]

\[
\frac{R_Y}{R_T} = \frac{1 - \theta}{1 - \eta} \frac{\Phi}{1 - \beta} \quad (38)
\]

After choosing initial values for \( \theta \), \( \eta \), and \( g \), equations (36), (37) and (38), together with the given initial value \( n(0) \) and equations (25), (32), (31), (34), and (35), allow us to calculate the extraction path. The initial values for \( \theta \), \( \eta \), and \( g \) must be chosen such that the no-depletion condition (15) holds and the transversality condition (22) holds. In a steady state without innovation, \( \lim_{t \to \infty} \dot{n}(t) = 0 \), discounted stock prices change at rate \( \hat{p}_n - r = -\pi / p_n < 0 \), see (11). The transversality condition (22) then always holds. In a steady state with innovation (\( \lim_{t \to \infty} g(t) > 0 \)), stock prices equal the cost of innovation, \( p_n = aw_t / n \), see (9), (11) and (12). Then, the transversality condition (22) boils down to:

\[
\lim_{t \to \infty} r(t) - \hat{w}_t(t) > 0 \quad \text{for } \lim_{t \to \infty} g(t) > 0 \quad (39)
\]

For future use, we express sectoral depletion rates in both final goods sectors in terms of the three key variables. Differentiating (36) and (37) with respect to time and substituting (31) and (32), we find, respectively:
\[
-\dot{R}_Y = \frac{1}{1-(1-\sigma)(1-\theta)} \left[ \sigma \rho + \nu g(1-\sigma)\theta \right] 
\]
\[
-\dot{R}_T = \frac{1}{1-(1-\omega)(1-\eta)} \left[ \omega \rho + \frac{\dot{g}}{S/a-g} (1-\omega)\eta \right] 
\]

4. Solutions for different substitution conditions

To see the different mechanisms in the model most clearly, it is useful to first consider three specific cases for parameter values which are obtained by setting either elasticity of substitution or both elasticities equal to one. After that, the general case is evaluated in section 4.4.

4.1 Cobb-Douglas Case

We first study unitary elasticities both in the knowledge-using and the knowledge-competing sector, i.e. \( \sigma = \omega = 1 \). From (32) and (31), we see that \( \theta \) and \( \eta \) are constant; (36) and (37), or equivalently (4) and (7), reveal that they equal the parameters \( \bar{\theta} \) and \( \bar{\eta} \), respectively. Then the dynamics is represented by a single differential equation for \( g \), given by (34), which can now be simplified as:

\[
\dot{g} = (S/a - g) \left\{ g \left[ 1 + \Phi \frac{\bar{\theta}}{\bar{\eta}} \right] - \left[ \Phi \frac{\bar{\theta}}{\bar{\eta}} \frac{S}{a} - \rho \right] \right\} \quad \text{if} \quad \Phi \frac{\bar{\theta}}{\bar{\eta}} \frac{S}{a} \geq \rho \\
g = 0 \quad \text{if} \quad \Phi \frac{\bar{\theta}}{\bar{\eta}} \frac{S}{a} < \rho
\]

The corresponding phase diagram is drawn in figure 2 for the case \( \Phi(\bar{\theta}/\bar{\eta})(S/a) > \rho \). The path converging to a negative growth rate must be ruled out. The same holds for the path converging to \( g = S/a \), since it violates the transversality condition (39) (first substituting \( \bar{\eta} = 0 \), (30) and (34) into (29), and then setting \( g = S/a \), we find \( r - \dot{\omega}_S = -S/a < 0 \)). Hence, the equilibrium growth rate jumps to the value for which \( \dot{g} = 0 \) and remains there. Thus, the equilibrium growth equals:

\[
\bar{g} = \max \left\{ 0, \frac{(\Phi \bar{\theta}/\bar{\eta})(S/a) - \rho}{1 + (\Phi \bar{\theta}/\bar{\eta})} \right\} 
\]

The rate of innovation is stimulated by a higher supply of skilled labour \( S \), a lower unit input coefficient research \( a \), and a lower discount rate \( \rho \). This corresponds to the findings in other R&D-models. Our multi-sector model reveals how innovation incentives depend on the expenditures shares and factor shares. In particular, the rate of innovation increases with \( \Phi \bar{\theta}/\bar{\eta} \), which captures three effects. First, since innovation takes place in the \( Y \)-sector only, a higher expenditure share on \( Y \)-goods \( (\Phi) \) boosts innovation. Second, since innovation is embodied in physical capital
goods in the Y-sector, a greater role for capital, as measured by a larger capital share in the Y-sector $\bar{\theta}$, increases the market for innovations and boosts research. Alternatively, a high value for $\bar{\theta}$ implies a low share of non-renewable resources in Y-production: the sector is less dependent on non-man-made inputs and this stimulates innovation. Finally, and most important, innovation is high when the share of non-renewable resources in the T-sector is high (low $\bar{\eta}$). If the T-sector relies heavily on resources rather than skilled labour input, less skilled labour is allocated in this sector, and more becomes available for the research sector. Hence, greater natural-resource dependence in the knowledge-competing sector reduces output in this sector, but raises innovation.

Fig. 2
(about here)

To study how resource dependence is related to growth of consumption rather than innovation, we need to calculate output growth in both final goods sectors. Besides innovation, only depletion of resource inputs drives growth, since labour and materials inputs are constant. The rate of depletion equals the discount rate ($-\dot{R}_Y = -\dot{R}_T = \rho$), see (40)-(41). Differentiating consumption and production functions (19), (3) and (5) with respect to time and substituting (40)-(41), we obtain the consumption growth rate according to:

$$\dot{C} = \left[ \bar{\theta} (1-\beta) / \beta + (1-\bar{\theta}) \delta \right] \phi g - \left[ \phi (1-\bar{\theta}) + (1-\phi)(1-\bar{\eta}) \right] \rho.$$  

Consumption grows at a positive rate only if the right-hand side of (43) is positive: innovation (at rate $g$, see first term at right-hand side) has to be sufficient to offset the decline in resource inputs (at rate $\rho$, see second term) and to overcome the constancy of physical capital inputs. For a given rate of innovation ($g$), consumption growth is the bigger, the higher are the gains from specialisation (low $\beta$), the larger are productivity spillovers ($\delta$), the lower is the discount rate, and the higher are the factor shares $\bar{\theta}$ and $\bar{\eta}$. A lower discount rate ($\rho$) reduces resource depletion and implies a smaller drag on growth from the scarcity of non-renewable resources. For a given rate of innovation $g$, a higher capital share in both sectors ($\bar{\theta}$ and $\bar{\eta}$) imply smaller dependence of production on non-man-made scarce resource inputs, which is good for growth.

Overall, resource dependence in the knowledge-competing sector (as measured by $1-\bar{\eta}$) has an ambiguous impact on growth. First, higher resource dependence makes T-goods more expensive and shifts skilled labour to innovation activities, which increases growth through innovation (see (42)). However, higher resource dependence implies that the decline in necessary resource inputs in production weighs more heavily, which reduces consumption growth (see (43)). Substituting (42) into (43) and differentiating growth with respect to $\bar{\eta}$, we find:

$$\frac{\partial \dot{C}}{\partial \bar{\eta}} < 0 \Leftrightarrow \frac{1}{\bar{\theta} (1-\beta)} \left( \frac{1-\phi}{\phi} \right)^2 + \left( \frac{1-\phi}{\phi} \right) - \tau \left( \frac{S}{a \rho} + 1 \right) < 0,$$
where $\tau$ stands for the expression in the first brackets in (43) and represents the effect of innovation on output growth in the Y-sector. The inequality reveals that for $\eta(1-\phi)/\phi$ sufficiently small, higher resource dependence in the knowledge-competing sector goes together with higher growth rates.

We finally need to solve for the initial levels. Initial resource use is calculated by using the fact that the rate of extraction $\dot{R}$ decreases with the discount rate (see 40 and 41) and cumulative extraction corresponds to total resource stock. This gives $R_\tau(0) + R_{\tau}(0) = \rho \cdot W_R(0)$. For a given initial knowledge stock $n(0)$, we can calculate the initial consumption and income levels. Note that a change in the initial knowledge stock, $n(0)$, has no effect on initial factor shares and the innovation rate. The reason is that with a Cobb-Douglas production function, technological change is neutral with respect to production factors and affects levels of output without changing relative prices.

4.2 Poor substitution in the knowledge-using sector

The assumption of a unitary elasticity of substitution in the knowledge-competing sector, i.e. setting $\omega = 1$, reduces the model to a two-dimensional system in $g$ and $\theta$, given by the differential equations:

$$\dot{g} = \left(\frac{S}{a} - g\right) \left\{ g \left[ 1 + \phi \frac{\theta}{\eta} \right] - \left[ \phi \frac{\theta}{\eta} \frac{S}{a} - \rho \right] \right\},$$

$$\dot{\theta} = - (\rho + \nu g) \cdot \theta \cdot \frac{(1-\sigma)(1-\theta)}{1 - (1-\sigma)(1-\theta)}.$$  

The corresponding phase diagram is depicted in figure 3. We have drawn the diagram assuming that $\nu$ is positive, so that the $\dot{\theta} = 0$ locus appears in the negative quadrant. If $\mu$ is positive, but sufficiently small to prevent the $\dot{\theta} = 0$ locus to intersect the $\dot{g} = 0$ locus, the dynamics will be qualitatively the same. Any path converging to $g = S/a$ violates the transversality condition and must be ruled out. Any path that hits the $g = 0$ line at $\theta > \bar{\eta} \rho / \Phi S$ must also be ruled out since it violates (35). It can be seen that there is a unique trajectory that neither does violate the transversality condition (39) nor condition (35). This saddle path lies below the $\dot{g} = 0$ locus. The economy jumps on the saddle path and asymptotically approaches the equilibrium with $\theta = g = 0$.

Which point on the saddle path is the equilibrium for a given initial resource and knowledge stock, is determined by (15), (36) and (38). The saddle path defines $\theta$ as a function of $g$, say $\theta(t) = f(g(t))$. Substituting this and $\bar{\eta} = \bar{\eta}$ into (37) and (38), we find aggregate resource use, $R_\tau(t) + R_{\tau}(t)$, as a function of $g(t)$. Since we know the equation of motion for $g$, this solves for the entire extraction path. In equilibrium, $g(0)$ must be such that cumulative extraction over the entire horizon exactly equals the initial resource stock $W_R(0)$. It now follows that a higher initial resource stock implies an initial point further to the right on the saddle path. So a (sufficiently large)
resource boom boosts short-run growth. A higher initial knowledge stock increases depletion for given $\theta$ and $g$, see (36). Hence to prevent running out of resources, a higher knowledge stock implies higher resource prices, and a lower initial growth rate in equilibrium.

During the adjustment, the rate of innovation $g$ gradually falls to zero and then remains zero; the share of capital $\theta$ steadily falls. With rising resource prices and poor substitution in the $Y$-sector, compensation for R&D-investments is steadily falling. Skilled labour moves from the R&D to the $T$-sector. From the phase diagram it is clear that innovation stops when $\theta$ reaches the level that is implied by the intersection between the $\dot{g} = 0$ locus and the $g = 0$ axis, $\theta = \bar{\eta} a \rho / \Phi \bar{S}$. This means that in finite time, resource prices reach such a high level that R&D becomes unprofitable. From then on, all skilled labour is in the knowledge-competing sector, knowledge growth is zero, and the growth rate of consumption is negative because of resource depletion.

Fig. 3
(about here)

The main conclusion from this case is that poor substitution in the knowledge-using sector is unambiguously unfavourable for innovation and growth.

4.3 Poor substitution in the knowledge-competing sector
Assuming a unitary elasticity for the knowledge-using sector, i.e. setting $\sigma = 1$ so that $\theta = \bar{\theta}$, see (31) and (36), the model reduces to a two-dimensional system in $g$ and $\eta$, that reads, according to (34) and (32):

$$\dot{g} = \left( \frac{S}{a} - g \right) \left[ g \left( 1 + \frac{\bar{\theta}}{\eta} \right) - \left( \frac{\bar{\theta}}{\eta} \frac{S}{a} - \frac{\rho}{1 - (1 - \omega)(1 - \eta)} \right) \right] \left[ 1 - (1 - \omega)(1 - \eta) \right],$$

$$\eta = \eta (1 - \omega)(1 - \eta) \left[ g \left( 1 + \frac{\bar{\theta}}{\eta} \right) - \frac{\bar{\theta}}{\eta} \frac{S}{a} \right].$$

The corresponding phase diagram is depicted in figure 4. Any path converging to $\eta = 1$ must be ruled out since it violates the transversality condition (it implies $\bar{\eta} > 0$, so that $r - \dot{\bar{\eta}} < 0$, see (27), which violates (39)). Any path converging to $g = 0$ and $\eta = 0$ must also be ruled out since it violates (35). Hence, the economy jumps on the saddle path, which lies between the $\eta = 0$ and $\dot{g} = 0$ loci, and asymptotically approaches the equilibrium with $\eta = 0$ and $g = S/a$.

Which point on the saddle path is the equilibrium for a given initial resource and knowledge stock, is determined by (15) and (37)-(38). The saddle path defines $\eta$ as a function of $g$, say $\eta(t) = F(g(t))$. Substituting this and $\theta = \bar{\theta}$ into (37) and (38), we
find aggregate resource use, \( R_T(t) + R_Y(t) \), as a function of \( g(t) \). Since we know the equation of motion for \( g \), this solves for the entire extraction path. In equilibrium, \( g(0) \) must be such that cumulative extraction over the entire horizon exactly equals the initial resource stock \( W_R(0) \). As in the Cobb-Douglas case in section 4.1, the initial condition \( n(0) \) has no effect on the growth rate. However, a higher initial resource stock implies an equilibrium with a higher cost share \( \eta(0) \), and a lower growth rate \( g(0) \).

During the adjustment, the growth rate increases. This happens because, with rising resource prices and poor substitution in the T-sector, T-production becomes relatively more expensive. Skilled labour moves from the T-sector to R&D. In the long run, all skilled labour is in research so that the asymptotic growth rate is \( S/a \) irrespective of further model parameters.

The main conclusion from this case is that poor substitution is in the knowledge-competing sector is not a problem for growth and investment in man-made (knowledge) capital. To the contrary: the rate of innovation in the steady state is higher than in the case with unitary elasticities in both sectors, the case considered in the previous section.

To draw conclusions about consumption growth rather than innovation, we need to calculate again the rate of consumption growth. In the long run, the rate of depletion is again equal to the discount rate. However, depletion has a greater weight in production in the case of poor substitution, since its share tends to one in the long run, \( (1 - \eta) \to 1 \). Therefore, on the one hand the poor substitution case yields higher growth because of faster innovation, but on the other hand it yields a bigger drag on growth through depletion. We can show that the former effect dominates the latter, so that less substitution in the knowledge-competing sector implies higher long-run growth. Equation (43) still holds, provided \( \eta \) is replaced by \( \eta = 0 \). After substituting \( g = S/a \) and \( \eta = 0 \), we find the long-run growth rate of consumption for the case with \( \sigma = 1 > \omega \):

\[
\hat{C}_{0} = \frac{S}{a} - \left[ \phi \frac{S}{a} - \left[ \phi (1 - \bar{\beta}) + (1 - \phi) \right] \rho \right].
\]  

This growth rate exceeds the growth rate of consumption with unitary elasticities in both sectors, cf. (42)-(43), by the following positive amount:

\[
\hat{C}_{0} - \hat{C}_{0} = \frac{1}{1 + \Phi \bar{\theta} / \bar{\eta}} \left[ \frac{S}{a} + \rho \left[ (1 - \phi)(1 - \bar{\eta}) + \phi (1 - (1 - \beta) \bar{\theta}) \right] \right].
\]

4.4 Poor substitution in both consumer sectors
We now turn to the general – and most interesting – case with elasticities unequal unity in both sectors. To be on the conservative side with respect to technological opportunities, we assume poor substitution, \( 0 < \sigma < 1 \), \( 0 < \omega < 1 \), and small spillovers
to resource augmenting so that technological change is resource-using, \( v = (1 - \beta) / \beta - \delta > 0 \). We have to examine the full system of three differential equations (32), (31), and (34), the latter to be replaced by (35) in a corner solution. Solving for \( g = \eta = \theta = 0 \) with \( g \geq 0 \), we can identify the different steady states.

From equation of motion (31), we see that \( \theta \) must approach zero. Furthermore, from (32) we see that constancy of \( \eta \) in the steady state requires either \( \eta = 0 \) or \( \eta = 1 \). Since \( \eta = 1 \) can only be reached if \( \dot{\eta} > 0 \) at time infinity, and since \( \dot{\eta} > 0 \) violates the transversality condition (see (27) and (39)), any path converging to \( \eta = 1 \) must be ruled out. Hence, in the long run both \( \theta \) and \( \eta \) approach zero:

\[
\eta(\infty) \to 0, \quad \theta(\infty) \to 0.
\] (45)

According to (34), the dynamics of \( g \) depend on the ratio \( \theta/\eta \). The growth rates of \( \theta \) and \( \eta \) approach asymptotically a (strictly negative) constant. Subtracting (32) from (31) and substituting (45), we find how the steady state ratio \( \theta/\eta \) evolves over time:

\[
\dot{\theta}(\infty) - \dot{\eta}(\infty) = \frac{\sigma - \omega}{\omega \sigma} - \frac{1 - \sigma}{\sigma} v g(\infty).
\] (46)

Depending on parameters, three types of steady states arise: an interior solution, a corner solution with zero innovation, or a corner solution with maximal innovation. First consider for which value of \( \theta(\infty)/\eta(\infty) \) an interior steady state, \( 0 < g(\infty) < S/a \), can arise. The inequality in (35) rules out \( \theta(\infty)/\eta(\infty) \to 0 \), since this would imply \( g = 0 \). Equation (34) rules out \( \theta(\infty)/\eta(\infty) \to \infty \) since this would imply \( \dot{g} < 0 \). Hence \( \theta(\infty)/\eta(\infty) \) must be a constant in an interior steady state. This requires the both sides of equation (46) to be zero, so that \( g(\infty) = \rho(\sigma - \omega)/\nu(1 - \sigma) \omega \). This solution is an interior solution, \( 0 < g(\infty) < S/a \), only if \( g(\infty) = \rho(\sigma - \omega)/\nu(1 - \sigma) \omega < S/a \), which can be reformulated as

\[
0 < (\sigma - \omega) \rho < (1 - \sigma) \omega S/a.
\] Second, consider the case \( \sigma < \omega \). We see from (46) that then \( \dot{\theta}(\infty) - \dot{\eta}(\infty) < 0 \), so that \( \theta(\infty)/\eta(\infty) \to 0 \), which implies, by (35), the corner solution \( g = 0 \). Third, if \( 0 < (1 - \sigma) \omega S/a < (\sigma - \omega) \rho \) and \( g(\infty) \to S/a \), we see from (46) that \( \theta(\infty) - \dot{\eta}(\infty) > 0 \) so that \( \theta(\infty)/\eta(\infty) \to \infty \). Equation (34) reveals that this is a steady state \( (g = 0) \) provided \( (\theta/\eta) \cdot (S/a - g) \) approaches a bounded constant that is smaller than \( \rho/\omega + S/a \). This is a rational expectations equilibrium as we show in the appendix, where we use (34) to solve for the steady state value of \( (\theta/\eta) \cdot (S/a - g) \) in each equilibrium.

Collecting these results we have:

\[
g(\infty) = 0 \quad \text{if } \sigma \leq \omega.
\] (47a)

\[
g(\infty) = \frac{\rho(\sigma - \omega)}{\nu(1 - \sigma) \omega} \quad \text{if } 0 < \frac{\sigma - \omega}{(1 - \sigma) \omega} < \frac{v S}{\rho a}
\] (47b)

\[
g(\infty) \to \frac{S}{a} \quad \text{if } \frac{\sigma - \omega}{(1 - \sigma) \omega} \geq \frac{v S}{\rho a}
\] (47c)
The equations in (48) show that for given parameters, there is a unique steady state. In the appendix we show the existence and stability of these steady states as well as the transition paths to the steady states, which - together with the initial stocks \( n(0) \) and \( W_R(0) \) - define the initial conditions for all endogenous variables. The remainder of the section discusses the results and the implications for consumption growth.

Equation (47b) reveals that innovation incentives keep intact and a constant innovation rate can be maintained in the long run even with poor substitution, provided substitution in the knowledge-using Y-sector is better than in the R&D-competing T-sector \((0 < \omega < \sigma < 1)\). To understand this result, we have to sort out why there is no incentive for skilled labour to move out of or into R&D in the long run. Two opposing – but inseparable – forces, from depletion and technological change respectively, determine labour allocation. On the one hand, as the resource stock is depleted and the amount of resource input per unit of labour falls, the wage falls, especially for the type of labour that is the poorest substitute for the resource. Thus, if \( \omega < \sigma \), the T-sector is hurt most by depletion and the relative wage of skilled labour, which is employed in this sector, falls. This lowers innovation costs and tends to raise innovation. On the other hand, any shift into R&D speeds up the pace of innovation, which makes capital goods relatively more abundant, lowers their reward (provided \((1 - \sigma)\nu > 0\), see (4)), and lowers the profits from innovation. On balance, in the interior steady state (47b), innovation takes place at a rate that makes profits from innovation fall at the same rate as costs of innovation (which happens because of depletion). The steady state with maximal R&D (47c) arises if the supply of skilled labour is small since then the supply of skilled labour constrains the rate of innovation such that the depletion effect dominates: the relative wage paid by the T-sector falls even if asymptotically all skilled labour has moved out of the T-sector into R&D. The zero innovation steady state (47a) arises if substitution is poorest in the Y-sector since then both depletion and innovation reduce the returns to innovation.

The interaction between depletion and innovation implies that the innovation rate becomes bounded by substitution elasticities when the supply of skilled labour grows large. With \( \omega < \sigma < 1 \), and \( \Sigma \) sufficiently large that (47b) applies, a rise in skilled labour supply does not affect the innovation rate. Hence, the so-called scale effect, for which endogenous growth model were criticised (notably by Jones 1995, 1999), is not present. The reason is that the growth rate is determined by the equality of depletion and innovation bias effect, so that \( g \) is solely governed by technical and preference parameters, notably the elasticities (note that the scale effect is present in the case with \( \sigma = 1 \), see section 4.1 and 4.3).

Another remarkable feature of the interior long-run innovation rate in (47b) is that it rises with the discount rate. In the Cobb-Douglas case (section 4.1), and in most endogenous growth models, the opposite happens. Usually, discounting disfavours investment in general and investment in R&D in particular. However, in the present model there are two types of investment, resource conservation and innovation. Higher discounting reduces investment in the resources by speeding up depletion, see (40)-(41). Thus the wage of skilled labour in the T-sector falls relatively faster, which reduces the cost of R&D and speeds up innovation.
In the long run, with $\eta = \theta = 0$ growth of consumption is (equation (43) still holds, provided $\pi$ and $\bar{\theta}$ are replaced by $\eta = 0$ and $\theta = 0$):

$$\dot{C} = \phi \delta g - \rho$$

From this equation it becomes clear that growing consumption requires $\delta > 0$, that is, endogenous knowledge has to affect the productivity of resource use in $Y$-production positively, or, in other words, technological change is resource-augmenting. In this case, long-run consumption growth is (technically) feasible in principle. However, our analysis shows that in the market equilibrium, consumption grows in the long run only if in addition to $\delta > 0$, substitution is higher in the knowledge-using sector than in the knowledge-competing sector ($\sigma > \omega$), and the discount rate is low enough.

5. Conclusions

This paper shows that unbounded economic growth can be sustained if non-renewable resources are an essential input in production, even without exogenous technological change and with elasticities of substitution between man-made capital and resources which lie below unity. We have used a multi-sector framework in which differences in substitution opportunities across sectors cause labour to move from production to R&D when the resource stock becomes depleted. Poor substitutability in the sector that competes for skilled labour input with the R&D sector turns out to be favourable for growth. Resource depletion makes final goods production activities that heavily rely on resources more expensive. Thus, increased resource scarcity lowers the opportunity costs of innovation and shifts labour from final goods production to innovation effort. The sectoral shift supplements input changes as a substitution mechanism. As a consequence, growth is higher with this kind of poor substitutability compared to the case of unitary elasticities. In contrast, strong dependence on resources in the sector that implements the innovations is bad for growth: with a poor substitutability in this case, resource depletion increases production costs and lowers the demand for innovations. We conclude that the relative resource dependence of the knowledge-using and knowledge-competing sectors (measured by cost shares and elasticities of substitution) determine whether incentives for investment and innovation are sustained and growth is unbounded in the presence of poor substitution possibilities. We also find that in the case of poor substitution, the size of the elasticities of substitution, rather than resource and labour endowments, bound the rate of growth. Hence in the interior solution, the scale of the economy has no effect on long-run growth.

We have made some simplifying assumptions that may be relaxed in future research. First, we have stressed that (in contrast to knowledge capital) physical capital inputs are bounded because material use is bounded. Instead of completely abstracting from increases in the physical capital stock, physical capital accumulation can be modelled subject to explicit material balances constraints. Second, we have modelled technological change embodied in capital goods and we have found that if research spillovers are large, technological change may become resource-saving.
Alternatively, we may model two types of innovation, one directed at improving capital productivity and the other at resource productivity. Third, we have abstracted from resource extraction costs and polluting resource use, which may be taxed by the government. These features may change the price profile of the resource but they hit both consumer sectors in the same way. As the effects of price changes in the two sectors work in opposite direction, as seen in sections 4.2 and 4.3, the quality of our results is not expected to change substantially when enlarging the general model set-up in this way. Fourth, to keep the set-up tractable we have assumed that there are two specific labour factors and that no innovation is possible in one of the sectors. The use of a single type of labour does not qualitatively change the results. The difference of the two sectors concerning knowledge use is an extreme form of input intensity which is not decisive for the outcome either. Finally, as the paper focuses on market solutions, the issue of optimal policies has not been treated. Resource use produces no negative externalities in this model, only R&D generates positive spillovers which leads, as in the original “Romer-type” approach to R&D, to positive subsidies for innovations in the social optimum.

References


Figures

Fig. 1

Fig. 2
Appendix to section 4.4

This appendix studies existence and stability of the steady state with poor substitution in both sectors \((0 < \sigma < 1, 0 < \omega < 1, \text{ and } v > 0)\). Because \(\hat{g}\) depends on \(\theta/\eta\), see (34), whereas \(\eta = 0\) in the steady state, see (45), we cannot directly differentiate the system in the steady state. Instead of studying the dynamics in terms of \(\theta, \eta,\) and \(g\), we therefore rewrite the system in terms of the three endogenous variables \(g, \eta,\) and \(h\), where \(h\) is defined as

\[
h = \Phi \frac{\theta}{\eta} \left( \frac{S}{a} - g \right) . \tag{A.1}\]

**Existence of steady state with positive growth**

We first examine a steady state with positive growth. Substituting \(\theta = h \eta / \Phi(S / a - g)\) into from (34), (32) and (31), and subsequently setting \(\theta = \eta = 0\), see (45), we find that the following must hold in such a steady state:

\[
\rho \left( \omega - \omega \right) = \omega - \omega \tag{A.2}
\]

\[
h = \frac{\rho}{\sigma} \left[ 1 + v \left( \frac{1 - \sigma}{\sigma} \right) \right] g \tag{A.3}
\]

Moreover, if \(g > 0, \eta \rightarrow 0\) and \(\theta \rightarrow 0\), the transversality condition boils down to (see (28), (33) and (39)):

\[
r - \hat{w}_S = h - g > 0 \tag{A.4}
\]

From these three equations, it follows immediately that a positive growth rate requires \(h \leq g + \rho / \omega\), which rules out that \(h\) goes to infinity, which requires by (A.3) that \(h \leq g[1 - \mu(1 - \sigma) / \sigma] + \rho / \sigma\). The transversality condition rules out that \(h\) goes to zero, which requires by (A.3) that \(h \geq g[1 - \mu(1 - \sigma) / \sigma] + \rho / \sigma\). Hence, a positive growth rate requires constant \(h\) and from setting (A.3) equal zero we get

\[
h(\infty) = g(\infty) \cdot [1 + v(1 - \sigma) / \sigma] + \rho / \sigma .
\]

Substituting this solution into (A.2), and setting \(\hat{g} = 0\), we find two solutions for the innovation rate, corresponding to (47b) and (47c).

**Existence of steady state without innovation.**

See main text.

**Local stability**

We prove that the steady state in the case of poor substitution in both sectors \((\omega < 1, \sigma < 1)\) has two negative eigenvalues and one positive eigenvalue. We save on
notation by defining $s = S / a$. Provided that $g$ is not at its corner $g = 0$, we may write from (32), (31), and (34):

\[
\begin{align*}
\dot{h} &= h \cdot \frac{1 - \eta h}{\Phi(s - g)} + \frac{(1 - \sigma)}{1 - (1 - \sigma)} \left( 1 - \frac{\eta h}{\Phi(s - g)} \right) \\
\dot{\eta} &= -\eta(1 - \eta)(1 - \omega)(h - g) \\
\dot{g} &= (s - g) \left\{ \rho - [\omega + (1 - \omega)\eta](h - g) \right\}
\end{align*}
\]

(A.5)

The Jacobian of this system is:

\[
J(h, \eta, g) =
\begin{bmatrix}
\frac{\partial \dot{h}}{\partial h} & \frac{\partial \dot{h}}{\partial \eta} & \frac{\partial \dot{h}}{\partial g} \\
\frac{\partial \dot{\eta}}{\partial h} & \frac{\partial \dot{\eta}}{\partial \eta} & \frac{\partial \dot{\eta}}{\partial g} \\
\frac{\partial \dot{g}}{\partial h} & \frac{\partial \dot{g}}{\partial \eta} & \frac{\partial \dot{g}}{\partial g}
\end{bmatrix}
\]

\[
\begin{bmatrix}
J_{11} & J_{12} & J_{13} \\
-\eta(1 - \eta)(1 - \omega) & -1 - 2\eta(1 - \omega)(h - g) & \eta(1 - \eta)(1 - \omega) \\
-(s - g)[\omega + (1 - \omega)\eta] & -(s - g)(1 - \omega)(h - g) & (h - g + s - g)[\omega + (1 - \omega)\eta] - \rho
\end{bmatrix}
\]

where

\[
\begin{align*}
J_{11} &= h + h - g - \rho - (\rho + \nu g)(1 - \sigma) \left( \frac{1 - \theta}{\sigma + (1 - \sigma)\theta} - \frac{\theta}{[\sigma + (1 - \sigma)\theta]^2} \right) \\
J_{12} &= \frac{h^2}{\Phi(s - g)}(\rho + \nu g)(1 - \sigma) \left( \frac{1}{[\sigma + (1 - \sigma)\theta]^2} \right) \\
J_{13} &= -h \left[ 1 + \nu \frac{(1 - \sigma)(1 - \theta)}{\sigma + (1 - \sigma)\theta} - (\rho + \nu g) \frac{\theta}{s - g} \left( \frac{1}{[\sigma + (1 - \sigma)\theta]^2} \right) \right]
\end{align*}
\]

**Interior growth rate, IG**

First, consider the steady state with $0 < g < s$. In this case, we have

\[
\begin{align*}
h &= (\rho / \omega)[\sigma - \omega + \nu(1 - \sigma)] / \nu(1 - \sigma) \equiv h_{IG}, \quad \eta = 0, \quad g = (\rho / \omega)(\sigma - \omega) / \nu(1 - \sigma) \equiv g_{IG}.
\end{align*}
\]

To facilitate calculations, note also that $h = g[1 + \nu(1 - \sigma) / \sigma] + \rho / \sigma = g + \rho / \omega$. For this equilibrium, all elements of the Jacobian $J$ turn out to be finite, and the Jacobian can be evaluated as:

\[
J(h_{IG}, 0, g_{IG}) =
\begin{bmatrix}
h_{IG} & J_{12} & -h_{IG} \left[ 1 + \nu(1 - \sigma) / \sigma \right] \\
0 & -\rho(1 - \omega) / \omega & 0 \\
-(s - g_{IG})\omega & -(s - g_{IG})\rho(1 - \omega) / \omega & (s - g_{IG})\omega
\end{bmatrix}
\]

We find that the determinant is positive:

\[
\text{Det} J(h_{IG}, 0, g_{IG}) = h_{IG}^2 \nu \left( \frac{1 - \sigma}{\sigma} (1 - \omega) \rho(s - g_{IG}) \right) > 0
\]
Because the second row has zero elements only, except for the diagonal element, the diagonal element is an eigenvalue. Hence it follows immediately that one eigenvalue is negative:

\[ \lambda_{IG,3} = -\left( \frac{1 - \omega}{\omega} \right) \rho. \]

Since the determinant of the Jacobian, which equals the product of the three eigenvalues, is positive, we must have \( \text{Det} J = \lambda_1 \lambda_2 \lambda_3 > 0 \), so there are two negative and one positive eigenvalue.

\[
\begin{align*}
\lambda_{IG,2} &= \frac{1}{2}[h_{IG} + \omega(s - g_{IG})] - \frac{1}{2} \sqrt{[h_{IG} + \omega(s - g_{IG})]^2 + 4\omega(s - g_{IG})h_{IG}v(1 - \sigma)/\sigma < 0} \\
\lambda_{IG,3} &= \frac{1}{2}[h_{IG} + \omega(s - g_{IG})] + \frac{1}{2} \sqrt{[h_{IG} + \omega(s - g_{IG})]^2 + 4\omega(s - g_{IG})h_{IG}v(1 - \sigma)/\sigma > 0}
\end{align*}
\]

**Maximum growth rate, MG**

Next consider the steady state equilibrium with \( g \to s \). For this case, we evaluate the Jacobian at \( h = s(1 + \nu(1 - \sigma)/\sigma) + \rho/\sigma \equiv h_{MG}, \ \eta = 0, \ g = s \). To facilitate calculations, note that it implies \( \theta = 0, \ h = g(1 + \nu(1 - \sigma)/\sigma) + \rho/\sigma < g + \rho/\omega \). For this equilibrium, \( J_{12} \) and \( J_{13} \) cannot be evaluated because they involve a division by zero. However, the determinant and the characteristic equation can be determined since multiplying elements from the first row with elements from the third row always gives finite expressions. In particular, the determinant and characteristic equation can be written as:

\[
\begin{align*}
\text{Det} J(h_{MG}, 0, s) &= h_{MG}(1 - \omega)(h_{MG} - s)[\rho - \omega(h_{MG} - s)] > 0 \\
0 &= [(1 - \omega)(h_{MG} - s) + \lambda_1][\rho - \omega(h_{MG} - s) + \lambda_3](h_{MG} - \lambda_3)
\end{align*}
\]

Hence, the eigenvalues are

\[
\begin{align*}
\lambda_{MG,1} &= -(1 - \omega)(h_{MG} - s) < 0, \\
\lambda_{MG,2} &= -[\rho - \omega(h_{MG} - s)] < 0 \\
\lambda_{MG,3} &= h_{MG} > 0
\end{align*}
\]

**Zero growth rate, ZG**

Finally, consider the steady state with \( g = \dot{g} = 0 \). The dynamics are now governed by (32) and (31) (note that we cannot use the system in (A.5), which is valid for \( g > 0 \) only). The Jacobian, evaluated at the steady state with \( \eta = \theta = g = 0 \) reads:

\[
\begin{bmatrix}
\frac{\partial \eta}{\partial \eta} & \frac{\partial \eta}{\partial \theta} \\
\frac{\partial \theta}{\partial \eta} & \frac{\partial \theta}{\partial \theta}
\end{bmatrix} = \begin{bmatrix}
-\rho(1 - \omega)/\omega & 0 \\
0 & -\rho(1 - \sigma)/\sigma
\end{bmatrix}
\]

So the two eigenvalues are negative:
\[
\begin{align*}
\lambda_{ZG,1} &= -\left(\frac{1-\omega}{\omega}\right)\rho \\
\lambda_{ZG,2} &= -\left(\frac{1-\sigma}{\sigma}\right)\rho
\end{align*}
\]

**Adjustment and initial conditions**

Two negative eigenvalues are associated with each steady state. This implies that the initial values of \((g, \eta, h)\) have to be located on the two-dimensional stable manifold, spanned by the eigenvectors associated with the two negative eigenvalues. In the linearised version, we can identify the initial condition as the intersection between the manifold and two planes to be defined as follows. First, the marginal product of resource use has to be equalized across the two sectors, as described in equations (36)-(38). By eliminating \(R_Y\) and \(R_T\) between these equations, we find a relation between \(g, \eta, \theta\) and \(n\), say \(J(g, \eta, \theta, n)=0\), which – after substitution of the definition of \(h\) (A.1) – defines a plane in the \((g, \eta, h)\) space. Second, the resource stock has to be asymptotically depleted, as described in equation (15). Substituting (36)-(37) into (15) and integrating, we find a relation between \(g, \eta, \theta, n\), and \(W_R\), say \(J(g, \eta, \theta, n, W_R)=0\), which – after substitution of the definition of \(h\) – defines a plane in the \((g, \eta, h)\) space. The intersection between the two planes, defined for initial values \(n(0)\) and \(W_R(0)\), and the stable manifold determines the initial equilibrium.
NOTE DI LAVORO DELLA FONDAZIONE ENI ENRICO MATTEI
Fondazione Eni Enrico Mattei Working Paper Series

Our working papers are available on the Internet at the following addresses:
http://www.feem.it/Feem/Pub/Publications/WPapers/default.html
http://papers.ssrn.com

SUST 1.2002  K. TANO, M.D. FAMINOW, M. KAMUANGA and B. SWALLOW: Using Conjoint Analysis to Estimate Farmers’ Preferences for Cattle Traits in West Africa
ETA 2.2002  Efrem CASTELNUOVO and Paolo SURICO: What Does Monetary Policy Reveal about Central Bank’s Preferences?
CLIM 4.2002  Andreas LÖSCHEL: Technological Change in Economic Models of Environmental Policy: A Survey
VOL 5.2002  Carlo CARRARO and Carmen MARCHIORI: Stable Coalitions
KNOW 8.2002  Alain DESDOIGTS: Neoclassical Convergence Versus Technological Catch-up: A Contribution for Reaching a Consensus
NRM 9.2002  Giuseppe DI VITA: Renewable Resources and Waste Recycling
KNOW 10.2002  Giorgio BRUNELLO: Is Training More Frequent when Wage Compression is Higher? Evidence from 11 European Countries
ETA 11.2002  Mordecai KURZ, Hehui JIN and Maurizio MOTOLESE: Endogenous Fluctuations and the Role of Monetary Policy
KNOW 12.2002  Reyer GERLAGH and Marjan W. HOFKES: Escaping Lock-in: The Scope for a Transition towards Sustainable Growth?
NRM 13.2002  Michele MORETTO and Paolo ROSATO: The Use of Common Property Resources: A Dynamic Model
CLIM 14.2002  Philippe QUIRION: Macroeconomic Effects of an Energy Saving Policy in the Public Sector
CLIM 16.2002  Francesco RICCI: Environmental Policy Growth when Inputs are Differentiated in Pollution Intensity
ETA 17.2002  Alberto PETRUCCI: Devaluation (Levels versus Rates) and Balance of Payments in a Cash-in-Advance Economy
Coalition Theory Network 18.2002  László Á. KÓCZY (liv): The Core in the Presence of Externalities
NRM 21.2002  Fausto CAVALLARO and Luigi CIRAULO: Economic and Environmental Sustainability: A Dynamic Approach in Insular Systems
CLIM 22.2002  Barbara BUCHNER, Carlo CARRARO, Igor CERSOSIMO and Carmen MARCHIORI: Back to Kyoto? US Participation and the Linkage between R&D and Climate Cooperation
CLIM 23.2002  Andreas LÖSCHEL and ZhongXIANG ZHANG: The Economic and Environmental Implications of the US Repudiation of the Kyoto Protocol and the Subsequent Deals in Bonn and Marrakech
ETA 24.2002  Marzio GALEOTTI, Louis J. MACCINI and Fabio SCHIANTARELLI: Inventories, Employment and Hours
ETA 26.2002  Adam B. JAFFE, Richard G. NEWELL and Robert N. STAVINS: Environmental Policy and Technological Change
SUST 27.2002  Joseph C. COOPER and Giovanni SIGNORELLO: Farmer Premiums for the Voluntary Adoption of Conservation Plans
SUST 28.2002  The ANSEA Network: Towards An Analytical Strategic Environmental Assessment
KNOW 29.2002  Paolo SURICO: Geographic Concentration and Increasing Returns: a Survey of Evidence
ETA 30.2002  Robert N. STAVINS: Lessons from the American Experiment with Market-Based Environmental Policies
SUST 71.2002 Carlo GIUPPONI and Paolo ROSATO: Multi-Criteria Analysis and Decision-Support for Water Management at the Catchment Scale: An Application to Diffuse Pollution Control in the Venice Lagoon

NRM 32.2002 Robert N. STAVINS: National Environmental Policy During the Clinton Years

KNOW 33.2002 A. SOUBEYRAN and H. STAHN: Do Investments in Specialized Knowledge Lead to Composite Good Industries?

KNOW 34.2002 G. BRUNELLO, M.L. PARISI and Daniela SONEDDA: Labor Taxes, Wage Setting and the Relative Wage Effect


CLIM 36.2002 T.TIETENBERG (iv): The Tradable Permits Approach to Protecting the Commons: What Have We Learned?


NRM 40.2002 S. M. CAVANAGH, W. M. HANEMANN and R. N. STAVINS: Muddled Price Signals: Household Water Demand under Increasing-Block Prices


CLIM 42.2002 C. OHL (ivii): Inducing Environmental Co-operation by the Design of Emission Permits

CLIM 43.2002 J. EYCKMANS, D. VAN REGEMORTER and V. VAN STEENBERGHE (ivii): Is Kyoto Fatally Flawed? An Analysis with MacGEM

CLIM 44.2002 A. ANTOCI and S. BORGHESI (ivii): Working Too Much in a Polluted World: A North-South Evolutionary Model

ETA 45.2002 P. G. FREDRIKSSON, Johan A. LIST and Daniel MILLIMET (ivii): Chasing the Smokestack: Strategic Policymaking with Multiple Instruments

ETA 46.2002 Z. YU (iv): A Theory of Strategic Vertical DF1 and the Missing Pollution-Haven Effect

SUST 47.2002 Y. H. FARZIN (iv): Can an Exhaustible Resource Economy Be Sustainable?

SUST 48.2002 Y. H. FARZIN: Sustainability and Hamiltonian Value

KNOW 49.2002 C. PIGA and M. VIVARELLI: Cooperation in R&D and Sample Selection

Coalition Theory Network 50.2002 M. SERTEL and A. SLINKO (iv): Ranking Committees, Words or Multisets

Coalition Theory Network 51.2002 Sergio CURRARINI (iv): Stable Organizations with Externalities

ETA 52.2002 Robert N. STAVINS: Experience with Market-Based Policy Instruments


CLIM 54.2002 Scott BARRETT (liviii): Towards a Better Climate Treaty

ETA 55.2002 Richard G. NEWELL and Robert N. STAVINS: Cost Heterogeneity and the Potential Savings from Market-Based Policies

SUST 56.2002 Paolo ROSATO and Edi DEFRANCESCO: Individual Travel Cost Method and Flow Fixed Costs

SUST 57.2002 Vladimir KOTOV and Elena NIKITINA (liviii): Reorganisation of Environmental Policy in Russia: The Decade of Success and Failures in Implementation of Perspective Quests


VOL 60.2002 Giovanni DI BARTOLEMO, Jacob ENGWERDA, Joseph PLASMANs and Bas VAN AARLE: Staying Together or Breaking Apart: Policy-Makers’ Endogenous Coalitions Formation in the European Economic and Monetary Union


PRIV 62.2002 Carlo CAFCANO: Demand Growth, Entry and Collusion Sustainability

PRIV 63.2002 Federico MUNARI and Raffaele ORIANI: Privatization and R&D Performance: An Empirical Analysis Based on Tobin’s Q

PRIV 64.2002 Federico MUNARI and Maurizio SOBRERO: The Effects of Privatization on R&D Investments and Patent Productivity

SUST 65.2002 Orley ASHENFELTER and Michael GREENSTONE: Using Mandated Speed Limits to Measure the Value of a Statistical Life


CLIM 68.2002 Barbara K. BUCHNER and Roberto ROSON: Conflicting Perspectives in Trade and Environmental Negotiations

CLIM 69.2002 Philippe QUIRION: Complying with the Kyoto Protocol under Uncertainty: Taxes or Tradable Permits?

SUST 70.2002 Anna ALBERINI, Patrizia RIGANTI and Alberto LONGO: Can People Value the Aesthetic and Use Services of Urban Sites? Evidence from a Survey of Belfast Residents

SUST 71.2002 Marco PERCOCO: Discounting Environmental Effects in Project Appraisal
PRIV 112.2002 Isaac OTCHERE: Intra-Industry Effects of Privatization Announcements: Evidence from Developed and Developing Countries
PRIV 113.2002 Yannis KATSOULAKOS and Elisavet LIKOYANNI: Fiscal and Other Macroeconomic Effects of Privatization
PRIV 115.2002 D. Teja FLOTTO: A Note on Consumption Correlations and European Financial Integration
PRIV 2.2003 Ilyona SCHINDELE: Theory of Privatization in Eastern Europe: Literature Review
PRIV 3.2003 Witze LISE, Claudia KEMFERT and Richard S.J. TOL: Strategic Action in the Liberalised German Electricity Market
KNOW 5.2003 Reyer GERLAGH: Induced Technological Change under Technological Competition
ETA 6.2003 Efrem CASTELNUOVO: Squeezing the Interest Rate Smoothing Weight with a Hybrid Expectations Model
SIEV 7.2003 Anna ALBERINI, Alberto LONGO, Stefania TONIN, Francesco TROMBETTA and Margherita TURVANI: The Role of Liability, Regulation and Economic Incentives in Brownfield Remediation and Redevelopment: Evidence from Surveys of Developers
NRM 8.2003 Elissaios PAPYRAKIS and Reyer GERLAGH: Natural Resources: A Blessing or a Curse?
CLIM 9.2003 A. CAPARROS, J.-C. PEREAU and T. TAZDAÏF: North-South Climate Change Negotiations: a Sequential Game with Asymmetric Information
KNOW 10.2003 Giorgio BRUNELLO and Daniele CHECCHI: School Quality and Family Background in Italy
CLIM 11.2003 Efrem CASTELNUOVO and Marzio GALEOTTI: Learning By Doing vs Learning By Researching in a Model of Climate Change Policy Analysis
KNOW 12.2003 Carole MAIGNAN, Gianmarco OTTAVIANO and Dino PINELLI (eds.): Economic Growth, Innovation, Cultural Diversity: What are we all talking about? A critical survey of the state-of-the-art
KNOW 15.2003 Tuzin BAYCAN LEVENT, Enno MASUREL and Peter NIJKAMP (lx): Diversity in Entrepreneurship: Ethnic and Female Roles in Urban Economic Life
KNOW 16.2003 Alexandra BITUSIKOVA (lx): Post-Communist City on its Way from Grey to Colourful: The Case Study from Slovakia
KNOW 17.2003 Billy E. VAUGHN and Katarina MLEKOV (lx): A Stage Model of Developing an Inclusive Community
KNOW 18.2003 Selma van LONDEN and Arie de RUIJTER (lx): Managing Diversity in a Glocalizing World
PRIV 22.2003 Marco LiCalzi and Alessandro PAVAN (lx): Tilting the Supply Schedule to Enhance Competition in Uniform-Price Auctions
PRIV 23.2003 David ETTINGER (lx): Bidding among Friends and Enemies
PRIV 24.2003 Hannu VARTIAINEN (lx): Auction Design without Commitment
PRIV 26.2003 Christine A. PARLOUR and Uday RAJAN (lx): Rationing in IPOs
PRIV 27.2003 Kjell G. NYBORG and Ilya A. STREBULAEV (lx): Multiple Unit Auctions and Short Squeezes
PRIV 28.2003 Anders LUNANDER and Jan-Eric NILSSON (lx): Taking the Lab to the Field: Experimental Tests of Alternative Mechanisms to Procure Multiple Contracts
PRIV 30.2003 Emiel MAASLAND and Sander ONDERSTAL (lx): Auctions with Financial Externalities
ETA 31.2003 Michael FINUS and Bianca RUNDHAGEN: A Non-cooperative Foundation of Core-Stability in Positive Externality NTU-Coalition Games
KNOW 32.2003 Michele MORETTO: Competition and Irreversible Investments under Uncertainty
PRIV 33.2003 Philippe QUIRION: Relative Quotas: Correct Answer to Uncertainty or Case of Regulatory Capture?
KNOW 34.2003 Giuseppe MEDA, Claudio PIGA and Donald SIEGEL: On the Relationship between R&D and Productivity: A Treatment Effect Analysis
ETA 35.2003 Alessandra DEL BOCA, Marzo GALEOTTI and Paola ROTA: Non-convexities in the Adjustment of Different Capital Inputs: A Firm-level Investigation
Carole MAIGNAN, Dino PINELLI and Gianmarco I.P. OTTAVIANO
Matthew HAAG and Roger LAGUNOFF
Lori SNYDER, Robert STAVINS and Alexander F. WAGNER:
Ana MAULEON and Vincent VANNETELBOSCH
Matthew O. JACKSON
Giorgio BELLETTINI and Gianmarco I.P. OTTAVIANO:
Santiago RUBIO and Alistair ULPH
Halis Murat YILDIZ
Giorgio BUSETTI and Matteo MANERA:
Carlo CARRARO and Carmen MARCHIORI
Slim BEN YOUSSEF
Sandra WALLMAN
Sandra WALLMAN
Catarina REIS OLIVEIRA
Kazuma MATOBA
Globalisation and Migration
Multicultural Environment: Saint-Petersburg’s Case
Natalya V. TARANOVA
Ljiljana DERU SIMIC
Ercole SORI
David FRANTZ
ZhongXiang ZHANG:
Fishing Management Practices in the Venice Lagoon: Results from a Stated Choice Exercise
Paulo A.L.D. NUNES, Luca ROSSETTO, Arianne DE BLAEIJ:
Monetary Value Assessment of Clam Environment
Klaus CONRAD
Edi DEFRANCESCO
Global Climate Policy Architectures
Joseph E. ALDY, Scott BARRETT and Robert N. STAVINS:
Thirteen Plus One: A Comparison of International Environmental Agreements
Environmental Agreements
Fernando VEGA-REDONDO
Revealed Preferences to Estimate Environmental Benefits
Disposal Methods
Effectiveness
Basin Region, Japan and US
Biotechnologies
Governance: the Role of Ownership Structure and Investor Protection
Katrin MILLOCK and Céline NAUGES: The French Tax on Air Pollution: Some Preliminary Results on its Effectiveness
Bernardo BORTOLOTTI and Paolo PINOTTI: The Political Economy of Privatization
Elbert DJUKGRAAF and Herman R.J. VOLLEBERGH: Burn or Bury? A Social Cost Comparison of Final Waste Disposal Methods
Jens HORBACH: Employment and Innovations in the Environmental Sector: Determinants and Econometrical Results for Germany
Lori SNYDER, Nolan MILLER and Robert STAVINS: The Effects of Environmental Regulation on Technology Diffusion: The Case of Chlorine Manufacturing
Lori SNYDER, Robert STAVINS and Alexander F. WAGNER: Private Options to Use Public Goods. Exploiting Revealed Preferences to Estimate Environmental Benefits
László A. KOCZY and Luc LAUWERS (lii): The Minimal Dominant Set is a Non-Empty Core-Extension
Matthew O. JACKSON (lii): Allocation Rules for Network Games
Ana MAULEON and Vincent VANNETELBOSCH (lii): Farsightedness and Cautiousness in Coalition Formation
Matthew HAAG and Roger LAGUNOFF (lii): On the Size and Structure of Group Cooperation
Taiji FURUSAWA and Hideo KONISHI (lii): Free Trade Networks
Halis Murat YILDIZ (lii): National Versus International Mergers and Trade Liberalization
Santiago RUBIO and Alistair ULPH (lii): An Infinite-Horizon Model of Dynamic Membership of International Environmental Agreements
Carole MAIGNAN, Dino PINELLI and Gianmarco I.P. OTTAVIANO: ICT, Clusters and Regional Cohesion: A Summary of Theoretical and Empirical Research
Giorgio BELLETTINI and Gianmarco I.P. OTTAVIANO: Special Interests and Technological Change
Rennie SCHÖB: The Double Dividend Hypothesis of Environmental Taxes: A Survey
Michael FINUS, Ekkio van IERLAND and Robert DELLINK: Stability of Climate Coalitions in a Cartel Formation Game
Michael FINUS and Bianca RUNDHAGEN: How the Rules of Coalition Formation Affect Stability of International Environmental Agreements
Alberto PETRUCCI: Taxing Land Rent in an Open Economy
Joseph E. ALDY, Scott BARRETT and Robert N. STAVINS: Thirteen Plus One: A Comparison of Global Climate Policy Architectures
Edi DEFRANCESCO: The Beginning of Organic Fish Farming in Italy
Klaus CONRAD: Price Competition and Product Differentiation when Consumers Care for the Environment
Paulo A.L.D. NUNES, Luca ROSSETTO, Arianne DE BLAEIJ: Monetary Value Assessment of Clam Fishing Management Practices in the Venice Lagoon: Results from a Stated Choice Exercise
ZhongXiang ZHANG: Open Trade with the U.S. Without Compromising Canada’s Ability to Comply with its Kyoto Target
David FRANTZ (lii): Lorenzo Market between Diversity and Mutation
Ercole SORI (lii): Mapping Diversity in Social History
Ljiljana DERU SIMIC (lii): What is Specific about Art/Cultural Projects?
Natalya V. TARANOVA (lii): The Role of the City in Fostering Intergroup Communication in a Multicultural Environment: Saint-Petersburg’s Case
Kristine CRANE (lii): The City as an Arena for the Expression of Multiple Identities in the Age of Globalisation and Migration
Kazuma MATOBA (lii): Global Dialogue- Transformation through Transcultural Communication
Catarina REIS OLIVEIRA (lii): Immigrants’ Entrepreneurial Opportunities: The Case of the Chinese in Portugal
Sandra WALLMAN (lii): The Diversity of Diversity - towards a typology of urban systems
KNOW 77.2003 Richard PEARCE (lxii): A Biologist’s View of Individual Cultural Identity for the Study of Cities

KNOW 78.2003 Vincent MERK (lxii): Communication Across Cultures: from Cultural Awareness to Reconciliation of the Dilemmas

KNOW 79.2003 Giorgio BELLETTINI, Carlotta BERTI CERONI and Gianmarco I.P. OTTAVIANO: Child Labor and Resistance to Change

ETA 80.2003 Michele MORETTO, Paolo M. PANTEGHINI and Carlo SCARPA: Investment Size and Firm’s Value under Profit Sharing Regulation

IEM 81.2003 Alessandro LANZA, Matteo MANERA and Massimo GIOVANNINI: Oil and Product Dynamics in International Petroleum Markets

CLIM 82.2003 Y. Hossein FARZIN and Jinhua ZHAO: Pollution Abatement Investment When Firms Lobby Against Environmental Regulation

CLIM 83.2003 Giuseppe DI VITA: Is the Discount Rate Relevant in Explaining the Environmental Kuznets Curve?

CLIM 84.2003 Reyer GERLAGH and Wietze LISE: Induced Technological Change Under Carbon Taxes

NRM 85.2003 Rinaldo BRAU, Alessandro LANZA and Francesco PIGLIARU: How Fast are the Tourism Countries Growing? The cross-country evidence

KNOW 86.2003 Elena BELLINI, Gianmarco I.P. OTTAVIANO and Dino PINELLI: The ICT Revolution: opportunities and risks for the Mezzogiorno

SIEV 87.2003 Lucas BRETSCGHER and Sjak SMULDERS: Sustainability and Substitution of Exhaustible Natural Resources. How resource prices affect long-term R&D investments

(i) This paper was presented at the Workshop “Growth, Environmental Policies and Sustainability” organised by the Fondazione Eni Enrico Mattei, Venice, June 1, 2001

(ii) This paper was presented at the Fourth Toulouse Conference on Environment and Resource Economics on “Property Rights, Institutions and Management of Environmental and Natural Resources”, organised by Fondazione Eni Enrico Mattei, IDEI and INRA and sponsored by MATE, Toulouse, May 3-4, 2001

(iii) This paper was presented at the International Conference on “Economic Valuation of Environmental Goods”, organised by Fondazione Eni Enrico Mattei in cooperation with CORILA, Venice, May 11, 2001

(iv) This paper was circulated at the International Conference on “Climate Policy – Do We Need a New Approach?”, jointly organised by Fondazione Eni Enrico Mattei, Stanford University and Venice International University, Isola di San Servolo, Venice, September 6-8, 2001

(v) This paper was presented at the Seventh Meeting of the Coalition Theory Network organised by the Fondazione Eni Enrico Mattei and the CORE, Università Catholique de Louvain, Venice, Italy, January 11-12, 2002

(vi) This paper was presented at the First Workshop of the Concerted Action on Tradable Emission Permits (CATEP) organised by the Fondazione Eni Enrico Mattei, Venice, Italy, December 3-4, 2001

(vii) This paper was presented at the ESF EURESCO Conference on Environmental Policy in a Global Economy “The International Dimension of Environmental Policy”, organised with the collaboration of the Fondazione Eni Enrico Mattei , Acquafredda di Maratea, October 6-11, 2001

(viii) This paper was presented at the First Workshop of “CFEWE – Carbon Flows between Eastern and Western Europe”, organised by the Fondazione Eni Enrico Mattei and Zentrum fur Europaische Integrationsforschung (ZEI), Milan, July 5-6, 2001

(ix) This paper was presented at the Workshop on “Game Practice and the Environment”, jointly organised by Università del Piemonte Orientale and Fondazione Eni Enrico Mattei, Alessandria, April 12-13, 2002

(x) This paper was presented at the ENGIME Workshop on “Mapping Diversity”, Leuven, May 16-17, 2002

(xi) This paper was presented at the EuroConference on “Auctions and Market Design: Theory, Evidence and Applications”, organised by the Fondazione Eni Enrico Mattei, Milan, September 26-28, 2002

(xii) This paper was presented at the Eighth Meeting of the Coalition Theory Network organised by the GREQAM, Aix-en-Provence, France, January 24-25, 2003

(xiii) This paper was presented at the ENGIME Workshop on “Communication across Cultures in Multicultural Cities”, The Hague, November 7-8, 2002
## 2002 SERIES

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Editor</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLIM</td>
<td>Climate Change Modelling and Policy</td>
<td>Marzio Galeotti</td>
</tr>
<tr>
<td>VOL</td>
<td>Voluntary and International Agreements</td>
<td>Carlo Carraro</td>
</tr>
<tr>
<td>SUST</td>
<td>Sustainability Indicators and Environmental Valuation</td>
<td>Carlo Carraro</td>
</tr>
<tr>
<td>NRM</td>
<td>Natural Resources Management</td>
<td>Carlo Giupponi</td>
</tr>
<tr>
<td>KNOW</td>
<td>Knowledge, Technology, Human Capital</td>
<td>Dino Pinelli</td>
</tr>
<tr>
<td>MGMT</td>
<td>Corporate Sustainable Management</td>
<td>Andrea Marsanich</td>
</tr>
<tr>
<td>PRIV</td>
<td>Privatisation, Regulation, Antitrust</td>
<td>Bernardo Bortolotti</td>
</tr>
<tr>
<td>ETA</td>
<td>Economic Theory and Applications</td>
<td>Carlo Carraro</td>
</tr>
</tbody>
</table>

## 2003 SERIES

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Editor</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLIM</td>
<td>Climate Change Modelling and Policy</td>
<td>Marzio Galeotti</td>
</tr>
<tr>
<td>GG</td>
<td>Global Governance</td>
<td>Carlo Carraro</td>
</tr>
<tr>
<td>SIEV</td>
<td>Sustainability Indicators and Environmental Valuation</td>
<td>Anna Alberini</td>
</tr>
<tr>
<td>NRM</td>
<td>Natural Resources Management</td>
<td>Carlo Giupponi</td>
</tr>
<tr>
<td>KNOW</td>
<td>Knowledge, Technology, Human Capital</td>
<td>Gianmarco Ottaviano</td>
</tr>
<tr>
<td>IEM</td>
<td>International Energy Markets</td>
<td>Anil Markandya</td>
</tr>
<tr>
<td>CSRM</td>
<td>Corporate Social Responsibility and Management</td>
<td>Sabina Ratti</td>
</tr>
<tr>
<td>PRIV</td>
<td>Privatisation, Regulation, Antitrust</td>
<td>Bernardo Bortolotti</td>
</tr>
<tr>
<td>ETA</td>
<td>Economic Theory and Applications</td>
<td>Carlo Carraro</td>
</tr>
<tr>
<td>CTN</td>
<td>Coalition Theory Network</td>
<td></td>
</tr>
</tbody>
</table>