SUSTAINABLE RESOURCE USE AND ECONOMIC DYNAMICS
THE ECONOMICS OF NON-MARKET GOODS AND RESOURCES

VOLUME 10

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Aims and Scope

The volumes which comprise The Economics of Non-Market Goods and Resources series have been specially commissioned to bring a new perspective to the greatest economic challenge facing society in the 21st Century; the successful incorporation of non-market goods within economic decision making. Only by addressing the complexity of the underlying issues raised by such a task can society hope to redirect global economies onto paths of sustainable development. To this end the series combines and contrasts perspectives from environmental, ecological and resource economics and contains a variety of volumes which will appeal to students, researchers, and decision makers at a range of expertise levels. The series will initially address two themes, the first examining the ways in which economists assess the value of non-market goods, the second looking at approaches to the sustainable use and management of such goods. These will be supplemented with further texts examining the fundamental theoretical and applied problems raised by public good decision making.

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Sustainable Resource Use and Economic Dynamics

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Preface

This volume includes a selection of papers presented at the conference “Sustainable Resource Use and Economic Dynamics” (SURED), held on Monte Verità in Ascona, Switzerland, in June 2004. Thirty years after the publication of the famous symposium issue of the Review of Economic Studies in 1974, which started the neoclassical literature on growth theory and resource economics. The conference sought to reinforce research efforts in order to provide adequate solutions for today’s challenges in the field of sustainable development. The conference compiled innovative research from resource, energy and environmental economics, and dynamic economic theory. By bringing together leading experts, junior and senior scholars in these fields, it covered a broad range of aspects regarding the relationship between natural resource use and long-term economic development.

The SURED conference made use of the wonderful surroundings on the “mountain of truth” and the remarkable history of the conference centre, which was shaped by the desire to return to a natural way of life. In this tradition, the conference aimed at finding ways of living in an economically developed world and at the same time taking into account the natural environment with its restrictions and requirements. We take the opportunity to thank the staff of the Monte Verità centre for the hospitality and the excellent service.

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1. Introduction to Sustainable Resource Use and Economic Dynamics

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1. Introduction

There are many compelling reasons why environmental and resource problems should be placed in a dynamic perspective. Traditionally, resource economics needs to study the dynamics of depletion of natural resources and environmental services. Current use of non-renewables, such as oil reserves, determines future resource availability. Renewable natural resources regenerate in a dynamic ecological process, which is disturbed by commercial harvesting activities. Similarly, environmental economics has to deal with pollution dynamics when pollution entails long-lasting cumulative effects in soil and marine resources or in the atmosphere. Looking at the impact of resource scarcity and pollution for the economy as a whole we additionally find that macroeconomic dynamics become highly relevant. To offset the increasing scarcity of natural resources and to promote sustainable development, capital accumulation and technological change are essential. In particular, the development and adoption of new technologies allow improving resource and abatement efficiency. Finally, social dynamics are important: the behaviour of polluters or natural resource users, as well as policymakers, changes over time because of learning behaviour, or because of changing perceptions, the building-up of new information, and the reaction thereupon.

The experience of the world economy with oil prices over the past few decades illustrates some of the interactions between resource dynamics and macroeconomic dynamics. The present situation shows similarities with the 1970s and 1980s, when oil prices rose sharply and pollution issues entered the political agenda. In the last four years, the increase in oil prices was similar in scale to the price jumps of 1973/74, 1978/80, and 1989/90, all of which were followed by worldwide recession and rising inflation. However, historical parallels have to be handled with great care. The big recession of the mid-1970s was not only due to oil shortages but was additionally caused by other factors like the breakdown of the Bretton-Woods currency system and a broad uncertainty about the growth perspectives in general. Also, in the recent past, price increases of raw materials have been more gradual, giving households and firms more time to adjust. The
most important difference to thirty years ago, however, is that developed countries use half as much oil per unit of real GDP as in the mid-1970s, thanks to improved energy efficiency, a switch to alternative energy sources, and the shift from manufacturing to services.

The concern for sustainability provides another illustration of the interaction between resource dynamics on the one hand and macroeconomic and social dynamics on the other. After a long process of growing awareness and changing perceptions of links between resource use, environmental problems, poverty, and intergenerational fairness, the notion of “sustainable development” is nowadays widely accepted as a main principle for environmental and development policies. However, the concept of sustainable development as used in the policy debate and among non-economists has been far away from the traditional welfare analysis in economics. Economists have succeeded to bridge a large part of the gap by taking explicitly into account natural resource constraints on output, studying resource markets, acknowledging externalities in resource use, and considering alternative ethical foundations for welfare functions and discounting principles. Accordingly, a large part of the formal literature on sustainability studies how utility levels can be sustained in a model world with (non-)renewable resources. Substitution has become the core of economists’ view on sustainability. Over time, decreasing per capita amounts of natural inputs have to be sufficiently compensated for by the accumulation of man-made inputs. The greater the saving effort of the present generation is, the more feasible becomes the substitution of natural resources in production and consumption. The key research question for economists is to determine the returns and incentives of these sustainability-enhancing investment activities.

The dynamics of technological change cannot be ignored in this context: both as a threat to sustainability (in the guise of resource-using or energy-using technological change) or as the solution (more efficient resource use, clean technologies, and backstops, i.e. resource-saving technological change). Understanding the sustainability of long-term development therefore requires insight into the pace, direction, and determinants of technical change. The new growth theory that started in the 1990s provides a modelling framework in which technological change is an endogenous variable: knowledge – embodied in new capital goods, production processes, and products – is an ultimate substitute for resource inputs, without making the latter unnecessary. Developing useful new knowledge is costly and time-consuming, which turns innovation into an economic investment problem. Theories of endogenous innovation examine the incentives for innovation in a particular direction (resource-using versus resource-saving), as well as the opportunity cost of technological change resulting from crowding out of conventional investment by environmentally oriented investment. Technological progress is often modelled as incremental, which leads to a steady, but possibly moderate improvement of resource efficiency. In addition, we need to look for technology options that bring about a quantum jump in the efficiency of using natural resources. Only with radical innovations will the economy be in a position to tame
the increasing resource demand in the future, given the rapid economic development today, for example, in China, India, and other emerging economies.

The complexity and breadth of sustainable development requires an even broader view, as reflected in the United Nations Millennium Development Goals, where the reduction of poverty, hunger, disease, illiteracy, and discrimination against women are the most important issues. In the future, economic analysis will be increasingly devoted to local community actions, the dynamics of social norms, and their impact on resource use in smaller groups.

The nine chapters following this introduction study different aspects of resource use, pollution, economic dynamics, and sustainability. Chapters 2–6 study the incentives to invest in clean technologies. Chapters 7 and 8 turn to substitution between energy or polluting inputs on the one hand and man-made inputs on the other. Of these chapters, Chapter 7 explores long-run growth and non-renewable resources and – together with the remainder of this introduction – provides an overview of the main modelling issues and insights from recent dynamic resource and environment modelling. Chapter 8 turns to the empirics of gradual improvement and international convergence in aggregate energy efficiency. Chapter 9 focuses on local communities and how social norms with respect to resource use evolve there. Chapter 10 uses insights from economics to reinterpret classical mechanics. In the remainder of this chapter we discuss the main common elements and a unifying modelling framework for the chapters in this volume.1

2. Growth and Pollution

2.1. POLLUTION IN DYNAMIC THEORY

Growth and pollution have been studied extensively over the last decade, both empirically and theoretically. From an empirical perspective, the Environmental Kuznets Curve (EKC) hypothesis has been most visible, although most of the earlier work under this heading looks into the relationship between levels of income and pollution. Only recently has growth been explicitly studied (Bradford et al. 2005; Brock and Taylor 2004). The theoretical analysis builds on the “endogenous growth” literature developed in macroeconomics (starting with Romer 1986, see Aghion and Howitt 1998 for a broad exposition). The most elementary endogenous growth model, the “AK model”, extended for basic environmental and resource aspects, provides important insights into the links between investment in production capacity and the resulting economic growth on the one hand, and the polluting consequences of production and environmental policy on the other.

There is still a big gap between the empirical and theoretical literature. The Environmental Kuznets Curve literature typically aims at characterizing the relationship between levels of income and pollution, without linking empirical model specification to theory, and without testing for underlying mechanisms. The theoretical literature normally restricts the analysis to constant growth (or balanced
growth) paths and ignores the richer dynamics emerging from the empirical EKC studies in which the pollution–income link changes over time or with income levels.

The chapters by Cunha-e-Sá and Reis, Egli and Steger, and Soretz, in this volume, fill some of the gaps. They further develop the AK model to investigate the relationship between economic growth and environmental policy. In particular, they introduce new dynamic elements that allow for a more detailed study of clean technology adoption, uncertainty, and the link to the EKC. In chapters by Hart, and Van Zon and Kronenberg, the dynamic impacts of environmental policy and induced innovation are discussed more in detail.

To give a clear view on how we can start to study environmental economic dynamics from the canonical AK model, we first briefly review the AK approach and then show how clean technology can be modelled, how the pollution–income link depends on abatement technology, and how uncertainty can matter in this context.

2.2. THE ENVIRONMENTAL AK FRAMEWORK

The distinguishing feature of the AK model is that aggregate production in the economy, $Y$, is linearly related to a broad measure of reproducible capital, $K$, in the following way:

$$Y = AK.$$  \hfill (1)

Accordingly, the marginal product of capital is given by $A$; it determines the rate of return and incentives to invest. The aggregation of all relevant man-made capital goods into one stock variable that is linearly proportional to output simplifies the analysis considerably.

To incorporate environmental aspects into the AK model, pollution can be modelled as a by-product of either inputs ($K$) or consumption ($C$); abatement expenditures ($E$) are assumed to reduce pollution for given polluting input levels. Hence, the general formulation for the pollution generating process can be written as:

$$P = p(K, C, E)$$  \hfill (2)

where $p_C \geq 0$, $p_K \geq 0$, $p_E \leq 0$ (with the subscripts denoting first-order partial derivatives).

Pollution$^2$ is assumed to affect (as an externality) both production, through an effect on productivity level $A$, and instantaneous utility $U$, which otherwise depends on consumption $C$. Thus we can write:

$$A = a(P)$$  \hfill (3)

$$U = u(C, P)$$  \hfill (4)

where $a_P \leq 0$, $u_C \geq 0$, $u_P \leq 0$. Growth of output and levels of pollution are determined by the allocation of total production over consumption, capital investment, and pollution abatement. Investment in the economy ($dK/dt$) and investment
in the environment \((E)\) come at the cost of consumption \((C)\), according to the following goods market equilibrium condition:

\[
Y = C + E + dK/dt. \tag{5}
\]

Now consider a balanced growth path along which all terms in (5) grow at the same rate so that the ratios \(C/Y\), \(E/Y\), and \((dK/dt)/Y\) are constant. If the pollution generating process in (2) has properties such that we can write it in the following specification:

\[
P = p(K/E, C/E, 1) \tag{6}
\]

pollution is constant along the balanced growth path, too.\(^3\) Thus, with the linear production function (equation 1) and “ratio-dependent” pollution function (equation 6), “sustainable growth” is feasible: output grows at a constant rate and pollution does not increase. There are no limits to growth in this case. If preferences are of the Cobb-Douglas type, a balanced growth path is not only feasible but also optimal with discounted utility maximization (see Smulders and Gradus 1996). A specification for preferences giving this result is

\[
U = (1 - \sigma)^{-1}C \cdot (\bar{P} - P)^\phi]^{1-\sigma}, \tag{7}
\]

where \(\bar{P}\) is the critical value of pollution beyond which welfare cannot be sustained. With additive preferences, however, e.g. \(U = (1 - \sigma)^{-1}C^{1-\sigma} + (\bar{P} - P)^\phi\), it is optimal to spend a larger and larger part of output on abatement and to invest less and less in capital accumulation so that the growth process comes to an end (Stokey 1998).

Analytically, the model defined by equations (1)–(6) is an extremely convenient specification. Only one stock variable matters, viz. \(K\), and no transitional dynamics arise. However, the specification in equation (6) might be seen as an overly optimistic view: doubling capital, consumption, and abatement does not double pollution but in fact leaves pollution unaffected. This implicitly assumes strong learning effects or technological change that offset the “scale effect”, defined as the tendency of pollution to expand with the scale of economic activity, keeping fixed the production technology and the composition of output (cf. Brock and Taylor 2005). A standard replication argument would produce a completely different result: doubling all inputs would double all outputs, like building next to a factory another identical factory would double pollution. The absence of constant returns to scale calls for an explanation in terms of increasing returns or technological change. First, when expanding the scale of the economy the productivity of abatement might increase (or the polluting consequences of capital might diminish) due to increasing returns: new firms that enter the economy bring new knowledge, broaden the scope for learning and experimenting, and might thus increase the productivity of abatement. Alternatively, over time technological change may improve the productivity of abatement or may cause pollution per unit of output to fall.

The environmental growth models by Cunha-e-Sá and Reis (Chapter 3) and Egli and Steger (Chapter 2) make the learning and technological change effects that are hidden in equation (6) more explicit. To connect these papers to the specification in equation (6), we need to disentangle the technology/productivity effect.
from the input effect of abatement. Capturing the former by $T_P$ and using a simple iso-elastic specification, we specify the pollution-generating process as:

$$P = \frac{K^\eta E^{1-\eta}}{T_P}$$

(7)

where $\eta > 1.4$. In this specification, doubling the rival inputs $E$ and $K$ doubles pollution, but improvements in the technology parameter $T_P$ reduce pollution. To capture learning-by-abating, we assume a positive link from abatement to technology:

$$T_P = E^{\gamma}.$$  

(8)

If $\gamma = 1$, equations (7) and (8) give $P = (K/E)^\eta$ which is consistent with equation (6) and thus allows for sustainable growth. This justifies the approach in older papers (e.g. Smulders and Gradus 1996) and newer ones (e.g. Soretz Chapter 6).

2.3. LEARNING-BY-ABATING

In Chapter 2, Egli and Steger open up the black box further and are more explicit about the sources of learning-by-abatement. Their parametric example of the pollution equation can be written as:

$$P = \frac{C - C^\delta E^{1-\delta} T_E}{T_P}$$

$T_E = E^{\gamma}$ 

(9)  

(10)

where $\delta \in (0, 1)$. In equation (9), consumption, $C$, rather than (capital) inputs, $K$, is polluting and abatement $E$ has an additive effect rather than a multiplicative effect. The consequence of the latter is that we can distinguish more productive abatement technology (reflected in increases in $T_E$) from cleaner production technology (reflected in increases in $T_P$). Equation (10) links abatement technology improvements to levels of abatement and thus captures learning-by-abating. As long as $\gamma > 0$, there are increasing returns so that abatement costs fall with the level of abatement. When consumption and abatement grow at a common growth rate, pollution will first rise and then fall. To see this, we rewrite equations (9)–(10) as:

$$P = C[1 - bC^\gamma]$$

$$b = (E/C)^{\gamma+1-\delta}.$$

Now assume $E$ and $C$ grow at the same rate so that $b$ is a constant. Then, for small $C$, $P$ grows, but for large $C$, $P$ declines. Andreoni and Levinson (2001) have shown this EKC pattern in a static model with an exogenous endowment from which consumption and abatement ($C + E$) can be financed. First, Egli and Steger demonstrate that when the specification of preferences is appropriately chosen, a corresponding AK-growth model generates a (quasi-) balanced growth path along which $E/C$ is indeed constant and $P$ follows the EKC pattern. Second, and more generally, incorporating the specification in equation (9) in an
AK model, the authors can show how the turning points of the EKC change with technology and preference parameters. Third, they also make explicit the role of (Marshallian) externalities and the implications for corrective taxation. For example, learning could take place on the economy-wide level so that technology $T_E$ is determined by economy-wide abatement and individual small firms can hardly affect $T_E$ and take the level of technology as given.

2.4. CLEAN TECHNOLOGY ADOPTION

Cunha-e-Sá and Reis (see Chapter 3) are even more explicit about the technological progress in abatement. They focus entirely on pollution reduction through changes in technology (increases in $T_P$) and abstract from instantaneous abatement possibilities (in terms of equation (7), they set $\eta = 1$). In particular, they assume that in order to have less pollution per unit of capital, a new technology has to be installed. Because of adjustment costs, technological change is discontinuous: at discrete times the economy adopts a cleaner technology, and at periods at which there is no switch to a new technology, pollution necessarily increases with production. Note that the cleaner technology is applicable nationwide, so that we may refer to a “general purpose technology” (as in Helpman 1998). Although the authors consider a single adoption only, a series of sequential adoptions could allow for a constant or declining trend in pollution. This would go along with a sequence of investment expenditures, which is similar to the ongoing abatement expenditures in the model with flow-abatement $E$ only.

The chapter investigates when economies optimally choose to adopt the cleaner technology and how the change in technology affects growth in the economy. While the usual EKC literature argues that environmental policy reacts to growth in income, the reverse effect is actually also important in a general dynamic equilibrium setting. Indeed, knowing that a cleaner technology that reduces pollution per unit of capital will be available in the future, society values capital more than without adoption, which boosts investment and growth. Accordingly, the paper finds that growth of consumption and capital accelerates prior to the adoption date, while these variables grow at a constant rate in the absence of adoption.

2.5. THE PORTER HYPOTHESIS AND DIFFUSION OF CLEAN TECHNOLOGY

According to the Porter Hypothesis strict environmental regulation can induce efficiency and encourage innovations that help improve competitiveness. In the chapter by Hart (Chapter 4), the incentives for innovation are studied in this perspective. There is no separate abatement technology for firms, so that, for given level of technology, firms can reduce pollution only by reducing production. However, changing the composition of output can reduce pollution per unit of aggregate output. Firms produce intermediate goods that are imperfect substitutes in final goods production (so that, the one-factor production function
(1) is replaced by a multi-input production function). Firms are heterogeneous in the sense that they differ according to vintages; newer firms pollute less per unit of output since they embody the newest pollution-saving technology; they also produce more output per unit of input. These assumptions imply that we need to replace the production function (1) and pollution function (7) by the following expressions, respectively:

\[ Y = \sum_{i=1}^{N} A_i K_i \]  
\[ P = \sum_{i=1}^{N} P_i = \sum_{i=1}^{N} \frac{1}{T_{Pi}} K_i \]

where \( K_i \) and \( P_i \) are capital and pollution in firm \( i \), respectively, \( T_{Pi} \) is the firm-specific pollution coefficient, \( N \) is the number of firms that are able to produce.

Over time, the number of firms expands. Research and development (R&D) activities provide entrants with new vintages of technology, which allows them to be more productive as well as less polluting. In particular, if successful in R&D, newer firms (with higher index \( i \)) have access to technology characterized by the following:

\[ T_{Pi} = T_P \cdot (\gamma_P)^i \]  
\[ A_i = A \cdot (\gamma_A)^i \]

where \( \gamma_P > 1 \) (\( \gamma_A > 1 \)) denotes the degree to which a new firm is cleaner (more productive) than the cleanest incumbent firm. The new technology becomes available with a certain probability, which increases with the amount of labour spent in R&D.

When newer firms increase their inputs (\( K \)) at the cost of older firms, production becomes less polluting. To introduce newer vintages, entrants have to incur an upfront investment cost. Now two channels arise through which environmental policy is effective. First, tougher environmental standards shift production from old to new vintages, thus reducing pollution on impact. Second, since new vintages attract a larger part of the total market and hence make more profits, tougher environmental standards trigger faster innovation, which reduces pollution in future also. Any new cleaner technology earns more profits than without the policy and firms have bigger incentives to innovate. Since by construction innovation implies higher productivity as well as cleaner production in the newest vintages, the Porter hypothesis materializes in the model: environmental policy not only reduces pollution but also increases growth.

Similar Porter-hypothesis effects arise in the vintage model by Van Zon and Kronenberg (Chapter 5), although their model is more complex. R&D produces two different types of innovations: radical or incremental ones. Radical innovations entail new General Purpose Technologies (GPTs), which are either carbon or non-carbon based. Incremental R&D improves the productivity of these
technologies by developing complementary inputs. Old vintages of GPTs may require carbon-based energy, while newer vintages may require non-carbon-based energy. A carbon tax shifts profits towards vintages that do not use carbon-based energy and promotes innovation associated with these vintages. The choice between the two types of R&D is endogenous in the model and is driven by expected profits. The model generates interesting diffusion patterns: carbon-free and other new technologies may gradually diffuse in the economy when applied research targeted at these technologies cumulates. Due to the stochastic nature of R&D, history plays a significant role. The characteristics of new technologies are unpredictable. When predominantly carbon-intensive technologies have been developed in the past, a carbon tax has a different effect on innovation and growth than when the economy happens to rely on alternative energy sources.

2.6. UNCERTAINTY AND THE VULNERABILITY EFFECT

In the benchmark model it is attractive to spend on pollution reduction because it boosts utility and productivity, cf. equations (3) and (4). In Chapter 6, Soretz adds a third reason to reduce pollution: reductions in vulnerability to shocks. She assumes expected aggregate production equals $AK$, as in equation (1), but actual income is subject to exogenous shocks, the effects of which are larger the poorer environmental quality is. In particular, actual output is given by:

$$Y_{dt} = K \cdot [Ad_{t} + P^{\psi} \nu dz]$$

where $dz$ is the stochastic variable (modeled as the increment of a Wiener process) capturing the shocks to aggregate income, and $\nu$ and $\psi$ are parameters. The bigger $P^{\psi} \nu$, the bigger the impact of a given shock $dz$. Hence $\psi$ measures the effect of pollution on vulnerability to shocks. A risk-averse society spends more on abatement to mitigate the vulnerability effect. This crowds out investment in physical capital and tends to reduce growth. However, the risk itself may at the same time increase savings for precautionary motives. Moreover, higher spending on abatement may strengthen the productivity effect (see equation (3)). Both forces tend to increase the rate of economic growth. The paper sorts out the counteracting effects and formulates implications for optimal environmental taxation.

3. RESOURCE USE AND GROWTH

3.1. INTRODUCING ADDITIONAL INPUTS

When adding additional inputs like natural resources and labour in the model, we can analyse at least two major issues. First, a more detailed study of pollution becomes possible. Whereas the AK model and its variants in the previous section focus on pollution from aggregate economic activity, most pollution in the real world is associated with particular inputs (e.g. chemical inputs or energy use), rather than economic output. Second, the dynamic effects of resource scarcity can
be studied. Both topics are closely related. Growth and environmental degradation may be decoupled through substitution of clean for dirty inputs in production. Only substitution at the highest aggregation level was incorporated in the one-factor AK models with abatement. To illustrate this point, suppose pollution stems from production, so that \( \partial p(K, C, E)/\partial C = 0 \). Then “net output”, or output available for consumption and investment, \( Y - E = C + dK/dt \), can be written as a function of pollution \( P \) and capital stock \( K \). In particular, inverting (2) to write \( E = b(K, P) \), we can write the production structure in equations (1), (2), (3), and (5) as:

\[
Y - E = a(P)K - b(K, P) \equiv F(K, P)
\]

(15)

\[
F(K, P) = C + dK/dt.
\]

(16)

In this reformulation pollution acts like an input that is a substitute for capital in the function \( F(.) \), which results from the fact that by varying the amount of abatement activities, a given amount of capital produces different levels of pollution and net output (cf. Stokey 1998; Copeland and Taylor 2003). Increasing \( K \) by one per cent without increasing pollution requires increases in abatement so that net output increases by less than one per cent. Hence, substitution and diminishing returns with respect to capital show up in the above-discussed AK framework once we consider net output rather than output including abatement activities. However, it is only substitution between “generic” capital and pollution; there is no distinction between clean and dirty inputs.

To make input substitution, e.g. of clean for dirty inputs or of abundant for scarce resources, as well as diminishing returns more explicit, it is useful to directly turn to a multi-input production like the following:

\[
Y = AK^\alpha L^\beta R^\omega
\]

(17)

where \( A \) is total factor productivity, \( K \) capital, \( L \) labour, and \( R \) a polluting input. Now \( Y \) should be interpreted as net output available for consumption and investment, as there is no need to distinguish separate abatement activities any more. With the example of climate change and air pollution in mind, one can interpret the polluting input \( R \) as energy. Pollution generated is proportional to energy, \( P = \pi_R R \), where \( \pi_R \) is the pollution content of energy (e.g. carbon content). The Cobb-Douglas specification in equation (17) implies a unitary elasticity of substitution, which is restrictive and perhaps unrealistic, but suffices to illustrate some insights that survive with lower substitution possibilities.

### 3.2. NON-RENEWABLE RESOURCES AND GROWTH

In Chapter 7, Groth uses the representation of production possibilities in equation (17) to study the impact of scarcity of resources on economic growth. Suppose \( R \) is the use (extraction) of a non-renewable resource, which implies that the total amount of input use from now on until the indefinite future is limited by the current stock of resources. Since no production is viable without resource use
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(Y = 0 whenever R = 0), production can only be sustained if in the end smaller and smaller resource flows are extracted over time. To sustain a constant or growing production level, the decline in resource use has to be offset by increases in substituting inputs or by increases in productivity of inputs through technological change.6 Suppose that the economy is on the balanced growth path along which production and produced capital goods grow at a common rate \( g \), so that \( (dY/dt)/Y = (dK/dt)/K \), and that a constant fraction of the population is in the workforce, so that \( (dL/dt)/L \) equals population growth. From (17), we can then express per capita output growth:

\[
\frac{dY/dt}{Y} - \frac{dL/dt}{L} = \frac{1}{1 - \alpha} \left[ \frac{dA/dt}{A} - (1 - \alpha - \beta) \frac{dL/dt}{L} + \omega \frac{dR/dt}{R} \right]. \tag{18}
\]

Since resource use has to ultimately decrease over time \( (dR/dt < 0) \), balanced per capita growth can only be positive if one or more of the following holds:

1. there is technical change \( (dA/dt > 0) \), so that higher productivity of inputs offsets the adverse effect of declining per capita resource use on production;
2. there is no technical change, non-increasing returns, and declining population \( (dA/dt = 0, \alpha + \beta + \omega \leq 1 \) and \( dL/dt < 0 \) \) so that the declining resource stock no longer translates into lower per capita resource endowments;
3. there is no technical change, positive population growth, but (mildly) increasing returns \( (dA/dt = 0, dL/dt > 0 \) and \( \alpha + \beta > 1 \) \), so that declining resource use is offset by productivity increases from scale economies;
4. there is no technological change and no population growth but (strong) increasing returns to scale \( (dA/dt = dL/dt = 0, \alpha > 1) \), so that the accumulation of capital offsets the productivity losses from declining resource use.

More precise conditions cannot be given until we know the determinants of resource use, technological change, and population growth. Keeping population growth as an exogenous variable, Groth explores in Chapter 7 how increasing returns and endogenous technological change in various guises, can provide the economy with increasing factor productivity to offset declining resource use.

Important policy implications can be drawn from equation (18). For example, conservation policies that slow down the rate of extraction result in a higher (but still negative) value for \( (dR/dt)/R \) and growth of output can be higher. In this sense promoting long-run growth and “supporting the environment” go hand in hand. Of course initial levels of output are lower with reduced resource use.

More broadly, equation (18) shows that regulation can affect the long-term growth rate only through affecting technological change, population growth or the rate of extraction. However, technological change and extraction should be considered as endogenous variables, and the important question is how these variables can be controlled separately. Groth shows that only in a special case can policy affect the rate of technological change permanently and independently.
of extraction. In this special case, the generation of new technology must be represented by an equation like

$$\frac{dA}{dt} = A \cdot g(L_A)$$  \hspace{0.5cm} (19)

where $L_A$ is the amount of labour devoted to R&D and $g(.)$ is an increasing function. The key characteristic is that a given rate of technological change, $(dA/dt)/A$, can be maintained as long as labour input in R&D is constant, as in most early endogenous growth models (Romer 1990; Grossman and Helpman 1991, see also equations (13) and (14)). Although this specification has been used in most of the literature on endogenous growth and non-renewable resources, it is non-robust and biases the conclusions in an optimistic direction. In the more general case, new technology creation requires labour ($L_A$), capital ($K_A$), resources ($R_A$), and existing knowledge incorporated in $A$:

$$\frac{dA}{dt} = G(A, L_A, K_A, R_A).$$  \hspace{0.5cm} (20)

Hence, the specification in equation (19) is limited to constant returns to $A$ and absence of capital and resources as inputs. Any relaxation of these knife-edge assumptions dramatically alters the possibilities to affect the long-run rate of technological change. First, when we deviate from constant returns to $A$, so that $dA/dt = h(A) \cdot g(L_A)$ with $h(.)$ a concave function, the long-run rate of technological change is determined by parameters that cannot be affected by policy easily (cf. Jones 1995). Second, when resource use enters the technological progress function (equation 20) either directly or indirectly because R&D requires capital and the production of capital requires resources, the rate of extraction affects the rate of technological change. Groth shows how in the general or robust case no taxation of any kind has long-term effects on growth unless they affect the depletion rate, which the usual taxes (e.g. a research subsidy, an interest income tax, and an investment subsidy) do not.

### 3.3. INTERNATIONAL PRODUCTIVITY CONVERGENCE

Growth without deteriorating environment is likely to require substitution of clean for dirty inputs and reduction of the use of energy or other polluting inputs per unit of output. To explore how we can accomplish this and what are the implications for growth, we assume constant returns to scale and derive from equation (17) the following expressions for average productivity of capital and the amount of pollution per unit of output (which we will label the pollution intensity):

$$\frac{Y}{K} = A \left( \frac{L}{K} \right)^{\beta} \left( \frac{R}{K} \right)^{1-\alpha-\beta}$$  \hspace{0.5cm} (21)

$$\frac{R}{Y} = A^{-1/(1-\alpha-\beta)} \left( \frac{Y}{L} \right)^{\beta/(1-\alpha-\beta)} \left( \frac{Y}{K} \right)^{\alpha/(1-\alpha-\beta)}.$$  \hspace{0.5cm} (22)

The productivity of capital is no longer a constant $A$, as it was in (1), but declines with capital under the standard neoclassical assumption of diminishing returns to
capital (i.e. \(0 < \alpha, \beta < 1\)). Due to input substitution, capital productivity increases with energy use (and hence with pollution). Furthermore, in equation (22) capital is no longer polluting, as it was in equation (7), but is in fact a clean substitute for polluting inputs in net production (cf. equation (15)). Finally, we note that technological change (increases in \(A\)) reduces the pollution intensity: it reduces inputs per unit of output and therefore reduces pollution per unit of output.

When pursuing sustainable growth, the reduction in energy use per unit of output is crucial. According to equation (22), this is possible by relying more on clean inputs, \(L\) and \(K\), in production. The question is whether and where this is possible. We find an elementary answer if we close the model by the Solow-like assumption of a fixed savings rate (cf. Brock and Taylor 2004, for a related argument). A fixed fraction, say \(s\), of output is assumed to be invested in capital so that capital grows at rate \(sY/K\). Hence capital grows quickly when capital productivity \(Y/K\) is large. Note from equation (22) that a large capital productivity \(Y/K\) also implies a high pollution intensity. A fast rate of growth of capital implies that capital productivity falls over time, see equation (21), and that pollution intensity falls, see equation (22). Hence, we arrive at a convergence result: a high initial pollution intensity implies fast reductions in pollution intensity over time, and vice versa, low pollution intensities imply slow reductions in pollution intensity. Countries with differences in pollution intensity therefore tend to converge in terms of pollution intensity.

An alternative source of convergence in pollution intensities is technology diffusion. There exist enormous international differences in technology (total factor productivity). Poor countries not only have relatively little capital (and hence high capital productivity \(Y/K\) and high pollution intensity \(R/Y\), but also relatively low technology levels \(A\), which gives scope for imitation and absorption of foreign technologies, relatively fast growth in \(A\) and hence relatively fast reductions in pollution intensities.

In Chapter 8, Mulder and De Groot test the convergence hypothesis for pollution intensities within a production function framework, assuming energy is the polluting input. In doing so, they compare their results with convergence in labour productivity. They emphasize the importance of studying dynamics both at the aggregate and sectoral levels, as data aggregation to single country observations may obscure sectoral convergence. They use data from 4 main sectors and 10 sub-sectors in manufacturing of 14 OECD countries in the period 1970–1997. They first observe that cross-country variation of energy productivity is much higher than that of labour productivity. In addition, the authors find evidence for conditional convergence of energy and labour productivities in most but not all sectors of the economy. It is important to note that the results for \(\beta\)-convergence in their paper are conditional on country-specific conditions, so that absolute international productivity differences are predicted to persist in the long run. Notably, in the \(\sigma\)-convergence analysis energy productivities are found to diverge on a macroeconomic level, so that scale, market and policy effects within countries are confirmed to be essential for the productive use of resources.
4. Intercommunity Social Dynamics

So far we have ignored spatial aspects of resource dynamics. We have seen in the previous section that different national economies have their own specific characteristics, and international contacts might give rise to convergence or divergence over time of resource-use patterns. Geographical specialization in resource use may change resource dynamics directly. Indirectly, resource use is affected by the macroeconomic dynamics stemming from the accumulation of complementary assets and spatial diffusion of new technologies, as well as the social dynamics related to the spatial spillovers of social rules. Such rules seem to be especially important when we leave the country level and focus on the level of local communities.

Local communities may not only differ with respect to resource availability and productivity in harvesting, they may also be governed by different social norms concerning cooperation. These norms are subject to their own (social) dynamics. Studying the interaction between resource dynamics and social dynamics is rewarding in at least two respects. First, often policy is faced with a situation characterized by local communities and a spatial distribution of activities. Second, the need for policy is weakened by the capacity of some of these systems to spontaneously generate social norms. Especially in relation to natural resource use, local communities can involve local mechanisms of monitoring and control, which (partially) replace hierarchical public policy. The combination of resource dynamics and spatial structure thus is of relevance to the formulation of optimal resource policies or institutional arrangements.

In Chapter 9 by Noailly, Van den Bergh, and Withagen, agents are assumed to harvest a common pool resource. The agents, who are either cooperators, defectors, or enforcers, are located on a circle, observing the actions of their nearest neighbours only. The specific assumption is that agents can enforce common harvesting norms by punishing the defectors not harvesting in a sustainable manner. Thus the set-up allows for a rich structure of local and global interactions in the economy; the latter consist of the impact of aggregate harvesting and the overall stock of the resource on harvesting strategies of individuals. After providing theoretical results and performing extensive numerical analysis, the authors conclude that, unlike in the previous literature, the three strategies can coexist in a large variety of constellations, while cooperators are very likely to be present at all times. Furthermore, the authors emphasize that, when resource dynamics are included, cooperative equilibria become even more likely.

5. Sustainable Motion in Classical Mechanics

Traditionally, formal dynamic modelling in economics has borrowed a lot from classical mechanics. In Chapter 10, Hartwick takes the opposite direction. He uses insights from economics to reinterpret classical mechanics. He observes that
“particle” motion in classical mechanics has an account in energy units of current product (a two element vector) balanced with current input (a two element vector). With sustainable or periodic motion each product element is balanced over the period of motion with its own input period after period. There is no cross-subsidization. With non-periodic (non-sustainable) motion, there is cross-subsidization and the values of the inputs are not maintained. The current balance energy account derives quite directly from Hamilton’s equations characterizing equilibrium motion.

6. Conclusions

We have argued that studies that combine resource dynamics with macroeconomic dynamics and/or social dynamics provide new insights into the issues of sustainability, the turning points of the Environmental Kuznets Curve, technology adoption, and induced innovation, protection against environmental disasters, long-term effects of resource scarcity, pollution intensity convergence, and local cooperative behaviour in resource extraction. We have shown an underlying and unifying framework of modelling production, pollution, and abatement for these topics. We expect future work to deal with a more detailed analysis of different types of technological progress in production and abatement technology, the role of uncertainty and radical technological change, and the microeconomic foundations of semi-reduced-form modelling of abatement. We hope that in the future the links between dynamic theoretical models and econometric time-series or panel analysis will be further strengthened.

Notes

1. This introduction partly reproduces and extends Bretschger and Smulders (2007). In particular, Sections 2.5, 3.1, 3.2, and 5 did not appear before.
2. To simplify our exposition, we assume that the flow of pollution determines productivity and utility. Many environmental problems, however, instead relate to the stock of cumulated pollution (concentration levels).
3. Let s be the savings rate \( s = (dK/dt)/Y \), which is by definition constant along a balanced growth path. Then \( K \) grows at rate \( (dK/dt)/K = sY/K = sA = sa(P) = sa(P(K/E, C/E, 1)) \), which is a constant. Since \( A \) is a constant, \( Y \) and \( K \) grow at the same constant growth rate.
4. The iso-elastic specification has the problem that zero abatement \( (E = 0) \) implies infinite pollution (Brock and Taylor 2005 P.1805). Therefore, equation (7) should be interpreted to hold only for a minimum level of abatement. A similar problem arises with the iso-elastic learning function in equation (8). These undesirable properties can be easily removed by replacing equations (7) and (8) by equation (7') \( P = T_p^{-1} K \min \{1, (E/K)^{-\gamma}\} \) and equation (8') \( T_P = \max \{T_0, E'\} \), respectively. The threshold in equation (7') implies that with zero abatement, pollution is proportional to capital and that a minimum amount of abatement is required before abatement starts to be effective. The threshold in equation (8') implies that learning starts only for large enough abatement levels. As long as \( \gamma = 1 \) and \( T_0 < K < E \), we still find \( P = (K/E)^\gamma \).
5. Alternative labels are pollution-augmenting and abatement-augmenting technological change. The distinction is impossible to make in the Cobb-Douglas specification of equation (7),
exactly like labour-augmenting and capital-augmenting technological change are equivalent in Cobb-Douglas production functions.

6. All that follows holds in a similar way for an economy that reduces polluting inputs over time (rather than non-renewable resources specifically), perhaps in order to improve environmental quality over time.

7. An interesting example of both these things happening is the case in which the function $G$ in equation (20) is the same function as the goods production function in equation (17). This case is equivalent to increasing returns in the model without changes in $A$, see Chapter 7, Section 4.1.

References