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Endogenous Technical Change, Natural Resources and Growth

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1. Introduction

England's spectacular industrial revolution was threatened to lose momentum by running out of coal in the nineteenth century, but growth over the subsequent century remained enormous. Many poor cities that have grown at a fast pace in developing countries have also experienced rapid growth in air pollution. Yet air quality in the large cities of the western world has improved rapidly in the last decades. Does growth lead to faster depletion of resources, or does it create the resources to clean up the environment? History and more recent experience show a diverse picture of many possible interactions between growth and scarcity of resources.

The main economic forces behind the interaction between growth and scarcity are substitution and technical change. In the absence of the two, each additional unit of output requires a given amount of resource use, for example energy input, and creates a given amount of pollution. In such a case, output cannot expand without reducing resource stocks and environmental quality. Almost all economists, and neoclassical economists in particular, have stressed that the amount of resources needed to produce a given amount of output is not constant on economy-wide level. Consumers may shift demand to goods that can be produced with less energy or pollution. Producers can switch to techniques that less intensively use resources. As a result, the interaction between growth and scarcity is shaped by household's preferences and willingness to adjust consumption patterns, as well as by technological possibilities and opportunities for producers.

Limits to growth are then determined by limits to substitution. When it is hard to substitute resources for man-made inputs, total production that can be produced over time from a finite resource is limited. However, even with ample substitution possibilities, resource substitution inevitably becomes harder when resource availability falls: the productivity of man-made inputs falls by the law of diminishing returns. Only technological change can offset the diminishing returns: new opportunities for substitution are opened up by shifts to new more productive technologies, less resource-dependent technologies and introduction of technologies that rely on completely new resources.

Technical change has played an enormous role in the past. The big waves in the history of economic growth can be attributed to major breakthroughs and subsequent incremental improvements in technology. The connection to natural resources is obvious when we consider the role of waterpower, steam power fueled by coal, the internal combustion engine run on fossil fuels. Part of the technological developments was due to luck and the genius of some individuals. A major part of the commercialization and diffusion of the new technologies, as well as their subsequent improvements and alternative applications, however, required deliberate investments and a well-thought business strategy. One of the major innovations in the 20th century is in fact the introduction of the R&D department. All in all, it is fair to say that a substantial part of technological change is the result of economic investment decisions. Technical change therefore occurs as a reaction to economic incentives and changes in opportunities to develop new technologies over time; that is, technology is endogenous.

Limits to growth must then not only be determined by substitution at a given moment in time, but also by innovation incentives or opportunities for the development of new technologies over time. Recently, economists have begun to explore the implications of endogenous technical change in formal models of scarcity and growth. Increased scarcity may, through rising prices, stimulate firms to develop new technologies. Thus endogenous technical change may alleviate scarcity limits. However, if technical change is a costly investment activity, it can also be crowded out by resource scarcity. If lower availability of resources reduces the productivity of man-made inputs, it becomes less rewarding to develop new technologies that are complementary to these inputs. Also, scarcity may provide the stimulus to develop new technologies that save on resource input, but this may imply a shift at the cost of innovation projects in other directions (for example labor-saving technical change). Changes in the direction of innovation efforts may at the same time reduce the effect of aggregate innovation effort on economic growth and thus reduce growth. Allowing technical change to respond endogenously to scarcity does therefore not necessarily lead to a more optimistic outlook with fewer problems of scarcity.

This chapter discusses how scarcity limits can be alleviated by substitution toward and development of less energy (material) intensive and cleaner technologies. We treat both substitution and technical change as *endogenous* and sort out the determinants behind them. Why is it that substitution towards clean or resource-extensive technologies not always occurs when the technical possibilities are there? When does faster growth speed up depletion? When does more growth go together with improving environmental quality? Must policies aimed at improving environmental quality or energy conservation harm growth? Do more stringent environmental policies induce innovation?

The interaction between growth and scarcity is complex because both growth and scarcity themselves must be treated as the result of economic decisions. The way in which the economy grows shapes the effect of growth on resource stocks. The other way around, resource availability will shape the opportunities for growth and the rates of return to investment. Economists have analyzed the elementary forces behind depletion and economic growth, by considering simple situations that abstract from many of the complexities of the real world. We will follow the main simplifications, which will help us in understanding the crucial economic forces: we focus on a single natural resource, first non-renewable resources like energy and materials, then environmental resources like fish, forests, clean air and water. We also aggregate economic activity into a single production activity. This single production activity requires several inputs. One of them is natural resource input. Different inputs can substitute for each other. We will focus on theoretical considerations, but we will review some of the main empirical evidence, in so far it is related to scarcity and growth on the aggregate level.

We first study the effects of given changes in production technology on resource use. It turns out that new technologies do not necessarily lead to less depletion. New technologies allow producing a certain amount of output with lower resource use (they facilitate substitution), but this implies that they also improve the productivity of resource use. Technical change may thus stimulate the demand for the resource. Second, we turn to the determinants behind technological change itself. That is, we treat technological change as an endogenous variable. We can sort out when the growth process comes to a halt because of scarcity and how growth rates are affected by resource policies or environmental policy. Here it turns out that scarcity is likely to crowd out innovation, but that knowledge spillovers may offset this tendency.

By moving from non-renewable to renewable resources and contrasting a given path of technological change to endogenous technological change, we follow more or less the chronological developments in the literature on growth and resource scarcity. This chapter first reviews the main insights from models of aggregate growth with a single resource, in the tradition of the economic growth literature (Stiglitz, 1974; Dasgupta and Heal, 1979). Here the focus is on non-renewable resources and capital-resource substitution, while technical change is treated as an exogenous variable. We then extend the scope of analysis to environmental problems and endogenous technological change. We will see how results from the older literature have to be revised or modified to be applied to renewable resources or to the situation in which technical change is endogenous rather than “manna-from-heaven”.

The recent literature has two strands in which endogenous technological change plays an important role. On the one hand, the interest came from growth theory, in which the assumption of exogenous technological change was considered more and more as unsatisfactory. One key question from this perspective is whether growth can be sustained if endogenous technical change requires investment and natural resources are essential for production. If by resource substitution the returns to man-made inputs fall, what happens to the incentive to invest in new technology, which can be seen as a man-made input too? On the other hand, environmental economists also became interested in endogenous technological change. They realized that the cost of environmental policies might be substantially lower if not only substitution within given technologies was available but also the possibility to develop new technologies.

The chapter proceeds in section 2 with the standard neoclassical model, which deals with non-renewable resource markets. We focus on the role of substitution and technological change. Section 3 turns to environmental resources, which are renewable and for which market failures are prevalent. We study in particular why these market failures change the role technological change plays in mitigating scarcity limits. Section 4 introduces the notion of endogenous technological change and discusses the main driving forces and implications. The core part of this section studies how environmental resource scarcity affects the rate and direction of technological change, and the policy implications. In Section 5, we turn to growth models. We are mainly interested in the conditions under which growth can be unlimited despite dependence on natural resources. In section 6, we discuss how environmental policy affects economic growth.

2. The neoclassical perspective: non-renewable resources

The debate on scarcity and growth has traditionally focused on the scarcity of non-renewable resources, like fossil fuels (oil, coal) and materials. “For there to be a meaningful natural resource problem, a resource must be in limited supply, must be non-renewable and non-recyclable, essential, and without perfect substitutes” as Stiglitz (1979, p. 40) noted when reviewing the neoclassical view of the problem of the scarcity of natural resources. The seminal work of Stiglitz, Solow, Dasgupta and Heal, published in the Review of Economic Studies 1974, has established the benchmark neoclassical framework to study scarcity of non-renewable resources.[1]

2.1. The neoclassical trinity: substitution, diminishing returns and technological change

In the neoclassical view, the economy can only produce if it extracts resource inputs, which implies that the resource is necessary for production and remains so in at least the near future. Each unit of resources used for production reduces the stock of available resources one-for-one and irreversibly. The stock of resources is privately owned and traded in markets, which also holds for other inputs that substitute for resource inputs (physical capital and labor). Inevitably, production depletes the resource stock. The question is whether such an increase in physical scarcity also implies an increase in economic scarcity: must economic production ultimately fall?

The main message from the neoclassical literature is that substitution of man-made capital inputs for the resource alleviates the economic consequences of physical resource scarcity. The market provides incentives for this substitution: thanks to the existence of markets in which resources are traded, rising prices signal increased scarcity and trigger substitution to less resource-intensive techniques. Capital replaces resources and limits to growth can be avoided if there are enough substitution possibilities.

Although substitution of capital for resources alleviates scarcity in the neoclassical model, the substitution mechanism itself tends to become less and less powerful. The reason is that the productivity of a piece of equipment tends to fall if a larger amount of capital is combined with fewer resources or other inputs. This law of diminishing returns with respect to capital makes capital accumulation increasingly less productive when the amount of available resource inputs falls. So while *substitution* mitigates the drag on growth from resource scarcity, *diminishing returns* constitute another drag on growth. The neoclassical model relies on a third assumption, the presence of ongoing exogenous *technological improvements*, by which growth can be sustained over time. Technological change exogenously improves the productivity of the factors of production –capital as well as resources. It offsets the diminishing returns so that growth can be sustained.

The empirical validity of the neoclassical model is subject to an ongoing debate, which is discussed at various other places in this book. Many empirical studies on technological change and substitution on the macro-level directly or indirectly support the neoclassical view. Energy use per unit of production has declined secularly in most industrialized countries over a very long period. Rates of technological change are almost unambiguously found to be the significant and relatively large.[2] In two studies, Weitzman (1997, 1999) provides a remarkable indirect way of testing and calibrating the model. He finds that roughly 40 per cent of annualized welfare is the result of technological change, while at most 1.5 per cent of income can be gained if the limited non-renewable resources we rely on would remain to be available unlimited at today's flow rates and extraction costs.

2.2. Depletion of non-renewable resources and technical change: basic results

What determines the rate of depletion, and therefore scarcity, in a world of substitution? The first insight is that *the resource stock is never fully depleted*, at least as long as the resource is necessary for production. Society as a whole ideally wants to avoid depletion. Once nothing of the resource stock is left, nothing could be produced and consumption would be impossible. In such a situation of extreme scarcity, a small amount of resources that would make production possible is extremely valuable. This indicates that full depletion can never be optimal, since society anticipates that it is extremely valuable to leave some resources to avoid zero production. Society can improve upon a situation where full depletion arises by consuming and depleting less today in exchange for a small increase in future consumption.

The avoidance of full depletion is not only optimal, but is also the likely outcome if resource markets function well. Households own the resource, so that they can trade property rights. Young generations want to secure future consumption so they are always willing to buy a resource stock from the older generations. When the stock becomes very small, the young are willing to pay a very high price, thus preventing the old generations to fully deplete the stock. Forward markets for the resource help establishing the dynamic efficiency of the resource market. Market participants may hold incorrect expectations about future scarcity, which leads to inefficient extraction of the resource. However, market participants are likely to arbitrage away systematically large discrepancies between expectations and realizations. Thus, with the existence of property rights and (forward) markets, there is not much reason for active resource policies.

Some readers may worry that individuals care not enough about the future to warrant resource conservation. When agents discount the future at a higher rate, they tend to speed up depletion in order to raise current consumption at the cost of future consumption. Yet, even with discounting, the necessity of the resource for production prevents full depletion.

The second insight is that (*exogenous) technical change has an ambiguous effect on the rate of depletion*. Consider the arrival of a new technology in future that allows a larger output level for given resource inputs (and other inputs). Households that anticipate this technical change attach a higher value to the resource stock, since it is more productive in future (younger generations are willing to pay a higher price for property rights on the resource stock). This makes it attractive to conserve more resources for future periods in which the productivity is higher (this is a substitution effect). However, at the same time, a given resource stock can produce more goods, which increases income and makes consumption more abundant in the future. With higher lifetime-income due to future technical progress, current demand for resources goes up, since richer households not only want to consume more in future but also at present, that is, they want to smooth consumption (this is an income effect). Thus, substitution and income effects work in opposite directions; which one dominates cannot be determined without knowledge of society's preferences. Most empirical research on how the pattern of consumption over time responds to changes in the rate of return to savings has found evidence that income effects dominate substitution effects.[3] Hence, we may expect productivity gains raise depletion.

3. From old to new scarcity: environmental resources

Since the 1970s attention has shifted from the scarcity of materials and energy resources to the scarcity of resources such as the quality and quantity of environmental resources like clean air, clean water, clean soil, and to biological resources like forests, fish stocks and rare species.[4] Economists have asked whether they could analyze the scarcity of environmental resources within the framework they developed for non-renewable energy and mineral resources. Certainly, both types of natural resources have some features in common – they are inputs in production processes and they can in principle be depleted. However, the fact that environmental resources are not priced or traded in markets and that their use has much in common with public goods makes environmental resources crucially different from non-renewable resources. Because of the lack of well-functioning markets, environmental resource scarcity might pose bigger economic problems than scarcity in non-renewable resource markets.

3.1. The characteristics of environmental resources

When we claim that environmental resources are an input in production, we refer to a link between environmental resource use and production that is less direct than the way energy and materials are an input in production. Production creates pollution as a side-product, which diminishes environmental quality. Pollution can therefore be regarded as the inevitable depletion of a resource stock due to production. In this sense pollution is similar to resource use in the standard neoclassical approach. Pollution is often linked to a particular input, for example chemicals, which cause in toxic waste, or energy use, which results in air pollution. Substitution between polluting inputs and other inputs takes place because firms can choose to undertake abatement activities, which reduce the amount of pollution generated or mitigate the effects of emissions. Technological progress may result in less polluting production processes, products that generate less waste when consumed ("cleaner products"), or more efficient (cheaper) abatement technologies such as filter, scrubbers and other add-on technologies.

We commonly distinguish environmental resources from mineral resources because the former are renewable and the latter are non-renewable. Pollution reduces environmental resources and thus creates environmental resource scarcity. The damage needs not to be long lasting, since nature has a capacity to neutralize pollution. For example soil and river water pollutants can be diluted and washed out by rainfall and flow currents. Thus the pollution absorption capacity of ecosystems makes environmental quality a renewable resource.

A second important distinction comes from the fact that the stock of environmental resources may directly matter for society's welfare. We care about the environment as an amenity (unique landscapes and species, clean air and nice sites). So while we care about mineral resources only indirectly because they yield productive inputs into production of goods that we value, we care about environmental resources also directly. For example, some industries might benefit from cleaner water supply: they save on water treatment costs, so that they can more cheaply produce useful goods. However, the benefits of clean water resources mainly come directly to consumers in terms of health benefits and amenity values.

A third important aspect of environmental resources is their public good character. While non-renewable resources like oil and minerals are traded as private goods in markets and protected by property rights, it is – in contrast – impossible to define the owner or enforce property rights of environmental resources like clean air, fish in the ocean, or the ozone layer and it is not straightforward to charge users of these resources a price. The essential properties of public goods apply to environmental resources: access is hard to exclude and consumption is non-rival. Markets fail and the price mechanism on its own cannot be relied upon to ensure that environmental resources are allocated and used in the socially best way: as long as users do not need to pay a price, they do not internalize the social cost of resource depletion and environmental degradation. This calls for public intervention, like pollution taxes or fish quota, to correct the resource market externalities.

3.2. Environmental degradation and technical change: basic results

What determines the rate of degradation (or improvement) of environmental quality; what drives scarcity of environmental resources? We can modify the standard neoclassical model to study the connection between production and environmental resource depletion. The natural resource is now renewable. We have to account for the public goods character of environmental resources: markets for resources are missing, but regulation may repair resource externalities.

To analyze environmental degradation, it is useful to deal separately with two cases. In the first case, the "first best case", institutions and regulation set optimally ensure best use of environmental resources. Society trades off degrading the environment for the sake of production, against maintaining environmental quality for the sake of its amenity value and its provision of resources in future. In the second case, the "unregulated market case", regulation is missing and market prices fail to reflect scarcity. Firms are typically not charged the full cost of depletion of these resources. If firms are allowed to pollute more and to emit pollutants without treatment, their unit production cost is lower and productivity is higher than when they have to spend resource to avoid pollution and wastes. Firms maximize profits by expanding production until the marginal product of additional natural resource use (read pollution) is zero. Clearly, if the environmental asset is provided for free, suboptimally high levels of production and pollution result.

In between these extreme cases is a situation with some, but inadequate, regulation. The regulation addresses some of the externalities, and to a certain degree, but regulation is insufficient to attain the socially efficient situation. Four basic insights now emerge.

The first insight is that *without adequate resource policy, environmental resources are easily over-exploited*. If the resource becomes scarcer, there is no price that reflects the growing scarcity and firms or household do not have a private incentive to reduce their pollution. Profitable low-cost options may be available to reverse environmental degradation, but individual agents free ride on the action of others to invest in the public good. In the absence of price signals, substitution possibilities towards clean production processes and products are not exploited. Also technical change may fail: if agents do not pay a cost to pollute, there is no incentive to develop cleaner technologies in order to save on costs.

The second insight is that *without adequate resource policy, technological change is likely to speed up environmental degradation*. With adequate resource policy, the effect of technological change on the environment is ambiguous, in principle, for reasons explained with respect to non-renewable resource depletion discussed in section 2.2: the expectation of higher productivity of resources (and other inputs) makes it worthwhile to conserve resources for the future (substitution effect), but the anticipation of higher income from the improved productivity makes society eager to increase resource consumption (income effect). However, in the absence of resource policy, firms extract resources without concern for future resource scarcity. Then, they have no reason to conserve resources for the future to exploit future productivity improvements. The substitution effect no longer works and the income effect remains, which speeds up resource degradation.

Technological change may come in different guises: as neutral or as biased technological change. Only resource-saving technological change can lower depletion. Technological change is *neutral* if it raises the productivity of all conventional (non-environmental) inputs in the same magnitude. For example, firms improve the organization of their production process such that more outputs are produced from the same inputs, or they redesign products without changing input requirements, such that these are more useful for their customers. The marginal products of all inputs, including polluting inputs, rise and firms want to employ more of all inputs, unless prices change. Without a price on pollution, however, pollution must increase. Neutral technical change makes it possible, in principle, to produce the same amount with *less* pollution, but this exactly gives firms the incentive to pollute *more* since the productivity of pollution rises.

Biased technological change, the second guise of technological change, affects the productivity of one input more than of the other. For example, an improvement in the design of gas-guzzling cars such that customers are attracted away from other less polluting cars, implies a higher productivity of energy and polluting inputs in particular; it is resource-biased technical change if consumers start to spend relatively more on gasoline because of this technological change. In contrast, a cost reduction for production of low-emission vehicles might reduce the expenditure share of gasoline, and the technological change is classified as resource saving.

Without regulation, new technology improves environmental quality only if the following two conditions are fulfilled. First, the new technology must decrease the unit production cost (which excludes the environmental cost if the environment is not priced). If not, the firm is better off using the old technology and would not adopt the new one. Producers pass through the decrease in unit costs in lower prices, which result in larger production compared to under the old technology. Second, the new technology must substantially reduce the marginal productivity of polluting inputs. If not, either firms increase pollution per unit of output, or they decrease pollution per unit of output, but due to the expansion of the scale of output, total pollution still increases (this is called the rebound effect).

If some market-based environmental policy is in place, the picture may change. Then we find the third insight that *market-based instruments may trigger resource-saving innovations*. In particular, incentives for adoption of cleaner technology change if regulation imposes a cost per unit of pollution, for example because of a pollution tax or a system of tradable pollution permits. Then, irrespective of the question whether the regulation is stringent enough to produce the social optimum, firms have an incentive to avoid pollution up to the point where the marginal returns to pollution equal the pollution tax or tradable permits price. Suppose regulation consists of a pollution tax, fixed at an arbitrary level. Now technical change occurs. On the one hand, if technical change takes the form of improvements in total factor productivity, pollution will increase. This happens because the marginal productivity of pollution increases, but the cost remains the same.[5] On the other hand, if technological change results in lower costs of reducing pollution (improvements in abatement technology), firms reduce pollution.

A final issue to be considered is what is the optimal – or adequate, as we have called it – level of regulation, such that the environmental degradation and polluting production are optimally traded off. As a fourth main insight, we may state that it *may well be optimal for a growing economy to aim at improving environmental quality* over time. That is, society should expand environmental resource availability, rather than deplete. The basic reason is that in a growing economy produced consumption goods become more abundant, so that they are valued at a lower marginal utility relative to environmental amenities. This increases the demand (willingness to pay) for environmental quality. In other words, the demand for both produced consumption and environmental quality goes up with income (economists have called this the "normal goods" property). Economic growth calls for higher environmental quality as long as there is some "satiation" in preferences with respect to produced consumption goods (Lieb 2002), which seems to be very plausible. Only when the availability of produced goods is low relative to environmental quality, as may be the case in poorer countries, scarcity of environmental resources is not a problem and society optimally gives priority to increasing production at the expense of environmental quality. Since this seems a temporary phenomenon, we can expect that when income grows large enough, demand shifts to environmental quality.

In the long run, environmental resources are conserved in the optimum. Whereas in the standard neoclassical model the non-renewable resource stock was never fully depleted because extractions from the stock are essential in production, in the case of non-renewable resources it is the stock itself that is essential. Environmental quality serves as an amenity in utility and as a productive asset in production: clean air is essential for health and for the workers' productivity;

soil quality is essential for agriculture. The environmental resource stock is not asymptotically depleted, but under normal conditions a non-zero optimal stock of environmental resources is approached in the long-run social optimum.[6]

3.3. Some empirics: the Environmental Kuznets Curve

The main pieces of evidence on environmental resource scarcity and economic growth come from the literature on the "Environmental Kuznets Curve" (EKC) hypothesis.[7] This literature tests how pollution changes with income levels. The relation between pollution and income is characterized as an EKC if pollution first rises with income, but starts to decline when income exceeds a certain threshold level.

On theoretical grounds, there is no reason to expect pollution and growth to be unambiguously related, because both income and pollution are endogenous variables (cf. Copeland and Taylor, 2003). The pattern of growth, choice of technology and nature of technological change determine how income and pollution evolve over time and a host of underlying variables can affect both variables. However, our review of the basic insights from theory helps us to sort out the various basic forces that affect pollution and environmental degradation in the process of growth. Note that the theory predicts an EKC pattern under two specific alternative sets of circumstances. First, we can expect an EKC if environmental policies sufficiently reflect social preferences for growth and environment, and thus reflect a rise in the demand for environmental quality because of its "normal goods". Second, the EKC may arise without environmental regulation if technological change happens to be such that for low income the productivity of polluting inputs increases, but for higher income, it falls.

Indeed for water pollution and several types of air pollution like sulphur dioxide (SO_2), suspended particulate matter (SPM) and oxides of nitrogen (NO_x), most studies agree that the relationship between per capita income and pollution per capita is inverted-U-shaped. There is mixed evidence of an EKC pattern for deforestation, but here variation in income level seems to be relatively unimportant in explaining cross-country deforestation differences. Municipal waste, carbon dioxide (CO_2) emissions and aggregate energy use are all monotonically related with income. It should be noted that the results are far from conclusive. Most estimates stem from cross-country analyses, so that we cannot immediately draw about the relationship between growth and pollution. Moreover, the results are biased because of selective data availability: typically, data are collected only for pollutants that are considered a problem for sufficiently long a period time in many countries.

The evidence that emissions fall with income growth is limited to a small number of pollutants (local pollutants with immediate health effects) and to higher income countries. Our theoretical considerations above can partly explain this. In an economy in which pollution is unregulated, it depends on the nature of growth and technical change whether pollution falls over time. Indeed, if economies grow in early stages by accumulating polluting capital and in later stages rely on clean human capital, the EKC might emerge as a side-product of the pattern of growth. Similarly, the EKC can be explained as a side-product of the process of structural change that accompanies growth. If in early stages a transition from agriculture to manufacturing is made, industrial pollution grows with income. In later stages a shift from manufacturing to services may explain the cleaning-up phase of the EKC. Empirically, this latter effect turns out to be weak, however. Structural change has lost most momentum in OECD countries in the last decades. Most reduction in pollution intensity takes place *within* the manufacturing sector. Moreover, the computerization of the service industry points out that services may become more energy and material intensive than suggested by the simple theory.

Connecting our insights about technological change and environmental resource scarcity to the empirical findings, we see two clear messages emerge. First, despite the finding of an EKC for several pollutants, pollution will not decline automatically if an economy grows richer. We may find an EKC pattern because richer economies implement more stringent environmental policies. Second, what allows pollution to fall is more likely to be a deliberate change in technology, rather than a side-product of technological change or growth.

4. From manna-from-heaven to innovation as an economic decision

Technological change is an essential driving force behind economic growth and a powerful mechanism to mitigate the cost of resource scarcity. So far, we have discussed only the effects of technological change. Now we turn to the determinants of and driving forces behind technological change.

The economic view on technological change has changed markedly over the past few decades. Economists have treated technological change for long as something that is too complex and too hard to explain on economy-wide level starting from the economist's standard assumption of competitive markets. However, commercial research and development have become increasingly important strategies in big multinational corporations and small firms in new product markets. Industry leaders and national policy makers stress more and more the role of innovation for national wealth and competitiveness. The way Japan in the 1960s and the small Asian industrializing countries later on achieved rapid growth has suggested that policy and economic incentives can influence the pace of technological change within a nation.

All this urged economists, and growth theorists since the late 1980s in particular, to view the pace and direction of technological developments as the outcome of economic decisions, rather than a given but unexplained fact of life. The process of growth as well as the reactions to changes in economic environments (such as increasing scarcity) can be much better understood if technology is seen as an endogenous rather than exogenous variable. When the path of technological change was fixed, firms and households could react to changes in resource availability only by changing the allocation of economic activity; resource scarcity would trigger only substitution. However, with endogenous technology, also innovation may be intensified or shifted in other directions in response to economic changes.

Economists have tried to incorporate endogenous technology into the neoclassical growth framework. It turns out that this involves a major change, since it requires abandoning the idea of perfect competition. Economists have identified new market failures, public goods and property rights problems, when shifting from exogenous technology to endogenous technology. These externalities interact with resources externalities that were introduced with the shift from modeling non-renewable resources to environmental resources.

4.1. Innovation incentives and opportunities

Little technological change would take place if no effort was spent on innovation (in the form of, for example, inventive activity, research and development expenditures, building prototype factories). The economic decision is how much effort to spend on innovation. The innovation decision requires the calculus of costs and benefits. The cost of innovation consists of the costs of inputs in the innovation process. We should think of laboratory equipment and tests, but mainly time and engineering labor. The returns are the discounted expected profits that can be reaped once the innovation is put in the market. The development of new knowledge (a new idea, a blueprint for a new product or technology) typically has a fixed cost character. Incurring once an upfront investment cost is sufficient to develop a new idea, which can subsequently be applied and put into practice many times, at no cost. Hence, the size of the market determines the rate of return, which implies increasing returns.

Innovators balance costs and expected benefits in determining how much they spend on innovation and on what kind of innovation projects they spend most. Hence, with endogenous innovation, the direction (bias) of technological change is endogenous. Innovators choose among different investment projects, some of which improve the productivity of resources, other improve the productivity of capital, or reduce the costs of extraction, and so on.[8] The higher the expected returns and the lower innovation costs are in a particular project (direction), the more innovation will take place on this project (in this direction). By this mechanism, high prices for certain inputs shift innovation efforts to projects that develop technologies that save on these inputs. Relative price may affect the direction of technical change, which is known as *induced innovation hypothesis*.[9]

Market failures show up at various stages of the innovation decision, because of monopolistic product markets, knowledge spillovers, and creative destruction. First, imperfections in the product market arise because innovation requires *monopoly power*: no person would invest in developing a new technology unless it could appropriate the returns by making firms that use the new technology pay for it, and exclude other firms. The monopoly profits are the carrot for the innovator, and thus enhance dynamic efficiency. However, they burden society with prices above marginal production costs at the cost of static efficiency. Second, *knowledge spillovers* occur when agents can benefit from new knowledge developed by other firms or research institutions without (fully) paying for it. Knowledge is hard to exclude by means of tight property rights. Patent laws may prevent producers to use blueprints to produce a specific product or use a specific technique, but it is hard to prevent other researchers to use the more general knowledge that can be inferred from the blueprints. Current innovators build on knowledge developed by earlier innovators, without compensation. Imitation and patent infringement is another reason for knowledge spillovers. Hence, the intertemporal knowledge spillovers make that the innovator can appropriate only part of the social returns and the incentive to research is suboptimally low. There are also tendencies to overinvestment in R&D: several firms may race for the same patent and duplication of research effort takes place. Innovating firms may replace other firms before these have recouped their investment costs. Such a process of *creative destruction* may impose a social cost since the innovator does not internalize the cost it imposes on the other firms. In theory, we cannot say which type of externality dominates. However, the consensus from the empirical literature is that the positive externalities dominate and that the social rate of return to innovation exceeds the private return.[10]

4.2. Resource scarcity and endogenous technology: basic insights

We can now study how natural resource scarcity affects innovation, and, in particular, how it affects the rate and direction of technological change. We formulate the main insights from endogenizing technology as an effort-consuming process with important market failures.

The first main insight is that a large *endowment of resources has an ambiguous effect on the* rate *of innovation*. On the one hand, abundant supply of production factors makes it more attractive to develop new knowledge that allows increasing the productivity of these resources. The reason is that the returns of R&D rise with the scale at which it is applied, but the cost of developing new knowledge is independent of scale: knowledge is non-rival and the development cost has a fixed cost nature. On the other hand, however, the opportunity cost of R&D also rises: with more (non-labor) resources available, the marginal product of labor in production is large which makes it attractive to allocate labor to production rather than to research.

A second insight is that the poorer substitution (between natural resource inputs and other inputs) is, the more likely the *direction* of technical change shifts to the scarce factor so that *induced technical change compensates for low substitution possibilities*. Lower resource availability drives up the prices of marketed resources. This results in higher prices of resource-intensive goods as well, which makes it attractive to invest more in innovation in resource-intensive sectors. However, the price effect is counteracted by a market size effect: lower resource availability reduces output in resource-intensive sectors and makes innovation in these sectors less attractive. With less production in the sector, the scale at which a given newly developed technology can be applied is smaller. Which effect dominates depends on the combined price and quantity effect of lower resource availability on revenue and profits in the sector, since innovation shifts to the sector in which profits of innovation increase. If goods from other sectors easily substitute for resource-intensive goods, the price increase due to lower resource availability will be small, revenues in resource-abundant sectors fall, and innovation will shift away from these sectors. In contrast, if goods from other sectors poorly substitute for resource-intensive goods, revenues in the resource-intensive sector will rise and innovation shifts to these sectors. In both cases, however, innovation results in lower demand for energy: in the poor-substitution case because innovations are directly energy-saving, in the good-substitution case because innovation makes substitute goods in energy-extensive sectors cheaper and demand shifts further to these sectors.

Since technology choices are determined by market responses, whether innovation is induced by resource scarcity crucially depends on to what degree resources markets exist and function efficiently. A third insight is that *resource market failures may cause induced technological change to inefficiently speed up environmental degradation and depletion*. Take the case of renewable resources like fish. Markets for fish exist, but excessive catch is likely to result because of the lack of property rights over world fish stocks. If because of inadequate fishery management fish populations decline, fish prices go up. This might actually stimulate investment in fishery and innovation in more powerful vessels. Hence, in a situation of excessive harvesting, induced technological change might even increase harvesting and depletion. The technological change moves in the “wrong” direction.

Technology responds to scarcity in an efficient way only if resource and environmental policies provide adequate price signals. However, policy itself has to come in place. It may be that environmental problems induce policy changes, which in turn induce the technological changes. The *induced policy response* seems to be empirically important, as is discussed above in the context of the Environmental Kuznets Curve.

4.3. Some empirics on energy, environment and innovation.

Studies on the correlation between resource endowments and economic growth produce mixed results, in line with theory. Resource booms have often deteriorated rather than improved economic performance in for example Latin America (Sachs and Warner 2001). However, resource-rich countries like the US and Norway provide counterexamples. Wright and Czelusta (2002) attribute the US growth success to a combination of large resource availability and targeted investment in skills and new technologies. Institutional quality and the correct innovation incentives prove to be essential in transforming resource availability into wealth and coping with problems of resource scarcity. Easterly and Levine (2003) find that resource abundance only affects growth through its effect on corruption and institutions.

Empirical studies into the link between environmental regulation and innovation typically find ambiguous results, as predicted by the theory. Research and development expenditures tend to rise with environmental compliance expenditures, but there is no correlation with innovative output as measured by patent applications (Jaffe and Palmer 1997).

There is some support for the induced innovation hypothesis for environmental innovation. Lanjouw and Mody (1996) find that increases in environmental compliance cost lead to increases in the patenting of new environmental technologies with a one- to two-year lag. This finding supports the poor substitution case: the price effect dominates the market size effect, which spurs innovation. There is also evidence that energy-saving technical change was especially important in periods of high prices of energy and oil shortages (Kuper and Van Soest, 2003).

Empirical studies point out that price changes and regulation explain only a relatively small part of the bias of innovation. Newell et al. (1999), for example, find evidence for the role of energy prices, regulation and market size on the direction of innovation. However, up to 62 per cent of the total change in energy efficiency must be attributed to other factors. They also find no effects of these three factors on the overall rate of technological change. Similarly, Popp (2001) finds that two-thirds of the change in energy consumption with respect to a price change is due to simple price-induced factor substitution, while the remaining third results from induced innovation. Popp (2002) finds evidence for knowledge spillovers: using patent citation data, he finds that innovation directed at energy improvements build on the total stock of knowledge embodied in the (quality-adjusted) stock of patents in for energy efficiency improvements. He also finds, however, that there are diminishing returns with this knowledge stock. One of the very few economy-wide studies on the bias of technical change, by Jorgenson and Fraumendi (1981), finds that the majority of sectors in the US economy experienced technical change that is not only material saving but also energy using.

In a famous article in the Scientific American, Michael Porter (1991) argued – on the base of case studies – that environmental regulation often increases profits of firms, because of first-mover advantages or because of the elimination of waste of input use. The economics profession has reacted sceptically. Environmental regulation restricts firms in their behaviour and reduces their choice menu. The Porter hypothesis seems to claim that firms choose an action from this smaller menu that gives higher profits than the action chosen from the larger choice set that is available in the absence of environmental regulation. But then it is unclear why firms did not choose this action without the regulation. In a world with endogenous technological change and knowledge spillovers, the Porter hypothesis may be valid, however, since technology, productivity, and profits of an individual firm now depend on aggregate innovation activities and knowledge stocks, which may change in reaction to environmental regulation. Unregulated firms' R&D strategies are suboptimal because of knowledge spillovers and other market failure in markets for technology. Environmental regulation may improve the incentives for innovation, thus improving not only social welfare, but possibly also firms' profits.

5. Limits to growth?

Despite substitution and technological change, the dependence on limited resources may ultimately result in declining economic output. Limits to growth can be avoided if incentives to accumulate substitutes for resources and to innovate for new technologies keep intact, even when resources become scarcer over time. To study limits to growth, we have to examine the long-run investment and innovation incentives and how they change if the economy grows and resource stocks change over time. Regulation affects incentives, so we must again distinguish between situations without or with inadequate intervention, and those with optimal policies that address market failures.

5.1. Long-run growth, capital accumulation and exogenous technical change

Capital accumulation allows society to invest in substitutes for natural resources. Households choose to invest up to the point where the marginal product of capital equals their required rate of return, which reflects their impatience (utility discount rate). They accumulate more capital the more patient are households and the less quickly the returns to capital fall with accumulation. The following basic results emerge in the neoclassical model.

First, substitution of capital for the depleted resource can prevent output to fall. But without technical change, output is likely to fall, unless very stringent conditions apply. The degree to which man-made capital can substitute for resources is crucial. If substitution is poor, the accumulation of capital cannot prevent production to fall in the long run. If substitution is sufficiently large, and if the production elasticity of capital is large as well, a constant level of production can in principle be maintained in the absence of exogenous technological progress (Solow 1974, Hartwick 1977). Even in this case, without government intervention households, who maximize the discounted lifetime utility, will not find it optimal to accumulate enough capital to sustain this constant level of income.[11] In other words, while non-decreasing production is feasible, it is not optimal. As we have seen before, the complementarity between resources and capital, together with the diminishing returns with respect to capital, imply that the returns to capital fall when more capital is used per unit of resource use. With the decline in the rate of return, investment falls and output ultimately declines.

Second, with a constant rate of exogenous technical change, growth and capital accumulation can be sustained. Technical change increases the productivity of capital and offsets the fall in returns due to capital-resource substitution. The presence of technical change is not sufficient; it must be of a specific nature and it must be large enough to sustain growth. In particular, if resource-capital substitution is poor, the nature of technical change has to be resource saving, increasing the productivity of capital relative more than the productivity of the resource.[12] The rate of technical change has to be large enough to counteract the fall in returns to capital. Accordingly, it has to be higher, the faster capital accumulation is and the poorer substitution is.

Third, growth can be sustained in the presence of ongoing technological change only if environmental policy is adequate. In particular, *in a growing economy, the tax on pollution must increase over time* to prevent environmental degradation. Environmental resources are bounded, so pollution must be bounded to ensure environmental resources are not completely depleted. In contrast, the stock of man-made assets expands continuously in a growing economy, driven by improvements in total factor productivity. With more man-made capital per unit of polluting input, the productivity of polluting inputs rises. To prevent firms to increase pollution, they have to face higher costs of pollution.

Fourth, with capital accumulation and depletion driven by exogenous technical change, preferences affect long-run growth and depletion rates. Lower discount rates reduce the pace at which the resource stock is depleted and speed up long-run growth. Faster technical change also boosts growth.

5.2. How to interpret capital and technological change in the neoclassical model

Capital, the key variable in the neoclassical model, is sometimes narrowly understood as machines and hardware. However, we would do more justice to the spirit of the neoclassical approach by interpreting capital in a broader sense, viz. as foregone consumption. Today's consumption is given up for new assets. Investment not only gives rise to a physically larger mass of machines, but also to qualitatively better, more efficient machines and organizations, perhaps even to new social attitudes toward waste of energy. The assets allow production of (at least) the same services with less use of the scarce non-renewable resource. The assets thus not only comprise capital in a narrow sense but also intangible assets and knowledge; similarly, not consuming implies investment and innovation.

The broad interpretation of capital clarifies the neoclassical assumption of substitution between capital and resources like oil and materials. An expanding capital stock is not necessarily a collection of ever more of the same type of machines. Instead, capital is "knowledge" frozen in material, rather than just material; capital embodies the knowledge stock and this knowledge stock expands in the process of accumulation. With a larger capital stock, production might require less material or lower total energy inputs, because the replacement of old machines by new ones allows to put into practice new ideas to harvest energy, to use materials, and so on. A larger capital stock produces new products and satisfies new wants, which may require less energy and materials. Thus conceptualized, capital does not so much provide the capacity to produce a given physical object, but it rather provides the capacity to create valuable things, where the exact nature and physical properties of these "things" may change a lot.[13] Society has the possibility to give up consumption in order to create assets that generate more value in future and replace resources. The degree of substitutability determines the degree to which this dematerialization is possible.

The broad interpretation of capital opens up some problems, however. The standard neoclassical framework treats investment as a single homogenous activity. It does not explicitly model investment as a joint process of, on the one hand, the creation of new knowledge and, on the other hand, the embodiment of new knowledge in capital goods.

A first important implication is that all investment is treated as an activity that requires the production and trade of private goods for which there are well-defined markets – perfectly competitive markets even, according to the model. Although this may hold true for equipment and mass-produced machinery, this is less likely to apply to knowledge. As argued above, knowledge has a public good character, is subject to increasing returns and gives rise to monopolistic markets. Thus the model sweeps some important sources of market failures under the carpet.

The second implication of the broad interpretation of capital in the neoclassical model is that foregone consumption result in not only physical capital accumulation, but also endogenous technical change. Paradoxically, according to the model, such *endogenous* technological change cannot prevent growth from falling due to diminishing returns, while *exogenous* technological change exactly does the opposite and is introduced in the model to keep growth going. If no exogenous changes in technology would take place and all technological progress resulted from foregone consumption converted into intangible assets, diminishing returns to capital (now including knowledge capital) cause the incentives to accumulate (now including the incentives to innovate) to fall over time. Thus, endogenizing innovation seems to change the role technological change plays in alleviating scarcity limits.

We can formulate three solutions to this paradox. First, the pessimistic view is to simply conclude that scarcity puts limits to growth because innovation is not automatically arriving as manna-from-heaven; it requires efforts, the return of which inevitably fall with the depletion of resources and the need to reduce pollution. Thus the endogeneity of technological progress undermines one of the central results from the standard neoclassical approach, viz. the power of the price mechanism, using its own cornerstone, viz. diminishing returns. As a second solution, recent developments in growth theory have suggested that the returns to investment are no longer diminishing if we take into account the accumulation of intangible goods with public good character like knowledge. This indeed generates ongoing growth if we can abstract from natural resources. However, even with constant returns to the broad concept of capital in production, if production requires non-renewable resource inputs, growth cannot be sustained unless there is another exogenously growing factor, e.g. population growth or technological change (Groth and Schou, 2002). Only if production only requires renewable resources and society keeps constant the stock of them, growth can be sustained with constant returns. In a third and most appealing solution, we treat innovation as a separate activity. That is, the production function of new ideas (the R&D technology) is completely different from the production function of equipment and physical capital goods (Bovenberg and Smulders 1995, 1996; Aghion and Howitt 1998). Then, if resource inputs are not important as an input in R&D growth can be sustained. It is this approach that we consider in the next section.

5.3. Endogenous technical change and endogenous growth

Only by explicitly introducing endogenous technical change in the neoclassical model, we can study the incentives for technical change. Technical progress requires considerable investment effort in the form of learning or research and development. Whether innovation is sufficiently fast to make growth sustainable thus depends on innovation opportunities and incentives.

The main approach to endogenous technological change is the *endogenous growth framework*.[14] Here it is assumed that there is a third asset that is relevant for production: not only the resource and capital stock matter, but also the stock of knowledge. Expansions of the physical capital stock and the knowledge stock require different types of investment. New productive knowledge is created when firms undertake research and development (R&D) activities.

Knowledge is a non-rival factor of production: it raises the productivity of the capital and resource inputs. The production of new knowledge, that is the innovation process, requires that some consumption is foregone: workers have to devote their labor effort to research instead of final goods production or some of the output of the economy serves as an intermediate input (research lab equipment) in R&D. In addition, knowledge is an input in R&D. Current research builds on the achievements of past research.

The key assumption in the endogenous growth framework is that foregoing consumption in order to accumulate productive man-made assets no longer runs into diminishing returns, because current research builds on past research. A higher stock of makes research easier to such a degree that, no matter how large the stock of knowledge grows, the returns to investment in new knowledge remain constant.[15] A society that is willing to spend enough on R&D can realize a steady rate of technical change that is sufficient to offset the diminishing returns from capital-resource substitution and sustain long-run growth. It turns out that if the private returns to innovation are large enough, the economy can grow without bounds as in the standard neoclassical model, but now we do not need to rely on exogenous technological change.

In most models of endogenous growth and natural resources, the market generates too little innovation, too little growth and typically suboptimal depletion. Whether depletion is too slow or too fast depends on the income and substitution effects. The market generates too little innovation, which affects the incentives to deplete as we have discussed above in the context of an exogenous change in innovation (see section 2.2). In the empirically relevant case (in which income effect dominate intertemporal substitution effects), this results in depletion at a pace that is slower than in the social optimum. The best policy is to subsidize research and development and this will increase growth. Implementing the optimal technology policy can be expected to speed up both depletion and growth though stimulating the rate of innovation: households expect higher consumption levels in future and respond with faster depletion to smooth consumption.

In the endogenous growth framework, society has the *possibility* to grow without bound and at the same time maintain a stable level of environmental quality. However, there is a trade-off between the rate of growth and the level of environmental quality. Society may find it *desirable* to aim at low growth, or even constant output, in order to maintain the environment at a high, or even a growing, quality level. On the other hand, societies that care little about the future (discount at high rates) may optimally choose to produce at high current levels, deplete resources and let environmental quality decline to low levels. So, while technological opportunities are less constraining because of the absence of diminishing returns, society's preferences and willingness to take action, its capability to implement resource and technology policies, become much more crucial for scarcity.

7. Conclusions

This chapter has reviewed several aspects of endogenous technical change and how it affects the growth-scarcity nexus. Substitution and technical changes are the main ways to alleviate scarcity limits in the neoclassical approach. Since resource-substitution is likely to run into diminishing returns, technical change is a necessary offsetting force to sustain growth.

Technical change is not necessarily a win-win event, though. For example, when technical change comes for free (like manna-from-heaven), it is not necessarily conducive to resource conservation or environmental improvements. Technical change that improves the productivity of resource inputs alleviates scarcity and boosts growth, but it also increases the demand for resources and may raise total depletion or pollution by a rebound effect. The guise in which technical change comes is crucial here: technical change in abatement technologies, for example, reduces pollution.

Technological change is to a large extent the result of economic decisions. As a result, the rate and direction of technological change is affected by resource scarcity. Recent developments in endogenous growth theory changes our understanding of scarcity and growth since it treats technological change as a costly process, in which innovators trade off costs and expected benefits, and which is subject to market failure and spillovers. Technological improvements that are necessary for sustainable growth cannot be assumed to continue to arrive as manna-from-heaven. Due to market failures, market responses cannot be expected to ensure technological change of high enough a rate and in the right direction. Regulation should try to cope with this. Policies should, first, create efficient resource markets and impose marked-based instruments, such that prices correctly reflect scarcity of natural resources. Only then profit maximizing entrepreneurs and innovators have an incentive to develop cleaner and resource-saving technology. Second, technology policy is needed since the returns of innovation are hard to appropriate by private investors. By compensating innovators for spillovers by research subsidies or innovation rewards, privately expected benefits more correctly reflect the social value of innovation.

If technical change responds to market signals, policies can induce technical change in response to increased resource scarcity. But this does not automatically give rise to win-win situations. With endogenous technology, there is the serious possibility that increased scarcity of resources slows down the overall rate of technical change, which could make scarcity limits more imminent. The reason is that the productivity of man-made capital and other inputs falls if complementary resource inputs levels decline. As a result, the returns to investment fall, not only with respect to capital investment, but also investment in new technology.

Endogenous technology makes policy important, much more than is suggested by the standard neoclassical approach to scarcity. Accordingly, finding the exactly right policy is harder, and policy mistakes have potentially large adverse effects. Policy not only affects depletion and substitution directly, but may also crowd out innovation or shift technological change in the wrong direction, which affects depletion and substitution in turn. Differences in policies among countries also have more persistent effects: once an economy has adopted and adjusted to certain technologies, it is costly to change to fundamentally different technologies. Counties may become locked in resource-intensive production structure, which may become a problem if resources are depleted rapidly or demand for environmental amenities rises. Countries that have chosen a growth strategy based on human capital rather than natural capital may be better off in the long run. Such scenarios differ markedly from the standard neoclassical view on growth, in which technology is a public good, freely available for all and producing convergence among countries.

Taking stock, we conclude that technical change is essential to sustain growth, especially in the presence of resource scarcity. Technical change has been pervasive and effective in the past. There is no reason to expect this will change, if human creativity, flexibility, and adaptability, combined with knowledge spillovers, keeps providing us with the opportunities to keep finding new lifestyles, new ways of production and organization. However, all these developments cannot be expected to take off until scarcity and market failures are properly acknowledged, until policy makers exploit innovation incentives to address natural resource problems, and translate vision into policies for a sustainable economy.

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Endnotes

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[1] See Dasgupta and Heal (1979) and Withagen (1991) for surveys of the standard neoclassical model and its ramifications.

[2] Berndt and Wood (1975) pioneered the estimation of substitution and technological change with respect to energy use. Kemfert (1998) and Kuper and Van Soest (2003) provide recent contributions. See Neumayer (2003, p. 64-65) for a comparison of estimates of substitution elasticities across studies. Jones (2002) summarizes stylized facts on energy use in the US postwar economy.

[3] For a classical overview, see Hall (1988). More recent estimates that take into account limited asset market participation are provided by Vissing-Jorgensen (2002).

[4] In the sequel we will mainly deal with environmental resources, but most arguments also apply to biological resources.

[5] The same will happen when it is not technology that changes, but when production factors are accumulated that are complementary to polluting inputs. We discuss factor accumulation in more detail below.

[6] Krautkraemer (1985) has introduced amenity values as a motive for resource conservation in the neoclassical model. The level of the optimum long-run resource stock has become known under the "green-golden-rule level", see Beltratti et al (1995). Smulders (2000) extends the analysis to an endogenously growing economy.

[7] The literature started with Grossman and Krueger (1995). Excellent surveys of the literature are given by Lieb (2003), Ansuategi et al (1998) and De Bruyn (2000).

[8] If technological change increases the productivity of, for example, resource inputs relative to other inputs, economists define technical change to be *biased* towards resources. In terms of costs, technological change is biased to a particular factor if it reduces that factors share in production costs. Resource-biased technological change implies resource-augmenting technological change if substitution is poor. Neutral (unbiased) technical change increases the productivity of all factors to the same degree. If the elasticity of substitution between factors is unity, no bias in technological change can arise.

[9] The hypothesis goes back to Hicks (1932). It was introduced in a growth context by Kennedy, (1964) and Samuelson (1965). The approach has been criticized heavily for its lack of clear microeconomic foundations (see Ruttan 2001 for a survey). Recently, however, a model of induced innovation has been developed that builds on the microeconomics of technical change and knowledge spillovers as developed in endogenous growth theory (see Acemoglu 2002, 2003). Also the empirics of induced technological change got a new impetus by moving to the micro level. Applying a product characteristics approach, Newell et al (1999) study innovation and substitution at the level of different vintages of energy-using household durable goods and are able to identify the effects of prices and regulation on substitution, the rate of innovation and the direction of innovation.

[10] Jones and Williams (1998).

[11] Intervention may change accumulation incentives in such an economy to guarantee "sustainability" of income, defined as a constant income level. These policies are basically policies to stimulate savings and investments, rather than interventions in resource markets. Thus, sustainability policy is different from resource policy. See Pezzey (2004).

[12] That is, technical change must be "resource augmenting": it make the resource effectively more abundant.

[13] Notice the difference in aggregation levels. At the level of an individual production process, thermodynamic principles impose limits in terms of output per unit of energy input (cf. Cleveland and Ruth 1997). These limits become increasingly less important the higher the level of aggregation: at a macro-economic level, substitution between processes, goods, or even life-styles become possible.

[14] Seminal contributions in this tradition are Romer (1990), Grossman and Helpman (1991) and Aghion and Howitt (1992, 1998).

[15] Schou (1999, 2000), Aghion and Howitt (1998, chapter 5), Scholz and Ziemes (1999), Barbier (1999).