Policy Research Working Paper 6230

Green Growth

Lessons from Growth Theory

Cees Withagen
Sjak Smulders

The World Bank
Development Research Group
Environment and Energy Team
&
Sustainable Development Network
Office of the Chief Economist
October 2012

Policy Research Working Paper 6230

Abstract

This paper reviews dynamic general equilibrium models in order to collect insights on the interaction between economic growth and environmental issues. The authors discuss the Ramsey model and extend it for natural resource inputs and pollution, as well as for endogenous technical change. Green growth becomes within reach if there is good substitution, a clean backstop technology, a small share of natural resources in gross domestic product, and/or green directed technical change.

This paper is a product of the Environment and Energy Team, Development Research Group, and the Office of the Chief Economist, Sustainable Development Network, in the World Bank. It was produced for the Green Growth Knowledge Platform (www.greengrowthknowledge.org), a joint initiative of the Global Green Growth Institute, Organisation for Economic Co-operation and Development, United Nations Environment Programme, and the World Bank. It is part of a larger effort by the World Bank to provide open access to its research and make a contribution to development policy discussions around the world. Policy Research Working Papers are posted on the Web at http:// econ.worldbank.org. The authors, Sjak Smulders and Cees Withagen may be contacted at j.a.smulders@tilburguniversity.edu and cwithagen@feweb.vu.nl.

Produced by the Research Support Team

GREEN GROWTH – LESSONS FROM GROWTH THEORY

Sjak Smulders

Tilburg University and CentER

j.a.smulders@tilburguniversity.edu

Cees Withagen

VU University Amsterdam and Tinbergen Institute

cwithagen@feweb.vu.nl

Key words: growth, environment, natural resources, innovation, R&D spillovers.

JEL codes: O1, O3, O4, Q2, Q3, Q4

Sectors: Environment, Economic Policy

*We thank Michael Toman for encouragement and comments. Views and errors remain ours alone, and should not be attributed to the World Bank Group or its member countries.

1. Introduction

For more than 80 years, economists have used more or less complex versions of a standard mathematical model to study the origins of overall economic growth (Ramsey, 1928; Solow, 1956; Dasgupta and Heal, 1974; Romer, 1986). Early versions of the model focused on how savings by households (from spending less on immediate consumption than total income), invested into increasing the overall stock of physical capital, could increase income per capita over time under different sets of circumstances for the productivity of capital and labor, the willingness to save for future consumption versus consume today, and the rate of population growth. Over the decades, substantially more sophisticated models have been developed – although the earlier "workhorse" models still are commonly used for empirical analysis of growth prospects.

For our purposes, the most important extensions have been (a) the incorporation of explicit roles for natural resources and the environment in production of goods and services, and direct contributions to human well-being; and (b) ways in which knowledge and skills can change over time to improve productivity and expand growth possibilities. The former types of extensions have examined how growth prospects are influenced by increases in natural resource scarcity because of depletion or degradation – from degraded soils to negative effects of climate change. The incorporation of technological change has brought new realism into the framework by recognizing that innovation responds to economic incentives like other expenditures, and that these processes can interact with other influences on growth in complex ways.

In this paper we review these types of models in order to shed light on different mechanisms for economy-wide "green growth." This term has many definitions. In the context of longer-term growth, we define it as growth in conventionally measured income and production without unsustainable deterioration of the environment (i.e., deterioration that is large scale and essentially irreversible). For nearer-term growth, we can view it as growth in conventional income with "modest" negative impacts on the environment.

The focus on conventional income versus a broader concept of economic well-being or welfare is motivated by the "realpolitik" of current debates in and about developing countries regarding their prospects for maintaining environmental and ecological services without “significant” negative impacts on income, especially in the nearer term. Thus, we can also view green growth as concerned with how environmental sustainability can be realized without “unacceptable” limitations on income expansion. More formally, green growth policy can be formulated in our view as the maximization of a broader concept of welfare under the constraint that environmental quality increases and that the growth rate of (conventionally measured) income does not deviate too much from a pre-specified target (where the target may be related to some “business as usual” growth rate).

The literature that looks at resource scarcity and the dynamics of environmental policy through the lens of economic growth theory directly sheds light on green growth. When reviewing this literature, we consider two crucial aspects of the temporal dimension: the long-run dynamics (how much can we sustainably grow?) and the transitional dynamics aspect (how will the nature of the growth process change over time?). We also need to account for how less-than efficient environmental and growth policies could change the story.

2. The Ramsey Framework

2.1 Introduction

“How much of its income should a nation save?” This is the question raised in a path breaking article by philosopher and mathematician Frank Ramsey in 1928 (Ramsey, 1928). The Ramsey framework offers an extremely useful tool for studying growth and welfare. In this section we review the original model. It will serve as a basis for extensions in subsequent sections.

2.2 Optimal investment

We study an economy on a highly aggregated level. All production takes place in a single production sector that uses two inputs, capital and labor. There is a representative producer and also a representative consumer. The latter is infinitely lived. An alternative interpretation is that the consumer represents a sequence of generations that form an infinitely lived dynasty. There is no population growth. The consumer is only interested in consumption. In the sequel we will use the following symbols. The stock of man-made capital is K, the labor force is denoted by L.

The combination of these inputs leads to output Y. The maximal output that can be obtained with given factor inputs is described by the production function F:

(1) $$Y = F(K, L)$$

Production is increasing in the inputs, but for a given input of labor the additional increase of production if more capital is used is decreasing. This property is called decreasing returns. Moreover, it is assumed that the marginal products are very high for low input of capital and close to zero for a large input of capital. The same properties hold for labor. Total production is used for consumption C and for investments consisting of net investments, which constitute the increase in the capital stock, and depreciation, which is usually assumed to be a constant fraction of the existing capital stock. The utility or happiness derived from consumption is represented by a utility function U that is increasing in consumption and exhibits decreasing marginal utility: utility increases at a decreasing rate with an increase in consumption. It is assumed that the instantaneous utility function is the same for all generations. Moreover, all consumption generated in a period of time is equally divided over the then existing population. So, with the entire population working each gets C / L. With a constant fraction of the population working the qualitative results are not affected.

The question we started with, “How much should a nation save?” can only be answered if the nation has an objective. Several possibilities arise. Two of them deserve special attention because they are commonly used in economics.

The first is the utilitarian framework. Here welfare is represented by the (discounted) sum of all future utilities:

(2) $$W_u = \int_0^\infty L e^{-\rho t} U(C(t) / L) dt$$

Hence, total welfare consists of the sum of all individual utilities, but consumption into a more distant future gets a lower weight. The rate at which the weight falls with time is represented by

$\rho \geq 0$, which denotes the pure rate of time preference: if, for example the rate of time preference is 2 percent and two generations are 25 years apart, then the weight given to the future generation compared to the present is 60 percent. Note that labor (or population) is not given as a function of time because in this section it is assumed that population is constant over time.

The second type of welfare concept is egalitarian. Welfare is determined by the instantaneous utility of the generation that is worst off.

(3) $$W_e = \min_t U(C(t)/L)$$

We first consider the implications of the egalitarian welfare concept. In an optimum the minimum rate of consumption over time should be maximized, because what counts for welfare is the minimum level of consumption. The golden rule capital stock K^* is defined as the constant capital stock that maximizes output net of depreciation. This capital stock is determined by the condition that the marginal product of capital equals the rate of depreciation. Indeed, if capital would be lower, then a marginally larger capital stock would yield more output than is needed to compensate for the higher depreciation. For a higher capital stock the reasoning is similar. The golden rule capital stock that yields the highest possible constant consumption rate, denoted by C^*. If the actual initial capital stock K_0 is smaller than K^* it is optimal to keep this capital stock intact. An increase in the capital stock goes at the expense of present consumption and therefore leads to lower social welfare, although it might considerably increase the utility experienced by future generations. In this welfare approach consumption is instantaneously fixed, even if maybe some initial investment in capital would lead to a much higher consumption level forever thereafter. One of the problems with this approach is precisely that giving up some consumption in the present in order to gain more consumption in the future is not considered optimal. In spite of this objection, the egalitarian approach emphasizes the equal treatment of generations, which is pertinent in many definitions of sustainability. If $K_0 > K^*$ then it isn't optimal to keep capital constant at its initial level. If it would, then disposing of some capital so that the golden rule capital stock remains, yields higher constant consumption forever. However, note that doing so is not efficient: one can increase consumption for an initial interval of time without endangering future consumption possibilities.

Turning to the utilitarian optimum, we have to make a distinction between discounting and no discounting. With discounting, optimum long-run consumption and capital levels are below their golden rule levels, with the consequence that investing more in the present would increase consumption for future generations. However, with discounting, the investment cost incurred today gets a bigger weight than the returns to investment that accrue only in future. Hence, any point in time, it is optimal to not invest too much (less than under the Golden Rule). The lower the discount rate, the higher consumption levels for future generations.

This raises the question what is the appropriate discount rate in view of our preferences to future generations. Instead of a constant rate of time preference, maybe all future generations should get the same weight, which is still below the weight of current generations (Schelling, 1995. See also Chichilnisky (2007), for a comparable notion of dealing with future generations). This would produce more investment but also time-inconsistency: the optimum for current generations would arise if they themselves invest relatively little (reflecting the low weight on the future) and if future generations invest a lot for future generations (reflecting the non-declining weight on future generations). However, if these investment plans are not binding for future generations, these generations will deviate from the plans and again plan for low investment during their life span. Hence in the absence of commitment, the result would be low investment again.

A more radical alternative is no discounting at all, giving all generations the same weight in the objective function. The optimal savings path then brings society to the golden rule levels of consumption and capital. In the Ramsey model sketched above the welfare integral (2) diverges if there is zero discounting, so that it seems that an optimum doesn’t exist. However, Ramsey found an elegant way out of this problem. The argument runs as follows. An optimal program has to be efficient, meaning that it should be impossible to find an alternative feasible program that never has smaller consumption but does have larger consumption during some interval of time. A useful benchmark is the golden rule level of consumption. It can be shown that, even in the case of no discounting, the total difference between optimal utility and the utility associated with the golden rule converges.

2.3 The Ramsey rule and growth

In the utilitarian optimum, the marginal cost of postponing consumption to the future should equal the marginal benefits, such that society is indifferent between investing now and investing later. The net benefit of investing equals, in terms of goods, the net marginal product of capital. To express the net benefits in terms of utility, one has to take into account that future consumption counts less than current consumption because of discounting and declining marginal utility of consumption. Hence, in utility terms, the net benefit of postponing consumption equals the net marginal product of capital minus the rate of decline of discounted marginal utility. The optimality condition, the so-called (Keynes-)Ramsey rule, says that this net benefit is zero.

There are various ways to express the Ramsey rule. The interest rate (to which firms equate the net marginal product of capital) should equal the sum of the rate of time preference (ρ) and the rate of decline of marginal utility. Since (marginal) utility depends on the level of consumption, the latter term is related to the growth rate of consumption and the Ramsey rule can be also written as a relationship between interest rate, discount rate and the optimal consumption growth rate. In particular, consumption optimally grows faster if the interest rate exceeds the rate of time preference more: although fast consumption growth quickly diminishes the marginal utility of consumption, such a cost is offset by the high benefits that accrue from the high interest rate.

An important role in the Ramsey rule is played by the so called elasticity of intertemporal substitution. This is defined as the percentage increase in consumption that generates a 1 percent decrease in marginal utility. Its role can be illustrated by considering an example in which this elasticity is constant and independent of the level of consumption. If the elasticity is small, then the optimal level of consumption changes only at a very small rate, even if the economy starts far away from its steady state. The reason is that even a small increase in consumption reduces the marginal utility a lot, which makes it less attractive to deviate from an egalitarian outcome.

Denoting the elasticity of intertemporal substitution by σ and the return to investment by r, the Ramsey rule can be written as:

$$(4) \qquad \dot{C}/C = \sigma(r - \rho),$$

In words, the growth rate of consumption is proportional to the difference between rate of return on investment and the rate of time preference, where the factor of proportionality is the elasticity of intertemporal substitution. With a positive rate of time preference ρ we define the modified golden rule by the stock of capital, K^{**}, that yields a marginal product equal to the sum of the rate of time preference and the depreciation rate (so that the interest rate equals the rate of time preference and consumption growth is zero). The optimal economy now converges to the modified golden rule state. Note that with a low rate of time preference, the steady state values are higher than with a high rate of time preference. Hence, with a low rate of time preference the future generations are better off.

If the economy starts with a low capital stock ($K_0 < K^{**}$), both the capital stock and consumption rate monotonically increase and approach the steady state. The reason is that the return to investment, *r*, equals the marginal product of capital net of depreciation; its value is high when the capital stock is still small (because of diminishing returns to capital), thus stimulating consumption growth according to the Ramsey rule (4). In contrast, consumption decreases over time if the economy is rich initially ($K_0 > K^{**}$).

Ramsey formulated his savings rule for answering the question how much a nation should save. However, the Ramsey rule (4) should also hold for any agent that maximizes utility from consumption C and can borrow and lend against the same rate r. The Ramsey rule therefore typically shows up as part of any model with optimizing households, no matter how much more complex than the economy described above. For example, in the case of multiple investment options, each with their own rate of return, and a single consumption good (or basket), the Ramsey rule should hold for all these assets and their rates of return should be equalized. In this setting it makes sense to interpret the Ramsey rule as the characterization of the total supply of savings as a function of the economy-wide interest rate, while the division of savings over different investment opportunities is governed by the equality of rates of return. However, for the optimum for individual households to coincide with the social optimum, it is necessary that the rates of time preference and the utility functions are identical in the two settings. Moreover, although in a world with externalities, such as environmental deterioration, the Ramsey rule may characterize growth of consumption, externalities may depress the private rate of return r below the social rate of return to investment. This reduces the growth rate of consumption below the socially desirable growth rate. If the externalities imply binding credit constraints on investors, however, the link between investment rates and investment returns becomes weaker and the Ramsey rule cannot be used directly. In the sequel we will address the crucial issue of the discrepancy between the market and the social optimum in more detail, because it plays an important role understanding what it means to get the prices right.

One final remark is in order. With labor growing exponentially at an exogenous rate and with constant returns to scale in production all variables can be written in per capita terms and the analysis is essentially unaffected.

3. Including Nature

3.1. Introduction

Numerous extensions of the Ramsey model present themselves. One could include other stocks than man-made capital, such as human capital, natural capital and social capital. One could also distinguish between many sectors. Or introduce technical change. The latter option will be pursued in section 4. In the present section we focus on introducing nature into the picture. An instructive way of doing so in general recognizes that nature has several functions. Nature as a stock provides direct benefits to consumers. A high quality forest has amenity value, the existence of a stock of whales has a value per se, the accumulated stock of CO2 poses a negative value or a negative externality, etc. So, there is good reason to incorporate nature, denoted by N, into the utility function. One could do the same for the production function: Pollution, the presence of lead, for example, may hurt the productivity of workers, whereas clean water is beneficial for the production process. In addition, nature provides services as a flow. Examples are the extraction of oil to be used for production, fish caught for consumption, timber for furniture. So, a rudimentary stylized model would have $Y = F(K, N, R)$ where R denotes the extraction rate from nature. The utility function would read $U(C, N)$, where consumption C could now include consumption of flows from nature, such as fish. Nature has many dimensions, so that one should think of the symbol N as multidimensional, representing the various relevant stocks. This also holds for R that represents the various flows from nature. Finally, we should add an equation describing how nature, or quality of nature, develops over time

(5) $$\dot{N} = E(N) - R$$

where $\dot{N}$ denotes the change in nature's stock and the function E describes how nature regenerates. If the stock is nonrenewable, then regeneration doesn't take place and $E(N) \equiv 0$. The stock N and its depletion rate R may both enter the utility and the production function. When it comes to fisheries the fish consumed is an argument of the utility function and oil extracted from an oil well is a factor of production. But the fish stock by itself will probably not enter the production function, nor will the oil stock be an element of the utility function (although some types of mining may cause a negative externality that appears in the utility function) . If N is an environmental or health characteristic, then it could appear in F (degradation of nature hurts output) and U through direct impacts. An example can be temperature or other indicators for climate change. In case of nonrenewables such as oil no regeneration is possible at all.

The model presented here is interesting from a conceptual point of view. But nature appears in many specific forms. Hence we now move on to particular interpretations of nature. We start by introducing nonrenewables in section 3.2 and link them to climate change in section 3.3. In section 3.4 we go more deeply into the ecosystem services. Section 3.5 deals with the phenomenon that natural resources may constitute an obstacle to economic growth, sometimes labeled as the resource curse.

3.2 Nonrenewables

The first substantial extension of the Ramsey model that we consider is a world with a commodity extracted from a nonrenewable resource as a production factor, say oil. In this world there is no alternative for the nonrenewable resource (no wind, no solar) as a source of energy inputs and in this first extension neither the use of oil nor the stock of oil brings about an externality. This approach proved very valuable in the seventies of the previous century, when the oil crises triggered the debate on ”limits to growth”, in the presence of scarce fossil fuel energy resources. Nowadays, it attracts much attention again because of the relationship between use of fossil fuels and CO2 emissions, causing climate change. Let us sketch the main results of the so called Dasgupta-Heal-Solow-Stiglitz model (Dasgupta and Heal, 1974; Solow, 1974; and Stiglitz, 1974). Several questions can be addressed.

The first one is related to sustainability: Is it possible to maintain a positive level of consumption and hence welfare? To answer this question we have a look at the new equation describing production

(6) $Y = F(K, L, R)$

To keep the analysis simple we maintain the assumption that labor input is constant and suppose that extraction from the nonrenewable resource is costless. Total production is used for consumption and investments. The sustainability issue has to do with the technology, which is determined by the production function and the depreciation of capital. If oil is not necessary for production, $F(K, L, 0) > 0$ for $K, L > 0$, then we are basically back in the Ramsey model. So we consider the opposite case where without oil there is no production. Since the stock of oil is finite, the use of oil will eventually approach zero. So, if the aim is to have a maintained positive level of consumption the loss of oil input should be compensated for by an unbounded increase in the use of capital. And then the question is how easily substitution between oil and capital can take place. Some technologies have the property of limited substitution possibilities. This would mean that total production over time is bounded regardless of the amount of capital and labor available, in view of the limited availability of oil. In that case it is impossible to maintain a positive level of output indefinitely, and consequently no constant positive level of consumption is feasible: The economy is unsustainable. But there are also production functions in which oil is indispensable for production, but that still allow for unbounded production over time, by substituting oil for capital. An example of such a production function is the Cobb-Douglas production function, where a 1 percent increase in an input, given the inputs of other production factors, leads to a fixed and constant percentage increase in output. This percentage is called the production elasticity of capital or oil or labor. We denote them by α, β and γ respectively.

The Cobb-Douglas production function is extensively studied in the literature. Several results are quite intuitive. A necessary condition for having the technological possibility to maintain a positive constant level of consumption is that the production elasticity of capital is larger than that of oil ($\alpha > \beta$). Indeed, since less and less oil is available over time in view of the limited stock of oil, an increasing capital stock must make up for the loss in output. The economy can only produce enough capital to replace oil if capital is sufficiently productive, i.e., has a relatively large production elasticity. But this is not a sufficient condition. If a fixed fraction of the capital stock depreciates per time period, the growing capital stock implies a growing burden of depreciation that cannot be financed out of a constant production level without hurting consumption. Hence a necessary and sufficient condition for sustainability is $\alpha > \beta$ and no depreciation of capital.

We could include population growth as well as labor growth in an exponential way, both growing at a constant rate. Growth of labor allows for larger output, but this is not enough to be able to maintain a positive *per capita* consumption rate, because labor as an input has decreasing returns. Under these circumstances, in particular without technological progress, population growth is bad for sustainability. However, if population growth is not exponential but quasi-arithmetic, allowing still for population going to infinity, but at a rate that approaches zero as the population gets large, the prospects are better. In particular, if the production elasticity of capital is large enough relative to the production elasticity of energy, then a positive maintained per capita consumption is feasible (see Asheim et al. (2007)). Technological progress might also help. Suppose that there is no capital depreciation and that exogenous technological progress causes labor productivity to grow at a constant rate. Then with a Cobb-Douglas production function and exponential labor growth, sustainability is enhanced by lower population growth, higher technological progress, a higher production elasticity of capital, and a higher production elasticity of labor.

In a utilitarian world many development paths can be optimal. We limit ourselves here to the case without population growth, technological change and capital depreciation. Then, with a positive rate of time preference, consumption will necessarily decline to zero in the long run. However, in the short and medium run various time patterns can emerge. In the Cobb-Douglas case, for a low rate of time preference the rate of consumption will rise initially and will then fall monotonically (see Benchekroun and Withagen (2011)). For high rates of time preference, consumption will be high initially and it will monotonically decrease over the entire future. With a rate of time preference equal to zero, it might be optimal to have ever increasing consumption over time. This occurs, as expected, when the rate of intertemporal substitution is small.

The next question that needs to be addressed is whether and how the optimum can be implemented in a market economy. Within the model, the answer to this question is obvious: If there are no externalities the market will realize the social optimum. However, in a more realistic situation, market failures should be taken into account. First, when it comes to the supply of nonrenewable resources, and in particular oil, the market is far from perfectly competitive. It goes beyond the scope of this paper to survey this literature. The reader is referred to Groot et al. (2003). A second obstacle to efficiency is the absence of perfect forward markets. It has been shown by Dasgupta and Heal (1979) that is this may lead to over- or under-exploitation of the natural resource.

An important extension of the Dasgupta-Heal-Solow-Stiglitz model discussed above can be attributed to Krautkraemer (1985). He maintains the assumption of costless extraction of oil. But the extraction of oil irreversibly damages the environment, which is modeled by including the existing remaining resource stock directly in the instantaneous welfare function. Krautkraemer interprets this as local damage, but an alternative is to argue that a small remaining resource stock implies that a lot of oil has been extracted, which has led to considerable accumulation of CO2, assuming there is no decay of CO2. The main question that is addressed is whether or not in these circumstances it is optimal to fully exhaust the resource. The answer is that with a low rate of time preference the optimal economy tends to preserve some of the oil reserves. The reason is that future generations should then benefit from the amenity value of the resource. In the next section we return to climate change as a consequence of burning fossil fuel.

3.3 Nonrenewable resources, renewable resources, and climate change

A particularly interesting example of nonrenewables is fossil fuels. These play a crucial role in the production process and the question addressed in the previous section was therefore whether, given the limited availability of fossil fuels, the economy is capable of maintaining welfare. But fossil fuels are important for another reason as well. Their use is causing the accumulation of CO2, which may lead to climate change. Although there is huge uncertainty regarding the exact processes that play a role, most economists take it that there is a relationship between the emissions of CO2 and climate change. Hence, nonrenewables are special in that they play a crucial part in aggregate production, but also cause a negative externality. This is what we address in the present section. One question that could be raised is how the existence of the negative externality will impact the optimal use of oil. The answer is that in a utilitarian framework the time profile use of oil should be flatter than without the externality: Since harmful emissions arise from extraction, it is optimal to postpone the extraction of polluting resources, and hence accept slower growth in output, such that the loss in output is traded off against the increase in damages from emissions. Another question that could be posed is how the ordering of the use of oil and coal should be? Coal is cheaper to extract but leads to more emission. So, there is another trade off there. We will focus on another question that involves renewables, such as wind energy or solar energy, which do not contribute to climate change. Then the question becomes at what instant of time a transition to these renewables should take place in a welfare framework. And, obviously, what policy instrument is most suited to provide an incentive to the market economy to achieve the socially desirable outcome?

In the sequel we study an economy that extends the original Ramsey framework in a number of ways, and that encompasses nonrenewables, renewables and climate change (see Van der Ploeg and Withagen (2011) and Golosov et al. (2010)). It is a simple vehicle to study green growth. As before, we work on the highest possible level of aggregation, the world economy. There are three stocks: oil, accumulated CO2 and man-made capital. The oil stock diminishes as extraction goes on. Total extraction over time cannot exceed the initial oil stock. We neglect exploration activities that might increase the available oil stock. Oil extraction is costly. The existing oil stock plays a role in the sense that a high oil stock makes it relatively easy to extract oil and the other way around. Growth in the stock of accumulated CO2 is proportional to emissions from burning oil. Without loss of generality the factor of proportionality is set equal to unity. To keep the analysis simple we abstract from natural degradation of CO2 in the atmosphere, so the stock of CO2 simply equals the initial stock plus the accumulated sum of past CO2 emissions, consisting of the initial CO2 stock plus the total extracted amount of oil. Oil serves as an input in the production process which can be represented as

$$(7)\quad Y = F(K, L, R + X)$$

Next to oil we have another energy input, which is denoted by X . This energy is generated from renewable sources such as solar and wind. Its production has a cost. When it comes to renewable energy there are high fixed costs in reality. We neglect these cost and assume in addition that the cost of producing one unit of energy from renewable is constant. A heroic assumption implicit in (7) is that these energy sources produce exactly the same type of energy. It is well known that oil is best suited for transportation purposes and wind not, but this is not taken into account in the chosen specification of the technology.

Total production is used for consumption and investments, as before, but in addition we need some of the output to extract oil and to produce the energy from renewable resources.

Social welfare W now has two components: Utility from consumption and damage from the accumulation of CO2. We know that climate change has detrimental effects. There are several ways to take that into account in a green growth model. One option is to let production be hampered by climate change. This could apply to agriculture in certain regions and certain fisheries. Alternatively, and this is the approach taken here, one introduces a damage function supposedly taking these effects into account. We will describe total welfare as the difference between utility from consumption and the damage from pollution. Another way would be to have a multiplicative welfare function, recognizing that marginal utility of consumption might be negatively impacted by CO2 accumulation and climate change. So, we write

$$(8)\qquad W = \int_0^\infty e^{-\rho t}\left[U(C(t)) - D(Z(t))\right]dt,$$

where D is the damage function, depending on the accumulated CO2 stock, Z.

This framework integrates the Ramsey growth model and climate change. We are back in the Ramsey model if there is no oil, if there are no climate change damages and if there are no renewables. So, we extend the Ramsey model in three ways and the DHSS model in two ways: renewables and climate change. However, technically, the mere introduction of renewables doesn't pose any additional problem. If only the renewable are used from some instant of time on, then they will be used up to the point where their marginal product equals their marginal cost. From this equality we can solve the use of renewables as a function of the capital stock. By substituting we are then back in the Ramsey model, with the same characteristics, including the absence of negative externalities. What makes the analysis essentially different from Krautkraemer's is the timing of the transition from fossil fuel to the so-called backstop technology, like solar of wind, that is not limited by a nonrenewable resource, and by the introduction of stock dependent extraction costs of oil. We assume that in the absence of the backstop technology the economy cannot maintain a constant positive level of consumption. As outlined in the previous section, this is warranted if the production function is Cobb-Douglas with a production elasticity of the resource being larger than the production elasticity of capital, or if in the Cobb-Douglas case the depreciation rate is positive, or if for any positive capital stock, the marginal product of oil goes to infinity as oil input approaches zero.

The problem posed is rather complicated. Nevertheless some simple economic reasoning provides valuable insights. The state in which the economy finds itself is given by the existing man-made capital stock, the oil stock, and the stock of accumulated CO2. For each of these stocks a shadow price can be calculated. The shadow price of capital can be interpreted as the increase in welfare were an additional unit of capital available. The same interpretation can be given to the shadow price of oil. Since CO2 accumulation reduces welfare, the shadow price of the accumulated CO2 stock is negative. The negative (or absolute value) of this shadow price is the social (marginal) cost of carbon: it measures the welfare cost of the marginal unit of accumulated CO2, or the value of a removing the marginal unit of CO2 from the atmosphere.

Renewable resources are used up to the point where the marginal product of energy they provide is equal to their marginal cost. If the marginal cost is higher than the marginal product, then the backstop is not used. The marginal product of oil should equal its marginal costs, if oil is in place. The marginal costs consist of three terms. First, there are direct marginal extraction costs that depend on the existing oil stock. Second, there are future extraction costs that are higher due to more extraction today, because easily extractible resources are extracted first. Third, there is additional extraction of oil bringing along additional climate change damages caused by the accumulation of CO2.

Most of the results depend on the scarcity of oil relative to capital. To that end we can compare two economies, with the same technology and preferences, but that differ in terms of initial situation. For example, if at some instant of time both have the same oil stock and have accumulated the same amount of CO2, but one economy has more physical capital, then in the latter economy the shadow price of oil relative to the shadow price of capital is bigger, because capital is relatively abundant and therefore its shadow price is low relative to that of oil.

At each instant of time three regimes are possible: a regime with only oil use, a regime with only backstop use and a regime with simultaneous use of oil and the backstop. We have restricted ourselves to economies that cannot sustain a positive level of consumption in case there were no renewable resources. Hence, a regime with only oil use cannot last forever. An economy that only uses renewable forever is called the carbon free economy. As has been argued before this economy bears close resemblance to the Ramsey economy discussed earlier, and it has a stable steady state, where the marginal product of capital equals the sum of the rate of depreciation and the rate of pure time preference. We will call an economy developing if its capital stock is below its carbon-free steady state. In such an economy consumption is low, meaning that the marginal utility of consumption is high, relative to the marginal damage of climate change. Hence, there will be a tendency to use only oil initially, because its climate costs a still low. For a given initial capital stock below the carbon-free steady state there exist several critical levels of the oil stock. If the oil stock is very low, only renewables are used forever. The economy converges to the carbon free steady state. For oil above some threshold, but not too high, the optimal sequence is to have an initial phase with only oil use, due to the fact that the oil extraction costs are now lower than in the first regime. But after a while oil use comes to an end and a transition to a phase with only renewable takes place. This phase lasts forever thereafter and the economy converges to the carbon free steady state. Some oil is left unexploited. For a high initial oil stock, it is optimal to start with oil again, but this goes on even in such a way that there occurs growth beyond the carbon-free steady state. But this regime cannot last forever, and there will be a final phase with simultaneous use of oil and the renewables along which the economy converges to the carbon-free steady state, from above. In the latter scenario the renewable are only used alongside oil. But, in the long run oil use vanishes. In a developed economy, an economy endowed with a capital stock larger than the carbon-free steady state stock, matters are different. Here consumption will be high, with a small marginal utility, compared to marginal damage. Hence, it is well possible to use the backstop only in an initial phase. The idea is not that this gives the economy the opportunity to recover from a state with high climate damages, since it has been assumed that damages are irreversible, due to the absence of decay of the CO2 stock. But, the point is that it is just too costly in environmental terms to use oil. If the oil stock is low, there will, as before, only be use of the renewables. For higher oil stock it is optimal to start with only renewables and then to make a switch to simultaneous use forever. Finally, with a very high oil stock, and hence low extraction costs, it is optimal to start with only oil and make the transition to simultaneous use later. So, although the model seems rather complicated at the outset, the results are quite intuitive.

Since climate change is a negative externality, it is interesting to consider the implementation of the optimum in a market economy. Without environmental policy, the market doesn’t take account of climate change and only trades off marginal extraction costs and costs of the renewables. Hence, there will be too much oil use, and less, if any, will be left unextracted. Since the only externality is the climate externality, brought about by the use of oil, a carbon tax corresponding with marginal damage will do the job. The carbon tax is increasing in a developing economy, but it might decrease in a developed economy. Introducing a carbon tax is an example of “getting the prices right”, generally considered a necessary condition for obtaining green growth. However, even if a carbon tax is politically feasible, getting the carbon tax right is not an easy task. This is not much of a problem if in the social optimum the same preference parameters (rate of time preference, utility function, damage function) are used as in the market economy. But, it is also clear from the analysis that the optimal carbon tax does depend on the rate of time preference used as well as on the elasticity of intertemporal substitution. For example, a lower rate of intertemporal substitution implies a more equal distribution of welfare over time, giving more welfare to the present poor generations, and therefore requires a lower carbon tax initially. Hence, “getting the prices right” cannot occur without precise knowledge of the preferences, and technology.

One may wonder what happens if the government is, for political or other reasons, unable to impose the appropriate carbon tax and relies, as in many western countries, on subsidizing the backstop technology. Then, for sure, this policy is suboptimal. But one may wonder how detrimental it is. This question is related to the green paradox, a concept introduced by the German economist Hans-Werner Sinn (see Sinn (2008a and 2008b)). In general the green paradox can be defined as the phenomenon that well-intended climate change policies have adverse effects. Subsidizing backstop might provide a good example. Oil suppliers, realizing that in the long run, they can sell less oil at high prices (since the backstop becomes cheaper) start to pump oil earlier and at higher rates, thereby enhancing rather than mitigating the climate problem in the short run. The question then arises whether, given the absence of an optimal carbon tax, the subsidy is bad, where not only green welfare but also, and maybe, in particular, overall social welfare should be taken into account. Let us concentrate on the developing economy, where it is optimal to start with only oil and to have a transition to the backstop before the carbon-free steady state is reached. If the backstop is very expensive, then the market will fully deplete the oil stock before the transition to the backstop is made. A (marginal) subsidy on the backstop leads to oil being pumped up faster. Oil will be depleted fully and the transition to the carbon free economy takes place earlier. Green welfare (the negative discounted total climate damages) as well as social welfare falls. But, since the economy is still in the early phase of development, the decrease in welfare need not be high, since marginal utility of consumption is low. If the backstop is relatively cheap, the market will not fully exhaust all oil. Nor will depletion occur in the optimum. The effect of a subsidy is that the market will leave more oil in the ground than before. Hence, compared with the laissez-faire economy, green welfare is enhanced. Still, aggregate social welfare is smaller than in the optimum because of the distorting effect of the subsidy. But in this case the subsidy is beneficial and there is no green paradox. Hence we see that the occurrence of the green paradox depends on oil being depleted or not, and, which is new in this analysis, on the development stage in which the economy finds itself.

Many extensions and modifications present themselves. Perfect substitutability of energy types is too extreme an assumption that calls for refinement. Moreover, the real world is composed of many different countries with different characteristics regarding preferences, technology, and endowments of natural and other types of capital. The question arises how to tackle the problems in our decentralized world.

Tsur and Zemel (2011) develop a theoretical framework to study transitions to alternative energy in developing countries. These countries are distinguished from developed countries by having a lower capital stock and a high marginal product of capital. Capital can be either operated by a conventional energy source (say fossil) at a constant cost (constant fossil price), or by a new energy source (say solar) that has a very low flow cost (the cost of operating the solar panels) but requires upfront investment in capacity (this makes their analysis different from Van der Ploeg and Withagen). A country has to decide whether to invest in capital only and fuel it with conventional sources or invest in solar capacity. Developing countries with low capital stocks have high opportunity costs of investing in solar capacity since the marginal product of capital is large and choose to postpone the transition. Within the same framework, Smulders et al (2012) study the impact of imperfect emission policies on short run emissions and growth. In particular, they study the effects of an emission tax that the country is committed to impose at some point in future, potentially to comply with an (international) agreement on combating pollution and climate change. When a future emission tax is announced, households expect a decrease in consumption possibilities in future as a result of the policy being implemented then. The best way to cope with this future negative shock is to start saving more and build up the economy's production capacity faster. Hence, the commitment to future environmental policy raises growth and future consumption, but at the cost of short-run consumption. As compared to the situation without the policy announcement, short-run emissions grow faster before the policy is implemented and stay higher even after the emission tax is in place. The reason is that, as long as the economy uses fossil energy, growth and emissions are coupled.

3.4 Ecosystem services

Many parts of nature and ecosystems are essential for production and wellbeing in the economy, either because they directly provide resource inputs in production and utility (as discussed above), or because they are essential for the regeneration of these inputs. The regeneration term

$E(N)$ in equation (5) can be seen as depending on other factors including environmental capital stocks that do not enter production or utility directly. When nature is overused, regeneration is impaired and this may hamper growth of the economy, be it in the short long run, then in the long run. Examples are agricultural land, forests, fisheries, water. These assets provide important and sometimes necessary services, but the assets themselves deteriorate and may even become obsolete if too much of the services is used. Many of these assets are closely related to biodiversity as a source of ecosystem services.

Until recently ecosystems have not played a prominent role in (environmental) economics (Dasgupta, 2010, Fisher et al., 2011). Hence, only few studies exist where the interrelationships between sustainable growth and ecosystems are explicitly modeled and discussed. This is surprising because conservation and equitable and efficient use of ecosystems affects present and future welfare. Here we go briefly into one example of such a dynamic model, analyzed by Lopez (2011), which considers a competitive economy with open access to a renewable resource. The resource develops according to (5) with a natural growth function and harvest, but there is an additional factor that causes depletion. This is the activity in another sector of the economy, the industrial sector. This activity may have a negative impact on the growth of the resource through, for example, oil spills as a consequence of nonrenewable resource use. Man-made capital accumulates through savings from profits in the industrial sector (workers don’t save). In the long run the equilibrium in this economy can be of two types. If the negative impact of industrialization on the natural resource is not too large, then industrialization will not threaten sustainable development, even if, as is assumed in the model, no property rights are defined on the natural resource. However, in less favorable circumstances that are identified in the analysis, expansion of the industrial sector will make economic development unsustainable.

In a development context many issues are still unresolved and need further study. In particular the physical interaction between economy and ecology is complex. Moreover, the issue of property rights and distributional elements should be addressed. Finally, many ecosystems deliver services on a global level and therefore constitute global positive externalities, whereas the direct services are local in nature. An example are forests that play a crucial role in the carbon cycle and are important for biodiversity, but also provide wood locally, and may be used for agriculture after burning.

3.5 The resource curse

In the framework of the optimal growth model outlined in sections 3.2 and 3.3 the availability of natural resources is beneficial for the development of the economy. In practice, however, some resource rich countries perform successfully, whereas other countries do not seem to benefit from their resource wealth at all. The latter phenomenon is called the resource curse. The question why these differences occur is relevant and interesting. We cannot give an exhaustive account here. We will just touch upon some of the explanations (see Van der Ploeg (2011) for an excellent survey of the existing literature). Several hypotheses have been put forward. One possibility is that the export of resources leads to an appreciation of the real exchange rate, implying less growth of the traditionally exporting sector of the economy and hence of the economy as a whole, if this sector was the engine of growth. Alternative explanations emphasize the role of institutions: Windfall profits may enhance corruption, but well-functioning financial markets may mitigate the negative effect on growth. It is also put forward that the discovery of resources may lead to armed conflicts. And, finally, some resource rich countries have high income inequality and less freedom, which could lead to low growth rates. Numerous studies have been carried out to test for these hypotheses. But still there is a long way to go. The research so far is inconclusive and may suffer from methodological problems. "...more work is needed on how to manage natural resource revenues in a way that promotes sustainable growth, alleviates poverty, and avoids conflict" (Van der Ploeg, o.c. p.408).

4. Long-run Growth and Technical Change

4.1. The role of technical change in sustaining growth

So far we have considered growth mainly as the result of the accumulation of man-made capital: growth takes place if the returns to capital are large enough to warrant net investment in the capital stock. With the expansion of the capital stock, however, the returns to capital fall, growth slows down, and at some point (in the Ramsey model when the net return equals the discount rate) growth stops. Output converges to a steady state without further growth if only physical capital accumulation drives growth and there are diminishing returns.

Real world growth rates have been fairly stable – or better trendless. This applies to the US over the past century, and to the OECD countries as well as some fast growing developing countries (India, China) over the past few decades. We can explain steady growth rates if some force offsets the diminishing returns to capital. Various forces can be identified. First, if investment rates increase over time, growth can be maintained at high levels (Jones, 2002), but this necessarily comes at the cost of consumption, and cannot be maintained for a very long period (as investment rates cannot grow forever). Second, technical change may improve the productivity of inputs, including capital, thus increasing the returns to capital. As long as capital grows fast relative to the rate of technical change, diminishing returns dominate and the growth rate slows down over time. But before the growth of capital has slowed down to zero, the rate of return becomes stable over time as soon as ongoing technical change (of the type that increases the marginal product of capital) keeps exactly offsetting the diminishing returns from capital investment. In the resulting *balanced growth* situation output grows thanks to technical change, not only because it directly increases output, but also because it sustains capital accumulation. The rate of technical change is therefore the most important source of long-run growth. Growth accounting studies (see Caselli (2006) for a survey) confirm that technological change is the main source of growth, dominating other important sources like (human) capital accumulation.

The question now arises what growth rate can be maintained in the long run, and how resource use affects this growth rate. In the subsections that follow we explore how technical change can sustain growth if natural resources are an important input in production, what are the different types of technological change that affect growth and resource use, and what forces account for sustained innovation.

4.2. Non-renewable resources and long-run growth

If non-renewable resources, like oil and other energy resources, are necessary complementary inputs in production and hard to substitute away from (i.e., if no backstop technology is available at a large scale), resource use over time must reduce – ceteris paribus – the return to capital and therefore the growth rate. This is because remaining reserves gradually get exhausted and resource inputs in production ultimately have to fall over time. Since less energy is available to run the capital stock, the return to capital falls. In this sense, non-renewable resources drag growth down for two reasons: directly, since fewer resources are available in production over time; and indirectly, since this scarcity reduces returns to investment and lowers the capital stock.

As a result, three forces shape the rate of return: capital accumulation, technical change, and changes in resource inputs. Growth can only be sustained in the long run if the diminishing returns from capital expansion and the drag from declining resource availability are offset by technical change. Based on this logic, countries that are more dependent on non-renewables, or in which capital and non-renewable resources are closer complements (countries that are more "oil addicted"), grow correspondingly slower in the long-run for a given rate of technical change. Also, an economy that extracts a bigger fraction of its reserves of non-renewables every period (and therefore runs down this stock quicker over time) faces a lower long-run growth rate. All these insights follow directly from the Dasgupta-Heal-Solow-Stiglitz model with given rates of technological change.

Groth and Schou (2002) study various (tax) policies in the DHSS model and show that the above logic also leads to the conclusion that policies that affect resource use are more important for long-run growth than policies that stimulate the accumulation of man-made capital. The latter has a temporary effect only because of diminishing returns. However, any policy that affects long-run resource use will affect the long-run growth rate: resource conservation will reduce the resource drag and stimulate growth. Extending their conclusion to Green Growth policies, one might state that moving from a development path along which resources ultimately have to fall quickly over time (because of exhaustion of reserves) to a more conservationist resource extraction path yields more sustained growth for future generations.

4.3 The effect of renewable resource conservation and environmental policy on growth

When the economy mainly depends on renewable (rather than non-renewable) resources, e.g., because of a large agricultural or fishery sector, a constant flow of resource inputs can be used in production (at the level that is equal to regeneration capacity) in principle, so that the resource drag on growth can be avoided. Nevertheless, when an economy starts from an unsustainably high level of extraction (e.g., one above the maximum sustainable harvest, defined by the maximum regeneration rate $E(N)$), resource use necessarily has to be reduced to a lower – sustainable – level, either as a once-off shock or more gradually over time, in order to prevent collapse of the resource. A resource drag then arises according to the same logic as above in the case of non-renewables. There is an important difference, however. Investing in a larger renewable resource stock is likely to generate production benefits. In the case of fishery, catching cost fall and this enhances surplus in the sector. More generally, reduced pressure on renewable resources can increase ecosystem services and improve the productivity of ecosystems and ultimately also the productivity of the economic sectors that depend on the ecosystems. The improved productivity (which typically takes time to materialize) may offset the reduced production that follows (typically immediately) the reduced harvesting. Short-run costs generate long-run benefits and the long-run rate of return may increase, thus stimulating investment and growth.

Similar effects are in place in the case of stock pollution. Reduced emission flows come at a direct abatement cost, but lower concentrations of emissions in the atmosphere, water bodies or soil generate productivity effects. These productivity gains could stem from health effects (healthier workers are more productive) or eco-system services (a cleaner environment produces more valuable services, such as more abundant fish stocks, lower costs of water treatment), or tourism income if tourists are attracted by natural amenities. The DICE model that Nordhaus (1994, 2008) developed to study the economics of climate change polices relies on a very similar assumption, since in this Ramsey-type model the avoidance of climate change improves productivity.

Whenever resource use policies affect the rate of return, i.e., the marginal productivity of man-made capital, there is an indirect effect on growth through capital investment. The cost of environmental policy is magnified (the policy lowers output directly, and through reducing the marginal product of capital it also reduces investment indirectly), but the benefits are magnified as well. How big these general equilibrium or interaction effects are depends on how important man-made capital inputs are relative to resource inputs and how strong the diminishing returns are (Smulders, 2000).

Environmental improvements can spur growth through alternative mechanisms, which are surveyed by Ricci (2007a). First, pollution taxes make consumption more expensive and production labor less productive so that labor might shift from production to leisure and time spent on education (e.g., Hettich (1998)). Second, the prospect of a cleaner environment might induce households to save more and postpone consumption to the future if consumption and amenities are complements (Michel and Rotillon, 1995; Mohtadi, 1996). Third, pollution taxes might fall disproportionately on old goods if new generations of products become cleaner. Thus a pollution tax speeds up obsolescence and stimulates innovation in new products (Hart, 2004; Ricci, 2007b).

4.4. Green technology to sustain growth

Not all possible forms of technological change are equally conducive to sustained or sustainable economic growth. Resource use is physically constrained: cumulative non-renewable resources are fixed and finite and the flow of renewable resources is ultimately constrained by the natural regeneration or natural growth rate of the resource stock. Hence, to reconcile growing output with non-increasing resource use, the resource intensity of the economy, R/Y, has to fall over time. This requires substitution (including substitution towards backstop use), or technical change, or both. While substitution involves, as discussed before, the change in the mix of inputs, technical change amounts to shifts of the production function for given amounts of inputs. Technical change can stem from increased productivity of conventional inputs, better skills of workers, higher thermodynamic efficiency to enhance the productivity of resource inputs, as well as improvements in the organization, management, and marketing of the firm. A key consideration in the context of Green Growth is the impact of technology on resource use and incentives to accumulate man-made capital, which implies that we should carefully distinguish between different types of technical change and sources of innovation.

A constant rate of growth can be sustained in the long run only if there is unbounded factor-augmenting technological change for each non-growing (i.e., bounded) necessary factor of production. The implication is that in an economy with limited natural resources, we need resource-augmenting technical change, which is defined to occur if technological change has the equivalent effect as an increase in resource inputs. Resource-augmenting technical change makes it possible that effective inputs grow, while the inputs themselves (*R*) do not grow. Examples are electricity-saving measures, fuel-efficiency improvements, improved drilling techniques that increase effective economic reserves of resources, cost reductions in the production of alternative energy.

It is important to note that this notion of resource-augmenting technical change does not necessarily play the same role as technical change in our previous section, where we focused on technical change that increases the marginal product of capital. Nevertheless, as long as capital and resources are complements, resource-augmenting technical change also enhances the return to capital.[1] This situation arises for example if aggregate output can be represented by the often used Cobb-Douglas production function. Technical change allows then for both reductions in resource intensity and a constant rate of return to capital in the long run (i.e. along a balanced growth path). Such a balanced growth path is technically feasible – whether it actually arises in a market equilibrium or is preferred by society over other feasible paths is a different question.

Another thing to notice from the definition and examples of resource-augmenting technical change is that these are likely to involve specific effort. Sustained growth requires sustained technical change, and there is no guarantee that it is technically feasible to sustain technical change indefinitely or that there are sufficient incentives to generate unbounded technical change in equilibrium. To say more about what drives innovation and technical change, we first need to examine where various new technologies come from.

---

[1] Consider a production function that increases in the inputs capital, labor, resources, and technology (A). If technology is resource augmenting, the function can be written as $Y = F(K, L, R, A) = \tilde{F}(K, L, \tilde{R})$, where $\tilde{R} \equiv AR$ is effective resource input and $F(.)$ and $\tilde{F}(.)$ are functions that increase in all their arguments. Complementarity between capital and resources means $F_{KR} > 0$. The return to capital is $r = F_K$. An increase in technology increases the rate of return since $\partial r / \partial A = F_{KA} = \tilde{F}_{K\tilde{R}} R = F_{KR} R / A > 0$.

Technical change can be most easily thought of as an increase over time in the availability of (technical) knowledge that allows producing more per unit of inputs. Thus, knowledge should be seen as a stock of ideas that changes only gradually over time. The total stock of patents partially measures this stock (with the caveat that not all inventions are patented), but also skills and experience that workers and firms accumulate are part of the knowledge stock. New ideas arise from innovation activities, through public and commercial R&D (Romer, 1990), learning-by-doing and learning-by-investing (Arrow, 1962; Romer, 1986) and imitation with adaption to local circumstances (Grossman and Helpman, 1991). How much of these activities take place is an economic decision with an associated cost-benefit calculation: R&D requires effort to be devoted to innovation at the cost of other (notably production) activities, learning-by-doing can be enhanced by producing (temporarily) more which requires higher input costs. Changes in the returns and opportunity costs of innovation activities will affect the equilibrium (or desired) level of innovation.

Changes in resource use, e.g., as part of green policies, might affect both costs and benefits of innovation activities and might change the rate and direction of technical change. This endogeneity of technical change adds another channel that shapes the relationship between growth and natural resources. The effect of resource use on technical change is in a way similar to its effect on man-made capital accumulation that we discussed above. We argued that a reduction in resource inputs or polluting inputs lowers the return to man-made or physical capital and thus crowds out capital investment. Knowledge is one particular form of man-made capital (since the stock of ideas can be expanded by innovation activities), which implies that reduced resource use will not only crowd out physical capital but also knowledge capital so that innovation might fall. For example, reduced energy use will reduce output and with it learning-by-doing. Moreover, the returns to inventing new products will be lower since less energy is available to manufacture these products, which makes them more costly and lowers the market size for them. This same mechanism would make environmental policy more costly. Various authors have analysed the effect of environmental policy in analytical growth models with endogenous technology and find this crowding out effect (e.g., Stokey, 1998; Aghion and Howitt, 1998). However, the mechanism also implies an increase in technical change (and hence more growth) if the productivity effect of a cleaner environment or improved eco-service systems dominates the effect from reduce resource inputs (Bovenberg and Smulders, 1995 and 1996). Thus, the more an economy has to endogenously generate its own technical change, the more sensitive its growth is to changes in resource and environmental variables, in both directions (Smulders, 2005). Growth in economies that mainly rely on imported (rather than home-grown) technologies and diffusion of technologies from abroad may therefore be less affected by resource and pollution policies, so that a Green Growth strategy (i.e. improving the environment without hurting growth) is more realistic.

The crowding out effect only arises for specific types of innovation (Smulders and Di Maria, 2012). In particular, reduced energy inputs and polluting inputs crowd out innovation that is complementary with polluting/resource inputs. These innovations can be characterized as pollution-intensive ("brown"): they rely on polluting inputs and any decrease in these inputs reduces the return to investing in physical capital or productivity-enhancing knowledge. These innovations have to be distinguished from new "green technologies" which are substitutes for polluting/resource inputs, i.e., the introduction of these technologies ceteris paribus reduces the demand for polluting inputs or resource inputs.[2] Examples are improvements in abatement technologies (like scrubbers or carbon capture and storage), cost reductions in alternative (cleaner) energy production, and (under some circumstances[3]) energy efficiency improvements. Reduction in resource use and emission cuts can be expected to stimulate the demand for these technologies, which implies crowding *in* of innovation.

Several models incorporate opportunities for innovations of both types, green and brown (e.g., Smulders and De Nooij (2003), Gerlagh (2008), Hart (2008), Grimaud and Rouge (2008), Di Maria and Valente (2008), Gans (2011)), and thus allow for "Directed Technical Change". The issue here is which forces affect the innovators' choices regarding the type of technical change at which they direct their research efforts, and how this affects the overall rate of

---

[2] Formally, for the general production function $Y = F(K, L, R, A)$, technology is defined to be brown if $F_{AR} > 0$. Similarly, capital is defined to be brown if $F_{KR} > 0$. As before, *K*, *A*, and *R* are physical capital, knowledge capital, and resource inputs respectively. Technology and capital are green if $F_{AR} < 0$ and $F_{KR} < 0$.

[3] The exception is when the "rebound effect" occurs: higher energy efficiency might lower prices so much that demand for energy increases.

technical change and growth. This literature returns to the question whether it is possible and profitable to continue investing in new technologies at the rate that is needed to sustain growth.

We identify four important lessons from the literature on DTC.

First, investment in green technologies is needed to sustain growth in the long run if it is hard to substitute man-made inputs for resource inputs. If there are opportunities for brown innovations only or if the cost of green innovation becomes relatively high, the incentives to innovate in the long run peter out. To see why this is so, recall that investment in brown technologies is similar to investment in man-made capital in the models described above. If man-made capital grows while the resource inputs, that are complements to this man-made capital, are constant or even declining (maybe needed for environmental or resource scarcity reasons), the return to investment in man-made capital stocks –including the return to brown innovation – falls until growth stops. However, the benefits from green technologies would increase with the reduction of pollution and resource use. This increases the incentives to invest in green technologies, and this in itself stimulates productivity and growth at the aggregate level. Indeed, in these types of models, a balanced growth path arises along which both innovations take place, but the rate of green innovation is faster than the rate of brown innovation so that the drag of reduced resource use is exactly offset by relatively green innovation (Smulders and De Nooij, 2003).

The second insight from the DTC literature is that there are well defined circumstances under which technology policy needs to focus more on green technologies than on conventional technologies. This is not an obvious conclusion when one takes externalities as the rationale for technology policies. As is well accepted, in general, the market for technology and innovation is imperfect. Innovation builds on existing knowledge so that knowledge spillovers occur between firms; innovators invent around previous patents and marginal improvements may drive existing businesses out of the market, when entrants sell the new products and make the products of incumbents obsolete (creative destruction). This implies that the reward that the innovator gets by marketing her invention does not reflect the social benefits of her invention: she does not get compensated for the knowledge spillovers that are created and she does not bear the cost of business stealing. Most empirical studies find that the positive knowledge-spillover externality dominates the negative externality from business stealing so that a subsidy to research is needed to correct underinvestment in innovation. There are no reasons to expect that these imperfections are different for brown and green innovations, so that one expects that both innovations should be subsidized. This makes Newell et al. (2005) point out that environmental policy (and hence green growth) is a problem of two interacting externalities: knowledge versus environmental externalities.

The general knowledge-externality-based argument in favor of technology policy has been extended to answer the question whether green technologies warrant a higher subsidy than brown ones. R&D subsidies should be bigger if the ideas that they generate benefit more producers. This is an expression of the well-known Samuelson (1954) condition for public goods: the social value of the innovation, which is a public good as far as it benefits many firms, equals the sum of the benefits that all the firms derive from it in the form of knowledge spillovers. With environmental policy, there will be a substitution to green methods of production and more firms (or firms with larger markets) will benefit from spillovers from green R&D. Hence, the total value of spillovers increases with environmental policy. For R&D related to polluting sectors, the opposite happens. Hence, the optimal R&D subsidy for green technologies is larger (Hart, 2008).

The third insight from DTC literature is that environmental policy is less costly if there is both green and brown innovation as compared to brown technology only, in so far as environmental policy redirects innovation to green technologies. This confirms the insights from the literature on innovation and environmental policy in a partial equilibrium context (cf., Goulder, 2004). It leads to the policy implication that environmental policy should harness innovation forces. Unfortunately, in a second-best world there is no guarantee that the direction of innovation responds to environmental policy in the socially desired way. For example, if intellectual property rights are not well defined and protected across countries, innovators face imitation and limited market potential for their innovations. It might imply that green technology development in countries that implement stringent environmental policies is more than offset by technical development in the opposite direction in other countries (see Di Maria and Van der Werf (2008) and Di Maria and Smulders (2004) for DTC in the context of transboundary pollution problems).

As a fourth insight from the DTC literature, we mention that an economy might get locked into a pollution-intensive model of production. Acemoglu et al. (2011) illustrate this. They distinguish between green and brown firms or sectors, which both produce a similar good, but only the former produces without emissions. In both sectors innovation can take place that enhances productivity. Hence, innovation taking place in the brown, pollution-intensive, sector increases the demand for polluting inputs and is bad for the environment. Innovation in the green sector reduces prices of clean goods relative to brown goods and reduces pollution if consumers substitute away from brown goods to green goods. Without environmental taxes, brown goods are initially cheaper because they have a longer history of cost-reducing R&D. Firms in the brown sector learn from other firms in the sector, and green firms learn from other green firms, both to the same degree; both types of firms also have the same cost of R&D. Without environmental policy, only brown firms undertake R&D since they have a larger market. Thus, brown firms become even more productive over time and capture an even larger market share: the economy becomes locked into a more polluting industry structure and the productivity gap between brown and green goods becomes wider.

4.5. General purpose technologies

For the long-run it seems reasonable to expect that both green and brown innovation opportunities are available. However, in the medium-run, past inventions and coincidental technological developments might favor one of the two types of innovation. For example, the invention of the transistor and micro-chip started a wave of innovations in information and communication technologies in the 1990; the invention of the dynamo paved the way for the introduction of electricity and development of a whole range of electricity-based appliances (David, 1990); and the steam engine in the 18th century is another classic case. The transistor, micro-chip, electricity, and steam engine can be called General Purpose Technologies (GTP, Bresnahan and Trajtenberg, 1995), with two essential characteristics: they have the potential to be applied in many sectors in the economy, and they open up room for subsequent marginal improvements. Green growth might require a green GPT, that is, a GPT that makes emission-free (or emission-poor) production more feasible and profitable. Examples are new ways to store electricity, thereby enhancing wind power, or cheap carbon capturing and sequestration (CCS) technologies. In contrast, green growth might be difficult to attain as long as an economy is still adapting to a brown GPT, i.e. a technology that, once introduced and gradually being improved, increases the demand for resources and polluting inputs.

Most models take the introduction of a new GPT as a random event (e.g., Helpman and Trajtenberg, 1998; an exception is Eriksson and Lindh, 2000). Following this tradition, Smulders et al. (2011) model the advent of a green GPT and the market response to it. The GPT is called green since it allows for producing output with environmentally less harmful inputs (e.g. switching from coal to gas or renewable in electricity plants or from gasoline to electricity in transport). The GPT is thus partly a product innovation, which creates new (energy) inputs, partly a process innovation, allowing producers to remodel their production process. The adoption of the GPT is costly for each firm. Hence firms have to invest in GPT adoption to be able to reduce pollution. The other type of innovation firms can opt for is improving the quality of their product. Before the GPT arrives, pollution can only be regulated by direct emission reduction policies or by reducing growth and output. Once the GPT arrives, a stringent emission reduction policy provides strong incentives for the different sectors in the economy to adopt the GPT and the economy gradually greens. At first this comes at the cost of regular investment in product quality, but after most sectors have made the transition to the new GPT, regular investment resumes and the economy grows at its old (pre-GPT) rate. The model provides a technology-based explanation of the empirical finding of the environmental Kuznets curve (EKC), but it also sheds light on the maybe more relevant issue of energy transitions.

The optimal regulatory response to the advent of a green GPT is likely to affect technology subsidies. Heggedal's (2008) analysis gives useful insights. He discusses the implications of diminishing returns on developing new knowledge in a specific field, here to be interpreted as green technologies. When a new technology field is opened by the advent of a new GPT, progress may initially be relatively easy, but will run into diminishing returns later on. In particular, the initial progress may be easy to absorb by other firms so that spillovers are relatively large in the early stages. Popp (2002) finds evidence of this pattern for green technologies. Large yet falling spillovers imply that R&D subsidies should be high initially but lower or phased out later on. In Heggedal's setting an exogenous event creates new technological opportunities, for example, a breakthrough in nanotechnology or carbon capture and storage. If this breakthrough is on a green technology, the green technology deserves a high subsidy. However, the breakthrough could easily be a non-environmentally-friendly breakthrough (a "brown GPT"), maybe nanotechnology with great increases in productivity but harmful effects on living organisms. In this case, additional technology support is justified on efficiency grounds for brown, rather than green, technology. Of course, emission taxes are still justified as well. In normal cases, the positive technology shock raises the efficient emission tax through an income effect: the innovation drives growth and richer economies have a higher willingness to pay for environmental quality improvements. As a result, efficient green policy has to shift from technology instruments to environmental instruments. However, it is also conceivable that the pollution-using breakthrough lowers the efficient pollution tax. Intuitively, a high pollution tax would kill too many of the opportunities opened up by the brown breakthrough (Smulders and Di Maria, 2012).

5. Conclusions

We have reviewed several mechanisms through which green policies are linked to economic growth in the literature on aggregate growth and resource use. Technical change and (human) capital accumulation drive growth in per capita income. Demand for resources and polluting inputs are likely to grow in tandem, unless their (relative) prices increase over time. For non-polluting non-renewable resources with well-developed (futures) markets, prices will reflect scarcities, but this is only one case. In other cases, policies are needed to correct externalities and fill the gap of missing markets. More practically, explicit policies must be implemented if the aim is to prevent pollution from rising and resources from being depleted too quickly. From our review of the mechanisms we can conclude that such policies do not necessarily reduce growth.

First, reducing pollution and enhancing eco-system services improves productivity and hence growth in the long run. Second, the policies may induce technical change to shift in the greener direction, thus making it easier to grow without increasing pollution or depleting natural resources in the future.

In the short run, however, investment in the environment seems to entail a necessary cost in terms of reducing energy and resource inputs. Before possible productivity effects have their full weight, this entails a drag on growth. The drag is augmented when capital accumulation and technical change are reduced in response to the green policies: pollution-intensive sectors suffer and cut back on investment and innovation. In contrast, green sectors may benefit. In a first-best world, the latter reallocation would not entail a first-order welfare change and only the aggregate crowding out of investment would matter. However, in a second-best world with initially distorted allocation between sectors, this reallocation could produce a growth bonus, in particular if pollution-extensive sectors are too small.

Even if reduced resource use drags down growth in the medium run, the cost may be still quite small. The share of resources in total GDP is typically low (with the exception of resource-dependent developing countries). In contrast the share of capital is much larger. This implies that modest reductions in resource use cannot dramatically affect income and capital formation.

Similarly, the effect of green policies on investment in technologies may be small on an aggregate level but large when confined to green technologies. In the most optimistic scenario, green technologies, i.e., technologies that make production without (or with less) pollution or resources possible, can be developed at the same cost as traditional pollution-using technologies. After a transition period during which firms and sectors introduce the new technology, the world would then grow as before but is greener.

It seems likely that long-run growth is not affected too much by green policies. The challenge is how to not affect growth in the medium run. On top of this come distributional issues and political economy obstacles to policy reform. Therefore, now that growth is still robust in many developing countries, this seems the best time to start green policies.

References

Acemoglu, D., Ph. Aghion, L. Bursztyn, and D. Hemous (2009): “The environment and directed technical change.” *Mimeo*, MIT and Harvard University, Cambridge, Mass.

Arrow, K. (1962): “The economic implications of learning by doing”, *Review of Economic Studies 29(3)*, pp. 155-173.

Asheim, G. (1986): “Hartwick’s rule in open economies”, *Canadian Journal of Economics 19*, pp. 395-402.

Asheim, G. (2000): “Green accounting: Why and how?”, *Environment and Development Economics 5*, pp. 25-48.

Asheim, G., W. Buchholz, J. Hartwick, T. Mitra and C. Withagen (2007): “Constant savings rates and quasi-arithmetic population growth under exhaustible resource constraints”, *Journal of Environmental Economics and Management 53*, pp. 213-229.

Benchekroun, H., A. Halsema and C. Withagen (2009): "On nonrenewable resource oligopolies: the asymmetric case", *Journal of Economic Dynamics and Control 33*, pp. 1867-1879.

Benchekroun, H. and C. Withagen, C. (2011): “The optimal depletion of exhaustible resources: A complete characterization”, *Resource and Energy Economics 33,* pp. 612-636

Bovenberg, A. and J. Smulders (1996): “Transitional impacts of environmental policy in an endogeneous growth model”, *International Economic* Review 37(4), pp. 861-893.

Bresnahan, T. and M. Trajtenberg (1995), “General Purpose Technologies: ‘Engines of Growth’?”, *Journal of Econometrics*, 65 (1), pp. 83-108.

Brock, W. and M.Scott Taylor (2010): “The Green Solow model”, *Journal of Economic Growth 15*, pp. 127-153.

Buchholz, W., S. Dasgupta and T. Mitra (2005): “Intertemporal equity and Hartwick’s rule in an exhaustible resource model”, *Scandinavian Journal of Economics 107*, pp. 547-561.

Caselli, Francesco (2005): “Accounting for Cross-Country Income Differences”, in P. Aghion and S. Durlauf (eds), *Handbook of Economic Growth*, Elsevier, Amsterdam.

Chakravorty, U., M. Moreaux and M. Tidball (2008): "Ordering the extraction of polluting nonrenewable resources”, *American Economic Review 98*, pp. 1128-1144.

Chichilnisky, G. (1997): “What is Sustainable Development?”, *Land Economics 73(4)*, pp. 467-491.

Dasgupta, P. and G. Heal (1974): “The optimal depletion of exhaustible resources”, *Review of Economic Studies, Symposium on the Economics of Exhaustible Resources*, pp 3-28.

Dasgupta, P. and Heal, G. (1979), *Economic Theory and Exhaustible Resources*, Cambridge University Press, Oxford.

Dasgupta, P., R. Eastwood and G. Heal (1979): “Resource management in a trading economy“, *Quarterly Journal of Economics 92*, pp. 297-306.

Dasgupta, P. (2010): “20th Anniversary of EAERE: The European Association of Environmental and Resource Economists”, *Environmental and Resource Economics 46*, pp 135-137.

David, P. 1990.“The Dynamo and the Computer; An Historical Perspective on the Modern Productivity Paradox.” American Economic Review 80 (May 1990), 355-361.

Di Maria, C. and E.van der Werf (2008):“Carbon leakage revisited: unilateral climate policy with directed technical change“, *Environmental and Resource Economics, 39(2)*, pp. 55-74.

Di Maria, C. and S. Smulders (2004): “Trade Pessimists vs Technology Optimists: Induced Technical Change and Pollution Havens", *Advances in Economic Analysis & Policy 4(2)*, Article 7.

Di Maria, C. and S. Valente (2008): “Hicks meets Hotelling: the direction of technical change in capital–resource economies”, *Environment and Development Economics 13*, pp. 691–717.

Edenhofer, O. and M. Kalkuhl (2009), *Das Grünen Paradox – Menetekel oder Prognose*. Potsdam: Potsdam Institute.

Eriksson, C. and T. Lindh (2000). “Growth cycles with technology shifts and externalities.” Economic Modelling 17, 139-170.

Fisher, B., Polasky, S. and Th. Sterner (2011): “Conservation and human welfare: Economic analysis of ecosystem services”, *Environmental and Resource Economics 48*, pp. 151-159.

Gans, J. (2011): “Innovation and climate change policy”, forthcoming in *American Economic Journal: Economic Policy*.

Gerlagh, R. (2011): “Too much oil”, *CESifo Economic Studies 57*, pp.79-102

Golosov, M., J. Hassler, P. Krusell and .A. Tsyvinski (2010): “Optimal taxes on fossil fuel in general equilibrium.” *Mimeo*., MIT, Cambridge, Mass.

Goulder, L. (2004): “Induced technological change and climate policy”, *Technical Report*, Pew Center on Global Climate Change.

Rouge, L. and A. Grimaud (2008). “Environment, Directed Technical Change and Economic Policy”. Environmental and Resource Economics (2008) 41:439-463.

Groot, F., C. Withagen, and A. de Zeeuw (2003): "Strong time-consistency in the cartel-versus-fringe model", *Journal of Economic Dynamics and Control 28*, pp.287-306.

Grossman, G., and E. Helpman (1991), *Innovation and Growth in the Global Economy,*MIT Press, Cambridge, MA

Groth, C. and P. Schou (2002): "Can Non-Renewable Resources Alleviate the Knife-Edge Character of Endogenous Growth?", *Oxford Economic Papers 54, pp.* 386–411.

Hamilton, K. and Withagen, C. (2007): "Savings growth and the path of utility", *Canadian Journal of Economics 40*, pp.703-713.

Hart, R. (2004): "Growth, environment and innovation--a model with production vintages and environmentally oriented research" ,*Journal of Environmental Economics and Management, 48(3),* pp. 1078-1098.

Hart, R. (2008): "The timing of taxes on CO_2 emissions when technological change is endogenous", *Journal of Environmental Economics and Management 55(2), pp. 194-212.*

Heggedal, T. (2008): "On R&D and the undersupply of emerging versus mature technologies", *Discussion Paper 571,* Statistics Norway.

Helpman, E. and M. Trajtenberg (1998): "A Time to Sow and a Time to Reap: growth based on general purpose technologies", in: E. Helpman (ed.) *General purpose technologies and economic growth*, MIT press, Cambridge, Mass, pp. 55-84.

Hettich, F. (1998): "Growth Effects of a Revenue-neutral Environmental Tax Reform", *Journal of Economics 67 (3),* pp. 287-316.

Hoel, M..(2008): "Bush meets Hotelling: effects of improved renewable energy technology on greenhouse gas emissions", *Working Paper No. 2492*, CESifo, Munich.

Hoel, M. and S. Kverndokk (1996): "Depletion of fossil fuels and the impacts of global warming", *Resource and Energy Economics 18(2)*, pp. 115-136.

Hotelling, H. (1931): "The economics of exhaustible resources", *Journal of Political Economy 39(2),* pp. 137-175.

Krautkraemer, J, (1985): "Optimal Growth, Resource Amenities and the Preservation of Natural Environments", *Review of Economic Studies 52(1),* pp. 153-169.

Lopez, R. (2010): "Sustainable development: "On the co-existence of resource-dependent and resource-impacting industries", *Environment and Development Economics 15*, pp. 687-705.

Michel, P., Rotillon, G. (1995): "Disutility of pollution and endogenous growth",. *Environmental and Resource Economics 6 (3),* pp. 279–300.

Michielsen, T. (2011): “Brown backstops versus the Green Paradox”, *CentER discussion paper No. 2011-76*, Tilburg University.

Mohtadi, H. (1996): “Environment, growth, and optimal policy design”, *Journal of Public Economics 63 (1)*, pp. 119–140.

Newell, R.G., A.B. Jaffe and R.N. Stavins (2005): “A Tale of Two Market Failures: Technology and Environmental Policy.” Ecological Economics, vol. 54, pp. 164-174.

Nordhaus, W.D. (1994), Managing the Global Commons; the economics of climate change, Cambridge MA: MIT Press.

Nordhaus, W.D. 2008. “A Question of Balance; Weighing the Options on Global Warming Policies.” New Haven & London: Yale University Press.

Paltsev, S., J. Reilly, H. Jacoby and J. Morris (2009): *“The Cost of Climate Policy in the United States”*, *Report No. 173*, MIT Joint Program on the Science and Policy of Global Change, MIT, Cambridge, Mass.

Popp, D. (2002): “Induced Innovation and Energy Prices”, *American Economic Review 92*, pp. 160–180.

Ploeg, F. van der (2011): “Natural resources: Curse or blessing?”, *Journal of Economic Literature 49*, pp. 366-420.

Ploeg, F. van der, and C. Withagen (1991): “Pollution control and the Ramsey problem.” *Environmental and Resource Economics 1(2)*, pp. 215-236.

Ploeg, F. van der, and C. Withagen (2010): “Is there really a Green Paradox?”, *OxCarre Research Paper No. 35*, University of Oxford.

Ploeg, F. van der, and C. Withagen (2011: “Growth, renewable and the optimal carbon tax”, *OxCarre Research Paper No. 55*, University of Oxford.

Ploeg, F. van der, and C. Withagen (2012): “Too much coal, too little oil”, *Journal of Public Economics 96*, pp. 62-77.

Ramsey, F. (1928): “A mathematical theory of saving”, *Economic Journal 38*, pp. 543-559.

Ricci, F. (2007a): “Channels of transmission of environmental policy to economic growth: A survey of the theory”, *Ecological Economics 60(4)*, pp. 688-699.

Ricci, F. (2007b): “Environmental Policy and Growth when Inputs are Differentiated in Pollution Intensity”, *Environmental and Resource Economics 38(3)*, pp. 285-310.

Romer, P. (1986): “Increasing Returns and Long-run Growth”, *Journal of Political Economy 94*, pp. 1002-1037.

Romer, P.(1990):”Endogenous Technological Change”, *Journal of Political Economy 98,* s71-s102.

Samuelson, P. (1954): “The Theory of Public Expenditure”, *Review of Economics and Statistics 36,* pp. 386–389.Schelling, T.(1995): “Intergenerational discounting”, *Energy Policy 23*, pp. 395-401.

Sinn, H. W. (2008a): "Public policies against global warming", *International Tax and Public Finance, 15,* pp. 360-394.

Sinn, H. W. (2008b). *Das Grüne Paradoxon. Plädoyer für eine Illusionsfreie Klimapolitik.* Berlin: Econ.

Smulders, S. and M. de Nooij (2003): “The impact of energy conservation on technology and economic growth”, *Resource and Energy Economics 25,* pp. 59-79.

Smulders, S. and C. Di Maria (2012). “The cost of environmental policy under induced climate change.” CentER discussion paper.

Smulders, S. Y. Tsur, and A. Zemel (2010). “Announcing Climate Policy: Can a Green Paradox

Arise without Scarcity?” CESIfo discussion paper 3307.

Smulders, S. and E. van der Werf (2008): “Climate policy and the optimal extraction of high- and low-carbon fossil fuels”, *Canadian Journal of Economics 41(4),* pp. 1421-1444

Solow, R. (1974): "Intergenerational equity and exhaustible resources", *Review of Economic Studies, Symposium on the Economics of Exhaustible Resources*, pp. 29-46.

Stern, N. (2007), *The Economics of Climate Change: The Stern Review,* Cambridge University Press, Cambridge, U.K.

Stiglitz, J. (1974): "Growth with exhaustible natural resources: Efficient and optimal growth paths", *Review of Economic Studies, Symposium on the Economics of Exhaustible Resources*, pp. 123-137.

Stokey, N. (1998): ”Are There Limits to Growth?”, *International Economic Review,* 39, pp. 1-31.

Tahvonen, O. (1997): “Fossil fuels, stock externalities, and backstop technology”, *Canadian Journal of Economics 30(4),* pp. 855-874.

Tsur, Y. and A. Zemel (2003): “Optimal transition to backstop substitutes for nonrenewable resources”, *Journal of Economic Dynamics and Control* 27, pp. 551-572.

Tsur, Y. and A. Zemel (2005): “Scarcity, growth and R&D”, *Journal of Environmental Economics and Management* 49(3), pp. 484-499.

Tsur, Y. and A. Zemel (2011): “On the dynamics of competing energy sources.” *Automatica* 47, 1357–1365.

Withagen, C. (1994): “Pollution and exhaustibility of fossil fuels”, *Resource and Energy Economics* 16(3), pp. 235-242.