Economic Growth and the Environment[1]

Anastasios Xepapadeas[2]
University of Crete, Department of Economics
University Campus, 74 100
Rethymno, Greece,
e-mail: xepapad@econ.soc.uoc.gr

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Abstract

Environmental pollution is introduced both as a joint product and as a source of disutility in growth models. The purpose is to explore vital questions such as: is environmental protection compatible with economic growth; is it possible to have sustained growth in the long run without accumulation of pollution; what is the impact of environmental concerns on growth, and in particular, how are the levels, the paths or the growth rates of crucial variables such as capital, income, consumption or environmental pollution affected if we take into account the environment; what type of deviations do we observe between market outcomes and the social optimum; what are the policy implications of these deviations; what does data tell us about stylized facts relating environmental quality and economic development (the environmental Kuznets curve); and how can total factor productivity be decomposed into its sources once we account for the fact that an economy produces not only the desired output, but also undesirable output (environmental pollution)?

Keywords: Economic growth, Pollution, Sustained growth, Technical Change.

JEL Classification

Contents

1 Introduction

Understanding the causes behind the huge differences in standards of living across countries, as well as the vast changes in the standards of living worldwide over long periods of time, has been a central issue in economics since the time of classical economists. Economic growth is an issue that, as Robert

Lucas (1988, p. 5) points out: “Once one starts to think about [economic growth], it is hard to think about anything else.”

Although traditionally growth theory has sought to analyze and explain “stylized facts” or regularities in the growth process, and to explore ways through which governments can affect growth rates, not much attention has been given to the relationship between economic growth and the environment until recent decades. To quote William Brock (1973, p. 441), “Received growth theory is biased. It neglects to take into account the pollution costs of economic growth.” Admittedly, in the last decades, extensive research has been undertaken which tries to explore the links between economic growth and the environment, especially regarding issues associated with the impact of natural resources on growth processes and sustainability.[1] This research has made clear the necessity for growth theory to delve deeply into the analysis of the interrelationships between environmental pollution, capital accumulations and the growth of variables which are of central importance in growth theory.

According to Paul Romer (1994, p. 12), “The evidence about growth that economists have long taken for granted and that poses a challenge for growth theorists can be distilled to five basic facts.” They are:

1. There are many firms in a market economy.
2. Discoveries differ from inputs in the sense that many people can use them at the same time.
3. It is possible to replicate physical activities.
4. Technological advance comes from things that people do.
5. Many individuals and firms have market power and earn monopoly rents from discoveries.

If the environmental dimension is to be incorporated into the main body of growth theory, then a sixth fact should be added:

6. There is joint production of a flow of waste material that degrades the environment, and environmental quality is positively valued by individuals.

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[1] For the early literature regarding the analysis of environmental pollution in neoclassical growth models, see for example Keeler, Spence and Zeckhauser (1971), Forster (1973), Mäler (1974), Brock (1973), Gruver (1976), Becker (1982) and Luptacik and Schubert (1982).

The purpose of this chapter is therefore to explore how fact six is incorporated into modern growth theory. In particular we seek to analyze its effects on theoretical predictions and associated policy implications regarding the levels and the growth of variables which have emerged as key in growth theory, and also to present empirical evidence of the relationship between economic growth and the environment. Thus, this chapter concentrates on the relationship between economic growth and environmental pollution, and refrains from analyzing closely related issues such as the economic growth - natural resources relationship, or issues related to national income and the environment. However, the general framework which is developed in this chapter by using pollution as the main example, carries over naturally to resource management problems.[2]

The evolution of growth theory since the 1950s has passed through two main stages. The basic feature of the first stage, which originated with the Solow model (Solow 1956, Swan 1956), is that technical change is exogenous.[3] In this context government policy can affect the levels of the key variables but not growth rates which are exogenously determined. In this stage, growth is analyzed either in terms of models with exogenous saving rates (the Solow-Swan model), or models where consumption and hence savings are determined by optimizing individuals. These are the so-called optimal growth or Ramsey models (Ramsey 1928, Cass 1965, Koopmans 1965). The main feature of the second stage that emerged in the 1980s[4] is that technical change is endogenized in such a way that economic growth is associated with an endogenous outcome of the economic system rather than with exogenous forces. In the context of endogenous growth models, growth rates can be affected by policies.

In this general framework of growth theory, the present chapter introduces environmental pollution both as a joint product and as a source of disutility in standard optimal growth and endogenous growth models. The purpose is to explore vital questions such as: is environmental protection compatible with economic growth; is it possible to have sustained growth in the long run without accumulation of pollution; what is the impact of environmental

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[2] For the analysis of the economic growth - natural resources relationship, see for example Solow (1974a,b); Dasgupta and Heal (1974, 1979); Dasgupta (1982); and Krautkraemer 1985), while for issues related to national income and the environment, see for example Weitzman (1976); Solow (1986); Hartwick (1990); Mäler (1991); and Dasgupta and Mäler (2000). These topics are covered in other chapters of this volume........

[3] It should be noted, however, that many features of the so-called new growth theory, such as endogeneous technical change, can be incorporated in the standard Solow model, as has been recently demonstrated by Robert Solow (1999).

[4] See Romer (1986) and Lucas (1988).

concerns on growth, and in particular, how are the levels, the paths or the growth rates of crucial variables such as capital, income, consumption or environmental pollution affected if we take into account the environment; what type of deviations do we observe between market outcomes and the social optimum; what are the policy implications of these deviations; what does data tell us about stylized facts relating environmental quality and economic development (the environmental Kuznets curve); and how can total factor productivity be decomposed into its sources once we account for the fact that an economy produces not only the desired output, but also undesirable output (environmental pollution)?

The rest of the chapter is organized as follows. Section 2 discusses how the environmental dimension can be introduced into the supply side and the demand side of growth models. Section 3 analyses the growth-environment relationship with fixed savings ratio and exogenous technical change. Section 4 introduces environmental pollution into optimal growth models with exogenous technical change, while section 5 introduces environmental concerns into endogenous growth models. Section 6 discusses the theoretical foundations and the empirical evidence regarding the environmental Kuznets curve, as well as the decomposition of total factor productivity when environmental pollution is taken into account. Section 7 concludes.

2 Modelling Environmental Pollution

In order to develop a model unifying the process of economic growth with the environment, an economic module describing technology and preferences which characterize the economic problem, should be linked to the environmental module which describes the natural process characterizing pollution accumulation. The environmental module is mainly related to the economic module by the fact that:

- Environmental pollution is a by-product of production or consumption processes taking place in the economic module.
- Emissions generated in the economic module affect the flow or the accumulation of pollutants in the ambient environment (e.g. emissions of sulphur oxides, noise, carbon dioxide accumulation in the atmosphere, or phosphorus accumulation in water bodies).
- Environmental pollution has detrimental effects on the utility of individuals.

- Environmental pollution could have detrimental productivity effects, while improvements in environmental quality might have productivity enhancing effects.

The above structure can be modeled along the following lines. The flow of emissions per unit time has been related mainly to output production.[5] Given a neoclassical aggregate production function for the economy:

$$Y = F\left(K, AL\right) \tag{1}$$

where AL is effective labour, to allow for labour augmenting technical change, the flow of emissions at time t can be written as

$$Z\left(t\right) = v\left(Y\left(t\right)\right) \tag{2}$$

A simple way to specify (2) is to write $Z = \phi Y$, where ϕ is the unit emission coefficient, that is, emissions per unit of output. Emissions reducing technologies can be incorporated by further specifying the unit emission coefficient as $\phi\left(K\right)$, with $\phi'\left(K\right) < 0$ for $K \in \mathcal{K} \subset \mathcal{R}_{+}$. This formulation reflects an implicit assumption that as capital stock accumulates, new "cleaner" techniques are used. The stock of capital can be further split into productive capital, which is the pollution generating capital K_p, and abatement capital K_a, which is the pollution reducing capital. In this case the production function can be written as

$$Y = F\left(K_p, AL, K_a\right) \tag{3}$$

and the flow of emissions can be specified as $Z = \phi\left(K_a\right)Y$.

Another formulation (Brock 1973) allows for the flow of pollution to be an input in the production function:

$$Y = F\left(K, AL, BZ\right) \tag{4}$$

where BZ is effective flow of pollution as an input, for input augmenting technical change.[6]

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[5] Consumption also generates pollution. This case is discussed in section 6.1.1.

[6] The idea behind this formulation is that "techniques of production are less costly in terms of capital inputs if more pollution is allowed" (Brock 1973, p. 443). A similar production function can be defined, if Stokey's (1996) formulation is adopted, where the production process is characterized by an index of the emission rate $z \in [0, 1]$, and the flow of pollution generated by output production is $Z = y\phi\left(z\right)$, where y is potential output. Then actual output is yz. By inverting $Z = y\phi\left(z\right)$, actual output can be defined in terms of the flow of pollution Z.

Another way of modeling the environment into production is to consider that environmental quality, E, is a factor of production. This formulation captures productivity effects of the environment such as health of workers and the production function can be written as:

$$Y = F\left(K, AL, E\right) \text{ , with } \frac{\partial Y}{\partial E} > 0^{7} \tag{5}$$

Damages from environmental pollution can be associated with either the flow of emissions per unit time, such as smoke or noise, or the stock of pollution as emissions are accumulated in the ambient environment, such as greenhouse gases, or heavy metals.[8] When the stock of pollution, denoted by P, is of interest, then its accumulation is usually represented by a transition equation :

$$\dot{P} = Z - mP + h\left(P\right) \tag{6}$$

where m reflects exponential pollution decay and $h\left(P\right)$ represents a nonlinear feedback, sometimes called internal loadings. In modelling the environmental system through (6), the introduction of the nonlinear feedback $h\left(P\right)$ could be important in analyzing the relationship between economic growth and the environment. This is because the modelling of natural systems in most cases indicates that the use of linear dynamics, as implied by the exponential pollution decay, to model natural processes might not be a good approximation and that a nonlinear structure induced by the feedbacks might be more appropriate. In general the $h\left(P\right)$ function is assumed to be S-shaped, and a common functional form used in applications is $h\left(P\right) = \frac{P^2}{1+P^2}$.[9] Ignoring these nonlinearities might obscure very important characteristics that we observe in reality, such as bifurcations of a natural system to alternative equilibrium

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[7] The aggregate production function (5) can be further specified to include both the flow of pollution as input and productivity enhancing environmental quality, or $Y = F\left(K, AL, BZ, E\right)$. See for example Bovenberg and Smulders (1995), Smulders and Gradus (1996), Mohtadi (1996), Rubio and Aznar (2000).

[8] For a more detailed presentation of this pollution taxonomy, see Tietenberg (1996, Ch. 14).

[9] Feedbacks could be positive if the impact is such that the initial perturbation is enhanced, or negative if the initial perturbation is reduced. For example in the study of climate change, a positive feedback exists when an increase in temperature - say due to increased accumulation of greenhouse gases - increases evaporation from the oceans, which brings more water vapor into the atmosphere and finally enhances greenhouse effects (Hansen et al. 1984). Similar feedbacks exist in the so-called shallow lake problem (Carpenter, Ludwig and Brock 1999; Brock and Starrett 2003; Mäler, Xepapadeas and de Zeeuw 2003).

states, irreversibilities or hysteresis, which could be important in exploring the true nature of the relationship between growth and the environment.[10]

The evolution of environmental quality, or equivalently the evolution of the stock of environmental goods, can be described by a formulation which is equivalent to modelling environmental quality as a renewable resource, or:

$$\dot{E} = R(E) - Z \tag{7}$$

where $R(E)$ is an environmental regeneration function and Z represents reduction in environmental quality, or natural capital, from the flow of emissions, through an extractive-like process.[11] It is clear that either (6) or (7) can be used to describe the state of the environment.

The environmental dimension is introduced into the utility function by defining a utility function which includes both consumption and environmental quality among the factors determining the satisfaction derived by individuals. Environmental quality appears as disutility from pollution. Thus we have for the ith individual

$$U(c_i, Z)\,, \text{or } U(c_i, P)$$

In a decentralized economy individuals treat environmental quality as fixed when maximizing their utility.

When discussing social optimization, the criterion function for the government or the social planner takes the form of a felicity functional[12] with additive utilities over time and identical individuals

$$\int_0^\infty e^{-\rho t} N(t)\, U(\overline{c}(t), P(t))\, dt$$

where $N(t)$ is the population at time t, $\overline{c}$ is per capita consumption and $\rho \geq 0$ represents the discount rate for future utilities, or rate of time preference.[13]

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[10] For analysis of environmental problems using a pollution accumulation equation with nonlinear pollution decay, see also Forster (1975), Dasgupta (1982), Pethig (1993), Cesar (1994), Tahvonen and Withagen (1996), and Tahvonen and Salo (1996). The underlying assumption in this approach is that if pollution is sufficiently high, then the environment's self-cleaning capacity deteriorates and may eventually become zero. Thus the decay function is not exponential, and may take an inverted U shape.

[11] For this approach - along with extensions where the regeneration function depends on other variables, such as the stock of manufactured capital, the stock of natural resources or labor input - see, for example, Krautkraemer (1985), Mäler (1991), Kolstad and Krautkraemer (1993), Bovenberg and Smulders (1996), Heal (1998) and Krutilla and Reuveny (2002).

[12] This follows terminology introduced by Arrow and Kurz (1970).

[13] For a more detailed analysis of the foundations of a welfare criterion that incorporates environmental concerns, see Heal (this Handbook). Further properties of this functional will also be presented in section 4 of this chapter.

If the analysis is carried out in terms of the stock of environmental quality, then the above functional should be written as:[14]

$$\int_0^{\infty} e^{-\rho t} N(t) U(\bar{c}(t), E(t)) \, dt$$

3 Growth and the environment when the Savings Ratio is Fixed

3.1 Environmental Pollution in the Solow Model

We explore the implications of the neoclassical growth theory in an economy with a fixed savings ratio, when the economic model is augmented with an environmental module describing pollution accumulation.[15] In this model there is no optimizing behavior regarding consumption-savings decisions. Furthermore, disutility from pollution (that is, damages from pollution in utility terms) is not taken into account, a situation that has sometimes been encountered in real world situations. Starting the analysis at this point provides useful information for the structure of optimal growth models, since in the optimizing models to follow the savings rate is endogenous, but also provides insights about endogenizing the effects of pollution on exogenous growth rates, or the effects of capital accumulation on emissions per unit of output.

We start with a standard constant returns to scale aggregate production function with exogenous labour-augmenting technical progress, or $Y = F(K, AL)$, with $\dot{A}/A = g$ the exogenous rate of labour augmenting technical change, and $\dot{L}/L = n$ the exogenous population growth rate. Then, under the "behaviorist" tradition that savings-investment is a given fraction s of income-output, the evolution of the stock of capital measured in efficiency, or per effective worker units, is determined by:[16]

$$\dot{k} = sf(k) - (\delta + n + g) k \tag{8}$$

where capital and output in efficiency units are defined respectively as $k = \frac{K}{AL} = Ke^{-(g+n)t}$, $y = \frac{Y}{AL} = Ye^{-(g+n)t}$, with the normalization $A(0) = L(0) =$

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[14] Most of the analysis in the rest of the chapter will use mainly the formulation where pollution causes disutility as a public bad. The use of the stock of environmental quality as a utility and productivity enhancing stock leads to approximately equivalent results, as will become clearer in the analysis of endogenous growth models.

[15] See Siebert (1992).

[16] See, for example, Romer (1996, Ch. 2).

1, δ is the depreciation rate of capital, and the production function $f(k)$ satisfies the standard neoclassical assumptions and the Inada conditions.

Assume that the production process generates emissions, that emissions per unit of output are constant at level ϕ, and that disutility from pollution is not taken into account. Pollution is accumulated in the ambient environment according to:

$$\dot{P} = \phi Y - mP \tag{9}$$

Defining pollution in efficiency units as $p = \frac{P}{AL} = P\ e^{-(g+n)t}$, the pollution accumulation equation becomes

$$\dot{p} = \phi f(k) - (m + g + n) p \tag{10}$$

In the economy described by (8) and (10), the steady-state capital stock in efficiency units is obtained from (8) as $k^* : sf(k^*) = (\delta + n + g) k^*$. Since the rate of growth of k is $\gamma_k = sf(k)/k - (n + \delta + g)$, under the standard Inada conditions at the steady state k^* we have that $\gamma_k = 0$, and output, consumption and capital in physical units grow at the rate $(n + g)$. The steady-state stock of pollution in efficiency units is obtained from (10) as $p^* = \phi f(k^*) / (m + g + n)$.[17] It is clear that in this model total pollution in the ambient environment measured in physical units, that is, P, grows at the rate $n + g$. In this economy where pollution is perceived as creating no cost in terms of utility or productivity, pollution will accumulate at a constant positive rate. Only in the case where there is no exogenous growth or $n = g = 0$, will pollution stop accumulating in physical units. In this case, however, the economy also stops growing since output, consumption and capital in physical units will also stop growing. That is, $\dot{Y}/Y = \dot{C}/C = \dot{K}/K = 0$.

Negative effects of accumulated pollution on the supply side of the economy can be modeled, through the reduction of labour's productivity, and population growth by environmental pollution, by specifying $g = g(P)$, with $g' < 0$, and $n = n(P)$, with $n' < 0$.[18] In this case, however, determining the paths for k and P requires the solution of a nonautonomous system of differential equations consisting of (8) with $n = n(P)$, $g = g(P)$

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[17] It is easy to show that the steady-state equilibrium (k^*, p^*) is stable. The Jacobian matrix of the system (8), (10) defined as: $J = \begin{bmatrix} sf'(k^*) - (\delta + n + g) & 0 \\ \phi f'(k^*) & -(m + g + n) \end{bmatrix}$ evaluated at the equilibrium point has a positive determinant, since at $k^*, sf(k^*)/k^* = (\delta + n + g)$, and from the assumptions about the production function, $f'(k^*) < f(k^*)/k^*$. Thus $sf'(k^*) - (\delta + n + g) < 0$ and $|J| > 0$,while $tr(J) < 0$. Hence the steady state is globally asymptotically stable.

[18] This essentially means that we endogenize technical progress and population growth in terms of pollution accumulation by adding the equations $\dot{A} = g(P) A$, and $\dot{L} = n(P) L$. See Solow (1999) for endogenizing the same rates in terms of capital intensity k.

and $\dot{P} = \phi f(k) e^{[n(P)+g(P)]t} - mP$. The analysis of this system is beyond the scope of this paper, but it represents an interesting problem of endogenizing the effects of pollution accumulation.

One way to prevent pollution from accumulating in this simple neoclassical model is to allow for cleaner production technology as the economy grows, in the sense that as capital accumulates, technology becomes less polluting and pollution per unit of output falls. This can be handled by endogenizing the unit emission coefficient in terms of capital intensity as $\phi = \phi(k)$, with $\phi'(k) < 0$, and $\lim_{k\to\infty} \phi(k) \to 0$, $\lim_{k\to\infty} \phi(k) f(k) \to 0$, to reflect the possibility of achieving a clean technology. The steady-state stock of capital in efficiency units is determined by (8) and is not affected by the fact that capital provides additional services in the form of clean technologies. In this case the rate of growth of the pollution stock in efficiency terms is $\gamma_p = \dot{p}/p = \phi(k^*) f(k^*)/p - (m+n+g)$, where k^* is the long-run equilibrium value of the capital stock in efficiency units determined by (8). If a steady-state pollution stock in efficiency terms p^* exists,[19] then pollution in physical units grows at the rate $(g+n)$. The effect of allowing for clean technology is to reduce the level of steady-state pollution relative to the case where there is no possibility of clean technology and ϕ is fixed and independent of k. However pollution in physical units still grows at an exogenous rate since k^* is a finite number and $\phi(k^*) f(k^*) > 0$. Pollution can be eliminated if we make the assumption that as k grows, both the average and the marginal product of capital are bounded below by $(n+\delta+g)$, or $\lim_{k\to\infty} [f(k)/k] = \lim_{k\to\infty} [f'(k)] = M > (n+\delta+g)/s > 0$. This assumption violates the Inada conditions which imply that diminishing returns to capital eventually ceases.[20] In this model the steady-state rate of growth of k is positive which means that k grows without bound. But then $\lim_{k\to\infty} \phi(k) f(k) = 0$, and $\gamma_p = -(m+n+g)$, which means that pollution is eventually eliminated.

Perhaps a more realistic way to model technological progress reducing the unit emission coefficient is to allow for two types of capital, productive or output generating capital, k_y, and abatement capital, k_a, which is not productive but reduces emissions per unit of output. Savings are split between the two types of capital in an arbitrary way. Thus the fraction s_y of output is invested in gross terms in productive capital, while s_a is invested in

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[19] $p^* = \frac{\phi(k^*) f(k^*)}{m+n+g}$.

[20] This is a form of endogenous growth model, with transition dynamics (see, for example, Barro and Sala-i-Martin (1995)).

abatement capital.[21] The capital and pollution accumulation equations are:

$$\begin{aligned}
\dot{k}_y &= s_y f(k_y) - (n+\delta+g)\,k_y \\
\dot{k}_a &= s_a f(k_y) - (n+\delta+g)\,k_a \\
\dot{p} &= \phi(k_a)\,f(k_y) - (m+n+g)\,p, \\
& \lim_{k_a\to\infty}\phi(k_a)\to 0,\ \lim_{k_a\to\infty}\phi(k_a)\,f(k_y)\to 0
\end{aligned}$$

Assuming again that the average and the marginal product of capital are bounded below by $(n+\delta+g)$ as $k \to \infty$, this model results in pollution elimination.

It is interesting to note that the transitional dynamics of the models with the declining unit emission coefficient could be consistent with the notion of a Kuznets curve for environmental data.

Assume that in the early stages of economic development with a relatively clean environment, that is low values for p, there is an open interval K_1 such that $\dot{p} > 0$ for $k \in K_1$. As the economy grows in these early stages, pollution also grows both in efficiency and physical units. As the economy keeps growing, the unit emission coefficient ϕ is declining. Since we know that as $k \to \infty$, $\dot{p}/p \to -(m+\delta+g)$, and $\dot{P}/P = \dot{p}/p + (n+g) \to -m$, there exists some critical value k^{cr} such that $\dot{p}/p = -(n+g)$ and $\dot{P}/P = 0$, for $k = k^{cr}$. As the economy grows without bound and the unit emission coefficient declines towards zero, we expect that $\dot{P}/P < 0$ for $k > k^{cr}$. Thus as the economy grows, pollution first increases and then declines.

Summarizing, the prediction from the Solow model regarding pollution accumulation is that when the disutility from pollution is not taken into account, and in the absence of pollution reducing technical change that can sufficiently reduce emissions per unit of output, pollution in physical units will grow at the same rate as the rest of the variables in the economy. These results indicate that an equilibrium steady-state pollution might not exist in this simple Solow model. A steady state could exist if we changed the production structure of the model and introduced, probably more realistically, the flow of emissions as an input in the production function.

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[21] The decisions of how s_y and s_a are chosen are not modeled here. The choice could reflect some kind of environmental policy decision.

3.1.1 Growth and Pollution Accumulation with Emissions as an Input

We now consider the Solow model using as a production function (4) where the flow of emissions is regarded as an input.[22] We assume exogenous input augmenting technical progress for the input "emissions" at a rate b, in addition to the standard exogenous labour augmenting technical progress at a rate g. That is, $\dot{B}/B = b$, and $\dot{A}/A = g$. The aggregate production function can then be written as:

$$Y = F\left(K, AL, BZ\right), \ \frac{\partial F}{\partial Z} > 0 \tag{11}$$

or in per capita terms under constant returns to scale,

$$\frac{Y}{L} = F\left(\frac{K}{L}, A, \frac{BZ}{L}\right) \tag{12}$$

In this formulation, Z can be interpreted as a flow of emissions that can be kept constant at different levels,[23] which can be determined either by technological conditions or by policy considerations. That is, Z can be interpreted as an emission standard. Then the fundamental differential equation for capital accumulation in per capita terms can be written as:

$$\dot{k} = sy - \left(n + \delta\right)k \tag{13}$$

Using (12) and the Cobb-Douglas assumption for (11) we obtain:

$$y = k^{a_1}\left(e^{gt}\right)^{a_2}\left(e^{(b-n)t}Z\right)^{a_3} = e^{\lambda t}k^{a_1}Z^{a_3} \ , \ \lambda = a_2 g + a_3\left(b - n\right) \tag{14}$$

In order to make (13) independent of time, we define $\hat{k} = ke^{-\xi t}$ and choose $\xi : \lambda + a_1\xi - \xi = 0$, thus $\xi = \frac{\lambda}{1-a_1}$. Therefore the differential equation of neoclassical growth becomes:[24]

$$\dot{\hat{k}} = s\hat{k}^{a_1}Z^{a_3} - \left(n + \delta + \xi\right)\hat{k} \tag{15}$$

From (15) the steady-state stock $\hat{k}^*$ is obtained as a function of the emission flow as

$$\hat{k}^*\left(Z\right) = \left(\frac{n + \delta + \xi}{s}\right)^{\frac{1}{a_1 - 1}} Z^{-\frac{a_3}{a_1 - 1}} \tag{16}$$

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[22] This type of modelling is useful for exploring the effects of nonlinearities in the pollution accumulation equation.

[23] For a similar formulation with Z interpreted as a resource, see Solow (1999).

[24] This is done by writing $k = \hat{k}e^{\xi t}$, then substituting for k and $\dot{k}$ in (13), dividing throughout by $e^{\xi t}$ and noting that in order to make sy, where $y = e^{\lambda t}k^{a_1}Z^{a_3}$, time independent, ξ should be chosen so that $\lambda + a_1\xi - \xi = 0$ (see Brock and Gale (1969)).

with $\frac{\partial \hat{k}^*}{\partial Z} > 0$, $\frac{\partial^2 \hat{k}^*}{\partial Z^2} < 0$. Thus an increase in the emission standard will increase the steady-state capital stock measured in efficiency units, at a decreasing rate.

At the steady state we also have $\hat{y}^*(Z)$ and $\hat{c}^*(Z) = (1-s)\,\hat{y}^*(Z)$ constant. Then the exogenous steady-state growth rates of per capita capital, output and consumption, k, y, c respectively, are equal to

$$\gamma = \gamma_k = \gamma_y = \gamma_c = \xi = \frac{a_2 g + a_3 (b - n)}{1 - a_1} \tag{17}$$

It is clear the if $a_3 = 0$, that is, the flow of emissions is ignored as in standard neoclassical growth theory, then under constant returns to scale the standard result in per capita terms $\gamma = g$ is obtained.

Again the Solow model predicts constant per-capita growth rates at the steady state and convergence through (15). The steady-state levels depend, however, on the emission flow through (16). Inverting (16) we obtain the emission level, or equivalently the emission standard, as a function of the steady-state capital stock $\hat{k}^*$, or

$$Z^*\left(\hat{k}^*\right) = \left(\frac{n + \delta + \xi}{s}\right)^{\frac{1}{a_3}} \left(\hat{k}^*\right)^{-\frac{a_1 - 1}{a_3}} \tag{18}$$

from which $\frac{\partial Z}{\partial \hat{k}^*} > 0$, $\frac{\partial^2 Z}{\partial \hat{k}^{*2}} < 0$. Since Z can be regarded as a policy variable, the steady-state equilibrium level Z^* can be chosen so that $\dot{P} = 0$. The steady-state pollution stock as a function of the different steady states of the economy is then obtained as:

$$0 = Z^* - mP + h(P) \tag{19}$$

We can use (19) to study the equilibrium stock of pollution as a function of the steady states of the economy. Since the steady states depend on the emission flow Z, and we can interpret Z as an emission standard determining one of the inputs in the aggregate production function, we have a direct link between the environmental policy, the steady state of the economic module, $\hat{k}^*$, and the corresponding steady state of the natural system. Using $h(P) = \frac{P^2}{1+P^2}$, the analysis of equilibria of (6) suggests that the steady states for the economy and the environment can be described by figure 1.

[Figure 1]

The graph on the right depicts the $Z^*\left(\hat{k}^*\right)$ function (18) while the left part depicts the equilibrium locus $Z^*(P)\,|_{\dot{P}=0} = 0$. The equilibrium locus passes through the origin and has a concave-convex shape as P increases. Its position depends on the value of m. The three curves, (a), (b), and (c), are generated for different values of m. Curve (c) corresponds to $m = 0.6$, while (a) corresponds to $m > 0.6$ and (b) to $m < 0.6$. The movement of the pollution stock towards the equilibrium locus is indicated by the arrows near each of the three curves.[25] It is clear that the steady-state pollution stock increases with Z^* or equivalently with $\hat{k}^*$.[26] However the way in which the steady-state pollution stock increases depends on the interaction between m and the nonlinear feedback affecting the environmental system. For feedback resulting in curve (a) in the graph on the left in figure 1, we have a conventional case, which is a unique steady-state pollution stock for each steady-state emission standard Z^*. Curves (b) and (c), however, characterize hysteresis and irreversibility. For curve (c) there is a high pollution stock basin of attraction in the neighborhood of P_2^*, and a low pollution stock basin of attraction in the neighborhood of P_1^*. If the emission standard exceeds Z_1^*, that is, more pollution than Z_1^* is allowed, there is fast accumulation of the pollutant towards the high pollution stock basin of attraction. Because of the *hysteresis effects,* small reductions in the standard in the neighborhood of Z_1^* will not move the system back to the low pollution stock basin of attraction. To bring the system back to the right of P_1^*, a large reduction in the standard, below Z_2^*, is required. Thus economies characterized by this type of environmental system might be in need of a very strict environmental policy to clean the environment substantially, in the sense of reaching a low pollution accumulation basin of attraction. The situation is more severe in the case depicted by curve (b). In this case an emission standard above Z_3^* will take the economy to pollution stock above P_3^*, but this change is *irreversible.* Once the economy goes beyond F_3, then it is trapped in a high pollution basin of attraction, and adoption of more stringent standards will not improve the state of the environment.

Therefore, when the disutility from environmental pollution is not taken into account in an economy, a situation that could be associated with certain periods of industrialized societies, but a maximum level of emissions Z exists determined either by technological constraints or an existing emission standard, then the "behaviorist" growth model augmented by the environmental sector and allowing for nonlinear feedbacks in the environmental system indicates that the *steady-state growth rates* of the important variables, in per

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[25] For a detailed analysis, see Mäler, Xepapadeas and de Zeeuw (2003).

[26] It should be noted that in this model, while the economic variables in per capita terms can grow at a exogenous rate at the steady state, the pollution stock in physical units does not grow at a stable steady state, because the emission level is kept constant. Of course this steady-state pollution level could be undesirably high.

capita terms, are constant and exogenous, while the *steady-state levels* of these variables are affected by the environmental standard. Furthermore, because of nonlinearities, specific choices of a standard might produce fast accumulation of the pollutant, that might be difficult, or even impossible, to reverse. For example, if we consider the possibility that climate change could reach irreversible states, this type of analysis suggests that once a threshold point is crossed, environmental policy will not be useful in restoring the state of the environment prior to the change. Since in this characterization of the economy there is no optimizing behavior, and in particular there is no disutility from environmental pollution, the irreversible change could be produced because the environmental standards are not properly designed to take into account damages due to environmental pollution.

This basic model can be further extended by allowing for endogenous population growth and endogenous technological change. In this case the population rate of growth can be written as $n(k,P)$ to capture the effects of capital intensity and pollution on population growth. The labour augmenting technical progress can be written as $g(k,P,)$, while the "emission augmenting technical change" can be endogenized by defining it as $b(k)$. Then the unified economic-environmental model can be written as:

$$\dot{\hat{k}} = s\hat{k}^{a_1}Z^{a_3} - \left[n(k,P) + \delta + \xi(k,P)\right]\hat{k} \tag{20}$$

$$\dot{P} = Z - mP + h(P) \ , \ h(P) = \frac{P^2}{1+P^2} \tag{21}$$

It is expected that the nonlinear system (20) and (21) will have multiple steady-state equilibria with different stability properties. Regarding Z as a policy variable and using the fact that the the solutions of the system (20) and (21) will depend on Z by the parameter dependence property of the solutions of differential equations, the design of environmental standards that could move the unified ecological/economic system to different basins of attraction can be studied.[27] These different basins of attraction indicate alternative combinations of steady-state capital and pollution.[28]

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[27] The emission standard, Z, is regarded here as a bifurcation parameter.

[28] In principle the study of the nonlinear system (20), (21) can provide a basis for the study of more general unified ecological-economic models as well as a departure point for studying more general optimizing models of the economy and the environment with exogenous or endogenous technical change.

4 Optimal Growth and Environmental Pollution

4.1 The Ramsey-Cass-Koopmans Model with Environmental Pollution

In this section we move away from the "behaviorist tradition" and we adopt the "optimizing tradition" where consumption-investment decisions are derived in the decentralized context of intertemporal utility-maximizing households and perfectly-competitive, profit-maximizing firms.[29] The environmental dimension is introduced into the problem by assuming, as indicated in section 2, that the utility of the representative household represents preferences over the flow of per person consumption $c(t)$, and the total stock of pollution $P(t)$, or $U(c(t), P(t))$. In this formulation the flow of consumption and the dissatisfaction or damages from the pollution stock yield a flow of *felicity* to the representative household. It is usually assumed that the utility function is increasing and concave in consumption with $\lim_{c\to\infty} U_c(c,P) = 0,$[30] to ensure interior solutions, and strictly decreasing and convex in the pollution stock.[31]

In the optimizing model we assume at this stage that there is no population growth or exogenous technical change, that is, $n = g = 0$.[32] The representative consumer treats the pollution level as fixed and solves the problem

$$\max_{\{c(t)\}} \int_0^\infty e^{-\rho t} U(c,P)\, dt \tag{22}$$

where ρ is the utility discount rate,[33] subject to an intertemporal budget constraint

$$\int_0^\infty e^{-R(t)} c(t)\, dt = k(0) + \int_0^\infty e^{-R(t)} w(t)\, dt \tag{23}$$

where $k(0)$ is the initial capital holding and $R(t) = \int_{\tau=0}^{t} r(\tau)\, d\tau$, with $r(\tau)$ being the real interest rate at time τ, so that $e^{-R(t)}$ is the appropriate discount

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[29] See also van der Ploeg and Withagen (1991), Gradus and Smulders (1993), Beltratti (1996) or Xepapadeas (1997a, Ch. 3) for a general overview.

[30] To simplify notation, subscripts will denote partial derivatives, and t will be dropped when no confusion arises.

[31] For example, separable utility functions in consumption and pollution can be specified as $U(c,P) = \frac{c^{1-\theta}}{1-\theta} - \frac{1}{\gamma} P^{\gamma}$, $\theta > 0$, $\gamma > 1$, while nonseparable utility functions can be specified as $U(c,P) = \frac{c^{1-\theta}}{1-\theta} P^{-\gamma}$.

[32] In this case measurements in per capita and per effect worker units coincide with the measurements in physical units for the representative household.

[33] The issue of discounting will be examined in more detail later in this section.

factor. Then the consumption path is determined as:[34]

$$\frac{\dot{c}}{c}=\frac{1}{\eta}\left[r-\rho+\frac{U_{cP}}{U_c}\dot{P}\right]\ ,\ \eta=-\frac{U_{cc}}{U_c}c \tag{24}$$

Under perfect competition, profit maximization which implies $f'(k)=r+\delta$, and identical households, the evolution of the economy is described by the following system where everything is measured in physical units:

$$\frac{\dot{c}}{c} = \frac{1}{\eta}\left[f'(k)-\rho-\delta+\frac{U_{cP}}{U_c}\dot{P}\right] \tag{25}$$

$$\dot{k} = f(k)-c-\delta k \tag{26}$$

From (25) it is clear that for $U_{cP}\leq 0$ an increase in pollution will not increase the consumption growth rate. The consumption growth rate will decrease if $U_{cP}<0$, but it will be unaffected if the utility function is separable in consumption and pollution.[35] With pollution accumulation given by (9), a steady state is determined as $(c^*,k^*,P^*):\dot{c}=\dot{k}=\dot{P}=0$. The steady state for (c^*,k^*) for the economy has the same characteristics as the standard Ramsey-Cass-Koopmans model without environmental pollution (Romer 1996), only if $\dot{P}=0$, because at the steady state the $\frac{U_{cP}}{U_c}\dot{P}$ term vanishes. The steady-state stock of pollution in this case is uniquely determined from the equilibrium of the economic system as $P^*=\frac{\phi f(k^*)}{m}$. Only the approach path to the steady state, which has the usual saddle point property, is affected. Since $U_{cP}<0$ the rate of growth of consumption is lowered relative to the case when pollution is not taken into account. Thus the outcome of the competitive economy indicates that although disutility from pollution enters the households' utility function, the steady-state outcome is not affected by this disutility. Only the approach path to the steady state is affected.

The steady state is, however, affected if we consider the problem of the so-called social planner. In this case (22) is considered to be a social welfare indicator. The social planner seeks to choose a time path for consumption in order to maximize (22), subject only to the technologically determined constraints (26) and (9). It is known that in the absence of externalities

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[34] Associating the Lagrangean multiplier λ with (23), the first-order condition for the household is:

$$e^{-\rho t}U_c(c,P)=\lambda e^{-R(t)}$$

Taking logarithms, differentiating with respect to time, using the definition for η, and the profit-maximizing condition for the competitive economy $f'(k(t))=r(t)+\delta$, we obtain (25).

[35] For the analysis of a growth model where the sign of the cross derivative U_{cP} is unrestricted, see Tahvonen and Kuuluvainen (1993).

there is an equivalence between the outcome of the social planner's problem and the outcome of the competitive equilibrium with perfect foresight (Becker and Boyd 1997). This equivalence principle expresses the duality between perfect markets and optimal planning in resource allocation problems. When an environmental externality exists, this equivalence breaks down, as can be seen from the solution to the planner's model.

The current value Hamiltonian associated with the planner's problem is:[36]

$$\mathcal{H} = U(c, P) + q(f(k) - c - \delta k) + \lambda(\phi f(k) - mP) \tag{27}$$

In (27) the costate variable $\lambda(t) < 0$ is interpreted as the shadow cost of the pollution stock. The necessary conditions for optimality, following from the maximum principle, imply

$$\begin{aligned} U_c(c, P) &= q && (28) \\ \dot{q} &= (\rho + \delta - f'(k))\, q - \lambda \phi f'(k) && (29) \\ \dot{\lambda} &= (\rho + m)\lambda - U_P(c, P) && (30) \end{aligned}$$

along with (26), (9) and the transversality conditions at infinity. Taking the time derivative of (28) and using it to eliminate $\dot{q}$ from (29), we obtain the dynamics of the economy as:

$$\frac{\dot{c}}{c} = \frac{1}{\eta}\left[f'(k)\left(1 + \frac{\lambda\phi}{U_c(c, P)}\right) - \rho - \delta + \frac{U_{cP}}{U_c}\dot{P}\right] \tag{31}$$

along with (26), (30) and (9). To make the exposition of the discrepancy between the planner's problem and the competitive outcome clearer, we assume that the utility function is separable, or $U_{cP} = 0$, and that the economic system adjusts to its steady state equilibrium faster than the environmental system which is assumed to evolve slowly.[37] The evolution of the economic system in fast time is obtained by treating the slow environmental variables as fixed and is characterized by

$$\frac{\dot{c}}{c} = \frac{1}{\eta}\left[f'(k)\left(1 + \frac{\lambda\phi}{U_c(c)}\right) - \rho - \delta\right] \tag{32}$$

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[36] See also van der Ploeg and Withagen (1991) for the analysis of the Ramsey problem with environmental pollution.

[37] This might be a plausible assumption if, for example, the pollutant refers to carbon dioxide accumulation. It should be noted that analyzing dynamic systems in different time scales is by no means a simple issue, and it is used here only for expository purposes. A dynamic system with state variables moving in different time scales, a fast one and a slow one, can be written as

$$\varepsilon \frac{dx_1}{d\tau} = f_1(x_1, x_2)\ ,\ \varepsilon > 0 \text{ where } \varepsilon \text{ is a small positive number, and } \frac{dx_2}{d\tau} = f_2(x_1, x_2)$$

In this system state variable x_1 moves fast while x_2 moves slowly. If we rescale time by and (26).[38] The difference between the socially-optimal solution and the outcome of the competitive market becomes clear if we compare (25) to (32). For a separable utility function the comparison is shown in figure 2. The $\dot{c} = 0$ isocine in the (c, k) space is not a vertical line, as is the case of the competitive outcome, but has a negative slope (van der Ploeg and Withagen 1991). As a result the steady-state capital stock, and consequently the equilibrium pollution stock, is less at the social optimum relative to the competitive outcome. Thus in this simple Ramsey model, environmental damages affect the steady-state levels of the variables.

[Figure 2]

Exogenous population growth at a rate n can be introduced into the above model but in this case steady-state analysis is not possible (Keeler, Spence and Zeckhauser 1971). The planner's problem can be written as:

$$\begin{aligned} &\max_{\{c(t)\}} \int_0^{\infty} e^{-\omega t} U\left(c, P\right) dt \ , \ \omega = \rho - n \\ &\text{s.t. } \dot{k} = f\left(k\right) - c - \left(n + \delta\right) k \\ &\dot{P} = \phi F\left(K, L\right) - mP \end{aligned}$$

$\tau \rightarrow t\varepsilon$, then the system in the time scale of the fast variable x_1, is defined as:

$$\frac{dx_1}{dt} = f_1\left(x_1, x_2\right), \ \frac{dx_2}{dt} = \varepsilon f_2\left(x_1, x_2\right)$$

This new system evolves in fast time. If we take $\varepsilon \rightarrow 0$, then two systems can be obtained: The *reduced system*

$$0 = f_1\left(x_1, x_2\right), \ \frac{dx_2}{d\tau} = f_2\left(x_1, x_2\right)$$

and the *layer system*

$$\frac{dx_1}{dt} = f_1\left(x_1, x_2\right), \ \frac{dx_2}{dt} = 0$$

In the layer system, the state variable x_2 is treated as fixed, and a steady state for x_1 is defined as $x_1 = \chi_1\left(x_2\right)$ (e.g. Fenichel 1979; Szmolyan 1991; Milik et al. 1996).

[38] The steady state for the "fast" economy is obtained by the solution of the system

$$f'\left(k\right)\left(1 + \frac{\lambda\phi}{U_c\left(c\right)}\right) = \rho + \delta, \ f\left(k\right) = c + \delta k$$

as $k^* = k\left(\lambda\right)$ and $c^* = c\left(\lambda\right)$. The steady state of the "slow" environment can then be determined as:

$$P^* = \phi f\left(k\left(\lambda\right)\right)/m, \ \lambda^* = U_P\left(P^*\right)/\left(\rho + m\right)$$

where lower case letters denote per capita variables and upper case letters denote variables in physical units. Since we have diminishing returns in production and depreciation of capital, consumption per capita is bounded. On the other hand, since paths of zero utility are feasible, total pollution in physical units must be bounded on any optimal path to avoid a doomsday situation, thus pollution cannot grow at an exogenous rate n.

4.2 Optimal Emission Taxes

It can easily be shown that the social optimum can be attained in a decentralized economy by an appropriate optimal emission tax.[39] This tax is a time dependent tax defined as

$$\tau(t) = \frac{-\phi\lambda(t)}{U_c(c, P)} \tag{33}$$

where all variables are evaluated along the optimal path. It is clear that the emission tax reflects the social damages from increasing the accumulation of pollution due to increasing output by one unit, which is the term $\phi\lambda(t)$, divided by the additional utility of the extra consumption which is realized by the output increase. Under the emission tax a profit-maximizing firm solves

$$\max_k \pi = f(k) - (r+\delta)k - \tau[\phi f(k)]$$

with first-order condition for an interior solution

$$f'(k)\left(1 + \frac{-\phi\lambda(t)}{U_c(c, P)}\right) = r + \delta \tag{34}$$

Substituting (34) into (24), we obtain (31). Thus the path of the optimally-regulated economy, under the emission tax (33), coincides with the socially-optimal path. The social planner can therefore attain the socially-optimal levels of output and pollution by imposing the emission tax. The equilibrium levels of output pollution and capital stock will be lower than those corresponding to the unregulated competitive economy. These losses correspond to the cost of internalizing pollution externalities.

4.3 Optimal Growth with Abatement

In the standard Ramsey model analyzed above, it was not possible to reduce emissions which emerge as a by-product of production by abatement

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[39] There is a large body of literature regarding optimal environmental or Pigouvian taxes. For dynamic problems see, for example, Xepapadeas (1997a).

activities. The model can, however, be easily extended to incorporate these activities. Carrying out abatement, however, requires diversion of resources from consumption or capital formation.

Assume that emission generation at each point in time is described by the emission function $v\left(k\left(t\right),a\left(t\right)\right)$ where $a\left(t\right)$ denotes abatement at time t. The emission function is increasing in k and decreasing in abatement. The planning problem, assuming no population growth or exogenous technical change, is:

$$\max_{\{c(t)\}} \int_0^\infty e^{-\rho t} U\left(c,P\right) dt \tag{35}$$

$$\text{s.t. } \dot{k} = f\left(k\right) - c - a - \delta k \tag{36}$$

$$\dot{P} = v\left(k,a\right) - mP \tag{37}$$

with the current value Hamiltonian defined as:

$$\mathcal{H} = U\left(c,P\right) + q\left(f\left(k\right) - c - a - \delta k\right) + \lambda\left(v\left(k,a\right) - mP\right)$$

and first-order conditions

$$U_c\left(c,P\right) = q \tag{38}$$

$$\lambda v_a\left(k,a\right) = q \tag{39}$$

indicating that in the short run the utility gains of marginal consumption should be equal to the shadow value of pollution savings due to abatement. The dynamic system characterizing the evolution of the economy along the optimal path can be written as:

$$\frac{\dot{c}}{c} = \frac{1}{\eta}\left[f'\left(k\right) - \rho - \delta + \frac{v_k}{v_a} + \frac{U_{cP}}{U_c}\dot{P}\right] \ , \ \eta = -\frac{U_{cc}}{U_c}c \tag{40}$$

$$\dot{\lambda} = \left(\rho + m\right)\lambda - U_P\left(c,P\right) \tag{41}$$

along with (36), (37), the transversality conditions at infinity and with short-run abatement activity defined from (38), (39) as $a = \alpha\left(k,c,P,\lambda\right)$. A full dynamic analysis can be obtained by appropriate concavity assumptions.[40] We can provide some clarifications by considering separable utility and abatement functions, with $v\left(a,k\right) = \phi f\left(k\right) - v\left(a\right)$, and assuming further that the

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[40] For example, assuming concavity and separable utility and abatement functions $U_{cP} = 0$, $v_{ak} = 0$, with $v\left(k,a\right) = \phi f\left(k\right) - v\left(a\right)$, then the maximized Hamiltonian associated with problem (35) is concave in the state variables $\left(k,P\right)$ and convex in the costate variables. It follows then from Brock and Scheinkman (1976) that a steady state is globally asymptotically stable for bounded solutions of the modified Hamiltonian dynamic system.

economic system adjusts rapidly to equilibrium. In this case the economy evolves according to:

$$\frac{\dot{c}}{c} = \frac{1}{\eta}\left[f'(k)\left(1+\frac{\phi}{v_a\left(\alpha\left(c,k,\lambda,P\right)\right)}\right)-\rho-\delta\right] \tag{42}$$

$$\dot{k} = f(k)-c-\alpha\left(c,k,\lambda,P\right)-\delta k \tag{43}$$

It is clear that since the term $\frac{\phi}{v_a}$ is negative for all values of c and k, the rate of growth of per capita consumption when the economy is not at a steady state is less, relative to the unregulated competitive outcome. This is because the social planner internalizes environmental damages. Furthermore if the marginal product of capital $f'(k)$ is monotonically decreasing, approaching zero as k tends to infinity, then for bounded $v_a(\cdot,\cdot)$ the economy will converge to a steady state $\frac{\dot{c}}{c}=\dot{k}=0$ as in the Ramsey model without abatement. Again only levels are affected by environmental concerns and not growth rates.

The case in which $f'(k)$ is bounded below by $\rho+\delta$ can be considered as an extension of the above results. When there is no concern about the environment, which is equivalent to setting $\phi=0$, $a=0$, the economy grows without bound.[41] In this case internalization of pollution affects the growth rates, since the rate of growth is reduced because of the negative term $\frac{\phi}{v_a}$. If the reduction is sufficient, then growth stops as the economy converges to a steady state.[42]

Abatement can be modeled in a more sophisticated way if we assume that the economy accumulates abatement capital, $k_a(t)$, along with capital used to produce output, $k_y(t)$. Denote gross investment in each type of capital by $i_y(t)$, $i_a(t)$, and assume a common depreciation rate so that $\dot{k}_j(t) = i_j(t)-\delta k_j(t)$, $j=y,a$. Total capital is defined as $k(t)=k_y(t)+k_a(t)$ and output allocation is determined as $i_y(t)+i_a(t)+c(t) \leq f(k_y(t))$. Furthermore, to simplify, assume that pollution is of the flow type so that $Z=\phi(k_y,k_a)$. Pollution is increasing in k_y and decreasing in k_a. In this case the capital stocks in each sector can be used as control variables along with

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[41] This is a result consistent with endogenous growth models (see section 5).

[42] It should be noted that we assume at this stage that $n=g=0$, so there is no possibility of exogenous growth.

consumption[43] and the planner's problem becomes:

$$\max_{\{c(t),k_y(t),k_a(t)\}} \int_0^{\infty} e^{-\rho t} U\left(c, \phi\left(k_y, k_a\right)\right) dt \tag{44}$$

$$\dot{k} = f\left(k_y\right) - c - \delta k \tag{45}$$

$$k = k_y + k_a \tag{46}$$

The current value Hamiltonian for this problem is defined as:

$$\mathcal{H} = U\left(c, \phi\left(k_y, k_a\right)\right) + q\left(f\left(k_y\right) - c - \delta k\right) + \mu\left(k - k_y - k_a\right) \tag{47}$$

with short-term optimality conditions implying

$$U_c = q \tag{48}$$

$$U_c f_{k_y} + U_\phi \phi_{k_y} = U_\phi \phi_{k_a} \tag{49}$$

expressing the equality of the contributions of productive and abatement capital. Then the short-run derived demand equations are determined as:

$$c = c\left(k, q\right), k_y = k_y\left(k, q\right), k_a = k_a\left(k, q\right)$$

Assuming a separable utility function, and replacing $\dot{q}$ with $\dot{c}$ after taking the time derivative of (48) and using (46) to derive $k_j = \hat{k}_j\left(k, c\right)$ $j = y, a$, the evolution of the economy is characterized by:

$$\frac{\dot{c}}{c} = \frac{1}{\eta}\left[f_{k_y}\left(\hat{k}_y\left(k, c\right)\right) - \rho - \delta + \frac{U_\phi \phi_{k_y}}{U_c}\right] \tag{50}$$

$$\dot{k} = f\left(\hat{k}_y\left(k, c\right)\right) - c - \delta k \tag{51}$$

Assume that with diminishing returns driving the marginal product of productive capital to zero, a steady state with $\dot{c} = \dot{k} = 0$ exists. At this steady state, since $\dot{Z} = \phi_{k_y}\dot{k}_y + \phi_{k_a}\dot{k}_a$, pollution remains constant.

If the marginal product of productive capital is bounded below by $M > \rho + \delta$, then there is sustained positive growth when there is no concern about the environment or $U_\phi = 0$. When $U_\phi < 0$ the social marginal productivity of capital is less than private marginal productivity of the productive capital. In this case, if the negative term $\frac{U_\phi \phi_{k_y}}{U_c}$ reflecting the marginal rate of substitution between pollution and consumption pushes the social marginal

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[43] For this type of transformation, see Arrow and Kurz (1970). It should also be noted that the model developed here can be derived from Arrow and Kurz (1970, chapter IV) by appropriate re-interpretation of capital in the private and the public sector.

productivity of capital below $\rho + \delta$, then a steady state with $\dot{c} = \dot{k} = 0$ is obtained and sustained growth ceases. Positive growth at the steady state can be sustained even if $U_\phi < 0$, but then restrictions are required on the functions of the problem to ensure that the ratio $\frac{U_\phi \phi_{k_y}}{U_c}$ remains sufficiently low.

4.4 Nonlinear Pollution Accumulation with Optimal Emission Choice

It might be interesting to try to trace the effects of nonlinearities in the pollution accumulation equation in the Ramsey model when emissions are regarded as an input in the production function, as in section 3.1.1.[44] The optimizing behavior adopted here allows us to treat emissions as a control and thus to choose them optimally. The planner's problem is written as:

$$\max_{\{c(t),Z(t)\}} \int_0^\infty e^{-\omega t} U(\hat{c}, P)\, dt \ , \ \omega = \rho - n - (1-\xi)\eta \ , \tag{52}$$

$$c = \hat{c} e^{\xi t} \ \xi = \frac{a_2 g + a_3 (b-n)}{1-a_1}$$

$$\text{s.t.} \qquad \dot{\hat{k}} = f\left(\hat{k}, Z\right) - \hat{c} - x\hat{k} \ , x = n + \delta + \xi$$

$$f\left(\hat{k}, Z\right) = \hat{k}^{a_1} Z^{a_3} \ , \ k = \hat{k} e^{\xi t} \tag{53}$$

$$\dot{P} = Z - mP + h(P)$$

where c is per capita consumption and $\hat{c}$ is consumption defined in efficiency units, after choosing an appropriate homogeneous non-separable utility function. The current value Hamiltonian is defined as:

$$\mathcal{H} = U(\hat{c}, P) + q\left[\hat{k}^{a_1} Z^{a_3} - c - xk\right] + \lambda\left[Z - mP + h(P)\right]$$

Since for short-run optimality, $U_{\hat{c}} = q$, it is clear from the maximization of the Hamiltonian that emissions are chosen optimally in the short run when the value of marginal product of emissions equals the shadow cost of the pollutant, or

$$q f_Z = -\lambda \tag{54}$$

Using a utility function with constant elasticity of marginal utility in consumption, the optimality conditions of the maximum principle imply the

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[44] I would like to thank William Brock for bringing this approach to my attention.

following dynamical system in the control-state space:

$$
\begin{aligned}
\frac{\dot{\hat{c}}}{\hat{c}} &= \frac{1}{\eta}\left[f_k\left(k,Z\right)-\omega-x\right] && (55)\\
\dot{\hat{k}} &= f\left(k,Z\right)-\hat{c}-xk && (56)\\
\dot{Z} &= \left(\omega+m-h'\left(P\right)\right)\frac{f_Z}{f_{ZZ}}+\frac{U_P}{U_c}\frac{1}{f_{ZZ}}-U_{cc}\dot{\hat{c}}\frac{f_Z}{f_{ZZ}}-\frac{f_{Zk}}{f_{ZZ}}\dot{k} && (57)\\
\dot{P} &= Z-mP+h\left(P\right) && (58)
\end{aligned}
$$

In order to simplify the exposition assume that the economic system adjusts quickly relative to the environmental system, so that $\dot{\hat{k}} = \dot{\hat{c}} = 0$.[45] Then equilibrium $\hat{c}$ and $\hat{k}$ are defined as functions of Z. Therefore the equilibrium for the environmental system is defined as $\dot{Z} = \dot{P} = 0$, or:

$$
\begin{aligned}
0 &= \left(\omega-m-h'\left(P\right)\right)f_Z\left(\hat{k}\left(Z\right),Z\right)+\frac{U_P\left(\hat{c}\left(Z\right),P\right)}{U_c\left(\hat{c}\left(Z\right),P\right)} && (59)\\
Z &= mP-h\left(P\right) && (60)
\end{aligned}
$$

Substituting Z from (60) into (59) we obtain a nonlinear equation in the pollution stock P. Its solutions, which in general would be more than one, characterize multiple equilibria for the environmental system which in turn induce multiplicity of equilibria for the economic system.[46] The analysis of the structural properties of these equilibria is beyond the scope of this present work. It is interesting to note, however, that in models with nonlinear pollution accumulation,[47] but without explicit growth considerations - that is, models without a capital accumulation equation - that Skiba type of equilibria exists.[48] These are unstable equilibria with the property that for initial conditions in their neighborhood, the system converges with oscillations to locally stable equilibria on either side of the so-called Skiba point. This interaction between the nonlinear natural system and the economic system, in the context of an optimizing model, is undoubtedly an interesting research area. It is also interesting to note that since $\dot{\hat{c}}/\hat{c} = \dot{c}/c - \xi$, then along a balanced growth path, per capita consumption grows at a rate ξ. This is the

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[45] It should be noticed that a feedback mechanism in the natural system related to carbon dioxide accumulation, suggests the type of nonlinearity introduced in the transition equation for the pollutant.

[46] Krutilla and Reuveny (2002) analyze multiple equilibria in an optimal growth model where environment enters the model as natural capital which is reduced by consumption.

[47] See, for example, Tahvonen and Salo (1996), Brock and Starrett (2003), Mäler, Xepapadeas and de Zeeuw (2003) or Wagener (1999).

[48] See Skiba (1978) or Brock and Malliaris (1989).

standard result of optimal growth with exogenous steady-state growth rate. Furthermore the economy will grow at the same exogenous rate irrespective of the steady state to which it converges in the presence of multiple equilibria. This is again a result in the tradition of growth models with exogenous technology. Only levels are affected by environmental concerns and possible nonlinearities but not growth rates.

This model has an interesting feature regarding the possibility of growth without pollution accumulation. Since the emission flow is chosen optimally, if a steady state such that $\dot{Z} = \dot{P} = 0$ exists, then the economy grows at an exogenous rate without pollution accumulation. This is, of course, the result of requiring that in equilibrium the external cost of pollution be internalized and that pollution stop accumulating in equilibrium, since the optimal additions of emissions are such that they are outweighed by the self-cleaning capacity of the environment.[49] This result is not, however, to be interpreted as indicating that in general there is the possibility of exogenous growth with no pollution accumulation, since the desired equilibrium will exist for specific technology and preference structure. The conditions under which such an equilibrium might exist could make this model an interesting case for further research.

The presence of multiple equilibria because of nonlinearities might also present some interesting problems for regulation. In this case optimal regulation should steer the system to the most desirable steady state, or the globally optimal steady state. This desired steady state should determine the costate variable that ultimately determines the optimal emission tax.

4.5 Discounting

There is extensive discussion in the literature regarding the choice of the discount rate, or rate of time preference ρ.[50] An important part of the discussion concentrates on whether $\rho = 0$ or $\rho > 0$. In the first case, a justification for a low discount rate $\rho \simeq 0$ can be given along two different lines. The first is the well-known Ramsey argument (Ramsey 1928) according to which discounting future utilities is 'ethically indefensible and arises mainly from weakness of the imagination'.[51] Therefore, according to this argument, the utility accruing to future generations should not be weighted less than the corresponding utility of the present generations.

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[49] One possible outcome of this model is that equilibrium exists at very low steady-state levels for the economic variables.

[50] See for example Lind (1982, 1990) and Heal (this volume).

[51] Solow (1974b) makes a similar claim.

Le Kama (2001) solves an undiscounted Ramsey problem with environmental pollution defined as:

$$\max_{\{c(t)\}} \int_0^\infty \left[U(c,E) - U^R\right] dt \text{ , s.t. (7)}$$

where U^R is the Green Golden Rule utility level used as Ramsey's bliss,[52] and characterizes the steady state.

Kawaguchi (2003) also assumes a zero discount rate and uses as a criterion average long-run welfare defined as

$$\lim \inf_{T \to \infty} \frac{1}{T} \int_0^T \left[U(c(t)) - D(P(t))\right] dt$$

where $D(P)$ is a convex damage function. By maximizing average long-run welfare subject to nonlinear pollution accumulation like (6), it is shown that an optimal consumption policy exists that leads to a unique steady-state pollution.[53]

Brock (1973) suggests that the observed real rates of interest, which are determined by the observed marginal physical product of capital and can be used as a discount rate for future utilities, are low - around 1% to 2% - and may be biased upwards. The upward bias arises when unpriced environmental services enter the aggregate production function as an input, along with aggregate capital, and the marginal product of capital is increasing in the unpriced environmental services. In this case the observed marginal product of capital is priced upwards. Thus not only are observed real rates of interest low, but if the above-described upward bias is taken into account, the discount rate chosen for future utilities could be close to zero. In the same context, Weitzman (1994) shows that environmental effects imply a lower social discount rate relative to the private one. The environmental effect is modeled in this case by introducing a correction factor $\hat{\rho} > 0$, and defining the discount rate as $\rho = \rho^P (1 - \hat{\rho})$, where ρ^P is the private discount rate.[54]

Weitzman (1998) shows that when the interest rate at which the discounting must occur is uncertain, then events occurring in the far distant future should be discounted at the lowest possible rate while the "near-future"

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[52] The green golden rule is an allocation rule under which the highest level of utility can be maintained forever (Chichilniski, Heal and Beltratti 1995).

[53] To solve this problem the concept of a viscosity solution is used which is a method that could be useful in solving problems of the kind discussed here, incorporating nonlinearities and uncertainty.

[54] Li and Lofgren (2000) analyze a renewable resource management problem with heterogenous discount rates for two different groups, utilitarians and conservationists.

should be discounted at a relatively higher rate. Newell and Pizer (2003) also demonstrate that when the future path of the discount rate is uncertain and highly correlated, the distant future should be discounted at significantly lower rates than suggested by the current rate.

Thus the recent approach to discounting puts forward the idea that discounting over short time horizons should occur at a higher rate than over long horizons. This feature is known as hyperbolic discounting and implies that rates of time preference would be high in the short run but much lower in the long run, as viewed from today's perspective. Weitzman (2001) finds that even if every individual believes in a constant discount rate, the wide range of opinions on what it should be makes the effective social discount rate decline significantly over time. This the so-called "gamma-discounting" approach. Dasgupta and Maskin (2002) show that with preferences being the outcome of an evolutionary process, waiting costs and uncertainty about when payoffs are realized entail discount rates that increase as the time horizon grows shorter that is, hyperbolic discounting.

In a more formal set-up, under hyperbolic discounting, the objective function of the standard Ramsey model augmented for the environment can be written, following (Barro 1999b), as:

$$\max_{\{c(t)\}} \int_{\tau}^{\infty} U\left(c, P\right) e^{-[\rho(t-\tau)t+\psi(t-\tau)]} dt$$

The instantaneous rate for discounting future utilities, that is, the instantaneous time preference rate is defined at time distance $u = t - \tau \geq 0$ by $\rho + \psi'\left(u\right),$ with the normalization $\psi\left(0\right) = 0$. It is assumed that $\psi'\left(u\right) \geq 0, \psi''\left(u\right) \leq 0$ and $\lim_{u \to \infty} \psi'\left(t\right) = 0$. Thus the rate of time preference is high in the near future and roughly constant at the lower value of ρ in the distant future. As shown by Barro, with full commitment to current and future consumption paths, the time preference rate should be equal to ρ for all $t \geq 0$. Thus the standard result of the Ramsey model applies both at the steady state and during the transition.[55]

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[55] The analysis of the case without commitment is not as straightforward, although Barro's result, without environmental pollution, indicates that there is a basic correspondence of the properties of the growth model with and without variable time preference rates.

5 Growth and the Environment when Technical Change is Endogenous

In models with exogenous technical change, the introduction of environmental concerns into the social planner's utility function does not affect the steady-state rate of growth of the key variables (income, consumption, capital) since this rate is determined exogenously. In these models it is the transition towards the steady state and the steady-state levels which are affected. Thus in a competitive equilibrium without regulation, when pollution is a negative externality since producers do not take into account the disutility from pollution, the basic result is that pollution in physical terms will accumulate in the environment as long as the economy grows at an exogenous rate, and the productivity of physical capital approaches zero in the long run.[56] In endogenous growth models, capital can be defined in broad terms to include human capital, while diminishing returns could be prevented. The engine of growth is the accumulation of knowledge, while technological progress is not exogenous, but rather part of R&D undertaken in the expectation of ex-post monopoly profits. In the context of endogenous growth theory, growth rates can be affected by government policies such as taxation, maintenance of law and order, regulations of international trade, and so forth (Barro and Sala-i-Martin 1995). Furthermore, growth rates which are determined endogenously can remain positive if the productivity of capital, defined in broad terms, does not approach zero in the long-run, or the production of knowledge is characterized by increasing returns. Therefore since growth is determined endogenously and can be affected by government policies, the main question related to the environment, is how environmental concerns affect growth in these models. That is, in contrast to the results of the models with exogenous technical change and diminishing productivity of capital, can growth be sustained without pollution accumulation, or equivalently, are economic growth and environmental protection compatible, and what is the impact of environmental policy on growth rates? The purpose of this section is to examine how the environmental dimension is embodied in endogenous growth models in order to help answer the above questions.[57]

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[56] This is, of course, the result of the Inada conditions.

[57] For a similar attempt, see for example the surveys by Smulders (1999, 2000) or Beltratti (1996).

5.1 AK Models and Models with Increasing Returns

In the simple AK model, the aggregate production function with constant population and no exogenous technical change can be written as:

$$y = Ak$$

where as usual k is interpreted in the broad sense to include human capital and $A > 0$ reflects the level of technology. Assuming pollution accumulation according to

$$\dot{P} = \phi k - mP,\ \phi > 0 \tag{61}$$

the problem of the social planner can be written as:[58]

$$\begin{aligned} & \max_{\{c(t)\}} \int_0^\infty e^{-\rho t} U\left(c, P\right) dt \\ \text{s.t. } \dot{k} &= Ak - c - \delta k \text{ and (61)} \end{aligned}$$

The problem is very similar to the one developed in section 4.1 with $f'\left(k\right) = A$. The consumption rate of growth along the optimal path is determined as

$$\frac{\dot{c}}{c} = \frac{1}{\eta}\left[A\left(1 + \frac{\lambda\phi}{U_c}\right) - \rho - \delta + \frac{U_{cP}}{U_c}\dot{P}\right] \tag{62}$$

It can easily be seen that if pollution is not taken into account, that is, $\lambda = 0$ and $U_{cP} = 0$, then the standard result of the AK model for $A > \rho + \delta$ implies that consumption, capital and output all grow at the same positive rate in the long run $\gamma = \frac{1}{\eta}\left(A - \rho - \delta\right)$, with no need to assume exogenous technical change.

Once pollution is taken into account, then it can be shown (Michel and Rotillon 1995) that for a separable utility function, $U_{cP} = 0$, or for a utility function exhibiting "distaste effects", $U_{cP} < 0$, a steady state (c^*, k^*, P^*) exists and a positive growth rate cannot be sustained in the long run. To put it differently, sustained long-term growth is not optimal.[59]

Thus environmental concerns in this model, which does not allow for pollution abatement, do not allow sustained positive growth in the long run.[60]

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[58] See also Huang and Cai (1994), Michel and Rotillon (1995), Withagen (1995), Stokey (1996), Aghion and Howitt (1998) and Shieh, Lai and Chen (2001). The formulation here follows mainly Michel and Rotillon.

[59] Sustained growth can be achieved if the utility function exhibits a "compensation effect", $U_{cP} > 0$.

[60] A similar result is derived from Stokey's formulation of the production function as $y = Akz$, where $z \in [0, 1]$ is pollution intensity and emissions rate is specified by $Akz^{\zeta+1}$. See also Aghion and Howitt (1998).

Positive sustained growth in the long run is possible if we introduce abatement. By allocating capital in two types along the lines of section 4.3 and keeping the same structure, the constraints in the problem of the social planner are:

$$\begin{aligned}\dot{k} &= Ak_y - c - \delta k \\ \dot{P} &= \phi k_y - \psi k_a - mP \\ k &= k_y + k_a\end{aligned}$$

Michel and Rotillon (1995) show that if abatement is sufficiently effective in the sense that $\frac{\psi}{\phi} > \frac{\rho+\delta}{A-(\rho+\delta)}$, then unlimited growth without pollution accumulation is possible, independent of the form of the utility function.[61]

In the same spirit, Xepapadeas (1997b) considers a model with two types of capital: productive capital for output production, and abatement capital for pollution abatement that reduces the emissions per unit of output, with increasing returns in aggregate capital (or knowledge) in two types of capital. The constraints in the problem of social welfare maximization take the following form, with the number of firms normalized to unity:

$$\begin{aligned}&\dot{k}_j = k_j \kappa_j \left(I_j / k_j \right) \ , \ j = y, a \\ &\dot{P} = \phi \left(k_a, K_a, K_y \right) f \left(k_y, K_y \right) - mP \\ &f \left(k_y, K_y \right) = c - I_y - I_a\end{aligned}$$

where K_y and K_a denote aggregate capital or knowledge in output production and pollution abatement respectively, I_y and I_a denote investment in each sector, and $\phi \left(k_a, K_a, K_y \right)$ is the unit emission coefficient characterized by increasing returns in aggregate abatement capital which captures the positive spillover effect. With a utility function separable in consumption and pollution stock, it is shown that when the unit emission coefficient is fixed, permanent growth is not optimal, confirming the previous results. Permanent growth without unlimited pollution accumulation can be achieved if increasing returns in pollution abatement reduce the unit emission coefficient towards zero. This formulation also allows the discussion of environmental traps in the sense that countries with low aggregate capital such that increasing returns in abatement can not be exploited, but with environmental concerns, can be trapped in a low growth region.

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[61] A similar result is obtained by Musu (1994). See also Chevé (2002) for a similar AK model when the assimilating capacity of the environment is not characterized by exponential decay but by nonlinearities. It should be noted that nonlinearities in pollution accumulation induce multiple equilibria as in section 4.4.

Another result of these models relates to policy design. Since three externalities can be identified, knowledge spillovers in production and pollution abatement along with environmental pollution, three instruments could be used to correct distortions: subsidies for investment in production and abatement to correct underinvestment of competitive markets in the two sectors, and emission taxes to correct for environmental pollution.

Considering that improvements in environmental quality, through pollution reductions, increase productivity along the lines of aggregate production function (5), Mohtadi (1996) studies a variant of an AK model where capital accumulation reduces environmental quality. In this case the social planner's problem is defined as

$$\begin{aligned} &\max_{\{c(t)\}} \int_0^\infty e^{-\rho t} U(c, E)\, dt,\ U_E > 0 \\ &\text{s. t. } \dot{k} = A(E)\, k - c\ ,\ E_k(k) < 0 \end{aligned}$$

where $A(E)$ captures the effects of environmental quality on productivity. It is shown that a socially-optimal balanced path exists with consumption and capital growing at the same rate. The socially-optimal path can be supported by a combination of quantity controls and optimal tax/subsidy schemes in the same general framework of AK models and pollution reducing technologies. In a model similar in spirit, with positive productivity effects from the environment, Smulders and Gradus (1996) introduce pollution abatement and show that the combination of productivity effects and low marginal abatement costs could increase the optimal growth rate. As before the social optimum can be sustained by tax/subsidy combinations. Rubio and Aznar (2000) also discuss the design of environmental policy in the context of a similar AK model with positive productivity effects from environmental quality and pollution abatement. They show that a tax on production and a subsidy on pollution abatement could increase growth if productivity gains from reducing pollution are sufficiently high.

Reis (2001) considers the case where there is a probability of discovering a technology that would eliminate pollution. If this probability is positive, then positive growth could be optimal.

5.2 Two-Sector Models

Two-sector models have been developed mainly by Bovenberg and Smulders (1995, 1996) and Hettich (...).[62] Bovenberg and Smulders (1995) extend

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[62] See also Gradus and Smulders (1993). Rosendahl (1997) uses the Lucas model with a concave assimilative function for the environment.

the models of Lucas (1988) and Rebelo (1991). They consider a process of development of technical knowledge that enables production to take place in a less polluting way and use renewable resources more efficiently. A two-sector model is developed with one sector producing a final good and the other sector generating knowledge in pollution reduction which is a public good. Production and pollution are modelled by a Brock-type model where output is produced according to the production function, $y = f(E, k_y, Z_y)$, where E is the stock of the environmental capital,[63] k_y is man-made capital used in the production of the final good, and Z_y is effective input of the harvested environmental capital interpreted as pollution. The knowledge sector generates knowledge of stock h, according to

$$\dot{h} = H = H(k_h, Z_h)$$

where k_h, Z_h are man-made capital and pollution input in the technology sector respectively. The total effective level of pollution is $Z = Z_y + Z_h$ with the economy-wide level of pollution P determined as $Z \equiv hP$, thus $Z_y = \alpha hP$ and $Z_h = (1-\alpha) hP$. Man-made capital stock accumulates according to $\dot{k} = y - c$, with $k = k_y + k_h$. Finally the environmental stock has a renewable resource characteristic, evolving according to a growth function $\dot{E} = R(E, P)$. The social optimum is determined by maximizing the functional:

$$\max_{\{k_y(t), k_h(t), Z_y(t), Z_h(t)\}} \int_0^\infty e^{-\rho t} U(c, E)\, dt$$

subject to the constraints defined above. The problem is solved to derive conditions for optimal sustainable balanced growth where consumption knowledge and man-made capital grow at a positive rate while the flow of pollution and the stock of environmental capital remain constant. The attainment of the social optimum requires government intervention in the form of taxes on pollution. Since knowledge is a public good, governments should earmark part of the revenues for investment in the knowledge sector. The optimal size of the government's budget tends to increase with environmental concerns.[64]

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[63] See the discussion in section 2.

[64] Schou (2000) considers a three-sector model where, in addition to the production sector and the knowledge sector, a resource extraction sector is introduced. The resource sector contributes to production in a positive way as an input and in a negative way by generating pollution that inversely affects productivity. In a recent working paper Fullerton and Kim (2003) extend the two-sector model of Bovenberg and Smulders to allow for distortionary taxation for financing public investment in abatement knowledge.

5.3 Models with Product Variety

These are models where environmental concerns are introduced into growth models in which profit-maximizing firms innovate by introducing new varieties of goods.[65] Following Aghion and Howitt (1998), the aggregate production function can be written as

$$y = k^a (BL)^{1-a} z \ , \ 0 < a < 1, \ z \in [0,1]$$

where B is the stock of intellectual capital and z is pollution intensity.[66] In this model intellectual capital evolves as

$$\dot{B} = \sigma B l \tag{63}$$

where σ is a positive parameter related to the innovation process and l is labour devoted to research, $L + l = 1$. Then output is produced according to $y = k^a (B(1-l))^{1-a} z$, and manufactured capital accumulates according to

$$\dot{k} = y - c \tag{64}$$

Environmental quality E evolves according to[67]

$$\dot{E} = -P - mE \ , \ E^{\min} \leq E(t) \leq 0 \tag{65}$$

where the flow of pollution P is defined as $P = yz^{\zeta}$, $\zeta > 0$ and m is the environmental regeneration rate.

The problem of the social planner is to choose controls c, z, l to maximize

$$\int_0^{\infty} e^{-\rho t} U(c, E)\, dt$$
$$\text{s.t. } (63), (64), (65)$$

Aghion and Howitt (1998) show that, provided that the elasticity of marginal utility of consumption exceeds one and $\sigma > \rho$, unlimited growth is possible

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[65] This is based on Romer (1987, 1990) and Grossman and Helpman (1991).

[66] In this economy, output is produced according to $y = L^{1-a}\left[\int_0^1 B(i)\, x(i)^a\, di\right] z$. Each intermediate good i is produced according to $x(i) = k(i)/B(i)$, where $k(i)$ is manufactured capital used to produce i and $B(i)$ is the productivity of intermediate good i. In equilibrium $x(i) = k/B$ where $B \equiv \int_0^1 B(i)\, di$ indicates average quality and the production function can be written as $y = k^a (BL)^{1-a} z$.

[67] In this set-up, environmental quality is measured as the difference $E - E^{\max}$, where $E^{\max}$ is an upper limit of environmental quality to be reached if pollution were to stop forever. Then E is negatively constrained as $E^{\min} \leq E(t) \leq 0$, where $E^{\min}$ is some minimum acceptable quality level.

along the optimal path. That is, output, capital, consumption and knowledge grow without bound, while pollution decreases and environmental quality improves.

Grimaud (1999) determines policy instruments that could implement the above socially-optimal path. Since there are three distortions which should be corrected at market equilibrium - monopoly in intermediate goods, and positive spillovers from knowledge and pollution - three instruments are introduced: subsidies to correct for the first two distortions, and pollution permits to correct for environmental pollution. Along the optimal path the number of permits decreases. Environmental policy affects growth performance by decreasing output growth due to the decrease in the number of permits, reducing the value of patents, and lowering the marginal cost of R&D.[68]

Elbasha and Roe (1996) follow Romer (1990) to introduce imperfect competition in the growth model with international trade considerations along the lines of Grossman and Helpman (1991) and Rivera-Batiz and Romer (1991). An open economy with two traded goods, Y and Q, is considered. The production functions for the two goods are given by:

$$Y = A_y K_y^{a_1} L_y^{a_2} D_y^{a_3}\ ,\ Q = A_q K_q^{\beta_1} L_q^{\beta_2} D_q^{\beta_3}\ ,\ \sum_{i=1}^{3} a_i = \sum_{i=1}^{3} \beta_i = 1$$

where K_i and $L_i (i = y, z)$ denote capital and labor inputs respectively and D_i is an index of differentiated inputs defined as:

$$D_i = \left(\int_0^{M(t)} X_i\left(j\right)^{\delta} dj \right)^{\frac{1}{\delta}}\ ,\ i = y, z,\ \delta > 0$$

where $M(t)$ is the number of differentiated inputs available at time t and $X(t)$ is the amount of differentiated input j. Each type (brand) of input j can be produced once a license is obtained from the R&D sector of the economy, according to the production function:

$$X\left(j\right) = A_x \left[K_x\left(j\right)\right]^{\eta} \left[L_x\left(j\right)\right]^{1-\eta}\ , 0 < \eta < 1,\ j \in [0, M]$$

where K_x and L_x are capital and labour inputs respectively in the production of differentiated products. The R&D sector produces new blueprints to increase the number of brands, by using capital, labour and knowledge capital

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[68] Ono (2002), in the context of an overlapping generations model, discusses the possibility that the reduction in permits might have harmful long-run effects in terms of lowering capital and environmental quality.

which is a public good, according to:

$$\dot{M} = A_m K_m^{\theta} L_m^{1-\theta} \ , \ 0 < \theta < 1$$

where M is the number of brands assumed proportional to the knowledge capital. In this model all markets are competitive, with the exception of the differentiated input market where producers sell their product in an imperfectly competitive market.

In the above-described framework, environmental quality is considered as a flow variable related either to the production of the two consumption goods or as a stock variable related to the use of the differentiated intermediate inputs. In the first case environmental quality is defined as:

$$E = A_a Z_y^{z_y} Z_q^{1-z_q} \ , \ z_y, z_q < 0$$

where Z_y and Z_q are emissions from the production of the traded goods Y and Q respectively. In the second case pollution is defined as:

$$P = \left(\int_0^{M(t)} X_i\left(j\right)^{\epsilon} dj \right)^{\frac{1}{\epsilon}} \ , \ \epsilon > 0$$

The model is solved for the market equilibrium and the social optimum and the two solutions are compared. The results indicate that if the elasticity of the intertemporal substitution of consumption is less than one then environmental concerns increase growth, while the opposite happens if the elasticity is greater than one. On the other hand, the effects of trade on the environment and welfare depend mainly on price elasticities, the terms of trade effects on growth and pollution intensities. Numerical simulations show that trade improves welfare but might worsen environmental quality.[69]

6 Empirical Evidence

The theoretical analysis performed above suggests that different possible links between growth and the environment might exist. That is, if disutility from pollution is not taken into account, pollution might grow with income. On the other hand, if pollution affects social welfare in a negative way, environmental concerns might decelerate growth if the productivity of capital in production and pollution abatement declines towards zero as capital accumulates. However sustained growth could be compatible with stable pollution in cases of

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[69] Models with product variety have been developed by Verdier (1993) and Hung, Chan and Blackburn (1992).

non-diminishing returns in output production or abatement processes. Another emerging result is that environmental policy affects both growth and pollution.

Therefore it is of great significance to explore empirical evidence in order to assess the relationship between economic growth and environmental pollution. We are going to explore three different approaches regarding the empirical analysis of the relationship between the environment and growth. The first relates to the relationship between ambient pollution and GDP per capita, the so-called environmental Kuznets curve (EKC), the second to the estimation of the impact of environmental regulation on GDP growth, and the third to the way in which environmental considerations might affect growth accounting.

6.1 The Environmental Kuznets Curve

The EKC has dominated the discussion regarding the empirical relationship between growth and environmental pollution.[70] The idea behind the EKC is that an inverted U relationship exists between ambient levels of pollution and GDP per capita. The first discussion about a possible decoupling of output growth and pollution growth came in the early 1990s, when it was suggested that a break exists in the link between growth and pollution, at least for OECD countries (World Bank 1992, Panayotou 1992). This break seems to be associated more with local pollutants than with global pollutants (e.g.,CO_2). At the same time, there is no indication that this link is breaking for lower income countries. Also, as found by Hettige, Lucas and Wheeler (1992), there is a long-term upward trend in industrial emissions relative to both GDP and manufacturing output, with emissions growing faster in low income countries than in high income countries. The results found by Hettige, Lucas and Wheeler (1992) also suggest an industrial displacement effect as a result of stricter regulations in developed countries, with dirtier industries moving towards low-income countries. This industrial displacement positively affects the environmental quality of the developed countries. In the same spirit, Arrow et al. (1995) note that the process of economic development from agrarian economies to polluting, industrialized economies and then to cleaner service economies suggests output growth-pollution growth decoupling.

The initial research based on the estimation of empirical relationships between environmental and development variables also seems to suggest the

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[70] There is a large body of literature regarding the EKC. See, for example, the surveys by Levinson (2002), Dasgupta et al. (2002) or Panayotou (2000).

de-linking of environmental pollution with economic growth. Studies by the World Bank (1992), Grossman and Krueger (1993, 1995) and Selden and Song (1994) suggest that an inverted U relationship exists between ambient environmental quality or emissions for certain types of pollutants, and per capita GDP, wherein after a turning point, emissions decline despite economic development. In general the results seem to indicate that economic growth may not cause harm to the environment, at least with regard to the pollutants examined. Grossman and Krueger (1995) calculate that the turning point of the inverted U curve is GDP per capita of $8000 (1985 dollars) for most of the pollutants examined. For countries with income above $10,000, the hypothesis that further growth will be associated with environmental degradation can be rejected at the 5 percent significance level for most of the pollutants examined.[71] These initial empirical results initiated widespread research activity that took two different approaches. The first was an attempt to provide a theoretical explanation of the EKC, and the second was efforts to verify, improve or extend the empirical analysis.

6.1.1 Theoretical foundations

The theoretical foundations of the pollution-income relationship which underlies the EKC discussion, are based on dynamic or static optimization models with environmental considerations. To clarify the point, consider a simple optimal growth model with flow pollution and abatement along the lines of the models developed in section 4.

Assume that flow of pollution generated at each point in time is described by the emission function $Z = v(k, a)$ where a denotes abatement at time t. The planning problem, assuming again no population growth or exogenous technical change and a separable utility function, is:

$$\begin{gathered} \max_{\{c(t)\}} \int_0^\infty e^{-\rho t} \left[U(c) - D(Z) \right] dt \ D' > 0, D'' \geq 0 \\ \text{s.t. } \dot{k} = f(k) - c - a - \delta k \end{gathered} \tag{66}$$

where $f(k)$ is the standard neoclassical production function. The current value Hamiltonian is defined as:

$$\mathcal{H} = U(c) - D(v(k, a)) + q(f(k) - c - a - \delta k)$$

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[71] Grossman and Krueger (1995) regard the upper tail of some estimated "N"-shaped relationships as an artificial construct.

The first-order conditions imply:

$$\begin{aligned} U_c(c) &= q && (67) \\ D' v_a(k,a) &= q && (68) \end{aligned}$$

where (67) and (68) can be solved to define the short-run optimal level of abatement as a function of c and k, or $a = \tilde{a}(c,k)$. By differentiating (67) with respect to time and making the appropriate substitutions, the dynamic system characterizing the evolution of the economy in the (c,k) space is

$$\begin{aligned} \frac{\dot{c}}{c} &= \frac{1}{\eta}\left[f'(k) - \frac{D' v_k(k, \tilde{a}(c,k))}{U_c(c)} - \rho - \delta\right] && (69) \\ \dot{k} &= f(k) - c - \tilde{a}(c,k) - \delta k && (70) \end{aligned}$$

Assume that a steady state (c^*, k^*) exists, and that it has the saddle point property with one stable arm converging to the steady state similar to figure 2. The stable arm expresses c as a function of k. This is the policy function $c = \hat{c}(k)$. Given the policy function, the pollution-income relationship (PIR) is defined by:

$$PIR = \{(Z,y) : Z = v(k, \tilde{a}(\hat{c}(k), k)),\ y = f(k)\} \qquad (71)$$

The policy function can be determined numerically following the time elimination method of Mulligan and Sala-i-Martin (1993).[72] Dividing (69) by (70) we obtain a differential equation for the policy function, or:

$$\hat{c}'(k) = \frac{\frac{1}{\eta}\left[f'(k) - \frac{D' v_k(k, \tilde{a}(\hat{c}(k),k))}{U_c(\hat{c}(k))} - \rho - \delta\right]\hat{c}(k)}{f(k) - \hat{c}(k) - \tilde{a}(\hat{c}(k), k) - \delta k} \qquad (72)$$

with boundary conditions (c^*, k^*) and $\hat{c}'(k^*)$ equal to the slope of the stable arm at the steady state, which turns out to be the slope of the negative eigen vector.

Equation (71) is the pollution-income relationship corresponding to an economy on the socially-optimal path. However, economies from which data are used to estimate the empirical pollution-income relationship are not likely to be on an optimal path. In this case, the pollution-income relationship is generated from a different model. Consider the case in which pollution is ignored and there is no environmental regulation. Then following section 4.1

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[72] See also Barro and Sala-i-Martin (1995) for another exposition and Beltratti (1996) for an application to the EKC.

the dynamics of the economy are given by

$$\begin{aligned} \frac{\dot{c}}{c} &= \frac{1}{\eta}\left[f'(k) - \rho - \delta\right] \\ \dot{k} &= f(k) - c - \delta k \end{aligned} \tag{73}$$

and the pollution-income relationship is given by

$$PIR_U = \{(Z, y) : Z = v(k, 0),\ y = f(k)\} \tag{74}$$

Under environmental regulation with an emission tax τ, the competitive profit-maximizing firm solves

$$\max_{k,a} f(k) - (r + \delta)k - a - \tau v(k, a)$$

with first-order conditions

$$f'(k) = r + \delta + \tau v_k(k, a) \tag{75}$$

$$1 = \tau v_a(k, a) \tag{76}$$

Substituting (75) into (73) and using (76) to solve for short-run abatement under regulation $a = \tilde{a}(k, \tau)$, the dynamics of the economy are defined as:

$$\begin{aligned} \frac{\dot{c}}{c} &= \frac{1}{\eta}\left[f'(k) - \tau v_k(k, \tilde{a}(k, \tau)) - \rho - \delta\right] \\ \dot{k} &= f(k) - c - \tilde{a}(k, \tau) - \delta k \end{aligned}$$

and the pollution-income relationship is defined as

$$PIR_R = \{(Z, y) : Z = v(k, \tilde{a}(k, \tau)),\ y = f(k)\} \tag{77}$$

In the case of (77), if the emission tax is chosen optimally so that

$$\tau = \frac{D'(v(k, k, \tilde{a}(\hat{c}(k), k)))}{U_c(\hat{c}(k))},$$

then it is clear from (67), (68), (69) and (70) that the income-pollution relationship implied by (71) is the same as the income-pollution relationship implied by (77). In all other cases the three curves deviate. Comparing the three income-pollution relationships - (71), (73), and (77) - it is clear that the shape of the PIR depends on preferences, technological parameters and regulation. Thus the shape of the estimated relationships could reflect, for example, that an optimal path is followed, or that during the sample period environmental policy was introduced or became tougher and this changed the shape of the income-pollution relationship. Furthermore (71), (73), and (77) imply that a variety of shapes could be consistent with the underlying model, or that the same shape could be derived from all three cases. Thus an observed inverted U shape, for example, is not to be interpreted as an indication of optimal or suboptimal policies.[73]

A similar result regarding the underlying structure of the shape of the EKC is obtained by Andreoni and Levinson (2001) and Levinson (2002), from a simple static Robinson-Crusoe style model where consumption, c, is the source of pollution. Then utility is defined as

$$U = c - Z$$

and pollution is defined as

$$Z = c - c^{\beta} a^{\zeta}$$

where a is abatement effort and $c^{\beta} a^{\zeta}$ denotes pollution abatement. The resource constraint is $c + a = y$ and the optimization problem is

$$\begin{aligned} \max_{c,a}\ c - Z,\ Z &= c - c^{\beta} a^{\zeta} \\ \text{s.t. } c + a &= y \end{aligned}$$

Then the pollution-income relationship is defined as

$$Z(y) = c(y) - [c(y)]^{\beta} [a(y)]^{\zeta}$$

where $c(y) = \frac{\beta}{\beta+\zeta}$, $a(y) = \frac{\zeta}{\beta+\zeta}$. For $\beta + \zeta = 1$ the pollution-income relationship is a line with positive slope, while for $\beta + \zeta > 1$ the pollution-income relationship has the inverted U shape.

In a multi-person extension of the above model, where individuals solve

$$\begin{aligned} &\max_{c_i,a_i} U_i = c_i - Z,\ i = 1, ..., n \\ &Z = c - c^{\beta} a^{\zeta},\ c = \sum_{i=1}^{n} c_i\ ,\ a = \sum_{i=1}^{n} a_i \\ &c_i + a_i = y_i \end{aligned}$$

the pollution-income relationship again has an inverted U shape when $\beta + \zeta > 1$.

The same result of the inverted U-shaped pollution-relationship, when $\beta + \zeta > 1$, holds for the planner's problem

$$\max_{c_i,a_i} \sum_{i=1}^{n} U_i = \sum_{i=1}^{n} c_i - nZ$$

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[73] See also Selden and Song (1995).

A conclusion derived from this approach is that for the technology parametrization $\beta + \zeta > 1$, the inverted U-shaped pollution-relationship is consistent with both market failures in the case of many agents, and efficient resource allocation in the case of the social planner's problem.

In the literature related to the theoretical foundation of the EKC, Selden and Song (1995) derive an EKC using an optimal growth model with flow pollution and abatement expenditure.[74] They suggest caution, however, in interpreting empirically-observed inverted U curves as indicating that actual pollution paths are derived from an approximately optimal path. Beltratti (1996) generates an EKC by calibrating optimal growth models with pollution accumulation and abatement expenditures.

Another set of theoretical models derives inverted V-shaped curves by having pollution increasing with income until some threshold point is passed, after which pollution is reduced. John and Pecchenino (1994) consider an overlapping generations model where economies with low income or high environmental quality are not engaged in environmental investment, that is, pollution abatement. When environmental quality deteriorates with growth, the economy moves to positive abatement, then the environment improves with growth and the relationship has an inverted V shape. Stokey (1996) generates an inverted V-shaped curve by considering a static optimization model where below a threshold income level only the dirtiest technologies are used. As economic activity and pollution increase, the threshold level is passed and cleaner activities are used. Jaeger (1998) derives the inverted V-shaped curve by considering a threshold in consumer preferences. Below the threshold the marginal benefits from improving environmental quality are small, whereas when pollution increases with growth and the threshold is passed, quality may be improved. Jones and Manuelli (2001) develop a different model which relates explicitly to environmental policy. Environmental policy is decided by majority voting and could take the form of either emission taxes or "minimum standards" in technology. In countries with low income, per capita emission taxes are chosen to be zero, and when income increases positive taxes are chosen and an inverted V-shaped curve is derived. When minimum standards are chosen, the pollution-income relationship is monotonic and converges to a limiting pollution level.

6.1.2 Empirical results

At the empirical level there is a large number of studies seeking to verify the early findings of the inverted U-shaped EKC, to expand the idea of the EKC

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[74] Selden and Song used Forster's (1973) model.

to more pollutants, or to improve on the econometrics used.[75] The estimated relationships are in a reduced form specification that takes mainly cubic or quadratic forms. Estimation methods include a variety of methods such as OLS estimation, panel data estimations with fixed or random effects, Tobit estimation, or semiparametric estimation. Explanatory variables - aside from GDP per capita - also include its lagged values, population density locational variables, micro or macro policy variables, distributional variables, trade variables, as well as non-economic variables[76] such as literacy rates or political rights.[77] Although the initial findings of the World Bank (1992) and Grossman and Krueger (1995) regarding the EKC seem to have gained acceptance over the last decade, Harbaugh, Levinson and Wilson (2002) suggest that the pollution-income relationship is less robust than previously thought in changes in data, extension of the lag-structure of the GDP per capita and inclusion of additional country specific covariates.

Table 1[78] shows selected results from the paper by Harbaugh, Levinson and Wilson (2002), which reexamined the evidence for an EKC presented in the influential paper by Grossman and Krueger (1995). As shown in column (1), Grossman and Krueger had found that the pattern of signs on a polynomial involving current and lagged income yielded an EKC for SO_2 for most of the data range. Harbaugh, Levinson and Wilson (2002) first examined the sensitivity of this finding to data quality and quantity. They took the original model from Grossman and Krueger and reestimated it with the World Health Organization's and the United Nations' revised estimates of the same observations (column (2)) and with an updated data set from those sources that includes more monitoring stations and years (column (3)). As can be seen, these changes reverse Grossman and Krueger's finding. Harbaugh, Levinson and Wilson (2002) then examined the impact of changing the specification to include additional explanatory variables (columns (4)-(6)). The impact is to further undermine support for an EKC, with the relationship instead evidently being U- shaped within the entire range of the data.

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[75] In empirical studies, an explanation of the EKC without the need to resort to an optimization model can be found in the decomposition approaches. For example, Panayotou (1997) and Islam, Vincent and Panayotou (1999) decompose the total income effect of pollution into three effects: (i) a scale effect where the pollution-income relationship is monotonically increasing, (ii) a compostion of the the GDP effect where the pollution-income relationship has an inverted U shape, and (iii) an abatement effect where the pollution-income relationship is monotonically decreasing.

[76] See Torras and Boyce (1998).

[77] For a very instructive presentation of these studies, see the reviews by Panayotou (2000) or Levinson (2002).

[78] I would like to thank Jeff Vincent for providing the table and the commentary.

[Table 1]

Harbaugh, Levinson and Wilson (2002) find that similar changes in the data and model specification also weaken the econometric case for an EKC for two other air pollutants, smoke and TSP. They conclude that “for these pollutants, the available empirical evidence cannot be used to support either the proposition that economic growth helps the environment or the proposition that it harms the environment” (p. 549). They also note that two of these three pollutants, SO_2 and smoke, “exhibit the most dramatic inverse U-shaped patterns in the World Bank’s report [i.e., the 1992 World Development Report] and in Grossman and Krueger” (p. 541).

6.2 Growth, Competitiveness and Environmental Regulation

Environmental quality can be preserved or improved by restructuring production towards cleaner activities and by adopting environmental regulations. By simulating the US economy with and without environmental regulation, using an intertemporal general equilibrium model, Jorgenson and Wilcoxen (1990, 1993) found that regulations associated with investment in pollution control equipment, motor vehicle emissions as well as operating costs in pollution abatement, were responsible for a drop in the growth of GDP by 0.191 percentage points for the period 1973-1985.

Another closely related issue is the relationship between environmental regulation and competitiveness. The conventional wisdom suggests that the cost of environmental regulation slows productivity growth and impedes competitiveness in international markets. The opposite view, expressed by the so-called Porter hypothesis and supported by a series of case studies, where firms under strict environmental regulation prove to be very successful, suggests that tough environmental regulation in the form of economic incentives can trigger innovation that may eventually increase a firm’s competitiveness and may outweigh the short-run private costs of this regulation (Porter 1991, Porter and van der Linde 1995). On the theoretical level the validity of this hypothesis has not been established without resorting to specific assumptions regarding X-efficiency, or strategic trade models (Simpson and Bradford 1996). It has also been criticized for introducing a “free lunch” idea and potentially distracting attention from the cost-benefit analysis of environmental policy (Palmer, Oates and Portney 1995). It has also been shown (Xepapadeas and de Zeeuw 1999) that modernization of capital stock induced by a tougher environmental policy might not provide the full benefits assumed by the Porter hypothesis, but is expected to increase the productivity of the capital stock, along with a relatively less severe impact on profits and more emission reductions.

On the empirical level studies on the relationship between competitiveness, reflected in changes in the trade and investment patterns, and environmental regulation (e.g., Kalt 1998; Tobey 1990; Jaffe et al. 1995) do not find either a significant adverse effect of more stringent environmental policies on competitiveness, or evidence supporting the idea the regulation promotes competitiveness. The existing data are limited in their ability to measure the stringency of regulation, but other possible explanations of these inconclusive results are that the compliance costs are only a small fraction of total costs of production, that stringency differentials are small, and that investments follow the current state-of-the-art in technology even if this is not required by the environmental regulation in that country.

6.3 Growth Accounting and the Environment

In the Solow growth model, growth is explained as a result of the combination of manufactured capital K, labour L, and technology A. Growth accounting provides a method of breaking down observed growth into components associated with the growth of observed factor inputs and a residual that reflects technological progress.[79]

With the neoclassical aggregate production function (1), the rate of technological progress g is defined as:[80]

$$\left(\frac{F_L L}{Y}\right)\left(\frac{\dot{A}}{A}\right) \equiv g = \frac{\dot{Y}}{Y} - \left(\frac{F_K K}{Y}\right)\left(\frac{\dot{K}}{K}\right) - \left(\frac{F_L L}{Y}\right)\frac{\dot{L}}{L} \tag{78}$$

In a competitive economy factors are paid their marginal products, or $F_K = w$, $F_L = r$. Thus the the estimate of technological progress, or the Solow residual or the total factor productivity growth (TFP), is defined as:

$$\hat{g} = \frac{\dot{Y}}{Y} - s_K\left(\frac{\dot{K}}{K}\right) - s_L\frac{\dot{L}}{L} \tag{79}$$

where s_K and s_L are the respective factor shares.[81]

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[79] For basic growth accounting, see Solow (1957), Kendrick (1961), Denison (1962) and Jorgenson and Griliches (1967). See Lau (1996) for recent empirical results and Barro (1999a) for a review of growth accounting in light of the recent advances in growth theory.

[80] See, for example, Romer (1996, ch 1.7).

[81] Estimates of TFP for the period 1947-1973 for the main OECD countries range from

Dasgupta and Mäler (2000) connected growth accounting with environmental variables.[82] They derive the growth accounting identity, along the lines of (78), by using the flow of natural resources - in addition to capital and labor - as an input in the production function. They conclude that if in conventional growth accounting environmental resources go unrecorded and the resource use has been growing, then the estimate of g could be too high.

In the same spirit, assume that the aggregate production function is of the form of (4) with no pollution augmenting technical change, or

$$Y = F(K, AL, Z) \tag{80}$$

Differentiating (80) and rearranging we obtain

$$\begin{aligned} &\left(\frac{F_L L}{Y}\right)\left(\frac{\dot{A}}{A}\right) = g_Z = \\ &\frac{\dot{Y}}{Y} - \left(\frac{F_K K}{Y}\right)\left(\frac{\dot{K}}{K}\right) - \left(\frac{F_L L}{Y}\right)\left(\frac{\dot{L}}{L}\right) - \left(\frac{F_Z Z}{Y}\right)\left(\frac{\dot{Z}}{Z}\right) \end{aligned} \tag{81}$$

As is implied from the discussion in section 4.2 and from the optimality condition (54), along the socially-optimal path $F_Z = -\lambda/q$, with $-\lambda/q = \tau$ being the optimal emission tax, $\frac{F_Z Z}{Y} = \frac{\tau Z}{Y}$. Therefore the counterpart of (79) can be written as

$$\hat{g}_Z = \frac{\dot{Y}}{Y} - s_K\left(\frac{\dot{K}}{K}\right) - s_L\left(\frac{\dot{L}}{L}\right) - s_Z\left(\frac{\dot{Z}}{Z}\right) \tag{82}$$

where s_Z is the share of optimal environmental taxes in total output. Essentially this formulation implies that the two conventional factors are paid their marginal products, but in addition the economy is charged with the environmental damage generated by using one more unit of emissions to generate output. This extra damage is equal to $-\lambda/q$, where λ is the shadow value (shadow cost) of one more unit of pollutant accumulation and q is the marginal utility realized from the production causing the pollutant accumulation.

Suppose that environmental policy is not optimal, in the sense that $0 \leq \tilde{\tau} < \tau$, which is an assumption that could be regarded as a plausible one in

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1.4% (USA) to 4% (Japan), while for the period from 1973-1989, they reflect the well-known productivity slow down and range from 0.3% (Canada) to 1.4% (France). See Barro (1999a).

[82] See also Denison (1982) for a similar attempt.

real economies, then measured TFP is actually

$$\tilde{g}_Z = \frac{\dot{Y}}{Y} - \tilde{s}_K \left(\frac{\dot{K}}{K}\right) - \tilde{s}_L \left(\frac{\dot{L}}{L}\right) - \tilde{s}_Z \left(\frac{\dot{Z}}{Z}\right) \tag{83}$$

where $\tilde{s}_Z$ is the share of environmental taxes actually paid in total output. Subtracting (83) from (82) we obtain

$$\begin{aligned} \hat{g}_Z - \tilde{g}_Z &= -(s_K - \tilde{s}_K)\left(\frac{\dot{K}}{K}\right) - (s_L - \tilde{s}_L)\left(\frac{\dot{L}}{L}\right) - (s_Z - \tilde{s}_Z)\left(\frac{\dot{Z}}{Z}\right) \quad (84) \\ \text{with } 0 &\leq \tilde{s}_Z < s_Z. \end{aligned}$$

Equation (84) indicates that when environmental policy is suboptimal, the estimated TFP deviates from the true TFP. It should be noted that (84) could be used as a basis for empirical analysis, since by regressing the estimated residual $\tilde{g}_Z$ on the growth rates of capital, labour and emissions, the true residual, $\hat{g}_Z$, would be the the intercept of this regression, and the coefficients of the input growth rates would indicate the deviations of the optimal shares from the actual share.[83]

7 Summary and Conclusions

The basic purpose of this chapter was to analyze the links between the processes of economic growth and the state of the environment and explore possible answers to questions regarding the compatibility of growth and environmental protection, the feasibility of sustained growth in the presence of environmental concerns, the impact of environmental protection on the levels and growth rates of crucial economic variables, and the empirical evidence relating growth to the environment.

To analyze the effects of environmental concerns on the growth process, we need as a starting point models capable of describing the growth process itself. Since the evolution of modern growth theory has produced such models, ranging from models of exogenous technical change and fixed savings ratio to models of optimal saving and endogenous technical change,[84] it is natural to analyze the growth - environment link using these models as our analytical framework.

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[83] In this estimation one should be aware of econometric problems such as possible correlation of the explanatory variables with the unobserved true residual, errors in measurement of the explanatory variables, and time varying factor shares (Barro 1999a).

[84] It should be noted that, as Solow (1999) shows, these models can be connected in a meaningful way.

It seems that the main messages emerging from the incorporation of environmental concerns into the existing growth models could be summarized in the following way:

- If no resources are devoted to pollution abatement and emissions per unit of output remain constant, than sustained growth is not optimal. Sustained growth will increase the accumulation of pollution when the unit emission coefficient is constant, and at some point the incremental benefits from growth will be outweighed by the incremental damages from environmental pollution, or some upper bound on the allowed accumulation of pollutants will be violated. In this context, growth and environmental pollution are not compatible. This is clear both from the fixed saving models and the optimal savings models with exogenous technical change and fixed unit emission coefficient. In these models, environmental concerns affect levels but not the rate of growth of certain key variables, which grow at an exogenous rate. So environmental concerns reduce the optimal levels but at the steady state the economy along with pollution grows at the exogenous rate. With a fixed unit emission coefficient, pollution accumulates at the same exogenous rate and this is not optimal. Pollution stops accumulating if the economy stops growing.

- If the economy chooses emissions in an optimal way, in a Ramsey type model with emissions as an input in the production function, by taking into account the shadow cost of emissions regarded as inputs in the production process, then it might be possible to have constant pollution with the economy growing at an exogenous rate for some specification of technology and preferences. This optimal choice of emissions could be regarded in this context as reflecting optimal pollution abatement.

- If the economy devotes resources to pollution abatement and development of clean technologies which reduce the unit emission coefficient, the growth - environment process depends basically on the productivity of abatement in the environmental sector.

    - Growth without pollution accumulation can be obtained in the standard Solow model if it is assumed that the marginal productivity of capital is bounded below and the unit emission coefficient tends to zero as capital keeps accumulating.
    - If, on the other hand, diminishing returns in abatement capital drive the productivity of the abatement sector to zero, and this

    prevents the unit emission coefficient from converging towards zero, then the economy will end up again in a fixed unit emission coefficient case and, although growth takes place in a cleaner environment, the fixed unit emission coefficient result will eventually prevail.

  - In cases where diminishing returns in the abatement sector are prevented, abatement is sufficiently effective and constant returns to capital defined in the broad sense prevail, then it is possible to have sustained growth without pollution accumulation.

- It is also possible to have growth without pollution accumulation in cases where intellectual capital has public good characteristics in multi-sector models, or models with product variety. Then - under certain structures of preferences and technology - output, capital, consumption and knowledge grow without bound, while pollution decreases and environmental quality improves.

- If pollution reductions that improve environmental quality have sufficiently large positive productivity effects, then environmental policy supporting the social optimum could increase growth.

Of course the above results of sustained growth without environmental degradation hold at the social optimum, which means that - given the negative externalities associated with pollution and positive externalities associated with the aggregate stock of knowledge or human capital - a competitive equilibrium will not attain the socially-optimal solutions. This of course implies that in order to attain the social optimum, provided that it is possible given the structure of the economy, private markets should be regulated by a combination of environmental policy, such as emissions taxes or tradable permits, to mitigate the negative externality, and industrial policy such as investment subsidies, to exploit the positive externalities.

It seems therefore that the general message from this discussion is that sustained growth and environmental protection could be compatible under certain conditions. An important factor in achieving this compatibility seems to be that resources be devoted to efficient methods for pollution prevention and knowledge capital. This could be interpreted as indicating that the same growth engines that might secure sustained growth in standard growth theory could also secure sustained growth with environmental protection. Since market outcome will not achieve the social optimum, this implies that the compatibility of growth and environmental protection requires regulation of private markets.

The achievement of optimal sustained growth is also closely related to the much discussed issue of sustainability.[85] Two implications regarding sustainability could be derived from the above discussion. If a steady state for the undiscounted optimal growth exists, this corresponds to a sustainable state for the economy and the environment. Furthermore, if sustained growth without pollution accumulation is possible, this is also a sustainable state for the economy, since the environmental stock does not decline in the long run. In this sense, as Heal (2001) notes, optimal growth paths are also sustainable.

Regarding the empirical evidence, it is clear that a pollution-environment relationship is implied, irrespective of whether the economy follows optimal or suboptimal environmental policies. The empirical question is whether the pollution - environment relationship is inverted U-shaped as suggested by early empirical evidence. Although early results provided support for the EKC, recent studies seem to indicate that this relationship might not be as stable as expected.

Environmental concerns could also be important in growth accounting. It seems that if environmental policy is not optimal, then there is a deviation between the estimated Solow residual and the true Solow residual corresponding to the case where the full cost of emissions is taken into account. Further research in this area might provide some useful results.

In conclusion, quite a number of models have been developed seeking to introduce environmental considerations into growth theory and analyze the "growth - environment puzzle"; this research is certainly expected to continue, especially in the area of developing endogenous growth models embodying environmental considerations and testing the empirical pollution - growth relationship. There are undoubtedly many interesting areas for extending these models as well as many unresolved problems to be addressed. What is the impact of population growth on environmental pollution and how is this incorporated into growth models with pollution accumulation? What is the impact of nonlinearities or thresholds in the environmental system on the growth process? What are the implications of multiple equilibria and instabilities for the whole system? Could environmental instabilities imply economic instabilities and how should environmental policy be designed in this case? What is the impact of uncertainty and irreversibility?[86] Although

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[85] They is a large body of literature on this issue. See, for example, Heal (1988), Heal and Kristrom in this volume, and Dasgupta and Mäler (2000).

[86] Uncertainty is an issue of considerable interest in the environmental and resource economics literature (see Beltratti (1996), Chichilnisky, Heal and Vercelli (1998)). When dynamics are introduced, interactions between uncertainty and irreversibility and the concepts of option value and learning are of special interest. See, for example, Weisbrod

uncertainty in growth models has been examined,[87] what is the impact of uncertainty in the environmental system on growth?[88] How can a precautionary principle be defined in an operational way by modelling environmental uncertainty,[89] and how does precaution affect growth? Although the list above is far from exhaustive, it is likely that these are issues that might provide useful insights leading to a more complete approach to the growth - environment puzzle.

(1964), Arrow and Fisher (1974), Henry (1974), Fisher and Hanemann (1986, 1987), Kolstad (1996a,b), or Mäler and Fisher (this volume).

[87] See, for example, Brock and Magill (1979) or Bismut (1975).

[88] Clarke and Reed (1994) consider the impact on the economy from the occurrence of a random environmental catastrophe. Although there are models considering the impact of uncertainty on the pollution accumulation processes - without, however, explicit reference to the growth process (see for example Plourde and Yeung (1989), Xepapadeas (1992)) - there do not seem to be a large number of models that incorporate pollution accumulation uncertainty into growth models.

[89] See Brock and Xepapadeas (2003) for an attempt at this.

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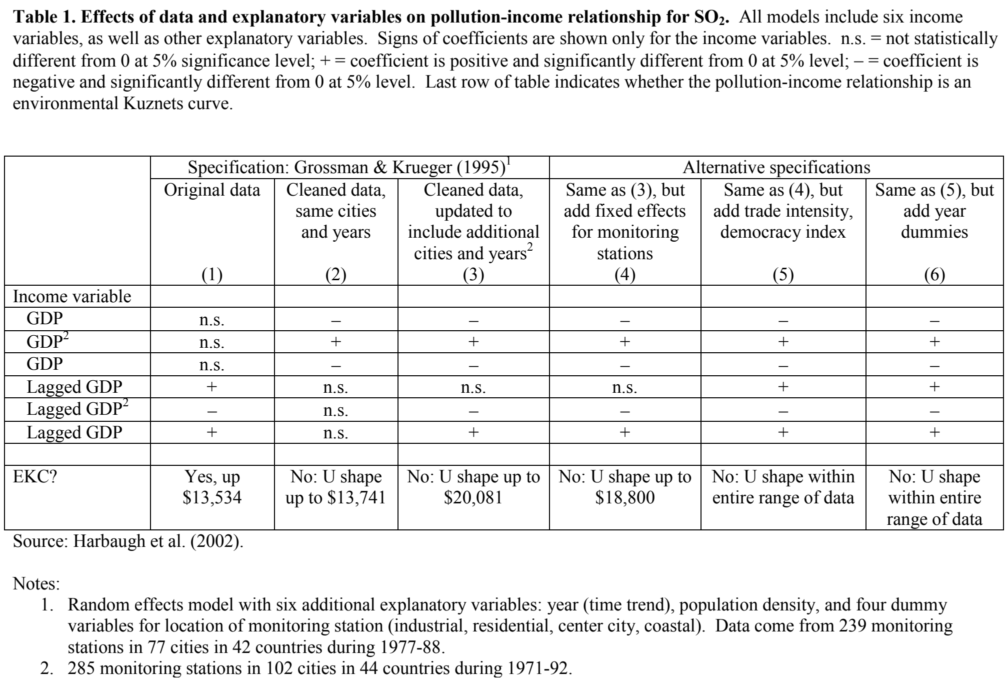

Table 1. Effects of data and explanatory variables on pollution-income relationship for SO_2. All models include six income variables, as well as other explanatory variables. Signs of coefficients are shown only for the income variables. n.s. = not statistically different from 0 at 5% significance level; + = coefficient is positive and significantly different from 0 at 5% level; – = coefficient is negative and significantly different from 0 at 5% level. Last row of table indicates whether the pollution-income relationship is an environmental Kuznets curve.

	Specification: Grossman & Krueger (1995)[1]			Alternative specifications		
	Original data (1)	Cleaned data, same cities and years (2)	Cleaned data, updated to include additional cities and years[2] (3)	Same as (3), but add fixed effects for monitoring stations (4)	Same as (4), but add trade intensity, democracy index (5)	Same as (5), but add year dummies (6)
Income variable						
GDP	n.s.	–	–	–	–	–
GDP^2	n.s.	+	+	+	+	+
GDP	n.s.	–	–	–	–	–
Lagged GDP	+	n.s.	n.s.	n.s.	+	+
Lagged GDP^2	–	n.s.	–	–	–	–
Lagged GDP	+	n.s.	+	+	+	+
EKC?	Yes, up $13,534	No: U shape up to $13,741	No: U shape up to $20,081	No: U shape up to $18,800	No: U shape within entire range of data	No: U shape within entire range of data

Source: Harbaugh et al. (2002).

Notes:

1. Random effects model with six additional explanatory variables: year (time trend), population density, and four dummy variables for location of monitoring station (industrial, residential, center city, coastal). Data come from 239 monitoring stations in 77 cities in 42 countries during 1977-88.
2. 285 monitoring stations in 102 cities in 44 countries during 1971-92.

Figure 1:

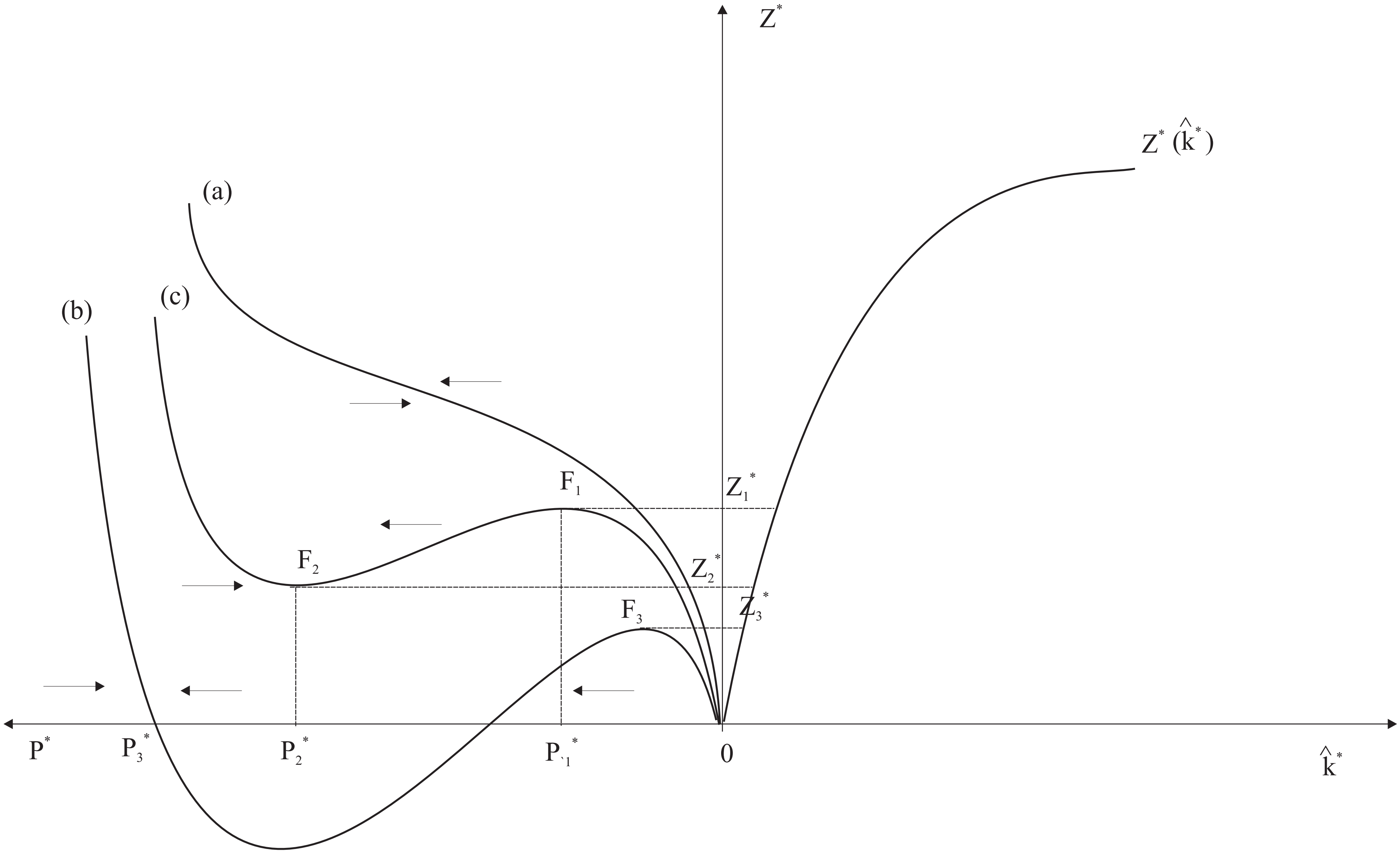

Figure 1.

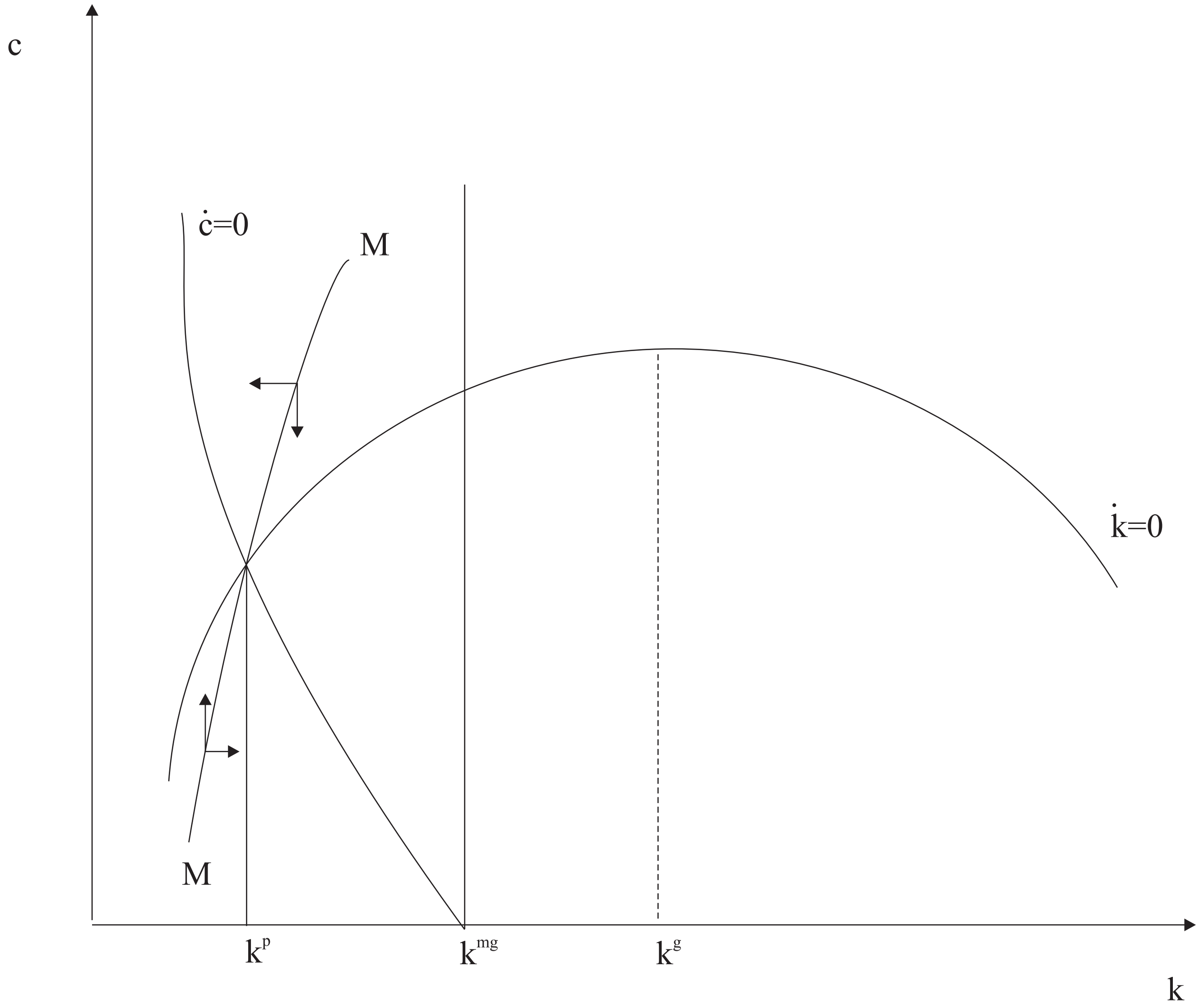

Figure 2