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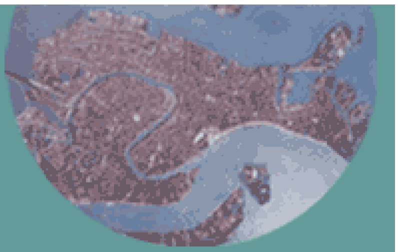

Does pollution affect economics growth?

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Abstract

The notion of *sustainable growth* has established itself as a main goal in the theoretical and political debate on the potential conflict between economic growth and environmental quality. Empirical evidence suggests that development gives rise to a structural transformation in *what* and *how* an economy produces towards cleaner activities. This work provides a new theoretical model *à la Romer* with pollution as a crucial variable and with a technological sector devoted to research in pollution-abatement programmes. Nevertheless, the only way for the economy to show a positive balanced growth is when the principles of weak sustainability are dealt with.

Keywords: Environmental quality; Endogenous economic growth; Pollution-augmenting technology.

JEL Classification: O41, Q01, Q32

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[*] I would like to thank Prof. S. Lahiri for his precious advice. Naturally, all the possible errors are only mine.

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1 Introduction

Almost all human activities directly or indirectly affect the ecological system of the Earth. Obviously, the effects on the environment become larger and more significant the more extensive is the activity of every single person, and the larger is the population. In a market economy, prices must express the scarcity of resources to guarantee an efficient allocation. However, some goods do not have a price although their availability is not unlimited in amount. This is the case for many environmental resources and can be explained by market failures caused by externalities. The non-existence of a price reflecting the scarcity of the environmental resource leads to its excessive use.

In the course of the 1970s, the concept of "limits to growth" dominated the discussion on the relationship between growth theory and environmental economics. Due to the exhaustibility of natural resources, many predicted an inevitable decrease in income for the distant future. In this debate on the limits of growth, various economic aspects did not attract enough attention. For example, in the judgement of economic theory, it is not the growth of economy itself which explains the increased pollution of the environment, but the wrong market signals which arise because of the negative externalities of certain market processes. Therefore, an internalisation of these external effects through policy instruments is an important contribution to the long-term compatibility of both environment and economy.

As one of the consequences of this counterposition, the notion of "sustainable growth" has lately established itself as a main goal in theoretical and political debate in the field of environmental economics and growth. Writers like Solow (1993) have pointed out that it would make no sense to interpret sustainable development as requiring us to leave each and every resource stock in its initial situation (Americans, for example, would be much worse off if early settlers had left the forests in their aboriginal state rather than clearing the land). Hitherto, the following definition of sustainability of the so-called "Brundtland Report" is the most widespread:

Definition 1 *A development is sustainable, if it meets the needs of the present generation without compromising the ability of future generations to meet their own needs (World Commission 1987, p. 43).*

When the term *development* is used in general, it refers to rising aggregate consumption and output but also includes aspects such as environmental quality, social factors, and the distribution of income. Thus, the utility function, which denotes the preferences of the representative agent, not only includes consumption possibilities but also environmental quality.

The potential conflict between economic growth and environmental quality was a prominent source of contention at the United Nations Conference on Environment and Development (the "Earth Summit") in Rio de Janeiro in June 1992. Developed countries, now coming to terms with the environmentally profligate policies of the past, are currently concerned about the long-run effects of global environmental degradation, whilst developing countries, concerned more with survival than greenery, seek faster growth.

The evidence on possible trade-offs between growth and environmental quality invites careful analysis. Cross-sectional studies by the World Bank suggest that some environmental problems, such as water pollution and sanitation, are most severe at low income levels, while others, such as emission of greenhouse gases, are worst in high income countries (see World Bank 1992). Perhaps most interestingly, air pollution seems to be worst in middle income countries.

The environment offers a great diversity of services to the human being:

- as a consumption good, for example, in the form of air to breathe, space for recovery and natural beauty;
- as a supplier of resources, for example water, sun, oil;
- as a recipient for waste: in the atmosphere, on the land, in the water, and so on;
- as a geographical location for economic activities.

Exhaustible and renewable natural resources serve as inputs into the production of many goods and services. If the composition of output and the methods of production were immutable, then damage to the environment would be inextricably linked to the scale of global economic activity. But substantial evidence suggests that development gives rise to a structural transformation in what an economy produces. In principle, the forces leading to a change in the composition and techniques of production may be sufficiently strong to more than offset the adverse effects of an increased economic activity on the environment.

The aim of this work is to provide an overview of the recent economic literature, concerning environmental issues and growth theory. Moreover — following Aghion-Howitt (1998) — I develop a new model *à la Romer* with pollution as a crucial variable and with a technological sector devoted to research in pollution-abatement activities. Conclusion to this analysis says that pollution, i.e. the use of “dirty” production processes, matters for growth. Nevertheless, it is shown that for a sustainable balanced growth path to be reached, it is necessary to relax the axiom of strong sustainability.

2 The problem of Sustainability

The link between environmental policy and economic growth is a controversial issue. Industrialists typically argue that environmental policy hurts capital accumulation and growth by raising abatement costs. Environmentalists, in contrast, maintain that environmental policy is needed to ensure that growth is sustainable. In order to investigate the connection between environmental quality and growth, many economists have developed models in which economic activity depends on the extractive use of natural environment, which is modelled as a renewable resource.

Although concerns about the long-run consequences of economic growth on the environment goes back much longer, dynamic models that specifically formalise the impact of growth on nature were not formalised before the early 1970s. Inspired by the work of the Club of Rome[1] and its pessimistic view on the scope for long-run growth under environmental constraints, these models were designed to depict the conflict between growth and environment. Over time the variety of models grew rapidly, differing not only with respect to the basic growth models adopted but also with respect to the types of environmental resources considered and the problems analysed.

Most of this literature assumes that technological progress is exogenous and thus not affected by environmental policy (see Tahvonen and Kuuluvainen, 1993). The experience of industrial countries, however, suggests that tighter environmental policies induce major technological advances in abatement technologies. Indeed, technological progress improving the productivity of natural resources plays a crucial role in relating sustained growth with a constant level of environmental quality. This different framework analyses the link between environmental quality and economic growth in the endogenous growth models that incorporate endogenous technological change. It examines the conditions under which sustainable growth is both feasible and optimal, as well as it establishes the conditions for a more ambitious environmental policy to raise long-run growth.

Ecological economists often doubt that sustainable growth is practically feasible, by questioning that humans have the capacity to sustain accelerating

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[1] The Club of Rome is a centre of innovation and initiative. As a non-profit, non governmental organisation (NGO), it brings together scientists, economists, businessmen, international high civil servants, heads of state and former heads of state from all five continents who are convinced that the future of humankind is not determined once and for all and that each human being can contribute to the improvement of our societies.

technical change. However, following the historical trend and acknowledging that the potential for technical progress might be beyond our current imagination, the prediction of limits to resource intensities is not an easy task.

The reason for this profound difference lies in the interpretation of the term *growth*. If someone argues that growth must be seen only in physical sense (quantitative growth), some others consider also the capabilities of humans to extract more and more value from a constant or even declining amount of natural resources due to technological progress and accumulation of knowledge (qualitative growth).[2]

This contrast can be also explained by means of two other concepts that dominate the discussion: weak and strong sustainability.

- **Definition 2** *Weak sustainability requires that the amount of natural capital necessary for the life-supporting system of the earth is non-decreasing, and the sum of man-made and non-critical natural capital is constant (Pearce and Turner, 1990).*

This definition has a tight rule for the use of critical, non-substitutable natural capital, but it allows some substitution between non-critical natural and man-made capital. The rule does not explicitly limit the scale of the economy but it facilitates the adjustment of economic growth towards an ecological direction.

- **Definition 3** *Strong sustainability, on the other hand, emphasises that natural capital cannot be sustained by other forms of capital. That is the amount of critical and non-critical natural capital is constant and the amount of man-made capital is non-decreasing (Turner et al., 1994).*

This formulation has, however, some logical problems. Even though it makes the distinction between critical and non-critical natural capital, it requires that non-critical capital must be non-decreasing. For example, suppose a non renewable resource. In order to allow its use, some substitution must be accepted or one is not allowed to use it at all. Thus, this formulation of strong sustainability fails to be meaningful despite its good intention.

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[2] Limits to growth can be deduced from the laws of thermodynamics (Georgescu-Roegen, 1971). Nevertheless, while quantitative growth is inevitably bounded, limits to growth in value do not have to exist.

3 Pollution and Growth: some empirics

A key question then is whether or not continued environmental degradation is a necessary part of the process of industrialisation. Will pollution continue to increase without bound as more and more countries pass through the development phase or will it be controlled? Intuitively, if "clean air" is a normal good, we would expect that societies might be *self-regulating* in the sense that as income increases, pollution controls also increase. However, this intuition is somewhat misleading as the presence of external effects is an essential feature of environmental regulation. Although there is a large literature on the relationship between economic activity and the environment, there are few papers that explicitly model the relationship between growth and environmental degradation. For example, in the endogenous growth literature there are papers which model the environment as an additional factor of production and concentrate on the impact of different criteria that a planner might choose to "allocate" this environmental input between households and firms (see Mohtadi, 1996). Some others assume that the stock of pollution is nonlinearly related to the stock of capital

$$P = K^{\beta} e^{-\gamma K}$$

Such a specification is interpretable as a reduced form for modelling the impact of technical change of the pollution-output ratio (see Beltratti, 1996).

As shown in Fig. 1, for certain values of β and γ one can describe an economy in which at low levels of capital an increase in capital also increases pollution, whilst at high levels the reverse happens, due to positive technological effects. This can result from a process of economic growth characterised by structural modifications like the building of public infrastructures that reduce substantially the impact of economic growth on the environment.

One of the main contributions of the recent economic literature is due to Grossman and Krueger (1995) that investigate the relationship between the scale of economic activity and environmental quality for a broad set of environmental indicators. They attempt to include in their study all of the dimensions of environmental quality for which comparable measurements have been taken in different countries. To this end, they use all of the available panel data in the Global Environmental Monitoring System (GEMS) concerning the urban air quality in different cities in the developed and developing world, and the water quality in river basins around the globe.

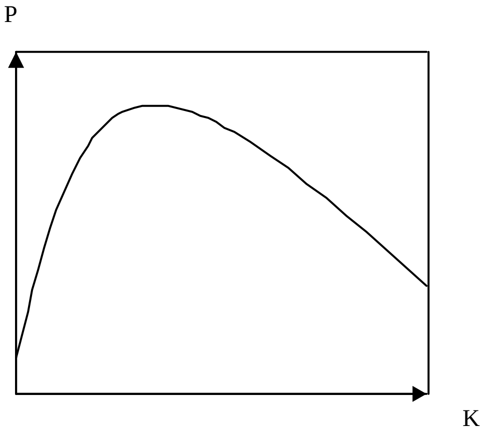

Figure 1: Pollution function

To study the relationship between pollution and growth, they estimate several reduced-form equations that relate the level of pollution in a location (air or water) to a function of the current and lagged income per capita in the country and to other covariates. Specifically, they estimate

$$Y_{it} = G_{it}\beta_1 + G_{it}^2\beta_2 + G_{it}^3\beta_3 + \overline{G}_{it-}\beta_4 + \overline{G}_{it-}^2\beta_5 + \overline{G}_{it-}^3\beta_6 + X_{it}\beta_7 + \epsilon_{it}$$

where Y_{it} is a measure of water or air pollution in station i in year t, G_{it} is GDP per capita in year t in the country in which station i is located, $\overline{G}_{it-}$ is the average GDP per capita over the prior three years, X_{it} is a vector of other covariates, and ϵ_{it} is an error term. The β's are parameters to be estimated.

If there are any characteristics of the monitoring sites that influence pollution but are not included in the list of independent variables, this will induce a temporal correlation in the error term, ϵ_{it}. To account for this, they estimate the previous equation by generalised least squares (GLS).

They find little evidence that environmental quality deteriorates steadily with economic growth. Rather, they find for most indicators that economic growth brings an initial phase of deterioration followed by a subsequent phase of improvement, probably due to an increased demand for (and supply of) environmental protection at higher levels of national income. The turning points for the different pollutants vary, but in most cases they occur before a country reaches a per capita income of $8000. The state of the environment may deteriorate with time if concentrations of pollutants accumulate or if consumer tastes shift towards pollution-intensive goods. The opposite may occur if technological innovation makes abatement less costly or if increasing awareness causes an autonomous shift in public demands for environmental safeguards.

Conclusions to this analysis say that, contrary to the alarmist cries of some environmental groups, there is no evidence that economic growth does unavoidable damage the natural habitat. Instead one can find that while increases in GDP may be associated with worsening environmental conditions in very poor countries, air and water quality appear to benefit from economic growth once the critical level of income has been reached.

As nations or regions experience greater prosperity, their citizens demand that more attention be paid to the noneconomic aspects of their living conditions. The richer countries which tend to have relatively cleaner urban air and river basins, also have relatively more stringent environmental standards and stricter enforcement of their environmental laws than the middle-income and poorer countries, many of which still have pressing environmental problems to address. Secondly, it is possible that downward sloping and inverted U-shaped patterns might arise because, as countries develop, they cease to produce certain pollution-intensive goods, and begin instead to import these products from other countries with less restrictive environmental protection laws. If this is the main explanation for the (eventual) inverse relationship between a country's income and pollution, then future development patterns could not mimic those of the past. Developing countries will not always be able to find still poorer countries to serve as havens for the production of pollution-intensive goods. However, the available evidence does not support the hypothesis that cross-country differences in environmental standards are an important determinant of the global pattern of international trade. Despite some forms of "environmental dumping" undoubtedly take place, the volume of such trade is probably too small to imply that the reduced pollution that has been observed does affect economic growth.

The less developed countries of today have a unique opportunity to learn from this history and thereby avoid some of the mistakes of earlier growth experiences. With the increased awareness of environmental problems and the development in recent years of new technologies that are cleaner than ever before, we might hope to see the low-income countries turn their attention to preservation of the environment at earlier stages of development than has previously been the case.

To summarise, empirical analysis on aggregate resource use indicates that declines in resource intensities may be overcompensated by increases in GDP. With respect to the relation between per capita growth and pollution, evidence was found for a bell-shaped relation between income and some air and water pollution indicators (environmental Kuznet's curve=EKC): pollution per capita increases for low income levels, but with rising income these increases become smaller until per capita pollution finally decreases. The income level for which per capita pollution is predicted to start falling, however, vary considerably not only over the respective pollutants, but also over the different studies.

Deducing from the EKC that income growth will automatically contribute to a relief of the environmental problems faced is however problematic:

- empirical evidence that other pollutants also follow bell-shaped paths is often either lacking or at best ambiguous, (accumulation of wastes, deterioration of resource stocks, CO_2 emissions), as shown in fig. 2;
- in many countries per capita income is still well below the predicted turning points, such that world-wide pollution intensities and levels might continue to rise over extended time periods;
- decreasing concentrations of specific pollutants in high income countries do not have to imply that aggregate pollution also decreases. Economic growth might lead to changes in output patterns that are associated with shifts to other pollutants. Or, increased environmental regulation in high-income countries might induce migration of pollution-intensive industries to low-income countries.

Finally, sustainable economic growth is theoretically feasible if it is of a qualitative and not quantitative nature. It requires that no upper limit to knowledge accumulation and no lower limit to resource intensities exist and that the market mechanism provides the necessary incentives to overcome natural resource scarcities.

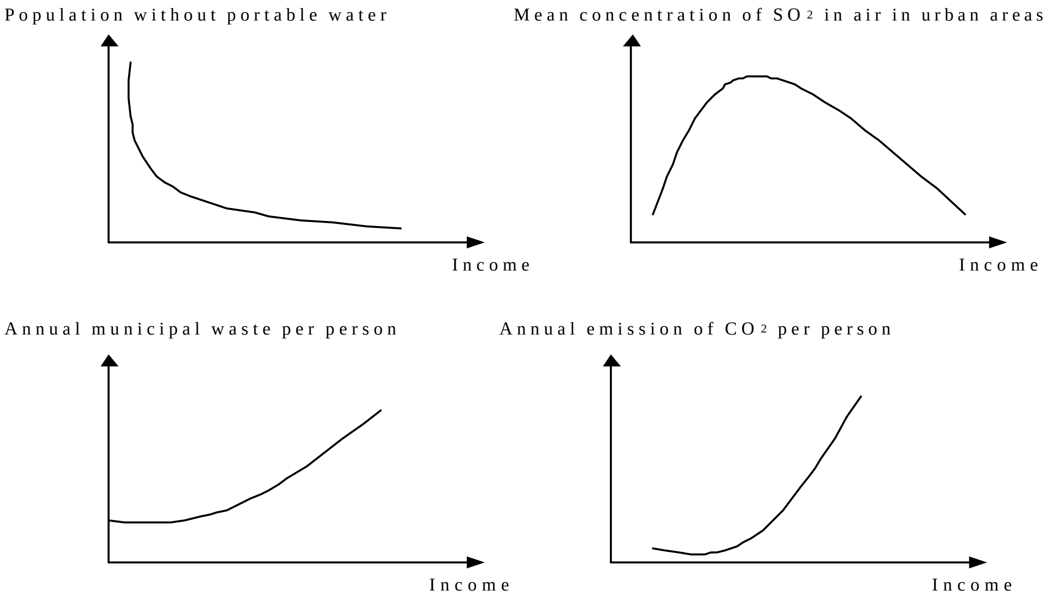

Figure 2: Shape of pollutants

4 A new model

The bulk of literature on environmental economics uses static models. This simplification may be justified for some problems. However, the dynamic dimension is central for many environmental issues. Since pollutants accumulate over time, and many natural resources are exhaustible through overuse, environmental policy measures inevitably affect several generations. Furthermore, economic growth and environmental quality affect each other mutually. On the other hand, economic growth may increase pollution and exacerbate environmental degradation. However, this trade-off is not necessarily trivial, as emissions per output may change due to structural changes, new resource-saving technologies, and innovation in abatement technologies.

Following Aghion-Howitt (1998), I propose a new endogenous growth model close to Romer (1990), with introduction of pollution amongst the choice variables (because of its distortions on productions), and where a technological sector is devoted to finding less polluting productions and abatement activities. I focus on social planner's maximisation problem but next step is to analyse the decentralised behaviour.

4.1 Technology

Knowledge, according to Romer (1990), can be classified into two major components. The first component, which may be broadly defined as *human capital*, is person-specific. It constitutes a "rival good" in the sense that its use by one firm precludes its use by another. The second component, to be referred to as *technology*, is generally available to the public. It is a "nonrival good" in the sense that its use by one firm does not limit its use by others. Therefore, the person who invests in accumulation of human capital receives the rewards arising therefrom. In contrast, the nonrivalry feature of technology implies knowledge spillovers, such that the discoverer of new technology will not be the sole beneficiary of that discovery. The inability of the discoverer to reap all the benefits creates an economic externality that causes private efforts at technological improvement to fall short of what is socially optimal.

Both human capital and technology are created by conscious actions. To reduce the number of state variables, however, human capital is simply assumed to be fixed and inelastically supplied, although its allocation to different uses is still to be endogenously determined.

Consider S_0 as the fixed amount of skilled labour, which can be devoted to production of the final good, S_Y, or to improvement of technology, S_A. Thus, we have

$$S_0 = S_Y + S_A \tag{1}$$

where technology A is not fixed. It can be created by engaging human capital in research, i.e. abatement activities or less polluting productions, growing over time

$$\dot{A} = \gamma S_A A \tag{2}$$

Consequently, technological growth rate is given by

$$\frac{\dot{A}}{A} = \gamma S_A \tag{2.a}$$

and γ is the research success parameter.[3] Note that $\dot{A}/A = \gamma S_A > 0$ as long as both γ and S_A are positive. Thus, technology can grow without bound. Note also that research activity is assumed to be human-capital-intensive and technology-intensive, with no capital (K) and ordinary unskilled labour (L) engaged in that activity.

In the production of the final good Y, however, K and L do enter as inputs along with human capital S_Y and technology A.[4] According to the assumptions made by Aghion and Howitt (1998), the main feature of this economy is that production is also affected by another variable indicating the "intensity of pollution", $z(t) \in [0,1]$, such that higher values of z yield more of the good but also more pollution

$$Y = \psi A^{\alpha+\beta} (S_0 - S_A)^{\alpha} K^{1-\alpha-\beta} z \tag{3}$$

where $\psi = \eta^{\alpha+\beta-1}$, and the amount of unskilled labour force is normalised to unity ($L = 1$).[5] Let us consider z as a measure of "dirtiness" of the

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[3] It is assumed that technology does not depreciate.

[4] Remember that in Romer (1990) technology is assumed to be made up of an infinite set of "designs" for capital, which (for simplicity) enter the production function in an additively separable manner, given by

$$Y = (S_Y A)^{\alpha} (LA)^{\beta} K^{1-\alpha-\beta} \eta^{\alpha+\beta-1} \qquad 0 < \alpha, \beta < 1$$

where η represents the units of capital goods to produce one unit of any type of design.

[5] This production function exhibits constant returns to scale at a disaggregate level because each firm takes z as given. On the contrary, a social planner can internalise this kind of externality, due to pollution intensity, thus obtaining increasing returns.

existing technique. For example, focus on cheese manufacturing. Only a fraction of the raw milk processed gives rise to white cheese (or other diary products), the remaining is called whey, a liquid by-product which constitutes the greater part of the resulting pollution loads.

It is also assumed that the flow of pollution P is proportional to the level of production, and that the use of cleaner technologies (which means low values of z) reduces the pollution/output ratio[6]

$$P = Yz^{\gamma} \tag{4}$$

Therefore, P depends also on the parameter expressing research success in abatement emissions, γ; that is the bigger γ-values the smaller the impact of “dirty” techniques on pollution, and then the cleaner the eco-system.

The level of investment is given by the usual functional form $\dot{K} = Y - C$.

4.2 Environment

Finally, we have to consider the environmental sector which is represented by the dynamics of the environmental quality indicator E.

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

The extractive use of natural resources in production Z diminishes environmental quality (or alternatively the stock of natural resources). $N(E)$ determines the speed at which nature regenerates.[7] This stock is constantly reduced not only by economic activities, but also by non-anthropogenic processes, such that ecosystems have to devote part of their regeneration capacity to the maintenance of their own structure.

If the capacity for regeneration exceeds the requirements for maintenance, $N(E)$ becomes positive. $N(E)$ can therefore be interpreted as the difference between natural resource reproduction and resource use for maintenance (Smulders, 1995a) that determines nature’s capacity to recuperate from pollution and resource extraction.

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[6] The extractive use of the environment in production can either be modelled as an input to production or, like here, as a by-product of production; that is, pollution influences output indirectly.

[7] While in my reference model the environmental sector is depicted by a renewable resource stock which serves as an indicator for environmental quality, other strands of literature deal with exhaustible resources or flows and stocks of pollution.

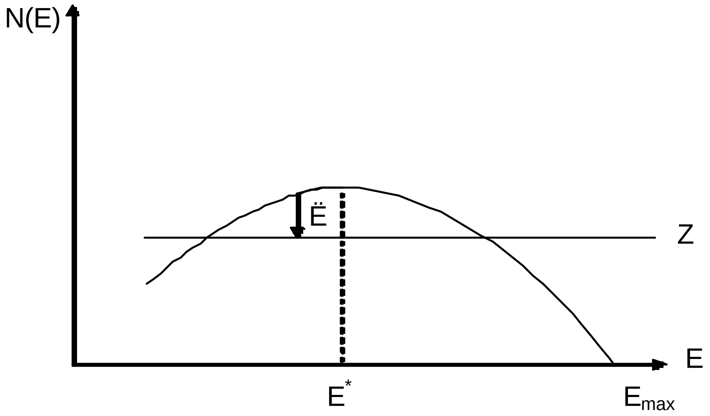

Figure 3: Environment Dynamics

A representation of equation (5) is drawn in figure 2.

Mostly, $N(E)$ is assumed to be strictly concave ($N_{EE} < 0$) and of an inverted U-shape ($N_E > 0$ for $E < E^*$ and $N_E < 0$ for $E > E^*$). This type of regeneration function was originally adopted to describe the population dynamics of fish stocks and other renewable resources (Scott, 1957) and was later applied to the analysis of aggregate stocks of natural resources (Smith, 1968). A justification for this application follows from physics and is provided by Bovenberg-Smulders (1996). They point out that the constant inflow of solar energy constitutes the upper limit to energy available for regeneration processes in the long run. It follows from the entropy law that regeneration is subject to diminishing returns. But maintenance of ecosystems requires a more or less proportional share of aggregate resources. As a consequence the regeneration capacity available for economic processes reduces with increasing E until the maximum sustainable level of environmental quality is reached ($E_{\max}$), the *virgin state* of the environment, which is only attainable in the absence of any anthropogenic depletion process. Extractive use of the environment lowers the maximal sustainable level of E.

Some approaches incorporate a simple form of irreversibility by assuming the existence of a minimum level of environmental quality $E_{\min}$ that can be sustained by natural regeneration process. If the degradation of the environment is too severe and E falls below $E_{\min}$, an irreversible degeneration process is assumed to start.

Environmental quality is constant over time if the extraction of resources equals the regeneration capacity of the environment ($Z = N(E)$). It can be shown that for this type of regeneration function balanced growth is only feasible if environmental quality is constant over time (see Musu, 1995).

Of the two equilibria ($\dot{E} = 0$) associated with every level of resource extraction below $N(E^*)$, only the equilibrium on the negatively sloped arm of $N(E)$ is stable. Any deviation from equilibrium level on the positively sloped arm either leads to a continuous improvement of environmental quality or induces increasing negative net rates of regeneration (e.g., Bovenberg-Smulders, 1995).

For algebraic simplicity some authors (see Musu, 1995) use a linear representation of the regeneration function

$$N(E) = \theta E$$

where θ denotes the constant rate of regeneration. Although this function is less well fitted to the empirical data, Rosendahl (1996) argues that it provides a reasonable approximation if only the positively sloped arm of the hump-shaped regeneration function is of interest. As an example, he refers to the case of developing countries in which the degradation of the environment is already advanced. Therefore, the advantage of the strictly concave specification, the constitution of an upper limit for environmental quality, is lost if the above linear specification is used.

Following the argument of Rosendahl, it is useful to take an approximation for the development of nature along the negatively sloped arm of the hump-shaped function

We can assume, as Aghion and Howitt (1998) did before, that there is also a finite lower limit below which environmental quality cannot fall without causing an irreversible deterioration with prohibitive social abatement costs.[8] It is assumed that E is depleted over time by pollution, but that it also has its own regenerative capacities (see Forster, 1980). Formally, the law of motion

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[8] Aghion and Howitt (1998) define the environment, E, as a capital good that can be measured as the difference between the actual environmental quality and its upper regeneration limit, such that E is constrained to be negative:

$$E^{\min} \leq E \leq 0 \qquad \text{for all } t$$

of E takes the form

$$\dot{E} = -P - \theta E \tag{6}$$

where $\theta > 0$ represents the maximal potential rate of regeneration of the environment (see Tahvonen and Kuuluvainen, 1991). E is defined to be non-positive and $E = 0$ represents the virgin state of nature. In contrast to the linear regeneration function, environmental quality cannot grow without bound under this specification, because environmental quality decreases when nature approaches the virgin state.[9]

4.3 Preferences

We can assume that preferences of the representative consumer are concerned not only with the level of optimal consumption but also with the quality of the environment available in the economy.[10] The intertemporal utility function is given by

$$\int_0^\infty U(C_t, E_t)e^{-\delta t}dt$$

where utility U is a function of C_t, consumption of man-made goods, and E_t, which represents the *stock* of natural resources or some indicator of environmental *quality*.[11] Future utility is discounted at rate δ.[12]

$U(\cdot)$ is continuous, twice differentiable, and possesses the following properties: $U_C > 0$, $U_E > 0$, U_{CC} □ 0. Also suppose that the $U(\cdot)$ is concave with respect to its two arguments: $U_{CC} \cdot U_{EE} - (U_{CE})^2 \geq 0$.

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[9] Solution to the model will show, using equation (4) and (6), that the law of motion of environmental quality becomes

$$\dot{E} = -Yz^{\gamma} - \theta E$$

and by substituting out equation (3), we derive the constraint to be used in the maximisation problem.

[10] One interpretation would be forests, which contribute to welfare both as sources of timber and also as stocks which provide many ecosystem services to society (for example, carbon's sequestration, preservation of bio-diversity).

[11] For simplicity, time subscripts will be omitted in the rest of the paper.

[12] There are various ways to describing utility funtions depending on the constancy or not of environmental quality (see King et al., 1988; Hofkes, 1996; Smulders, 1998; Aghion-Howitt, 1998; Grimaud, 1999).

Theoretically, sustainable development usually comprises two conditions. Firstly, non-decreasing consumption or utility levels (sustainable economic development) and secondly, a constant or improving state of the environment. Whether sustainable development in this sense can be optimal, depends on the functional form of utility function.

For balanced growth to be optimal, when consumption and environmental quality enter the utility function, two conditions have to hold. The intertemporal substitution elasticity of consumption has to be constant and the elasticity of substitution between consumption and environmental quality has to be unity along the balanced path (Smulders-Gradus, 1996). To this end, let us define

$$\phi\left(C,E\right)=\frac{E\cdot U_E}{C\cdot U_C} \tag{7}$$

as the ratio of the values of environmental quality and consumption, both evaluated at their marginal utilities. That is, $\phi\left(\cdot\right)$ reflects the "relative preference for the environment" of the representative agent.

Hence, we can adopt a specific constant-elasticity utility function, which contains two substitutable arguments, C and E, given by

$$U(C,E)=\frac{\left(CE\right)^{1-\sigma}}{1-\sigma}$$

with the useful properties of unitarian "green preferences", $\phi=1$.

4.4 Planner's solution

Social planner has to solve the following maximisation problem

$$\text{Maximise} \qquad \int_0^{\infty}\frac{\left(CE\right)^{1-\sigma}}{1-\sigma}e^{-\delta t}dt$$

$$\text{subject to} \qquad \begin{aligned}\dot{K} &= \psi A^{\alpha+\beta}\left(S_0-S_A\right)^{\alpha}K^{1-\alpha-\beta}z-C\\ \dot{A} &= \rho S_A A\\ \dot{E} &= -\psi A^{\alpha+\beta}\left(S_0-S_A\right)^{\alpha}K^{1-\alpha-\beta}z^{1+\gamma}-\theta E\end{aligned}$$

$$\text{and} \qquad A\left(0\right)=A_0 \quad K(0)=K_0 \quad E^{\min}\ \square\ E\ \square\ 0$$

From the first order conditions, we can derive[13]

$$\frac{\dot{\lambda}}{\lambda} = -\sigma\frac{\dot{C}}{C} + (1-\sigma)\frac{\dot{E}}{E} \tag{8}$$

and

$$\lambda = \mu\,(1+\gamma)\,z^{\gamma} \tag{9}$$

Questions of interest include: what is the rate of growth in the steady state? How is the growth rate affected by the various parameters? Does pollution affect the rate of growth of the economy? What economic policies can be pursued to promote growth? We can focus the discussion on the properties of the balanced growth equilibrium inherent in the model. The basic feature of such a steady state is that the variables Y, K, C, and A all grow at the same rate. Thus, we should have

$$g = \frac{\dot{K}}{K} = \frac{\dot{C}}{C} = \frac{\dot{Y}}{Y} = \frac{\dot{A}}{A} = \gamma S_A \tag{10}$$

But from expression (4) we can derive

$$\frac{\dot{P}}{P} = \frac{\dot{Y}}{Y} + \gamma\frac{\dot{z}}{z} \tag{11}$$

Moreover, from function (3) follows

$$\frac{\dot{Y}}{Y} = (\alpha+\beta)\,\frac{\dot{A}}{A} + (1-\alpha-\beta)\,\frac{\dot{K}}{K} + \frac{\dot{z}}{z} \tag{12}$$

which clearly implies that the intensity of pollution, z, must be held constant over time (i.e. its growth rate is zero): at some value called ω. Again from relation (4), this means that pollution must grow at the same rate at which the economy grows itself, g.

Another strong result follows consequently. It can be derived, from equation (6), that the dynamic behaviour of E follows the same path as P. In other words, environmental quality and pollution grow at the same rate,

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[13] Appendix A derives the optimality conditions, which will be discussed in the rest of this section.

or better, natural resource use reduces at the same rate at which pollution increases, since we have constrained E to be negative.[14]

Now, from the law of motion of the costate variable, μ (the shadow price of environmental quality), we obtain

$$\frac{\dot{\mu}}{\mu} = -\frac{C^{1-\sigma}E^{-\sigma}}{\mu} + \theta + \delta = -\frac{U_E}{U_C}(1+\gamma)\omega^{\gamma} + \theta + \delta \tag{13}$$

Furthermore, we can derive that the marginal rate of substitution between environment and consumption (both growing at the same rate, g) is constant

$$MRS_{E,C} = \frac{U_E}{U_C} = \frac{C_t}{E_t} = \frac{C_0 e^{gt}}{E_0 e^{gt}} = \frac{C_0}{E_0} = \varepsilon \tag{13a}$$

such that equation (13), finally, becomes

$$\frac{\dot{\mu}}{\mu} = -\varepsilon(1+\gamma)\omega^{\gamma} + (\theta + \delta) \tag{14}$$

4.4.1 Strong sustainability

We can define now a sustainable economy, or better a strong sustainable growth, as an economy or growth path in which the stock of the environmental asset is constant (which also means that $\dot{E} = 0$), and consequently from (6) follows $\dot{P}/P = 0$, such that there is no more space for new polluting activities (see Musu, 1995). But we have shown before that in balance growth, output, Y, must grow at the same rate as P. Unfortunately, the consequence

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[14] By dividing both sides of equation (6), and rearranging, we obtain

$$\frac{\dot{E}}{E} + \theta = -\frac{P}{E}$$

Since E is constrained to be negative, both sides are clearly positive. Specifically, the left hand side is constant, because either environmental quality is assumed to grow constantly over time, or Nature regenerates at the constant rate, θ. Hence, applying logarithms to both sides of this equation, we can derive the following equality condition

$$\frac{\dot{P}}{P} = \frac{\dot{E}}{E} = g$$

is that the only way for this economy to lie in a path of balanced growth is when all the growth rates equal zero, and there is no growth in the system.

Conclusion to this approach says that with a strong vision of total preservation of the environment, economy will replicate itself forever, at a virgin state of nature, with no pollution, and no need of workers devoted to abatement research. This situation might simply represent a pre-industrial framework, which is out of our analysis.

4.4.2 Weak sustainability

Aghion and Howitt (1998) found that unlimited growth can indeed be sustained, when account is taken of environmental resources use and innovations in abatement activities. A similar solution can be explained by the different approach used here. The assumption of weak sustainability permits to overcome environmental constraints, by considering Nature as a part of the total amount of capital, which is held constant. Thus, natural capital and physical capital are good substitutes, thanks to technological progress that allows agents to extract more and more values from a declining amount of natural resources.

Here it is shown that — under this weak approach — sustained growth is always attainable, by assuming the non constancy of environmental quality, E.

As noted before, for a constant z at some critical value ω, output, Y, as well as consumption, C, and pollution, P, and consequently E, must all grow at the same rate g, thus changing condition (8) into

$$\frac{\dot{\lambda}}{\lambda} = (1 - 2\sigma)g \tag{15}$$

It can be shown also that all shadow prices (the costate variables λ, μ, and ϑ) have the same value. This allows us to derive the growth rate of the economy, as a function of all parameters, by equating equations (14) and (15), thus obtaining

$$g = \frac{\varepsilon(1+\gamma)\omega^{\gamma} - \theta - \delta}{2\sigma - 1} \tag{16}$$

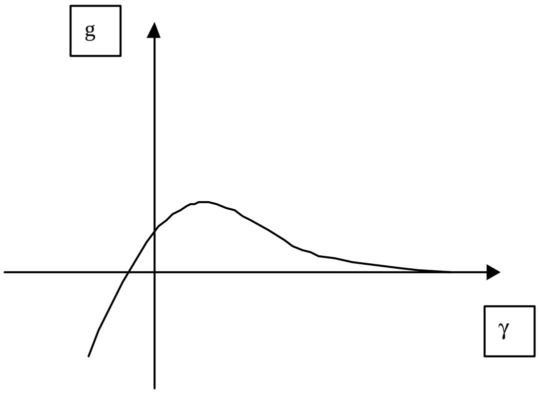

Figure 4: Growth rate properties

which is positive only for a "dirtiness" threshold given by $\omega > \left[\frac{\theta+\delta}{\varepsilon(1+\gamma)}\right]^{\frac{1}{\gamma}}$, and mainly for $\sigma > \frac{1}{2}$.[15]

Graphic representation of equation (16) is possible by considering g as a function of parameter γ, which can be interpreted as the degree at which "dirty" production techniques generate the flow of pollution, P, in the ecosystem (i.e. the larger is γ the smaller is P). But a too large value of γ leads the growth rate towards zero. We can conclude that the bigger is the amount of polluting emissions the larger is the growth rate of the economy, despite the presence of a research sector devoted towards abatements.

A possible solution to this trade-off could be that governments subsidise the implementation of clean production techniques, thus shifting the drawn curve towards right, and allowing the system to reach a positive balanced growth rate with a low level of pollution and a large degree of research developments either.

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[15] The higher σ, the less willing households are to accept deviations from a uniform pattern of consumption over time (See Barro and Sala-i-Martin, 1995).

Stokey (1998) found condition $\sigma > 1$ to be necessary, in a model with exogenous technological progress, for the existence of an optimal balanced growth path with environmental quality bounded below. Nonetheless, this assumption can be found also in Aghion-Howitt (1998).

5 Concluding remarks

Sustainability is a world-wide political aim. Moreover, the state of the environment and economic growth are both largely influenced by the economic relations amongst world regions. Thus the combination of dynamics, trade and the environment is a promising field for further economic research. Many results of growth theory are valid only for closed economies. By opening these systems, one should try to confirm, reject or refine these model outcomes. In many cases, results on the closed economy are expected to be confirmed as free trade, under appropriate conditions, leads to a more efficient allocation of resources.

The impact of international know-how transfers requires more careful study. Moreover, a more subtle analysis (for example, the dynamic consequences of the international joint implementation of environmental policy) should be a focus in future research. Finally, more empirical results on the relation amongst environmental policy, natural resource use and growth in open economies are highly desirable.

With the global orientation towards sustainability, we can note that less developed countries have a comparative advantage in the supply of natural resources. Expenditure for protection of the environment is smaller in less developed countries, and benefits are substantial for everybody, even industrialised ones. Through international compensation for services to protect the environment, resulting income transfer acts as a stimulus to development of lower income countries. When additional knowledge transfers are added, Third World countries are better equipped to realise a sustainable development under these new circumstances.

In particular, the environment acts as a sink for wastes generated by economic activities and a source of natural inputs into production. Moreover, as a public consumption good, the environment yields amenities. Finally, it constitutes a life support system: environmental quality determines the capacity of nature to grow, and affects living and working conditions. Therefore, environmental quality acts as a public production factor by enhancing the productivity of man-made inputs into production. Indeed, empirical evidence suggests that pollution causes serious productivity losses. Despite this evidence, most studies dealing with the impact of environmental policy on growth ignore the adverse effect of pollution on productivity.

This work has analysed the main economic literature concerned with the field of environmental economics. In particular, I focused the attention on those papers that provide a link between pollution and economic growth. Many economists disagree with the assumption that pollution matters for growth, whilst others believe that economies are undoubtedly influenced by polluting processes, depending on the type of natural resources taken into account (for example, exhaustible and non renewable).

Finally, I have developed a new model which considers pollution as a choice variable, entering the production function as a measure of *dirtiness*. The analysis shows that high levels of this externality increase both output and pollution. However, the crucial feature of this model is the existence of a sector devoted to research in pollution-abatement technologies. This is consistent with the empirical evidence that developed societies seek less polluted environment.

Conclusions to this model say that for a sustainable and positive balanced growth path to be guaranteed the principle of weak sustainability must be taken into account. This implies that constraints to the use of natural resource are less stringent, since the existence of a technological sector enhances cleaner production techniques.

My reference model — Aghion-Howitt (1998) — examines the problem of sustainable growth in a Schumpeterian framework, and in presence of pollution. It shows that under certain conditions a sustained growth is attainable. The main difference with my analysis regards the definition of a non-separable utility function where consumption and environment are good substitutes. Particularly, I focus on the balanced growth path as defined in Romer (1990), with output and technology growing at the same rate.

While Aghion-Howitt (1998) demonstrates that z (intensity of pollution) must decrease over time to lead positive economic growth, here it is shown that for balanced growth to be reached it is necessary that pollution grow at the same rate as output, and that the level of dirtiness, z, be maintained constant over time (i.e. zero growth rate). Therefore, economy grows only at the expenses of a polluted environment despite the presence of a research sector in cleaner technologies.

It seems to be interpreted as pollution is a necessary part of production and economic growth with no care about possible abatement opportunities.

The analysis has uncovered the critical question of what policies might implement the optimal sustainable growth path. To find out how the balanced growth path is reached in the long run, it could be useful to simulate numerically the short- and medium-term economic performances along the transition path after a change in environmental policy, calibrating the model so as to capture stylised empirical facts of industrialised countries. The fact is that the most widely raised ecological problems nowadays are ones involving open-access common property resources, such as the depletion of the ozone layer and the emission of greenhouse gases, and this suggests that the implementation of a sustainable growth policy will require new institutions of international cooperation, so that we can achieve with the global environment what many advanced industrial countries seem now to be achieving with their local environments.

A Appendix

- The current value Hamiltonian for the maximisation problem is given by

$$
\begin{aligned}
H_c &= \frac{(CE)^{1-\sigma}}{1-\sigma} + \lambda \left[\psi A^{\alpha+\beta} \left(S_0 - S_A\right)^{\alpha} K^{1-\alpha-\beta} z - C\right] + \\
&\quad + \mu \left[-\psi A^{\alpha+\beta} \left(S_0 - S_A\right)^{\alpha} K^{1-\alpha-\beta} z^{1+\gamma} - \theta E\right] + \vartheta \left[\rho S_A A\right]
\end{aligned}
$$

where λ, μ and ϑ denote the costate variables associated with the accumulation of physical capital, natural capital and knowledge capital, respectively. In particular, equations (8) and (9) follow from the first-order conditions $\frac{\partial H_c}{\partial C} = 0$ and $\frac{\partial H_c}{\partial z} = 0$, respectively.

$$\frac{\partial H_c}{\partial C} = C^{-\sigma} E^{1-\sigma} - \lambda = 0$$

by taking logs and differentiating, we have

$$\frac{\dot{\lambda}}{\lambda} = -\sigma \frac{\dot{C}}{C} + (1-\sigma) \frac{\dot{E}}{E}$$

$$\frac{\partial H_c}{\partial z} = \lambda \psi A^{\alpha+\beta} \left(S_0 - S_A\right)^{\alpha} K^{1-\alpha-\beta} - \mu(1+\gamma) \psi A^{\alpha+\beta} \left(S_0 - S_A\right)^{\alpha} K^{1-\alpha-\beta} z^{\gamma} = 0$$

by simplifying common terms, we derive

$$\lambda = \mu(1+\gamma) z^{\gamma}$$

- Equation (13) derives from the law of motion of the shadow price of the environment, the costate variable μ

$$\dot{\mu} = -\frac{\partial H_c}{\partial E} + \mu \delta$$

which becomes

$$\dot{\mu} = -C^{1-\sigma}E^{-\sigma} + \mu\theta + \mu\delta$$

or, alternatively,

$$\frac{\dot{\mu}}{\mu} = -\frac{U_E}{\mu} + (\theta + \delta)$$

But substituting out μ in the RHS from equation (9), we obtain

$$\frac{\dot{\mu}}{\mu} = -\frac{U_E}{\lambda}(1+\gamma)z^{\gamma} + (\theta + \delta)$$

Since $\lambda = U_C$, from FOC, given the equality of growth rates of consumption and environment, from condition (13.a), and given constancy of z at some value ω, in equilibrium, we have

$$\frac{\dot{\mu}}{\mu} = -\frac{U_E}{U_C}(1+\gamma)\omega^{\gamma} + (\theta + \delta)$$

and finally

$$\frac{\dot{\mu}}{\mu} = -\varepsilon(1+\gamma)\omega^{\gamma} + (\theta + \delta)$$

- Transversality conditions are identically given, for all shadow prices, by

$$\begin{cases} \lim_{t\to\infty} \lambda K e^{-\delta t} = 0 \\ \lim_{t\to\infty} \lambda_0 e^{(1-2\sigma)gt} K_0 e^{gt} e^{-\delta t} = 0 \\ \lim_{t\to\infty} \lambda_0 K_0 e^{-(2\sigma g+\delta)t} = 0 \end{cases}$$

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