Is the Discount Rate Relevant in Explaining the Environmental Kuznets Curve?

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NOTA DI LAVORO 83.2003

SEPTEMBER 2003

CLIM – Climate Change Modelling and Policy

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Summary

In this paper we use Pindyck's model (2002) to show that the discount rate may play an important role in explaining for the income-pollution pattern observed in the real world. Low levels of income involve high values of discount rate, that are obstacles to the adoption of a pollution abatement policy. Only when the discount rate falls, as a consequence of growth, will it be possible to implement measures for emissions reduction. Thus we are able to derive an inverse U-shaped income-pollution pattern, making use of an argument that has never yet been introduced in the economic debate on this issue.

Keywords: Discount rate, Environmental Kuznets Curve, Income, Stock pollutants

JEL: Q2, D61

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1 Introduction

In economic literature there is a heated debate around the causes of the inverse U-shaped income-pollution pattern, that has been denominated "Environmental Kuznets Curve" (EKC). Since the seminal paper by Grossman and Krueger (1991), a lot of theoretical explanations have been supplied for this relationship. For example John and Pecchenino (1994), to account for the EKC, propose an overlapping generations model in which, as a consequence of economic growth, the economy moves from a situation with zero investment in environmental improvements, to an equilibrium with positive expenses to reduce ecological damage. Some suggest that the income-pollution pattern depicted in the EKC simply reflects the transition from a rural economy to a more polluted world, as a consequence of industrialization, and towards a cleaner environment for developed economies that may pay for "green" services (Arrow *et al.*, 1995). There are models in which satiation of the consumers at a low level of pollution is assumed, where additional improvement of the environment has a marginal utility equal to zero (Jaeger, 1998), such that only with economic growth and more harmful emissions do people become willing to devote scarce resources to adopting clean technologies. Stokey (1998) considers that only dirty production processes are implemented at the low level of per-capita income, and only when the individual income reaches some threshold level will clean technologies be available. Suri and Chapman (1998) and Rothman (1998) highlight the role of industry decisions to transfer defiling productions from rich to poor countries, to justify the EKC (but it is not a process that we may repeat indefinitely, WTO, 1999). Others emphasize the importance of creating stronger institutions formation in developing countries, to internalize the environmental externalities (Jones and Manuelli, 2000). Recently, López and Mitra (2000) have suggested that differences in corruption levels among developing and wealthy countries may explain the EKC. New attempts to clarify the income-pollution pattern refer to the individual revenue inequalities inside countries and political choice mechanisms (Magnani, 2000). Andreoni and Levinson (2001), in a very simple static model, emphasize the role of increasing returns to scale in pollution abatement technology, in supporting the hypothesis of the inverse U-shaped relationships between the variables we are considering. Tahvonen and Salo (2001) affirm that carbon emissions first rise and then fall with income growth without any environmental policy. This happens just as a consequence of backstop technologies phenomena, at a high level of income and as a result of the increasing scarcity of non-renewable resources. The changes in preferences for environmental quality, as the people become more wealthy, have also been utilized to explain the EKC (Di Vita, 2002). Finally, Horbach (2002) reproposes the "ecological structural change" hypothesis, based on the shift of output composition that becomes less pollution-intensive as income increases, to justify the inverse U-shaped income-pollution pattern.[2]

This short and incomplete survey regarding the possible economic explana-

[2]For a more detailed survey of the literature on the EKC, see Borghesi (1999).

tions of the EKC is useful to affirm that no one has previously attempted to explain the income-pollution pattern through the differences in discount rates among countries. Neither is it considered in recent econometric analyses regarding the topic of this paper, that include new independent variables in the regressions (Hannes, 2002, Harbaugh, *et al.* 2002, Horbach, 2002). Nevertheless the problem of choosing an appropriate discount rate for evaluating projects to ameliorate environmental quality, has stimulated research to find the optimal rate to make topical the 'far-distant future', for problems that will influence the life of future generations, like global warming, lost of biodiversity, etc.. This is a subject for discussion among general and environmental economists (Caplin and Leahy, 1999, Henry, 1974, Percoco, 2002,Weitzman, 1998, 2001). Weitzman (2001) recently affirmed " ... *The concept of a 'discount rate' is central to economic analysis, as it allows effects occurring at different future times to be compared by converting each future dollar into equivalent present dollar ...* ".

The choice of a correct rate to make up-to-date future benefits is particularly relevant in cases where problems of irreversibilities (for example lost of biodiversity) and uncertainty (like future costs of pollution accumulation or climatic changes) emerge about some environmental damage (Pindyck, 1996, 2000), and we want to know if it is worth implementing some environmental policy now rather than delaying its adoption.

To highlight the relevance of the discount rate in economic decisions, we may remember that the effects of a fall in it are similar to those of a rise in the saving rate in the Solow model, with an increase in capital stock and income (Romer, 1996). The neoclassical growth models assume an exogenous discount rate, this makes the analysis simple, but, as shown by Joshi (1993), this condition may bias the results, because it does not consider that this variable declines as income and consumption rise (Fisher, 1930). This is the reason why some affirm that the neoclassical school of thought is not able to account for the differences in discount rates between rich and poor countries (Hibbs, 2001).

There are other theoretical reasons to clarify why the discount rate is high in poor and developing nations. Without trying to be exhaustive, we refer to the scarcity of capital, the high risk premium in the financial market, the high leverage of debt (foreign and domestic), political instability, the necessity to devote scarce resources to satisfy present needs (Samwick, 1998), without taking into account the rights of future generations, different intertemporal preferences (Holden *et al.*, 1998) and, finally, the misspecification of property rights of some natural resources. All those reasons and statistical observations (Pearce *et al.*, 1999) univocally support our assumption. The social intertemporal preferences of the countries are revealed by the discount rate, but the data of the latter, unlike the former, could easily be found and used in empirical analyses.

At any point of time, the social planner of the economy we consider in the model has to choose whether to adopt a costly social policy now to reduce pollution, or to delay this decision until some other point in the future. The environmental policy will be undertaken if the present value of the net social benefits is positive. Under *ceteris paribus* conditions low discount rates encourage the policy adoption, while if it is high no measure will be launched to reduce pollution emissions.

Thus cross-countries differences in the discount rates may be helpful to justify why in poor nations we find a positive relationship between income and pollution, while the opposite happens in wealthy ones, in which the policy to preserve the ecological system is implemented.

The main topic of this paper is to show that the inverse U-shaped income-pollution pattern could be explained simply by referring to the differences in discount rate among countries, without any additional specification in the model or ad *hoc* assumptions. In particular, here we simply ignore the problem if the EKC is caused by some market failures, because we agree with Levinson (2000), who has shown that this phenomenon may be consistent either with or without Pareto-optimality.

To the aims of this study we use the dynamic two-stage model developed by Pindyck (2000, 2002). This theoretical framework is at the same time easy and utilizable to investigate how emissions change as a result of income changes. In its simple version, the behavior during the time of pollution stock depends on the flow of emissions and on two coefficients, that account for the static and dynamic absorptive capacity of the natural environment. The choice whether to adopt or not a costly environmental policy is based on the simple cost-benefit analysis. The discount rate plays a remarkable role in the decision regarding the implementation of the policy, because a low level of it implies a higher present value of future benefits, while if it is high this makes the adoption of measures to reduce the environmental burden more difficult.

We introduce in Pindyck's model a function of the social cost of pollution reduction, in which the income and emissions are considered. This is necessary to deal with the EKC, a problem not considered in the original version of this theoretical framework.[3] The income-pollution pattern is derived under two different conditions. First, it is assumed that pollution emissions go immediately to zero if a policy is adopted, and second the case of partial reduction of emissions is considered. These two different hypotheses do not influence the relationships among pollution, discount rate and income. They determine very different income-pollution patterns according to which assumption we adopt.

Here we confine ourselves to the relevance of the discount rate in explaining the EKC, without considering some other important hypotheses accounted for in Pindyck's model, such as uncertainty and irreversibility, but our analysis could be extended to the more complete version of Pindyck's theoretical framework.

After this introduction, the rest of the paper is organized as follows. In the next section we report Pindyck's model briefly (2002). Section three is devoted to showing how the discount rate and income levels may influence the pollution stock dynamics, under two different hypotheses, that pollution emissions go immediately to zero, as a result of policy implementation, or that emissions may be partially reduced. Section four aims to discuss our findings and implications for economic policy.

[3] Note that Pindyck in his paper (2002) refers to CO_2 and SO_2 that are typical pollutants considered in studies on the EKC (see Grossman and Krueger, 1995, Harbaugh *et al.*, 2002).

2 The Simple Version of Pindyck's Model

To the aims of this paper we make use of the same theoretical framework as Pindyck (2002); just to render the reading of this work more easy, the basic assumptions of his model are reported here. In the simple two-period model, a state variable M_t is considered that represents one (or more) stock pollutants, and the pollution emission E_t is the flow variable that controls M_t. In the absence of an environmental policy E_t follows an exogenous trajectory, and stays at the constant initial level E_0. Ignoring uncertainty, the motion equation of M_t is

$$(1) \qquad \dot{M} = \beta E(t) - \delta M(t),$$

where $0 < \beta \leq 1$ is a parameter that measures the quantity of emissions absorbed by the ecosystem, and δ is the natural rate at which M dissipates over time. In Pindyck's model the pollution stock rises continuously following its motion equation, if a policy is not adopted. The flow of social cost is given by the function $B(M_t, \theta_t)$, where θ_t changes stochastically during time, reflecting changes in tastes and technologies. Assuming that B is linear in M, we set

$$(2) \qquad B(M_t, \theta_t) = -\theta_t M_t.$$

The social costs of undertaking an environmental measure are assumed to be completely sunk, and its present value at the time of adoption, which is denoted by $K(E_1)$, is a function of the size of the emission reduction.

The function that we want to maximize is the present value of social welfare W

$$(3) \qquad W = \xi_0 \int_0^\infty B(M_t, \theta_t) e^{-rt} dt - \xi_0 K(E_1) e^{-r\tilde{T}},$$

where ξ_0 are the expectations at time $t = 0$, $\tilde{T}$ is the unknown time at which the policy is adopted, and r is the discount rate.

To keep the analysis simple, we ignore, for the moment, the problems of uncertainty and irreversibilities brought about by pollution emissions.

Solving (1), we may express M_t as a function of time (Pindyck, 2002, p. 1681). Assuming that the policy is adopted at time T, such that $E_t = E_0$ for $t < T$ and $E_t = 0$ for $t \geq T$, then

$$(4) \qquad M_t = \begin{cases} (\beta E_0/\delta)\left(1 - e^{-\delta t}\right) + M_0 e^{-\delta t}, & \text{for } 0 \leq t \leq T \\ (\beta E_0/\delta)\left(e^{\delta T} - 1\right) e^{-\delta t} + M_0 e^{-\delta t}, & \text{for } t > T \end{cases}.$$

Let M_0 be the initial value of M_t; we may calculate the values of social welfare W_N, in cases where the policy is never adopted,

$$(5) \qquad W_N = -\int_0^\infty \theta_0 M_t e^{-rt} dt = -\frac{\theta_0 M_0}{(r+\delta)} - \frac{\beta E_0 \theta_0}{r(r+\delta)},$$

and in cases in which the environmental policy is implemented at time $t = 0$, such that the social cost is immediately carried and $E_t = 0$. The social welfare in this hypothesis will be W_0,

(6) $$W_0 = -\frac{\theta_0 M_0}{r+\delta} - K.$$

The standard cost-benefit analysis suggests adopting the policy if $W_0 > W_N$. This simple theoretical framework is the starting point for our analysis, but we may extend our findings to the more complicated version of Pindyck's model.

3 The Role of the Discount Rate in Explaining Pollution Abatement Decisions

Here we observe that, under *ceteris paribus* conditions, there will be some threshold level of the discount rate $\hat{r}$ such that $W_N = W_0$. Why are we interested in this value of the discount rate? The answer is simple: $\hat{r}$ is the watershed discount rate between the area in which the environmental policy will be adopted, and the area in which pollution rises along its motion equation. In fact, if $r > \hat{r}$ the environmental policy will never be undertaken, because it will always be true that $W_0 < W_N$, such that M_t increases continuously following its motion equation. However, when $r < \hat{r}$, the measure to reduce pollution will be implemented, such that M will decline during time. To calculate $\hat{r}$ we assume $W_0 = W_N$, and after some little algebra we get

(7) $$Kr^2 + rK\delta - \beta E_0 \theta_0 = 0,$$

that is a quadratic equation, that we can easily solve to obtain the values of the discount rate that make W_0 and W_N equal.

We may give a numerical example, using the same values of parameters as in Pindyck (2002), that we report in Table 1.

Table 1

Parameters	**Values**
β (emissions absorbed by the ecosystem)	1
K (PV of cost of policy adoption)	\$2.000.000.000
E_0 (emission rate)	300.000 tons/yr
θ_0 (current social cost)	\$20 tons/yr
δ (pollutant decay rate)	0.02

Using (7), we find that there are two values of $\hat{r}$, $\hat{r}_1 = 0.04863$ and $\hat{r}_2 = -0.05586$. The positive threshold discount rate is greater than that used by Pindyck in his paper, such that our findings are compatible with his results and parameter constellations.

All the values of the variable considered included between $\hat{r}_1$ and $\hat{r}_2$ allow us to say that $W_N > W_0$.

The negative values of the discount rate imply too high preferences for the future. We may suppose that values of r close or equal to zero will be considered by a benevolent planner who attributes great value to the future, especially, if she takes into account the rights of future generations not represented at present (Weitzman, 2001).

Using (7), and calculating the partial derivative of E with respect to r, we get

(8) $$\frac{\partial E}{\partial r} = K \frac{2r + \delta}{\beta \theta_0} > 0,$$

such that $\partial^2 K/\partial r^2 = 2K/\beta\theta_0 > 0$. We may draw the relationship described by equation (8), in Figure 1,

[Figure 1, about here]

in which we report the discount rate in the horizontal axis and the pollution emissions in the vertical axis. The discount rate-pollution emissions pattern, without any environmental policy, is described by an increasing and convex curve $E(r)$. The threshold $\hat{r}$ line splits the positive quadrant in two parts, such that for $r < \hat{r}$ the pollution emissions will be equal to zero, because the environmental policy will be adopted, until the threshold level of the discount rate is achieved and the environmental policy no longer undertaken, such that E jumps to its optimal level without a social planner action. This implies that in the first case the pollution stock declines at a rate δM_t, while in the second case (i.e. $r > \hat{r}$) M_t rises according to (1). The arrows show the dynamics of $E(r)$ in this model, when the choice to invest or not in environmental issues is considered.

Our previous results imply that, under *ceteris paribus* conditions, all the countries that have a discount rate lower than $\hat{r}$ will show declining emissions and stock of pollution, as a consequence of expenses to improve the environmental quality, while nations where $r > \hat{r}$ will see E and M increase over time. The link between the discount rate and pollution emissions is almost new, and it is not fully investigated in the economic literature regarding explanations for the inverse U-shaped income-pollution pattern. The problem is that in the EKC, pollution is considered as a function of income and not of r. In particular, in Pindyck's model I is not considered, because he takes directly into account the costs of environmental policy adoption K, and considers it as a parameter, in the numerical example.

To study how the discount rate affects the income-pollution pattern we have to amend Pindyck's model, introducing a function of the pollution abatement costs, that satisfies the common assumption posed in the economic literature about this issue, and in which the income (output) is considered. In particular, it is assumed that

(9) $$K = f(I, E) = I^{\alpha} + E^{1-\gamma},$$

this functional form of K respects the conditions $\partial K/\partial I > 0$, $\partial K/\partial E < 0$ used by McKitrick (1999, p. 309), and $\partial^2 K/\partial E^2 > 0$ (Andreoni and Levinson, 2001, Pindyck, 2002), $\partial^2 K/\partial I^2 < 0$. Under this assumption the social cost of pollution abatement policy is concave-increasing in I (output), while K is convex-decreasing in E. The parameter $0 < \alpha \leq 1$ expresses K as a direct function of the income, while $\gamma > 1$ considers pollution abatement costs change as the emission changes.[4]

Through (9) we define the social cost of environmental improvement at any point of time, given the values of parameters α and γ, and the level of income and E.

Substituting for K $\left(I^{\alpha} + E^{1-\gamma}\right)$ in (7), and deriving E with respect to I, we obtain

$$\frac{\partial E}{\partial I} = I^{\alpha-1}\alpha\frac{E^{\gamma}}{-1+\gamma} > 0. \tag{10}$$

Thus we may affirm that pollution emissions are increasing with income. In the absence of social expenditure in environmental aims, the stock of pollution will rise during time along with its motion equation as the income growth.

Finally, to know the link existing between the discount rate and I, we employ again (7), after putting $\left(I^{\alpha} + E^{1-\gamma}\right)$ for K, and calculating the implicit derivative of r with respect to I, the result is

$$\frac{\partial r}{\partial I} = -\frac{I^{\alpha-1}\alpha r\left(r+\delta\right)}{\left(I^{\alpha} + E^{1-\gamma}\right)\left(2r+\delta\right)} < 0. \tag{11}$$

This means that there is an inverse relationship between r and I. In other words, countries with a low income level will have a high discount rate, such that this alone may explain why in poor nations the environmental policy will not be adopted, therefore growth in the poor countries (where $r > \hat{r}$) involves an increase in the pollution stock. Only when the threshold level of the discount rate is reached, as a result of growth, will ecologically friendly measures be implemented and M_t decline. For $r < \hat{r}$, an increase in income implies a reduction in pollution stock.

To analyse how M changes during time with changes in I, thus deriving the income-pollution pattern in this theoretical framework, we put in evidence E_0 in (7), under the assumption $K = \left(I^{\alpha} + E^{1-\gamma}\right)$, and substituting in (4) for E_0, and then in (1) for M_t. After some little algebra, remembering that $E = 0$ if a policy is adopted, we get

$$\dot{M} = \begin{cases} \dfrac{\left(I^{\alpha} + E^{1-\gamma}\right)r\left(r+\delta\right)}{\theta_0}e^{-\delta t} - \delta M_0 e^{-\delta t}, \\ -\dfrac{I^{\alpha} r\left(r+\delta\right)}{\theta_0}\left(e^{\delta T} - 1\right)e^{-\delta t} - \delta M_0 e^{-\delta t}. \end{cases} \tag{12}$$

The first row of (12) describes $\dot{M}$ when $0 \leq t \leq T$ and $r > \hat{r}$, while the second line of the equation above represents the dynamics of pollution stock when $t > T$ and $r < \hat{r}$.

Taking the first partial derivative of $\dot{M}$ with respect to I, the results will be

[4] It is worth highlighting that even using (8) and substituting in (7) to K, it is still verified that $\partial E/\partial r > 0$ and $\partial^2 E/\partial r^2 > 0$.

$$\frac{\partial \dot{M}}{\partial I} = \begin{cases} I^{\alpha-1}\alpha \dfrac{r\,(r+\delta)}{\theta_0} e^{-\delta t} > 0, & \text{for } r > \hat{r}, \\ -I^{\alpha-1}\alpha \dfrac{r\,(r+\delta)}{\theta_0}\left(e^{\delta T}-1\right) e^{-\delta t} < 0, & \text{for } r < \hat{r}. \end{cases} \tag{13}$$

It is worth noting that $\dot{M}$ is a concave-increasing function of income for $r > \hat{r}$ and a convex-decreasing function of I for $r < \hat{r}$. This means that the stock of pollution increases as income rises, following the motion equation described by (1), until r decreases to its threshold level $\hat{r}$, at which M_t reaches its maximum level. For levels of the discount rate lower than $\hat{r}$, $E_t = 0$ (remember that in this simple version of the model the pollution emissions are entirely eliminated as a consequence of environmental policy adoption) and M_t will decline during time at the rate δM_t.

We may summarize the information obtained from the previous analysis in Figure 2 below,

[Figure 2, about here]

in which we report the income in the horizontal axis and the dynamics of pollution stock in the vertical axis, and account for the second horizontal axis where the discount rate is considered. Thus we are able to show that the income-pollution pattern, in a modified Pindyck's model, is first concave-increasing and then convex-decreasing, starting from the discount rate level at which the policy is adopted. The irregular form of the curve we draw in Figure 2 may be explained remembering that we assume that when an environmental policy is undertaken the pollution emissions immediately drop to zero. The maximum point of $\dot{M}(I)$ occurs when the discount rate is equal to its threshold value $\hat{r}$, and a compatible level of income.

The bold line and arrows show the behavior of $\dot{M}$ as income changes. Note that $\dot{M}(I)$ increases slowly until the threshold level of the discount rate is achieved, and then declines quickly because $\left|I^{\alpha-1}\alpha r\,(r+\delta)\, e^{-\delta t}/\theta_0\right| < \left|I^{\alpha-1}\alpha r\,(r+\delta)\left(e^{\delta T}-1\right) e^{-\delta t}\,/\theta_0\right|$. This result holds because $\left(e^{\delta T}-1\right) e^{-\delta t} > e^{-\delta t}$. The income-pollution pattern that we have derived could be not consistent with the empirical evidence, which suggests that pollution emissions first increase quickly and, after policy adoption, decline slowly.

3.1 Allowing for Partial Reduction of Pollution Emissions

The condition that emissions drop immediately to zero when an expense to ameliorate the environmental quality is implemented could be unrealistic, because usually the process to reduce pollution emissions is not instantaneous. Thus we find it interesting to consider the case of a partial reduction of E as a consequence of environmental policy adoption, and that K is a function of the reduction in the pollution emissions.

Here we use the same functional form of the social cost of partial pollution abatement policy as in Pindyck's paper (2002, p. 1686), that is

$$(14) \qquad K = k_1(E_0 - E_1) + k_2(E_0 - E_1)^2,$$

such that $dK/dE < 0$ and $d^2K/dE^2 > 0$, i.e. K is convex-decreasing in E_1. With k_1, $k_2 \geq 0$, and E_1 is the new level of pollution emissions after the pollution abatement policy is implemented. Note that (14) is the same as the equation [17] in Pindyck (2002).

In this case the problems are when to adopt a provision to preserve the environment and how much to reduce E. We assume that θ_T may be equal to $\overline{\theta}$ or $\underline{\theta}$ with the same probability, that it does not change after time T, and that the policy adopted cannot be reversed. Solving (1) in the case in which the measure is adopted at time T, such that $E_t = E_1 \geq 0$ for $t \geq T$, we get

$$(15) \qquad M_t = \begin{cases} (\beta E_0/\delta)\left(1 - e^{-\delta t}\right) + M_0 e^{-\delta t}, & \text{for } 0 \leq t \leq T, \\ (\beta E_0/\delta)\left(e^{\delta T} - 1\right) e^{-\delta t} + (\beta E_1/\delta)\left[1 - e^{-\delta(t-T)}\right] + M_0 e^{-\delta t}, & \text{for } t > T. \end{cases}$$

Suppose we reduce E from E_0 to an arbitrary level E_1 at $t = 0$, such that the welfare function, as denoted by $W_0(E_1)$, is

$$(16) \qquad W_0(E_1) = -\frac{\theta_0 M_0}{r + \delta} - \frac{\beta E_1 \theta_0}{r\,(r + \delta)} - K\,(E_1)\,.$$

If the environmental investment is never adopted, the value of welfare function is

$$(17) \qquad W_N = -\frac{\theta_0 M_0}{r + \delta} - \frac{\beta E_0 \theta_0}{r\,(r + \delta)}.$$

Such that the pollution abatement policy will be launched if and only if $W_0(E_1) \geq W_N$.[5] Letting $W_0(E_1) = W_N$ after some little algebra, we find

$$(18) \qquad \frac{\beta \theta_0}{r\,(r + \delta)}\,(E_0 - E_1) - K(E_1) = 0,$$

that we may rewrite, using (13) for K, as

$$(18') \qquad \frac{\beta \theta_0}{r\,(r + \delta)} - k_1 - k_2\,(E_0 - E_1) = 0.$$

Considering (18) and assuming known the time at which the environmental measure is undertaken and the amount of pollution emissions to reduce, we may find the threshold discount rate $\hat{r}$ that discriminates the values for which the policy is adopted or not, as in the simplest version of the model. We may again utilize (18) to derive the relationship between the pollution emissions and the discount rate. Calculating the derivative, the result is

$$(19) \qquad \frac{\partial E}{\partial r} = \beta \theta_0 \frac{2r + \delta}{r^2\,(r + \delta)^2\,k_2} > 0.$$

This result confirms that there is a positive relationship between E and r. Finally, we are able to highlight the link between E and income by (18′), putting

[5] Until here we have reported a piece of Pindyck's model, dealing with the case of partial reduction of emissions, that he handles in section 2.3 of his paper (Pindyck, 2002, p. 1686 ss.).

in evidence E_1 and substituting for E_0 its value $\sqrt[1-\gamma]{K-I^{\alpha}}$, coming from (9), and to calculate the implicit derivative, such that we get

$$(20) \qquad \frac{\partial E}{\partial I} = \frac{(K-I^{\alpha})^{-\frac{\gamma}{-1+\gamma}} I^{\alpha-1}\alpha}{-1+\gamma} > 0,$$

Even in cases of partial reduction of pollution emissions we are able to show that E and I increase together if a pollution policy is not implemented. Now we may consider the dynamics of pollution as the income changes when a partial reduction of emissions is allowed. As in the previous version of the model we employ (1), and substituting (15) for $M(t)$, we obtain

$$(21) \qquad \dot{M} = \begin{cases} \beta E_0 - (\beta E_0)\left(1-e^{-\delta t}\right) + \delta M_0 e^{-\delta t}, \\ \beta E_1 - \left\{(\beta E_0)\left(e^{\delta T}-1\right)e^{-\delta t} + (\beta E_1)\left[1-e^{-\delta(t-T)}\right] + \delta M_0 e^{-\delta t}\right\}. \end{cases}$$

The first line of (21) describes $\dot{M}$ when $0 \leq t \leq T$ and $r > \hat{r}$, while the second row explains the dynamics of pollution stock when $t > T$ and $r < \hat{r}$, i.e. the policy is launched.

Taking the partial derivative of $\dot{M}$ with respect to I, the results will be

$$(22) \qquad \frac{\partial \dot{M}}{\partial I} = \begin{cases} I^{\alpha-1}\alpha\frac{r(r+\delta)}{\theta_0}e^{-\delta t} > 0, & \text{for } r > \hat{r} \\ -\beta\frac{(K-I^{\alpha})^{-\frac{\gamma}{-1+\gamma}} I^{\alpha-1}\alpha}{-1+\gamma}\left\{\left(e^{\delta T}-1\right)e^{-\delta t} - \left[1-e^{-\delta(t-T)}\right]\right\} < 0, & \text{for } r < \hat{r} \end{cases}.$$

It is easy to note that when $0 \leq t \leq T$ and $r > \hat{r}$, the dynamics of $\dot{M}$ with respect to the income are the same as in cases where the policy adoption implies that E falls instantaneously to zero, while in the hypothesis of expenses for partial reduction of pollution emissions ($t > T$ and $r > \hat{r}$), $\dot{M}$ will decline slowly. Note that $\left|I^{\alpha-1}\alpha r\,(r+\delta)\,e^{-\delta t}/\theta_0\right| < \left|\beta\,(K-I^{\alpha})^{-\frac{\gamma}{-1+\gamma}} I^{\alpha-1}\alpha/\,(-1+\gamma)\left\{\left(e^{\delta T}-1\right)e^{-\delta t} - \left[1-e^{-\delta(t-T)}\right]\right\}\right|$. We may prove this result letting the partial derivative of $\dot{M}$ with respect to the income be equal to zero, when $0 \leq t \leq T$ and $t > T$, to see that $\left|r\,(r+\delta)\,e^{-\delta t}/\theta_0\right| > \left|\beta\,(K-I^{\alpha})^{-\frac{\gamma}{-1+\gamma}}/\,(-1+\gamma)\left(e^{\delta T}-1\right)e^{-\delta t} - [1 - e^{-\delta(t-T)}]\right.$, such that the result holds.

Observe that $\dot{M}$ is a concave-increasing function of income for $r > \hat{r}$ and concave-decreasing in I for $r < \hat{r}$. In this way we are able to represent in Figure three, that we report below, the income-pollution pattern in case of partial reduction of pollution emissions.

[Figure 3, about here]

Note that the variables reported in both axes are as in picture two. Here we obtain an inverse U-shaped EKC, in which the decreasing part of the curve falls more slowly than the rising one. When the partial reduction of E is considered, a more realistic representation of the income-pollution pattern comes. The EKC reaches its maximum point when $r = \hat{r}$ at time $t = T$, at which the policy is adopted and for a compatible level of the income I_t.

3.2 Generalization of the Model's results

Up to now we have ignored the problems of uncertainty and irreversibilities explicitly considered by Pindyck in the more complicated version of his model, that he sets out in the final part of the second paragraph of his paper. Uncertainty is introduced in the theoretical framework, assuming that the social planners may wait until time T to adopt the environmental policy, and do it if and only if $\theta_T = \bar{\theta}$ (where θ is the future social cost, that could be either high $\bar{\theta}$ or low $\underline{\theta}$), and assuming that the probability that $\theta_T = \bar{\theta}$ is equal to 0.5. In this way the function of social welfare changes and becomes a little bit more complicated (see equation [8] in Pindyck's paper).

The effects of irreversibilities are taken into account via a sensitive analysis of the values that the pollution decay rate δ may assume. These two extensions of the more simple model we deal with in the first part of the paper do not change our conclusions, but rather reinforce our findings. In particular, uncertainty and irreversibility reduce the net benefits of an activity with environmental costs (Arrow and Fisher, 1974, Henry 1974), recommending the adoption of an environmental measure even for values of the discount rate higher than in the hypothesis in which we ignore the existence of these two phenomena. In other words, the more complete version of Pindyck's model does not change the main findings of this paper, but rather emphasizes the role of the discount rate in the choice whether or not to adopt costly social measures to preserve the environment. In the presence of uncertainty and irreversibility we may affirm that $\hat{r}$ will be higher than in cases where these two effects are not considered in the analysis. We can arrive at the same conclusions in the continuous time model set out by Pindyck in section three of his paper, but for the limited purposes of this paper, it is not worth using here the more complicated version of his theoretical framework.

4 Result Comments

In this paper we have shown that a direct relationship exists between the discount rate and pollution emissions. This relation has hitherto been ignored in the economic literature dealing with the problem of explaining the income-pollution pattern, at the micro and macroeconomic levels. This implies that in countries with high discount rates environmentally harmful production processes could be adopted, to satisfy the present needs of the population, without taking into account the rights of future generations.

A threshold level of the discount rate could be found such that for all its values higher than $\hat{r}$, the environmental policy will not be adopted and pollution will continue to rise. Note that Pindyck himself affirms that an increase in the discount rate reduces future benefits and raises future costs, thus motivating the decision to delay adoption of the policy. In such a way he suggests a positive link between the discount rate and pollution emissions.

The range of r values that we found such that the net value of social welfare is positive (at the time at which the policy is adopted), using Pindyck's parameters, is consistent with the recent analysis of Weitzman (2001), that suggests discounting the future at a rate included between four and zero per cent, depending on the length of the temporal horizon considered.

Even in the modified version of Pindyck's model, the discount rate and income move in opposite directions, so that for the pair of values of low income and high discount rate the net present value of social welfare will be negative, if the policy is implemented, such that emissions and pollution stock both increase. This happens until the growth reduces the discount rate to its threshold level, such that environmental measure will be undertaken, because the net present value of social welfare is positive.

In this way we are able to demonstrate why for low levels of income - and high discount rates - countries show a positive relationship between income and pollution, while the opposite happens when countries become wealthier and show a low discount rate. Rich nations adopt a lower r in their decisions than poor countries (showing high preferences for the future), in the choice whether to adopt a costly policy to preserve the environment, even in cases in which irreversibilities and uncertainty are involved.

From equations (13) and (22) it is evident that for $r > \hat{r}$ there is a positive relationship between the discount rate and pollution stock dynamics, while for $r < \hat{r}$ the stock of pollution declines during time, as a consequence of pollution abatement expenditure.

In this paper we have considered two versions of the same model. In the first, we undertake the hypothesis that when a policy is launched the pollution emissions go immediately to zero. In the other, we consider a partial reduction of pollutions emissions as a consequence of an environmentally friendly investment. The main differences emerge in the income-pollution pattern, that is first concave-increasing and then, when $r = \hat{r}$, convex-decreasing in cases where the pollution emissions go instantaneously to zero when the policy is adopted. A more realistic behavior of the EKC is shown in cases of partial reduction of pollution emission in which we derive an inverse U-shaped curve, that is asymmetric, because the decreasing branch has a lower slope than the increasing part of the curve. This accounts for the fact that usually many pollutants need to be reduced sometime.

In the modified version of Pindyck's model used here, an inverse U-shaped pollution-income pattern emerges, without any *ad hoc* assumption or particular specification of functions, only referring to the discount rate.

This new possible explanation of the EKC has the advantage of being analytically simple, and immediately testable, adding to the existing data-set the discount rate data, or making new regressions changing the econometric model specification. The discount rate could be entirely used in time series analysis referred to a single country, and cross countries econometric studies involving cross-section or panel data. Recently, some authors (Kaufmann *et al.,* 1998, Stern and Common, 2001, Suri and Chapman, 1998, Unruh and Moomaw, 1998) have expressed their dissatisfaction with the existing specifications of econometric models to testify the existence of the EKC, suggesting the need to introduce new independent variables in applied studies on the income-pollution pattern. In particular, the search for a correct specification of the econometric model is relevant if the recent empirical analysis does not univocally support the existence of the inverse U-shaped EKC, leaving open the question of the real shape of income-pollution relationships.

The implications of our analysis for policy are twofold. International grants in interest accounts, from industrialized countries to developing nations, could incentivise poor countries to implement costly environmental policies to reduce their pollution emissions. Promoting growth in developing countries reduces the discount rate of the economy, making possible the adoption of expensive investments to improve the quality of the environment. The first measure is almost new and has never been proposed in the attempt to solve or mitigate environmental problems. The second policy is quite mainstream, but the increase in income does not reduce pollution by itself, only through the discount rate reduction channel.

From a theoretical point of view, more research is necessary to support the basic intuition behind this paper, with which we may explain the inverse U-shaped income-pollution pattern in terms of differences in the discount rate among countries with different income levels. In particular, our findings could be useful in other studies to explain the behavior of pollutants that does not follow inverse U-shaped dynamics.

Econometric investigation is still necessary to estimate the empirical relevance of the discount rate in explaining the inverse U-shape of the income-pollution pattern.

In particular, cross-countries analyses regarding the income-pollution pattern may shed light on the role of international movements of capital among countries, as a consequence of differences in discount rates, in explaining the EKC. We think that this issue could be interesting for further research.

Acknowledgments

Thanks to an anonymous referee, Roberto Cellini, Robert Pindyck and seminar participants at the University of Catania, for their invaluable suggestions and comments on a previous draft of this paper. All remaining errors are the responsibility of the author.

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Figure 1

Discount rate-Pollution emissions pattern

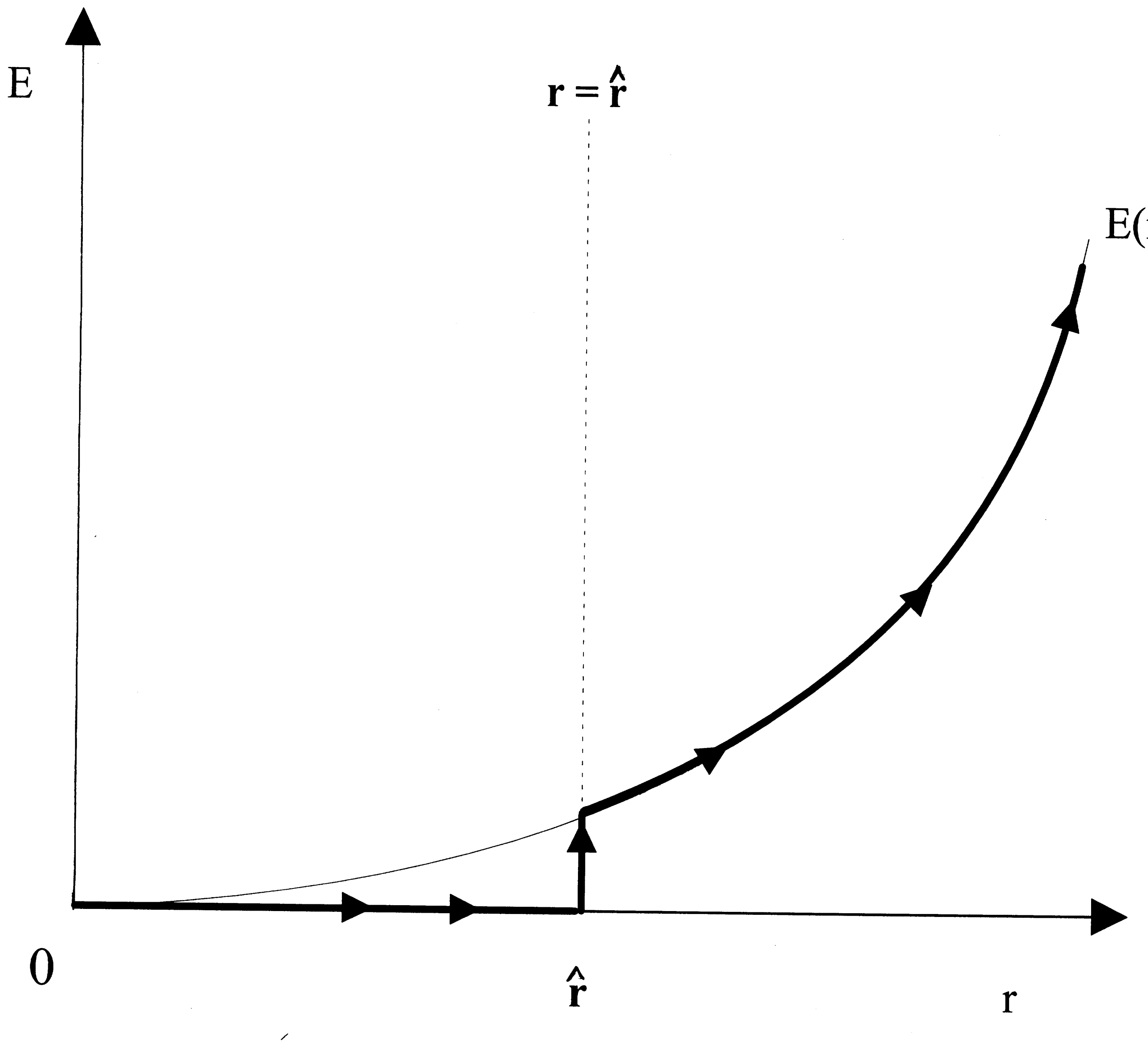


FIGURE 2

Income-pollution pattern

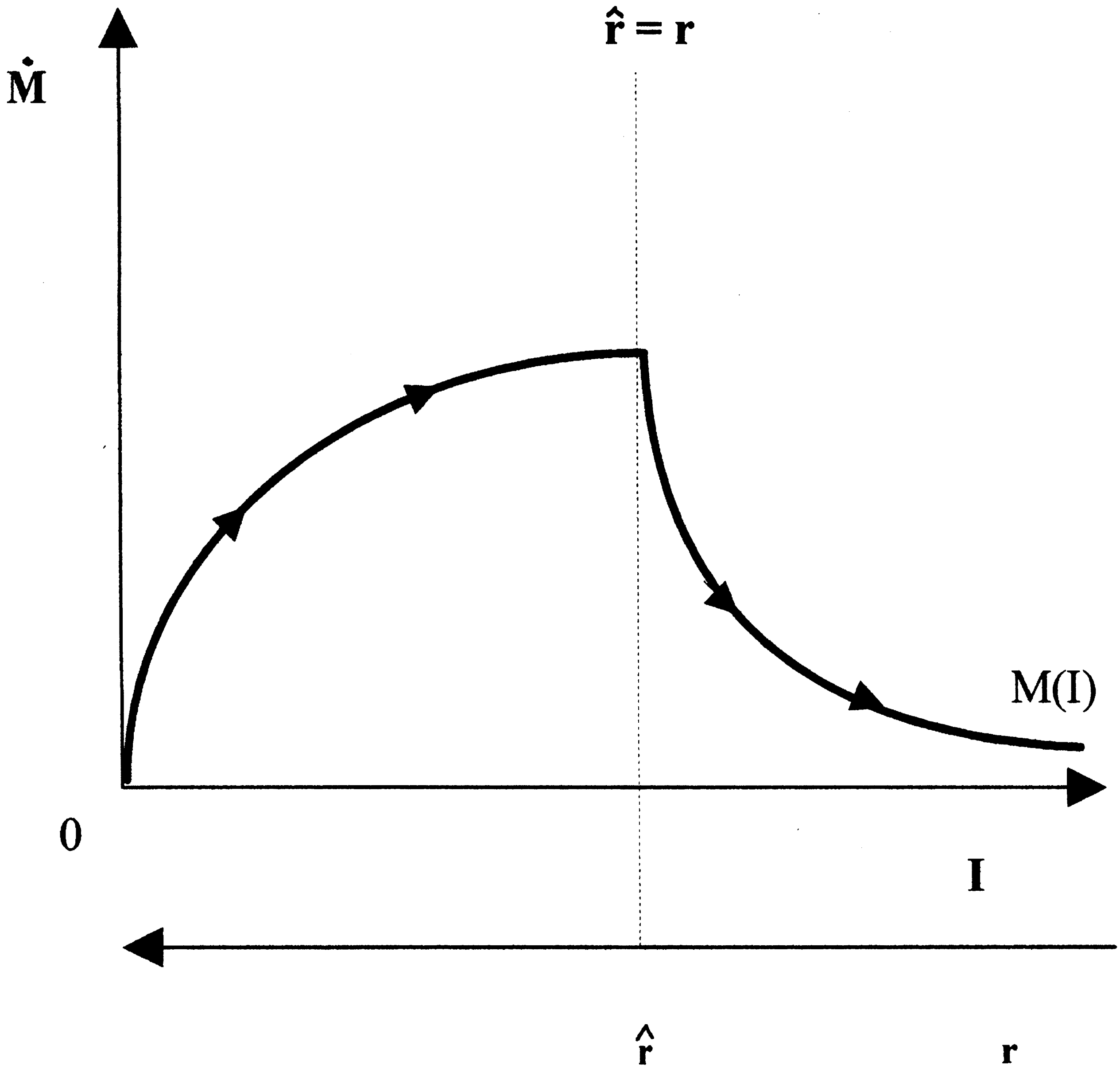
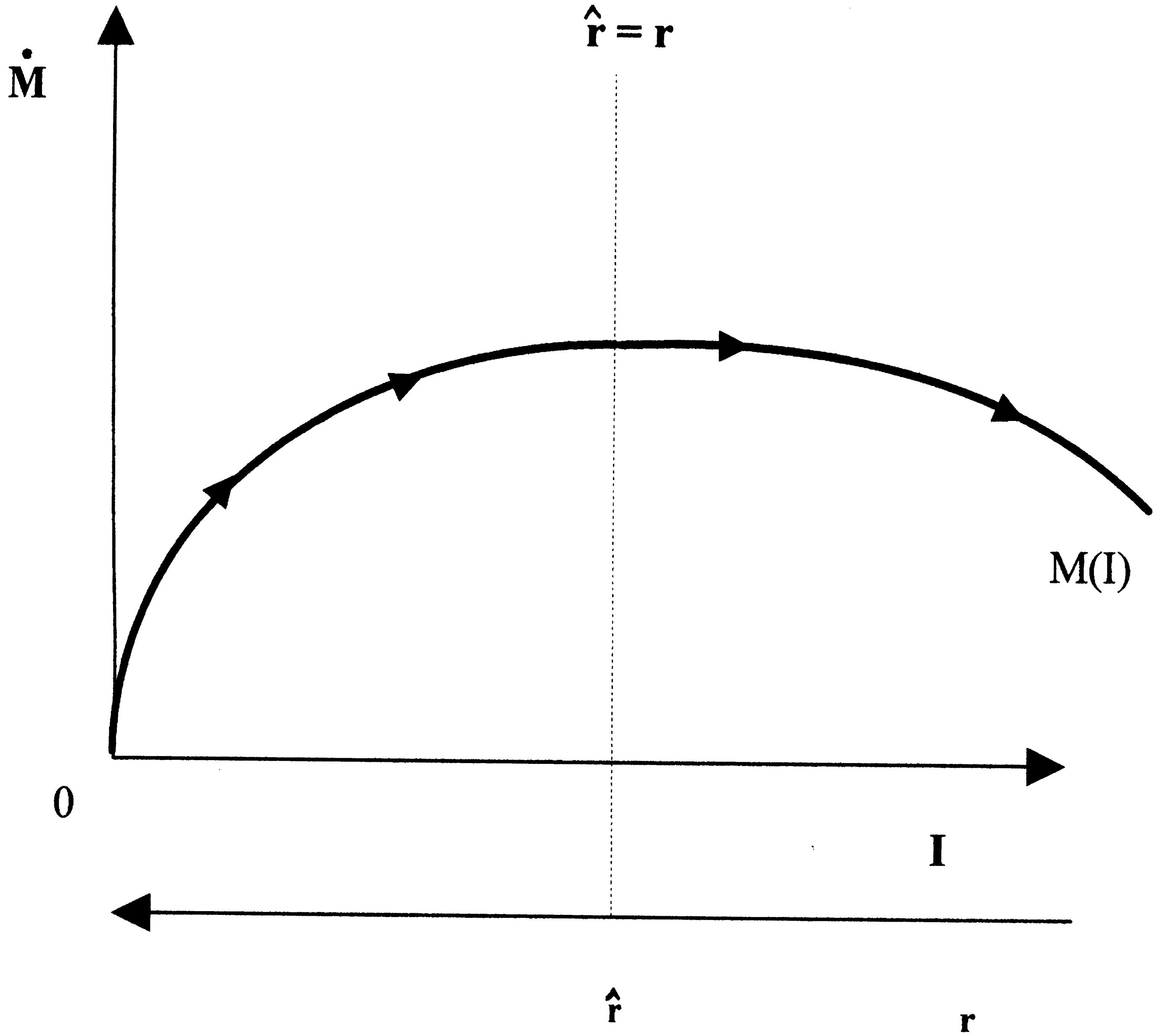


FIGURE 3

Income-pollution pattern in case of partial reduction of pollution emissions



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(l) This paper was presented at the Workshop "Growth, Environmental Policies and Sustainability" organised by the Fondazione Eni Enrico Mattei, Venice, June 1, 2001
(li) This paper was presented at the Fourth Toulouse Conference on Environment and Resource Economics on "Property Rights, Institutions and Management of Environmental and Natural Resources", organised by Fondazione Eni Enrico Mattei, IDEI and INRA and sponsored by MATE, Toulouse, May 3-4, 2001
(lii) This paper was presented at the International Conference on "Economic Valuation of Environmental Goods", organised by Fondazione Eni Enrico Mattei in cooperation with CORILA, Venice, May 11, 2001
(liii) This paper was circulated at the International Conference on "Climate Policy – Do We Need a New Approach?", jointly organised by Fondazione Eni Enrico Mattei, Stanford University and Venice International University, Isola di San Servolo, Venice, September 6-8, 2001
(liv) This paper was presented at the Seventh Meeting of the Coalition Theory Network organised by the Fondazione Eni Enrico Mattei and the CORE, Université Catholique de Louvain, Venice, Italy, January 11-12, 2002
(lv) This paper was presented at the First Workshop of the Concerted Action on Tradable Emission Permits (CATEP) organised by the Fondazione Eni Enrico Mattei, Venice, Italy, December 3-4, 2001
(lvi) This paper was presented at the ESF EURESCO Conference on Environmental Policy in a Global Economy "The International Dimension of Environmental Policy", organised with the collaboration of the Fondazione Eni Enrico Mattei , Acquafredda di Maratea, October 6-11, 2001
(lvii) This paper was presented at the First Workshop of "CFEWE – Carbon Flows between Eastern and Western Europe", organised by the Fondazione Eni Enrico Mattei and Zentrum fur Europaische Integrationsforschung (ZEI), Milan, July 5-6, 2001
(lviii) This paper was presented at the Workshop on "Game Practice and the Environment", jointly organised by Università del Piemonte Orientale and Fondazione Eni Enrico Mattei, Alessandria, April 12-13, 2002
(lix) This paper was presented at the ENGIME Workshop on "Mapping Diversity", Leuven, May 16-17, 2002
(lx) This paper was presented at the EuroConference on "Auctions and Market Design: Theory, Evidence and Applications", organised by the Fondazione Eni Enrico Mattei, Milan, September 26-28, 2002
(lxi) This paper was presented at the Eighth Meeting of the Coalition Theory Network organised by the GREQAM, Aix-en-Provence, France, January 24-25, 2003
(lxii) This paper was presented at the ENGIME Workshop on "Communication across Cultures in Multicultural Cities", The Hague, November 7-8, 2002

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