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"Environment, Development, and Growth: Designing Optimal Policies and Explaining the Evidence"

By

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Foreword

This "Supplementary Paper" is a product of the Environmental and Natural Resources Policy and Training (EPAT) Project funded by the United States Agency for International Development (USAID). EPAT is part of USAID's effort to provide environmental policy information to policymakers and practitioners in developing countries. The objective is to encourage the adoption of economic policies for promoting sustainable use of natural resources and enhancing environmental quality.

"Supplementary Papers" are intended to augment the EPAT publication series. They typically focus on technical aspects or contain extensive details on a topic of interest to a particular segment of the EPAT audience. They may also assist development professionals, civil servants, project officers, and researchers who are directly involved in the implementation of development activities.

This "Supplementary Paper" presents an analysis of the relationship between economic growth and environmental quality. It is a technical paper which uses a theoretical economic model to study these interrelationships. Several conclusions may provide useful insights for development professionals and researchers who are studying these topics.

USAID has supported part of the preparation costs of this paper and the nominal costs of duplication and mailing in response to requests from interested EPAT readers. The total amount is estimated to be $5,000. The availability of the paper is being announced to more than 2,000 professionals in developing countries. We will assess its effectiveness by soliciting the views of recipients. An evaluation sheet is enclosed with each mailing of EPAT documents for that purpose.

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ENVIRONMENT, DEVELOPMENT AND GROWTH: DESIGNING OPTIMAL POLICIES & EXPLAINING THE EVIDENCE

Hamid Mohtadi

April 1994

Abstract

This paper analyzes the relation between economic growth, economic development, and environmental quality. First it analyzes the long-run growth in an economy faced with environmental pollution. It derives first best optimal policies by a regulator in which the equilibrium growth path *mimics* the efficient growth path. Two policy instruments that are considered are production taxes (subsidies) and quantitative restrictions on pollutants.

Second, it "explains" the cross-sectional evidence on the observed relation between environmental quality and per capita income. This explanation is based on showing that such a pattern can emerge from the optimizing government policies *combined with* changing preference structure towards cleaner environment as per capita income rises.

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ENVIRONMENT, DEVELOPMENT AND GROWTH: EXPLAINING THE EVIDENCE & DESIGNING OPTIMAL POLICIES

I. INTRODUCTION

Recent evidence suggests that the way in which environmental quality is affected by industrialization and growth is by no means uniform. For example in a cross national study conducted by the World Bank (World Development Report, 1992)[1] it appears that some indicators of environmental quality continue to worsen with higher levels of per capita income (e.g, municipal waste), others experience an improvement (e.g., public sanitation and sewer), and yet a third group of environmental indicators experience an "inverted U" pattern (e.g., sulphur dioxide and air particulate matter), deteriorating upto some level of per capita income and improving beyond that (see figure 1). Other studies, notably one by Grossman and Krueger (1991), also find evidence of an inverted U pattern in the case of sulphur dioxide.

What accounts for such differences in the environmental effects as a function per capita income? In general, explanations for the improvement of environmental quality as a function of economic development range, from the role of cleaner technologies, to more strict regulation, to changes on the preference structure, to the mere positive effects of economic growth, while arguments for the adverse effects of development on environmental quality focus on the excessive use of "environmental resources" associated with development and growth. While each of these explanations may be true in the case of some pollutant, none provide consistent explanation for all the

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[1]Based on a World Bank background paper by Shafik and Bandyopadhyay (1992).

different patterns observed in figure 1. For example if growth helps with improvements in safe water or sanitation why should it not also reduce SO_2 or suspended particulate levels at *all* levels of income? Alternatively if technological innovation or more stringent regulations are the reason for a "turn-around" of SO_2 and air particulate discharge at some mid level of per capita income, as per inverted U pattern, why would these same factors fail to induce an inverted U pattern in the case of municipal waste?

Adopting a dynamic growth framework, one purpose of this paper is to show how changes in environmental quality as a function of the level of development may emerge from optimizing behavior that are approximately consistent with the pattern observed in figure 1. Specifically, it is shown that as economies develop and accumulate capital, a combination of *optimal regulation* and *gradually evolving preference structure* in favor of cleaner environment, explain much of the observed pattern in figure 1. By trying to "explain" observed patterns, this part of the paper constitutes a "positive" approach. The differences in the outcome turn out to depend on how society's preferences influence optimal regulatory policies and the speed with which such preferences change as countries accumulate capital.

A second purpose, related to a "normative" approach is to investigate the prospects for optimal long-run growth based on optimal policy design, when the quality of the environment is considered.

Optimal regulation in this paper means choosing policy instruments, by an actual government, rather than a central planner, that induce the market driven path of growth to achieve first or second best results. Where first best policies are attainable, this approach requires analyzing both the socially efficient path of economic growth *as well as* the equilibrium or market driven paths. The latter diverges from the efficient path, due to the externalities of the environment. Optimal policies are then chosen to "align"

the two paths. Thus for example, Peguvian taxes, subsidies or quantity controls on pollution are analyzed within a dynamic growth context. One interesting finding of the paper in this section is that a combination of quantity control on pollution and optimal tax or subsidy scheme lead to a higher level of social welfare than any optimal tax or subsidy scheme alone.

The focus on both the efficient and the equilibrium growth paths is different from the prevailing tradition in natural resource economics which often emphasizes the efficient path only.[2] A focus *only* on the efficient path without a comparison of this path with the actual market driven (or equilibrium) path has two shortcomings. On the normative policy issues it cannot satisfactorily address *how* actual policies should be designed to reach the first best outcomes, and on the positive issues it cannot "explain" actual or observed outcomes.

The model is based on a representative agent economy consisting of many infinitely lived agents. Evidence suggests that environment affects the economy through amenity, health and productivity effects (e.g World Bank, 1992, p. 44). The first two effects will be indicated in this paper by an overall "consumption" effect in which environmental quality enters the utility function of agents directly.[3] The third effect is captured by allowing environmental quality to enter the production function.

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[2]On the exhaustible resource and growth literature see for example, Solow (1974) and Solow and Wan (1976), Hartwick (1978), Ayers (1988). On the environment and growth literature see Foster (1973), D'arge and Kogiku (1973) Krautkraemer (1985) and Smith (1977). Smith's is the only one which contains some decentralized interpretations of optimal control theory.

[3]For a separate treatment of the effects of environmental quality on health see Mohtadi and Roe (1992).

We note that the emphasis on dynamics and externalities resemble the theories of endogenous growth such as the works of Lucas (1988), Romer (1990), Barro (1990) and Rebelo (1990). However, for the most part the technology here is simply defined as constant returns to scale in capital stock (i.e. in some part of the economy machines produce machines), which is more akin to Rebelo than to other contributors of endogenous growth.

It is recognized, of course, that there may be other types of pollutants whose pattern of change, as a function of per capital income, does not conform to figure 1. However, the three trends in this figure certainly represent some major indicators of pollution and explaining them would be add to our understanding of an important set of environmental indicators. Also, because the paper focuses on domestic environmental policies, abstracting from international policies, its focus will be on local rather than global environmental pollutants such as those causing Greenhouse gases or depletion of the ozone level.[4]

In what follows, Section II presents the general model and renders some general observations; Section III presents a parameterized specification of the model, followed by the derivation of the long run optimal policy instruments in steady-state. Section IV returns to non-steady state results and allows for preferences to be determined *endogenously* and as a function of the level of development. The results are then used to "explain" the observed patterns of environmental change presented in figure 1. Section V offers brief summary and concluding remarks.

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[4]In the context of figure 1, this means that our explanation of the pattern observed in the third row is really applicable mainly to the case of municipal waste, but not CO_2, since the latter is a light gas escaping to the high atmosphere and is therefore relevant only at the global level. For an example of policies in the context of global effects see Mohtadi (1992).

II. BASIC MODEL

Each agent maximizes his (her) present value of utility streams,

$$W = \int_0^\infty U(C(t),\bar{E}(t))e^{-\rho t}dt \qquad U_C, U_E > 0 \tag{1}$$

where C is a composite consumption bundle and E is an index which represents the quality of the environment. The bar on E indicates that each agent views environmental quality as *given*, although E(t) varied in the aggregate.

Decentralized (Equilibrium) Path

In the absence of any government intervention (e.g. taxes, subsidies) the agents' budget constraint will be given by,

$$C(t) = f(K(t),\bar{E}(t)) - \dot{K}(t) \qquad (f_K, f_E > 0) \tag{2}$$

where $\bar{E}(t)$ in the production function captures the productivity effect of environment and is not a choice variable to individual agents. K(t) is the stock of capital. Maximizing (1) subject to (2), the Current Value Hamiltonian for an interior solution is:

$$\mathcal{H} = U(C,\bar{E}) + \lambda[f(K)-C]. \tag{3}$$

The first order conditions for this interior solution are:

$$\mathcal{H}_C = 0 \qquad \longrightarrow \qquad U_C = \lambda, \tag{4}$$

$$\mathcal{H}_K = \rho\lambda - \dot{\lambda} \qquad \longrightarrow \qquad \dot{\lambda} = \lambda(\rho - r) \tag{5}$$

Differentiating (4) in time, substituting for λ and $\dot{\lambda}$ into (5), and rearranging the terms, the optimal path of consumption in the private economy along the equilibrium path is:

$$\left(\frac{\dot{C}}{C}\right)_{*} = -\frac{U_C}{CU_{CC}} \cdot \left[f_K(E) - \rho + \frac{U_{CE}}{U_C} \dot{E} \right] \tag{6}$$

where the dependence on C, K, and t are suppressed. Note that although consumers cannot influence E in their decision, changes in E *does* effect the consumption path of atomistic agents and thus it is taken into account by rational consumer. This shown up as $\dot{E}$ in equation (6). This effect depends on the sign of the cross-effect, U_{CE}. Following the tradition in the literature, we shall assume that $U_{CE} > 0$.[5] This implies that a secular improvement in environmental quality, *increases* equilibrium growth rate, *ceteris paribus*, and a secular deterioration in environmental quality, *reduces* equilibrium growth rate, *ceteris paribus*. This is an interesting result, for it suggest the possibility of win-win outcomes may exist in which both equilibrium growth increase and environmental quality improves. Thus,

1. A secular improvement in environmental quality, ceteris paribus, increases the rate of growth at equilibrium (a "win-win" outcome), if $U_{CE} > 0$.

However, this result is of limited use, since the real world is not characterized by *ceteris paribus* conditions. In particular the quality of the environment itself is an endogenous variable as will be discussed presently.

Efficient Path

In the aggregate E is *endogenous* to the decision maker. $\dot{E}$ is assumed to be a flow concept, inversely related to the flow of pollutants X that occurs

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[5]Or equivalently that the cross effect of pollution and consumption is negative, as is the more common formulation. See for example, Becker, R. (1982), D'arge and Kogiku (1973), Foster (1973), and others.

in production process. Specifically X is assumed to be an *increasing* function of the average capital stock (per capita) in the economy, such that:

$$X = X(K) \qquad X'(K) > 0 \tag{7}$$

The assumption that because production is an inherently polluting process larger amounts of aggregate (or average) capital stock cause greater pollution ignores the possibility that technology may change spontaneously towards cleaner environment as a result of new innovations, etc., in ways similar to the endogenous growth literature (Romer, 1990). However, because environment is an *external* factor, technological change towards improved environmental quality cannot be spontaneous but a *consequence* of incentives created by government regulations. In other words, because of the market failure associated with environment, environmental externalities are not automatically internalized but rather internalized through government incentive schemes such as taxes/subsidies, etc.[6] This is different from Romer's (1990) technological change in which innovation actually occurs in the R. & D. sector of the economy and in response to direct market incentives. Evidence for this argument may be seen for example in the reduction in the US of pollution by gasoline as a result of catalytic converters. This technical innovation was a clear response to more strict regulatory requirements. Similarly, the

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[6]The only other possibility, i.e. that of endogenous *technical* change may also be ruled out in the present context. An example of this approach is in Krautkraemer (1985) in which an environmentally friendly factor of production substitutes for an environment depleting factor over time. This model is based on a "stock" concept of the environment which is exhausted over time. However, even here no market mechanism exist that signals an exhaustion of the environmental "good" to the producer. A rise in the shadow price of the environment leading to an optimal rate of factor substitution occurs only along the efficient, not the equilibrium growth path.

increased fuel efficiency of automobiles over the past 20 years has been brought about by technological changes which responded to government requirements for gasoline efficiency (e.g., the clean air act.)

Since E is inversely related to X, in the absence of a government, E is given by,

$$E = E[K)] \qquad \text{with} \quad E_K(K) < 0 \tag{7'}$$

The efficient growth path is then found by maximizing (1) subject to the budget constraints (3) and E endogenous as per equation (7'). The Current Value Hamiltonian for an *interior* is:

$$\mathcal{H} = U[C,E(K)] + \lambda[F(K,E(K))-C] \tag{8}$$

and the first order conditions for an interior solution are:

$$\mathcal{H}_C = 0 \qquad \longrightarrow \qquad U_C = \lambda \tag{9}$$

$$\mathcal{H}_K = \rho\lambda - \dot{\lambda} \quad \longrightarrow \quad \dot{\lambda} = (\rho - F_K - F_E E_K)\lambda - U_E E_K \tag{10}$$

Again, differentiation (9) in t, substituting for λ and $\dot{\lambda}$ in (10), and rearranging the terms, consumption along the efficient path grows at the rate:

$$\left(\frac{\dot{C}}{C}\right)_s = -\frac{U_C}{CU_{CC}}\left(f_K + f_E E_K - \rho + \frac{U_E}{U_C}.E_K + \frac{U_{CE}}{U_C}\underbrace{E_K\dot{K}}_{\dot{E}}\right) \tag{11}$$

where $E_K\dot{K} = \dot{E}$ as shown. Comparing the growth of consumption along the equilibrium and efficient paths, we see that the equilibrium path (equation 6) is now augmented by two terms; the first term, $f_E E_K$, represents the productivity effect of the environment; the second term, $(U_{CE}/U_C)\dot{E}$, involves the consumption effect of the environment. In (11), environment enters through the marginal impact of capital accumulation on the quality of the environment, E_K. Since $E_K < 0$, as discussed, the terms $f_E E_K$ and $(U_E/U_C)E_K$ are

negative, reflecting the adverse effect of capital accumulation on the efficient growth path via a loss of productivity and also social preference away from capital accumulation. Although a positive E_K is technically possible, reversing the above effect (via both a productivity gain and preference structure) in favor of greater accumulation, this assumption is conceptually unrealistic in a free market, as discussed. Finally, the last term in (11) is the same as under the equilibrium path, which can now also be expressed as the effect of new investments $\dot{K}$ on the environmental quality, E_K.

III. MODEL SPECIFICATION, STEADY-STATE PATHS AND OPTIMAL POLICIES

We begin this section by parameterizing some of the functional relationships. This has to be done for analytic tractability but also in order to be able to identify certain key concepts, such as preference structure, with a parameter so as to analyze its evolution as incomes rise and capital accumulation takes place. We begin by positing a simple relationship for the environment function, i.e.,

$$E(t) = E_o K(t)^{-\beta}. \quad (\alpha,\beta>0) \tag{12}$$

This formulation will mean that as $t \longrightarrow \infty$, and $K(t) \longrightarrow \infty$, $E(t) \longrightarrow 0$. Thus environmental quality approaches zero only asymptotically. When a steady-state growth path exists, $\dot{E}/E$ will decline at a constant rate, but $E(t)$ itself will fall at an increasingly slower rate so that it will approach zero only asymptotically and is therefore positive for all finite time.

We represent the production function by a technology that is separable in the effects of E and K, and is linear in K but not necessarily in E. Specifically we use $f(K,E) = A(E)K$, where $A(E)$ captures the effect of

environmental quality on productivity.

The utility function is given by the customary form of constant elasticity (CE) of marginal utility with respect to its argument. However we generalize this to allow for *different* weights of C and E in the utility function: $U(C,E) = [(C^{\nu}E^{\mu})^{1-\sigma}-1]/(1-\sigma)$, $(\sigma>0)$. This generalization is important for our paper because the parameter μ captures the importance of preferences towards environment in the utility function and will play a key role in later analysis. Here, σ is the usual elasticity of the marginal utility with respect its argument, also known as the intertemporal elasticity of substitution. Imposing the condition $U_{CE} > 0$, discussed earlier, implies that $\sigma < 1$. Conditions $U_{CC} < 0$, $U_{EE} < 0$ imply that $\nu(1-\sigma) < 1$ and $\mu(1-\sigma) < 1$.

With these specifications, the equilibrium growth rate of consumption will be given by:

$$\left(\frac{\dot{C}}{C}\right)_e = \frac{1}{1-\nu(1-\sigma)}.[A(E)-\rho + \mu(1-\sigma)\frac{\dot{E}}{E}] \tag{13a}$$

or, equivalently, by:

$$\left(\frac{\dot{C}}{C}\right)_e = \frac{1}{1-\nu(1-\sigma)}.[A(E)-\rho - \beta\mu(1-\sigma)\frac{\dot{K}}{K}] \tag{13b}$$

where the second form comes from using the environment function (12). The above result has the distinctive feature that the level of environment E appears as a determinant of the equilibrium growth rate, through the productivity effect. This *level* effect suggests a "path dependence" of the growth rate, similar to that found in the theories of endogenous growth, as seen for example in Romer's (1990) treatment of human capital. However, because E is itself determined by the path rather than being exogenous as in Romer's human capital, one will not in general obtain a steady state growth path. A steady state growth path will exist, however, in the absence of the productivity effect of the environment, as will be discussed shortly.

Using the functional forms above, the parameter-specific efficient growth path is found, in analogy to equations (13) as:

$$\left(\frac{\dot{C}}{C}\right)_s = \frac{1}{1-\nu(1-\sigma)}\left([1-\beta\mu(1-\sigma)]A(E) - \rho - \beta EA_E(E) - \frac{\beta\mu}{\nu}\frac{C}{K} + \mu(1-\sigma)\frac{\dot{E}}{E}\right) \quad (14a)$$

or, equivalently, by:

$$\left(\frac{\dot{C}}{C}\right)_s = \frac{1}{1-\nu(1-\sigma)}\left((1-\frac{\beta\mu}{\nu})A(E) - \rho - \beta EA_E(E) + \frac{\beta\mu}{\nu}[1-\nu(1-\sigma)]\frac{\dot{K}}{K}\right) \quad (14b)$$

where equation (12) and the budget constraint $C = AK - \dot{K}$ have been used in the second form. In addition to $1-\nu(1-\sigma) > 0$, seen earlier, we note that ν must exceed $\beta\mu$ if productivity is to be *positively* related to growth. Thus, we shall impose this constraint from here on. Intuitively, imposing this constraint implies that the benefits of growth to individuals, through an increase in consumption, must *dominate* (in elasticity terms) the disutility of growth--via a deterioration in the quality of the environment--brought about by an increase in capital accumulation. Finally, another form of expression (14b) can be derived if the impact of environmental quality on productivity were characterized by a constant elasticity, η such that $EA_E(E)/A(E) = \eta$. Then (14b) can be written as:

$$\left(\frac{\dot{C}}{C}\right)_s = \frac{1}{1-\nu(1-\sigma)}\left([1-\frac{\beta\mu}{\nu} - \beta\eta]A(E) - \rho + \frac{\beta\mu}{\nu}[1-\nu(1-\sigma)]\frac{\dot{K}}{K}\right) \quad (14c)$$

We will first study equations (13) and (14) under a simplifying assumption that yields steady-state paths. Having derived optimal policies instruments, under steady state, we will then relax this condition and look at non-steady-state paths to "explain" observed outcomes.

Steady State Results Under zero Productivity Effect

If environmental quality does not have an appreciable influence on productivity, A will be exogenous and A_E will be zero. Then both the equilibrium and the efficient paths can be characterized by constant (steady-state) growth path in which $\dot{C}/C = \dot{K}/K$. Using this result in equations (13b) and (14b) respectively, the steady state paths of equilibrium and efficient growth are given by:

$$\gamma_e = \frac{1}{1-(\nu-\beta\mu)(1-\sigma)}\cdot(A-\rho) \tag{15}$$

and,

$$\gamma_s = \frac{1}{1-\nu(1-\sigma)}(A - \frac{\rho}{1-\beta\mu/\nu}) \tag{16}$$

Observe that β and μ appear jointly in both equations. An increase in $\beta\mu$ either due to a rise in the environmental decay response, β, or due to a rise in preference bias towards environment, μ, *reduces* both growth rates.[7] Also in (16) the quantity $\rho/(1-\beta\mu/\nu)$ may be thought of as effective discount rate, which is larger than ρ. In effect concern for the environment reduces tendency to accumulate capital by increasing the discount rate. This should not however be interpreted as a preference away from the preservation of the environment since environment is not modeled as a stock here. In addition, to $\beta\mu < \nu$, established earlier, other constraints on the parameters also exist. For example, the denominator of (15) must be positive if γ_e is to be positively related to productivity and negatively to the discount rate. Also, the transversality condition on the stock of capital yields the same condition, $(\nu-\beta\mu)(1-\sigma) < \rho/A$, for both growth paths and this condition in turn

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[7]The denominator of (15) must be positive if γ_e is to be positively related to productivity and negatively to the discount rate.

guarantees that $\gamma_e < 1$.[8]

Although both growth rates γ_e and γ_s fall in β, it can be easily verified that they exhibit *different* curvatures in β, with $\partial^2\gamma_e/\partial(\beta)^2 > 0$, implying γ_e is *convex* and $\partial^2\gamma_s/\partial\beta^2 < 0$, implying γ_s is *concave* in β. Furthermore, since the growth rates are equal at $\beta = 0$ (equaling $(A-\rho)/[1-\nu(1-\sigma)]$), this implies that γ_s lies *above* γ_e for the early range of β and below γ_e for the larger values of β. This result which is depicted in figure 2a, means that a large enough value of β is able to drive the socially desirable rate of growth to zero, even though atomistic agents behave in such a way that the equilibrium rate of growth remains above zero. In any case this pattern of behavior of γ_e and γ_s with respect to β has important implications for the analysis of policy that we will now turn to. Thus,

2. If environment effects utility (and not production), then a low incremental pollution caused by production implies that growth is "too low" from a social point and a high incremental pollution caused by production implies that growth is "too high" from a social point.

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[8]The transversality condition is, $\lim_{t\to\infty} e^{-\rho t}\lambda(t)K(t) = 0$. In the case of equilibrium path, equation (5) yields $\dot{\lambda}/\lambda = (\rho-A)$ or $\lambda(t) = \lambda_o e^{(\rho-A)t}$. Substituting for $\lambda(t)$ and for $K(t) = K_o e^{\gamma_e t}$ into the transversality condition we find this condition is satisfied if $\gamma_e < A$. From equation (15) this inequality implies that:

$$(\nu-\beta\mu)(1-\sigma) < \rho/A. \qquad \text{(a)}$$

In the case of the efficient path, with $F_E = 0$ here, equation (10) also gives $\dot{\lambda}/\lambda = (\rho-A)$, so that we find $\gamma_s < A$. From (16) this yields (a) again.

Finally $\gamma_e < 1$ if and only if $(\nu-\beta\mu)(1-\sigma) < 1-(A-\rho)$. Comparing the RHS of this inequality with the RHS of (a), we find $\rho/A < 1-(A-\rho)$ because $\rho<A$. Thus condition (a) guarantees that $\gamma_e<1$.

1. *Government's Tax/Subsidy Policy in Steady State*

The reason for analyzing the efficient and the equilibrium paths jointly is to design policies and regulations that can take the economy from a suboptimal path prevailing in equilibrium because of market failures, to the socially efficient path. In a sense we can speak of "aligning" the two paths. To illustrate how policy instruments may be used for the purpose of such an alignment, consider a proportional scheme, in which a tax or subsidy is imposed on output (income) at a flat rate of τ where $\tau > 0$, if a tax is imposed and $\tau < 0$, if a subsidy is imposed. The equation for the steady-state equilibrium path (15) is amended as:

$$\gamma_e(\tau) = \frac{1}{1-(\nu-\beta\mu)(1-\sigma)} \cdot \left((1-\tau)A - \rho \right) \tag{15'}$$

Equating this with γ_s in (16) and solving for τ we find:

$$\tau_o = \frac{\beta\mu}{1-\nu(1-\sigma)} - \left(\frac{1}{\nu-\beta\mu} \cdot \frac{\rho}{A} - (1-\sigma) \right) \tag{17}$$

From equation (17) $\tau_o \gtrless 0$, if and only if $\rho \gtrless (1-\sigma)(\nu-\beta\mu)A$, since the denominator is already positive. But subtracting (17) from (16) one also finds that $\gamma_e - \gamma_s \gtrless 0$, if and only if the same condition, $\rho \gtrless (1-\sigma)(\nu-\beta\mu)A$ is imposed. Thus it follows, expectedly, that a Peguvian tax on output would be necessary if the pre-tax equilibrium growth rate exceeded the efficient growth rate; a Peguvian subsidy would be necessary if the per-subsidy equilibrium growth rate was *below* the efficient rate. This result is shown in figure 2b. The tax would then lower γ_e to the level of γ_s for any *given* β, while the subsidy would raise γ_e to the level of γ_s. Since γ_e is below γ_s for the low range of β and above it for high range of β, as shown in figure 2b, it follows

that:[9]

2'. If environment effects utility (and not production), then in the case of a low polluting production process optimal policy implies an output subsidy and in the case of high polluting production process it implies an output tax. Optimality aligns the equilibrium path with the efficient path.

Note that since γ_s maximizes W in equation (1) (say W*), setting τ to equalize γ_e to γ_s allows the welfare level under *prevailing* market conditions to equalize W*. Thus, τ_o is a first best policy instrument, *given* β. But β need not be exogenous and allowing it to be a choice variable may increase the value of W*. This is done in the following sub-section. Here, we shall see how a tax/subsidy policy may be combined with policy of regulating the pollution response β to achieve even a higher welfare level.

2. *Optimal Quantity Restriction-cum-Tax/Subsidy in Steady State*

The parameter β may be viewed an another key policy instrument. For example, it would be desirable for the regulator to seek lower values of β in order to reduce the relative increase in the deterioration of environment quality for given relative increase in per capita income. However, at the

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[9]Note that given a stock of capital K_o, the initial level of consumption under the command economy C_{os} is chosen such as to yield a constant C_{os}/K_o ratio found from γ_s and from the budget constraint, $C/K = A-\dot{K}/K$, i.e., $C_{os} = K_o(A-\gamma_s)$. Under the market economy agents maximize (1) subject to the after-tax (subsidy) budget constraint, $C = (1-\tau)AK - \dot{K} + \bar{T}$, where $\bar{T}$ represents a lump-sum credit (charge) that is fixed to the agents, but variable in the aggregate such that $T=\tau f(K)$. T serves to *restore* the initial "level" effect of the taxes so that the private economy can consume at a level $C_o' = C_o + \bar{T} = C_{os}$ to guarantee the existence of steady-state path. The two paths will then coincide in this case.

firm level, mandating a lower β may be costly to *individual* economic agents because it involves the adoption of more expensive techniques, even as it may improve productivity in the *aggregate* (see below for an example). Since the *ex-anti* decision to employ a technique involves capital in "putty-putty" form, any cost increases from the adoption of more expensive techniques can be translated into less output per capital outlay (dollar invested) and thus into reduced productivity. In sum, the productivity A may fall with β to the individual producers but rise as an externality in the aggregate. We can write this as:

$$A = A[\beta, \overline{E(\beta)}] \qquad A_\beta<0,\ A_E>0 \tag{18}$$

In the context of the example of municipal waste, restricting the extent of industrial dumping per firm may restrict access to easy disposal by individual firms, causing higher costs and reducing productivity per firm, *given* the quality of the environment ($A_\beta<0$). However, as environmental quality improves (in this case landfills fall in size or their content become less harmful to health) labor productivity may rise, thus lowering costs and raising productivity ($A_E E_\beta>0$) as an external effect. This suggests a trade-off on the production side, even in the absence of any consumption effects. Adding consumption effects certainly involve additional trade-offs.

In order to analyze the simple case of steady-state growth, we ignore, for the present, the external productivity effects of the environment (setting $A_E=0$), focusing instead on the trade-offs from the *direct* productivity effects of β versus the consumption effects. This will yield steady-state equilibrium and efficient paths similar to those in equations (15) and (16) but with an explicit dependence of A on β:

$$\gamma_* = \frac{1}{1-(\nu-\beta\mu)(1-\sigma)}\cdot[A(\beta)-\rho] \tag{19}$$

$$\gamma_s = \frac{1}{1-\nu(1-\sigma)}[A(\beta) - \frac{\rho}{1-\beta\mu/\nu}] \tag{20}$$

Note the existence of a trade-off, via β, in both equations. Because of this trade-off, both curves will now exhibit a "peak" in β as opposed to their monotonic decline in β which was the case before.

Although a value of β that maximizes γ_e may be chosen, this value will not maximize social welfare and therefore will not be a first best policy instrument. In this case, We follow a two-staged approach: first, we will chose a β, say $\beta*$, that maximizes γ_s, and in the second stage, we will choose a tax/subsidy rate that equalizes γ_s with $\gamma_e(\tau)$. In analogy with equation (15)' the equilibrium growth path of (19) incorporates a tax/subsidy term:

$$\gamma_e(\tau) = \frac{1}{1-(\nu-\beta\mu)(1-\sigma)}\cdot[(1-\tau)A(\beta)-\rho] \tag{15''}$$

This procedure is depicted in figure (3). The value of β that maximizes γ_s in (20) is given by the first order condition:

$$\frac{\partial\gamma_s}{\partial\beta} = 0 \longrightarrow (1-\beta*\mu/\nu)^2 A'(\beta*) = \mu\rho/\nu \tag{21}$$

The second order condition for this optimum β is satisfied, if $A''(\beta) < 0$.[10] The tax/subsidy rate which equalizes γ_e with γ_s was earlier given by equation (17). Substituting $\beta*$ into this expression, we now find:

$$\tau_o* = \frac{\beta^*\mu}{1-\nu(1-\sigma)}\left(\frac{1}{\nu-\beta*\mu}\cdot\frac{\rho}{A} - (1-\sigma)\right) \tag{17'}$$

This value of τ in effect forces γ_e to intersect γ_s through the maximum of the

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[10]Sign $[\partial^2\gamma_s/\partial\beta^2]$ = sign $[A''(\beta) - 2\rho(\mu/\nu)^2(1-\beta\mu/\nu)^{-3}] < 0$, if $A''(\beta) < 0$.

latter, as shown in figure 3. The figure indicates both a tax and a subsidy case depending on whether the "τ-absent" equilibrium growth curve is above or below γ_s at β^*. The combined $[\beta^*, \tau_o^*(\beta^*)]$ pair will thus induce the market economy to grow along a socially optimal path. To summarize:

3. In steady-state (when considering only utility effects of environment), there exists an optimal level of pollution control which when combined with an optimal tax/subsidy rate, yields a higher social welfare than any optimal tax/subsidy rate, alone.

Thus far, the analysis has been on a normative level, trying to prescribe policies in steady-state. In the next section we move towards a positive approach, trying to use optimal regulatory behavior in "explaining" evidence.

IV. OPTIMAL POLICIES AND CHANGING PREFERENCE STRUCTURE: "EXPLAINING" CROSS-SECTIONAL EVIDENCE

The analysis of the previous section focused primarily on steady-state path. But this outcome is possible only if there is no effect of environmental quality on productivity. Evidence suggests that this oversimplification may not always hold. For example, many environmental factors which effect health will probably effect labor productivity which in this model (in which variables are implicitly in per capita terms) shows up as A in the production function. Thus, to explain the evidence, we must begin with this fuller and more realistic model is which A_E is not zero.

Using the parameterized form of $E=E_oK^{\beta}$, the equilibrium and the efficient paths are given from equations (13) and (14), but with the direct effect of β on productivity also incorporated [i.e., replacing $A(E(\beta))$ with $A(E(\beta),\beta)$]. It is clear here that because neither path is in steady-state, no parametric

time-independent value of tax or subsidy may be found--unlike the previous section--that equates the two paths. Thus, the path γ_s is no longer accessible to the regulator through a tax/subsidy scheme. Here, then we shall pursue a (second best) policy of choosing β to maximize γ_e rather than to maximize γ_s. This is consistent with the goal in this section, which is to explain *actual* or observed pattern, rather than to find what a first best policy ought to be.[11]

Using the budget constraint to express $\dot{K}/K$ as A-C/K in (13b) and expressing the direct effect of β on A we have:

$$\left(\frac{\dot{C}}{C}\right)_e = \frac{1}{1-\nu(1-\sigma)} \cdot \left(\{A[E(\beta),\beta]\} - \beta\mu(1-\sigma)\} - \rho + \beta\mu(1-\sigma)\frac{C}{K} \right) \tag{22}$$

The explicit appearance of β here implies trade-offs between the growth-inhibiting effect of a higher β, via its external effect on the environment and thus productivity $A[E(\beta),..]$, and via consumption effect (last term in 22), *versus*, and the growth-enhancing effect of higher β, via the direct productivity effect of β, $A(..,\beta)$. Thus, a value of β to maximize the expression on the right hand side of (22) may be potentially available.

Although the ratio C/K in (22) is endogenous and changes over time, we assume that C/K is given *within* each country at any point in time but varies across countries. This is justified because we would like to use equation (22) to explain *cross-sectional* evidence consistent with figure 1, at a point in time, rather than the evolution of pollution over time per country. In other words, although an alternative approach is available in which the instrument (β) is a *control* variable whose *dynamic* path is subject to choice,

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[11]In other words, maximizing the efficient path, becomes "irrelevant" in the positive sense of "explaining" actual patterns.

such an approach would be appropriate for an understanding of how pollution and optimal policy evolve over time for a *given* country, rather than an explanation of *cross-sectional* evidence, at a point in time. The present contemporaneous treatment of the policy instrument, besides analytical simplicity, is better suited for the latter purpose.

Given this background, the first order condition in (22) in this contemporaneous approach yields[12]:

$$\frac{\partial(\frac{\dot{C}}{C})_e}{\partial\beta}\Big|_{\overline{C/K}} = 0 \longrightarrow [A_E E_\beta + A_\beta][1-\beta\mu(1-\sigma)] - \mu(1-\sigma)(\overline{C/K} - A) = 0 \qquad (23)$$

Specifying the effects of environment E and the elasticity parameter β on productivity is the next task. Assume a constant elasticity form as follows:

$$A = A_o E(\beta)^{\eta}.\beta^{\theta} \qquad (24)$$

where η is the response of productivity to environmental quality, which was introduced in equation (14c), and θ is the response of productivity to changes in the policy parameter β (itself the response of environment to industrialization). Then, equation (23) becomes:

$$(\theta/\beta^* - \eta \ln K)[1-\beta^*\mu(1-\sigma)] = \mu(1-\sigma)(1- APC) \qquad (25)$$

where *APC* is the average propensity to consume, C/AK. As in the case of C/K ratio, both *APC* and capital stock K are assumed to be given *data points* per

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[12]The second order condition is:

$$\frac{\partial^2(\frac{\dot{C}}{C})_e}{\partial\beta^2}\Big|_{\overline{C/K}} = -A(\beta)\Big((\theta/\beta^2[1-\beta\mu(1-\sigma)] + \mu(1-\sigma)(\theta/\beta - \eta \ln K)\Big) + A_\beta \frac{\partial(\frac{\dot{C}}{C})_e}{\partial\beta}\Big|_{\overline{C/K}}$$

The second term is = 0 at β^*. Hence the second order condition is locally satisfied.

country at a given time. Thus, the discussion involving C/K applied to C/AK and K as well. Equation (25) is then the first order condition for optimum β. Note that since the right hand side of (25) is positive, and since $\beta\mu(1-\sigma) < 1$[13], it follows that:

$$\theta/\beta^* - \eta \ln K > 0. \tag{26}$$

Case of Constant Preferences

The parameter μ represents the degree to which individuals care for environment quality. In the present subsection we assume μ is constant, and explore change in the quality of the environmental as a function of accumulation, K. First, using inequality we show that $d\beta^*/dK < 0$, i.e., that countries at higher levels of development find it necessary to apply a more strict regulatory policy. To see this implicitly differentiate (25) in K to find:

$$\frac{d\beta^*}{dK} = - \frac{\eta[1-\beta^*\mu(1-\sigma)]}{\theta/\beta^{*2} - \eta\mu(1-\sigma)\ln K} \tag{27}$$

Now, the denominator of (27) can be written as, $\theta(1-\beta^*\mu(1-\sigma))/\beta^{*2} + \mu(1-\sigma)(\theta/\beta^* - \eta \ln K)$. By the inequality $\beta\mu(1-\sigma) < 1$, as was just shown, and by the inequality (26), both the denominator and numerator are positive and thus,

$$\frac{d\beta^*}{dK} < 0.$$

4. *Optimum Regulation on environmental Quality is more strict the higher is per capita capital stock, representing higher per capita income.*

We recall that the quality of the environment E is inversely related to

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[13]Recall that $\beta\mu < \nu$. Multiply both sides by $1-\sigma$ which is positive because $U_{CE} > 0$, as discussed earlier. Thus, $\beta\mu(1-\sigma) < \nu(1-\sigma)$. But recall that $\nu(1-\sigma) < 1$, as $U_{CC} < 0$. It follows that $\beta\mu(1-\sigma) < 1$.

the flow of pollutants X. Since $E = E_o K^{-\beta}$, it follows that:

$$X = X_o K^{\beta} \tag{28}$$

where X_o is some constant. In an economy characterized by a *given* preference structure μ (later, we relax this), the optimal pattern of pollution X* is found by solving β^* in terms of K from (25) and then substituting into equation (28). That is:

$$X^* = X_o K^{\beta^*(K)} \tag{29}$$

To see how the flow of pollutants X changes across countries as capital stock rises, differentiate (29) in K:

$$\frac{dX^*}{dK} = K^{\beta^*(K)} \left(\underset{(-)}{\frac{d\beta^*(K)}{dK}} + \underset{(+)}{\frac{\beta^*(K)}{K}} \right) \tag{30}$$

As indicated by the signs in parenthesis it can be seen that this effect is the result of two opposite effects; increased pollution at higher capital levels of accumulation (second term) and more strict regulation at higher levels of accumulation. To see the outcome of these two terms, substitute for $d\beta^*/dK$ from equation (27). Upon simplifying we find:

$$\frac{dX^*}{dK} = K^{\beta^*-1} \left(\frac{\theta/\beta^* - \eta \ln K}{\theta/\beta^{*2} - \eta\mu(1-\sigma)\ln K} \right) > 0. \tag{31}$$

That this expression is positive follows from both numerator and denominator being positive (from inequality 26 and the discussion following equation 27) This result is of course derived for the case where the preference structure μ is constant. In terms of equation (30) this shows that for constant μ the size of the second term dominates the first, at all levels of K, i.e.,

$$\frac{\beta^*(K)}{K}\Big|_{\bar{\mu}} > \frac{d\beta^*(K)}{dK}\Big|_{\bar{\mu}} \qquad \forall\ K \tag{32}$$

Under these circumstances, no matter how restrict is regulatory policy, pollution rises at higher levels of per capita income, replication the results of figure 1-row 3. Thus,

5. When preference structure is constant, pollution shows an increase at higher levels of per capita income because no increase in the extent of optimal regulation is sufficient to induce a "turn around" in the upward sloping curve.

From figure 1, increased municipal waste shows such a pattern. Assuming rationality on the part of governments, such an outcome would result if individual citizens in each country did not show an increase in their degree of concern for municipal waste. Such an explanation may well be plausible in comparison with the other two indicators in figure 1. In both those other cases the type of pollutant involved (SO_2 or lack of safe water) affects individual health and well being *more visibly* that may be the case in the instance of municipal waste. As it turns out (below), only when preference structure also changes, tending towards increasing care for the environment (rising μ as a function of K), is it possible to find patterns similar to those found in the other two rows of figure 1, corresponding to an improvement in environmental quality at some point (or at all point) in the path of development. This will be studied presently. However, before we turn to the case of changing preferences, a numerical simulation of the results for the case of constant preferences illustrates the finding of equation (31).

In this case we depict X* as a function of per capita income ranging from

the poor to the rich countries.[14] The results, depicted in figure 4 for values of parameters, $\mu = .5$, $\sigma = .5$, $\eta = .5$, $\theta = .1$ and APC = .6, show that X* rises as a function of per capital income, in accordance with the evidence. Although the concavity of the curve in figure 1 (i.e, X* rising at a diminishing rates) is not seen shared by the evidence in the third row of figure 1, we note that the underlying empirical regression line for the graph in figure 1 is logarithmic, and is therefore also concave.[15]

Case of Endogenous Preferences Evolving with Accumulation

Suppose that preferences tend towards cleaner environment as per capita income rises. This can be indicated by allowing μ to be a *slowly* increasing function of per capital accumulation, K. Evidence indicates that income elasticities of goods do not change rapidly as countries become richer. Thus,

$$\mu = \mu(K) \qquad \mu'(K) > 0, \text{ but small} \tag{33}$$

The logic governing the role of μ in our analysis is similar to that for K.

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[14]In 1990, per capital GNP across the world ranged from $ US 100 to $ US 30,000 and the share of investments in GDP ranged from .4 for poor countries to .2 for the high income countries (World Bank, 1992, tables 1 and 9). Assuming a 10 year depreciation rate, this yields capital output ratios ranging from 4 for low income countries to 2 for high income countries. Thus, K = (K/GDP)GDP corresponds to the range of $ 1200 to $ 60,000 or 1 to 50. Values of X* are thus generated for K=1...50 and depicted against GDP/capita in logarithmic scale.

[15]The empirical basis of figure 1, is the work by- Shafik, N. and S. Bandyopadhyay (1992) , "Economic Growth and Environmental Quality: Time Series and Cross-Country Evidence," Working Paper, World Bank (WPS 904). In the case of municipal waste the authors find the form, E = a + b.ln(Y) + c.time (where Y = per capita income) to be yield the best fit.

In particular equation (33) means that μ varies across countries (very slowly) but is given to the policy maker at any point in time. The first modification to be made is the impact of accumulation K on regulation β With $\mu' > 0$, differentiating equation (25) leads to an additional negative term in numerator of equation (27):

$$\frac{d\beta^*}{dK} = \frac{-\eta[1-\beta^*\mu(1-\sigma)] - \mu'[(1-APC)+\beta(1-\sigma)(\theta/\beta-\eta\ln K)]}{\theta/\beta^{*2} - \eta\mu(1-\sigma)\ln K} \qquad (27)'$$

It is clear that $d\beta^*/dK$ in (27)′ is still negative and even *larger* in absolute value than in equation (27). This means that as incomes increase, optimal level environmental regulation now becomes more strict, not only to counter the increasing pollution caused by more output, but also as a result of rising preferences rise towards a cleaner environment.

4′. Result 4 remains valid and is even more pronounced when preferences evolve towards cleaner environment.

This is not surprising and can be seen from the fact that β^* itself declines as μ rises. This is seen by implicitly differentiating (25), given K, to find: $\partial\beta^*/\partial\mu|_{\bar{K}} = -\beta^*(1-\sigma)(\theta/\beta-\eta\ln K) < 0$.

With β^* declining faster with higher K now, is it possible to find a reduction in the optimal flow of pollution X* as K increases? To answer this question first, we substitute for $d\beta^*/dK$ from equation (27)′ into (31) to find that,

$$\frac{dX^*}{dK} = K^{\beta^*-1}\left(\frac{\theta/\beta^* - \eta\ln K - \mu'[(1-APC)+\beta^*(1-\sigma)(\theta/\beta^*-\eta\ln K)]}{\theta/\beta^{*2} - \eta\mu(1-\sigma)\ln K}\right) \qquad (31)'$$

Now in the numerator of (31′) $\theta/\beta^* - \eta\ln K > 0$, but preference response μ' shows

up through a new negative term. Analytically, this increases the chance that X* can be a *decreasing* function of μ. Empirical simulation of this result is carried out for values of μ that increase gradually with per capita accumulation and thus income, but for the same set of parameters as before. This is depicted in figures 5 and 6. It is found that when incremental increases in μ are large relative to its initial value, pollution flow *falls at all levels of income* (figure 5); when such initial increases are smaller relative to its original value pollution exhibits an *inverted U effect* with respect to income (figure 6). The actual values used are $\mu = .3 + .01K$ for figure 5, and $\mu = .5 + .001K$ for figure 6. To summarize.

5'. When preference for a cleaner environment increases as a function of higher per capita income, optimal regulation becomes more strict than in result 5. This increase in regulation is sufficient to render pollution either decreasing at all level of income, or induce a "turn around" in the upswing of the curve. Which outcome entails depends on the speed with which preferences adjust towards cleaner a environment.

To corroborate this result with actual evidence, note from figure 1 that the contamination of the water and sanitation, which decline in per capita income in conformity with figure 5, are likely to experience a rapid rise in the degree of concern as per capita incomes rise, since they impact households so readily and directly. On the other hand, SO_2 and suspended particles do not rise in environmental consciousness as rapidly and thus for some time as countries develop the effect of development on increasing pollution dominate before environmental concern rise sufficiently high to yield a stricter regulatory standard and to induce a "turn-around" in the curve.

V. SUMMARY AND CONCLUSION

We have used a simple dynamic macro-model in which enivronment enters into the agents' utility and production functions to (a) investigate the prospects of long run economic growth and normative optimal policy design, when the quality of the environment is considered, and (b) to "explain" (in the positive sense) the actual pattern of change in environmental quality as a function of per capital accumulation and income.

With respect to task (a) the paper first derives the equilibrium or market driven path, emerging from resulting from the behavior of the atomistic agents. It also derives the efficient path, emerging from internalizing the aggregate environmental affects. It then devises first best policy instruments, aimed at aligning the two paths under steady-state. Two main instruments considered are Peguvian taxes and quantity controls on pollution.

With respect to task (b) the paper reverts to the more general non-steady-state and show how the pattern of change in the quality of the environment, such as that observed in figure 1, is consistent with the optimizing behavior of the regulators. A key and interesting determinant of how optimal policies are able to generate the observed pattern of pollution is the role of preference structure as it evolves, with accumulation and development, towards greater concern for the quality of the environment.

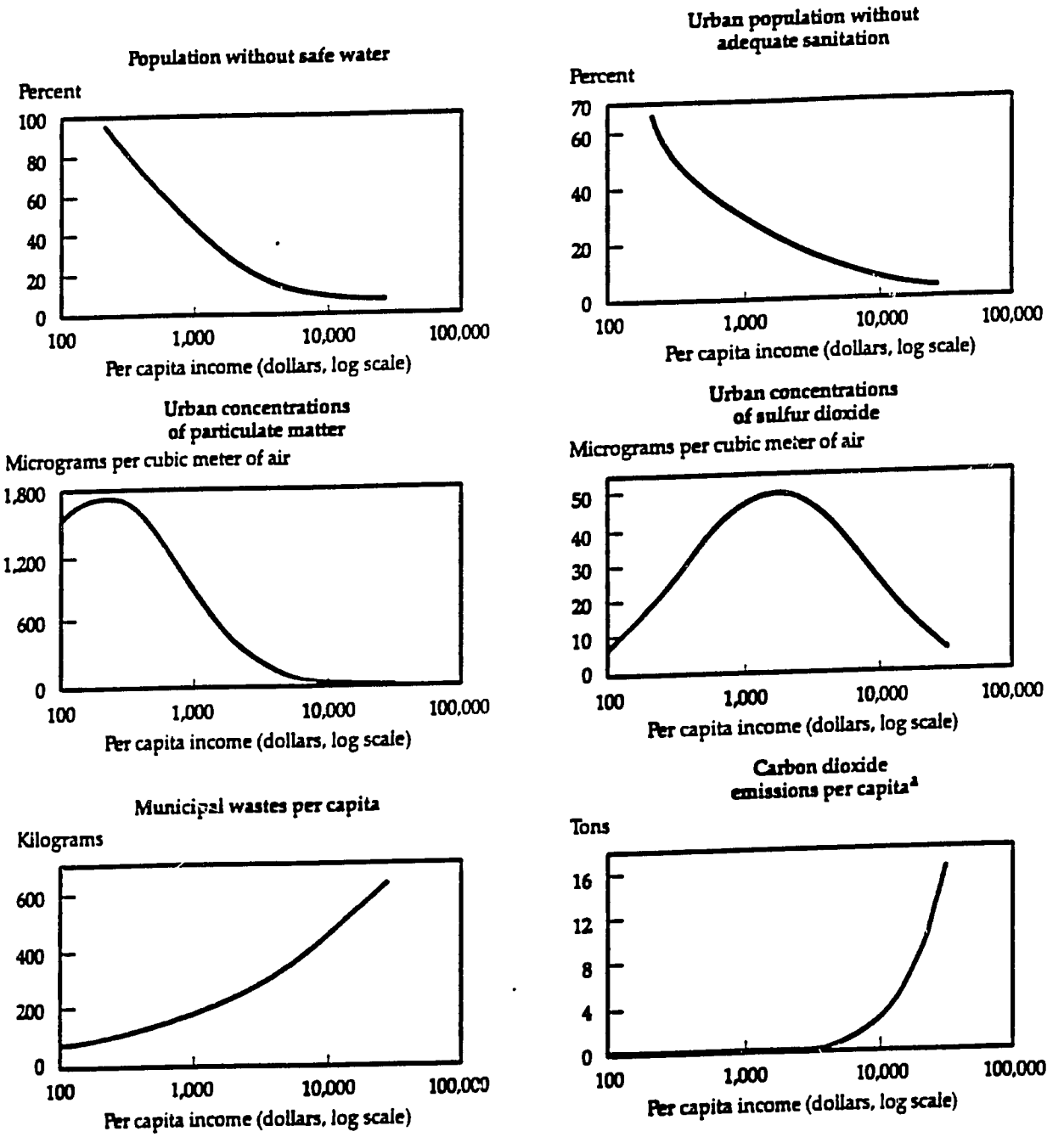
Not all environmental indicators need to follow the three alternative patterns of figure 1. However, these are certainly important indicators of the environment. Moreover, a important contribution of this paper is not its claim to have explained *all* patterns of environmental change as a function of per capita income, but rather to focus on the interaction between two concepts, preference structure and optimal policies. This is important because the literature often stresses one factor or the other, but not the

two. Furthermore, to the author's knowledge this is the first paper of its kind to try to "explain" observed pattern using optimal control theory.

In using the model--in one part of the paper--to produce results compatible with cross-sectional evidence, we have designed optimal policies corresponding to a *given* capital stock and consumption/capita ratios at any point in time. Although an alternative approach is available in which the instrument (β) is a *control* variable whose *dynamic* path is subject to choice, such an approach would be appropriate for an understanding of how pollution and optimal policy evolve over time for a *given* country, rather than an explanation of *cross-sectional* evidence, at a point in time. The present contemporaneous treatment of the policy instrument, besides analytical simplicity, is better suited for the latter purpose.

Figure 1

Environmental problems may worsen or improve with income growth; some worsen, then improve



Note: Estimates are based on cross-country regression analysis of data from the 1980s.

Source: World Bank, World Development Report, 1992, p. 11.

Growth as a function of pollution response to output

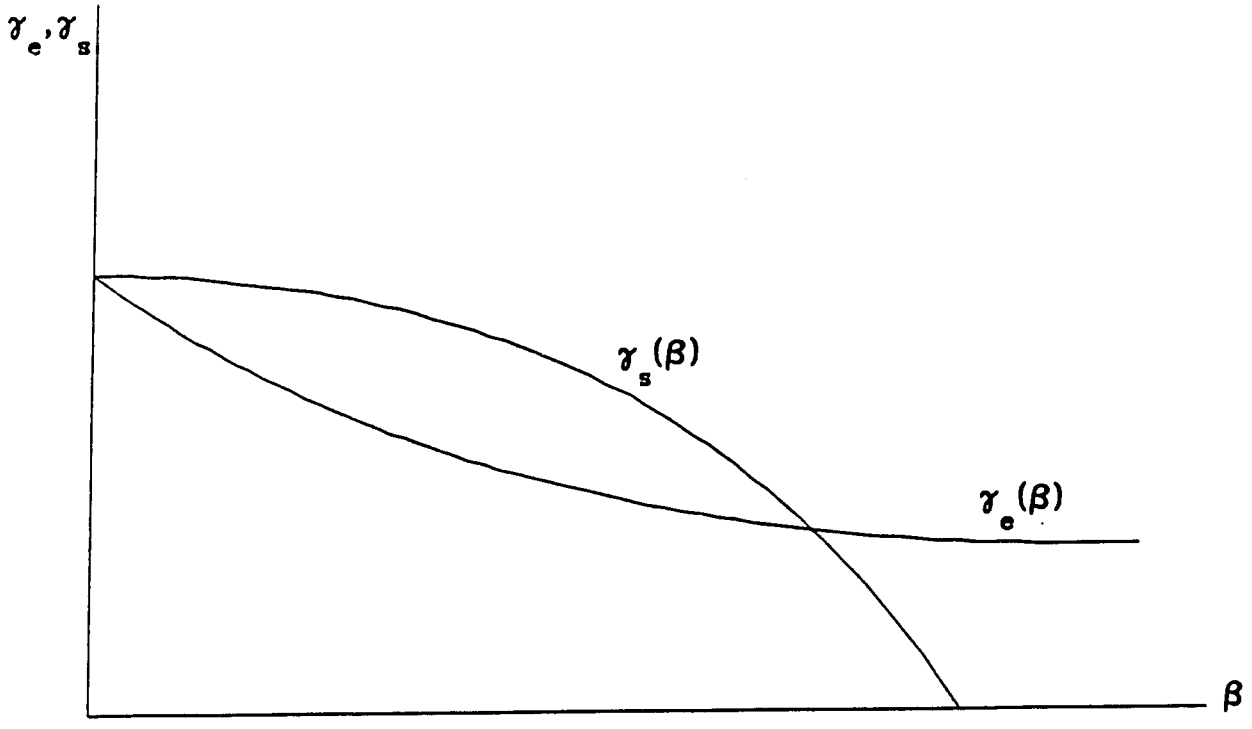


Fig 2a

Region of taxes VS subsidies

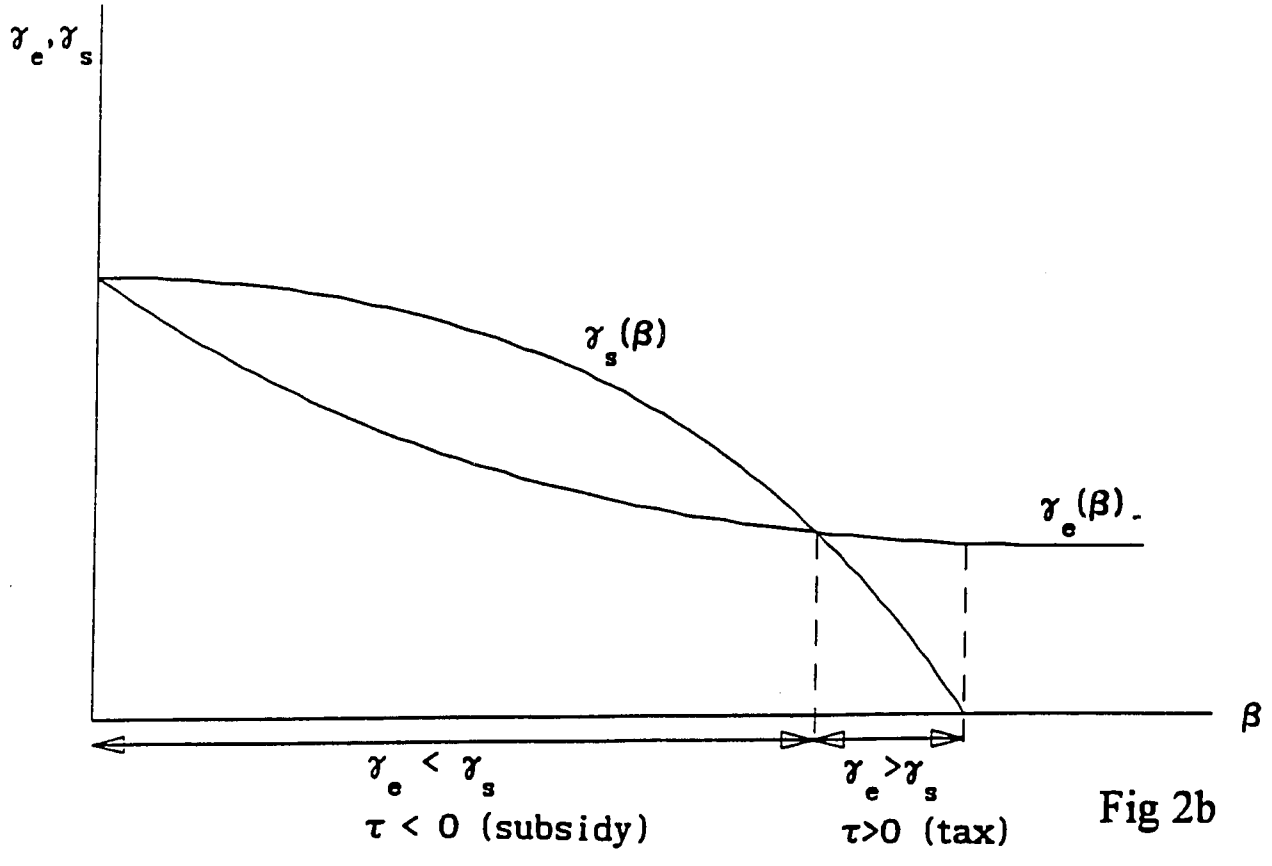
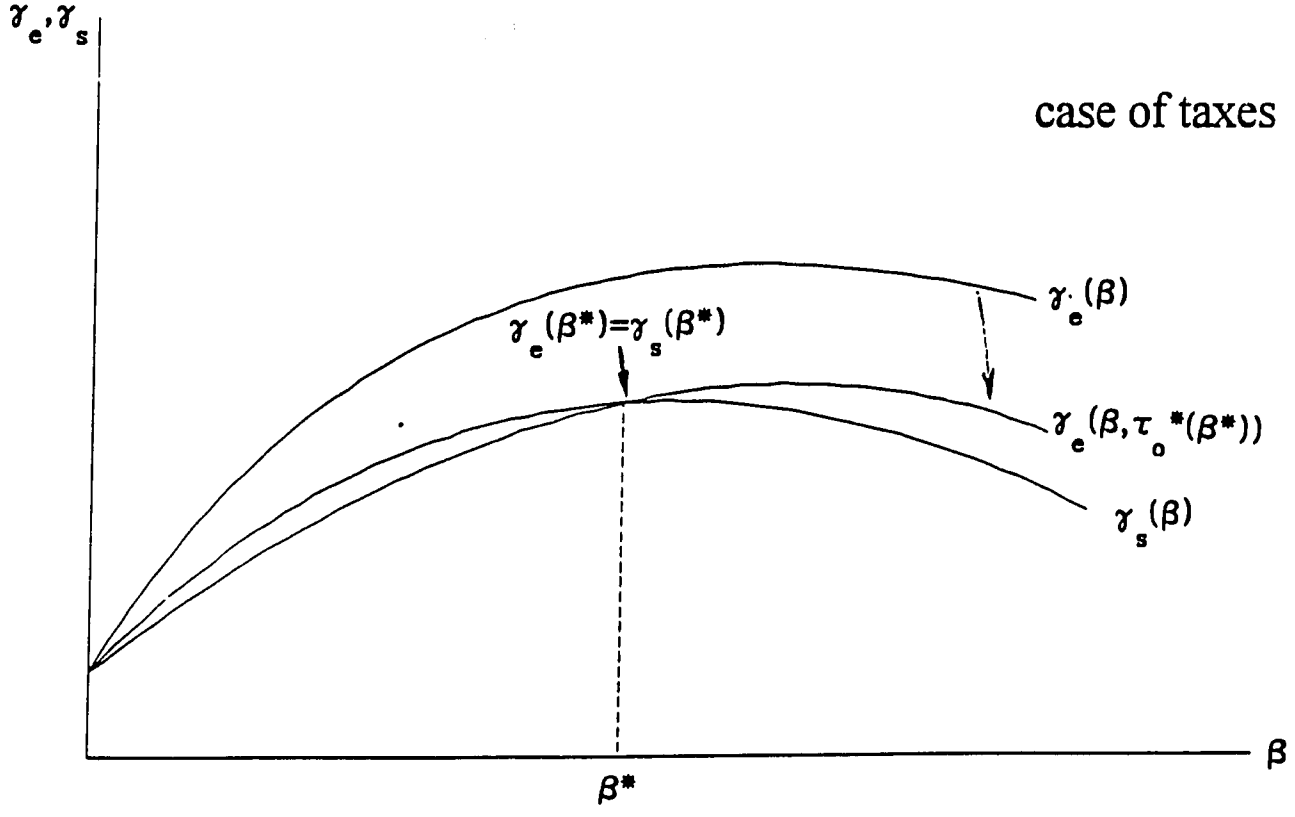


Fig 2b

Optimal pollution Control-cum-tax (subsidy) scheme



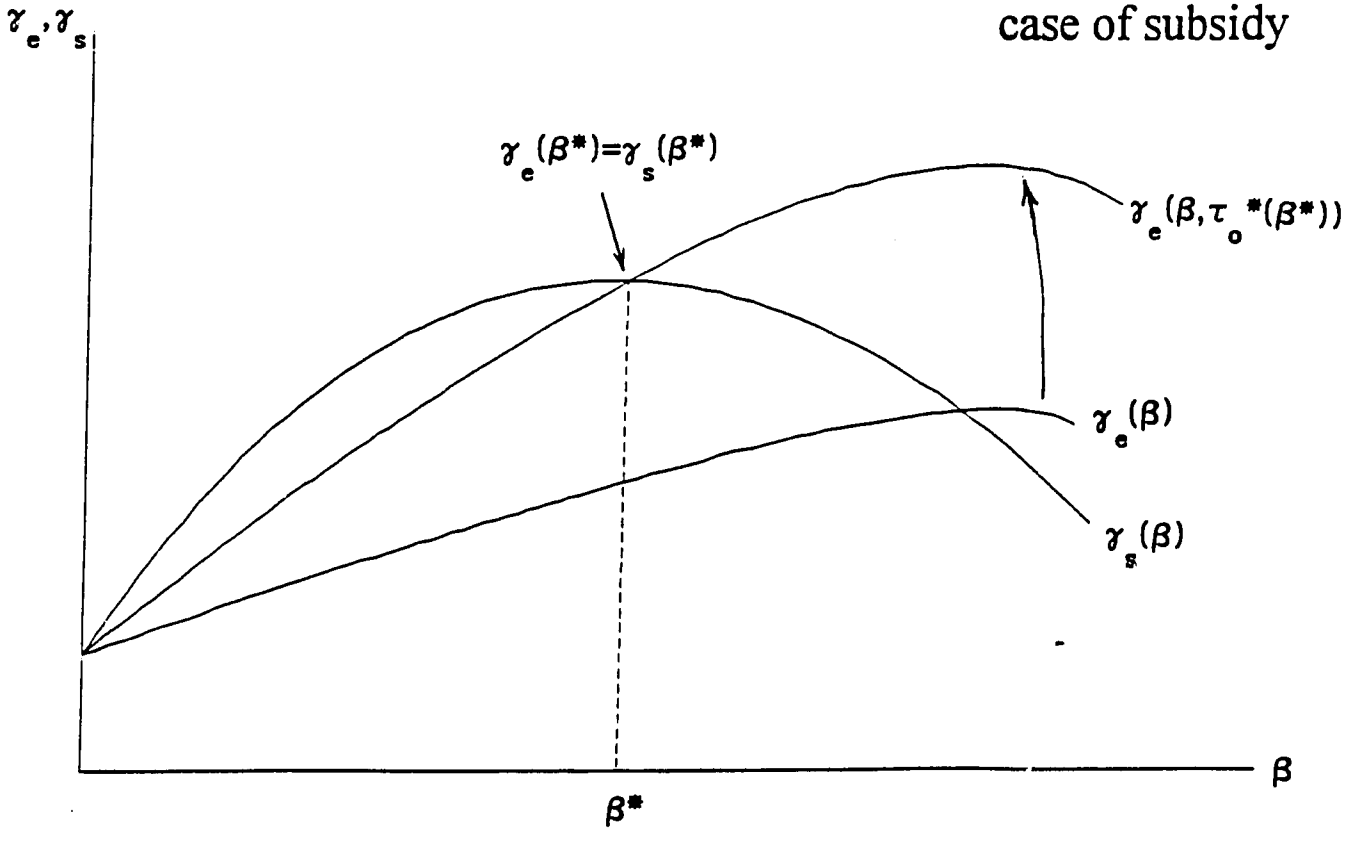


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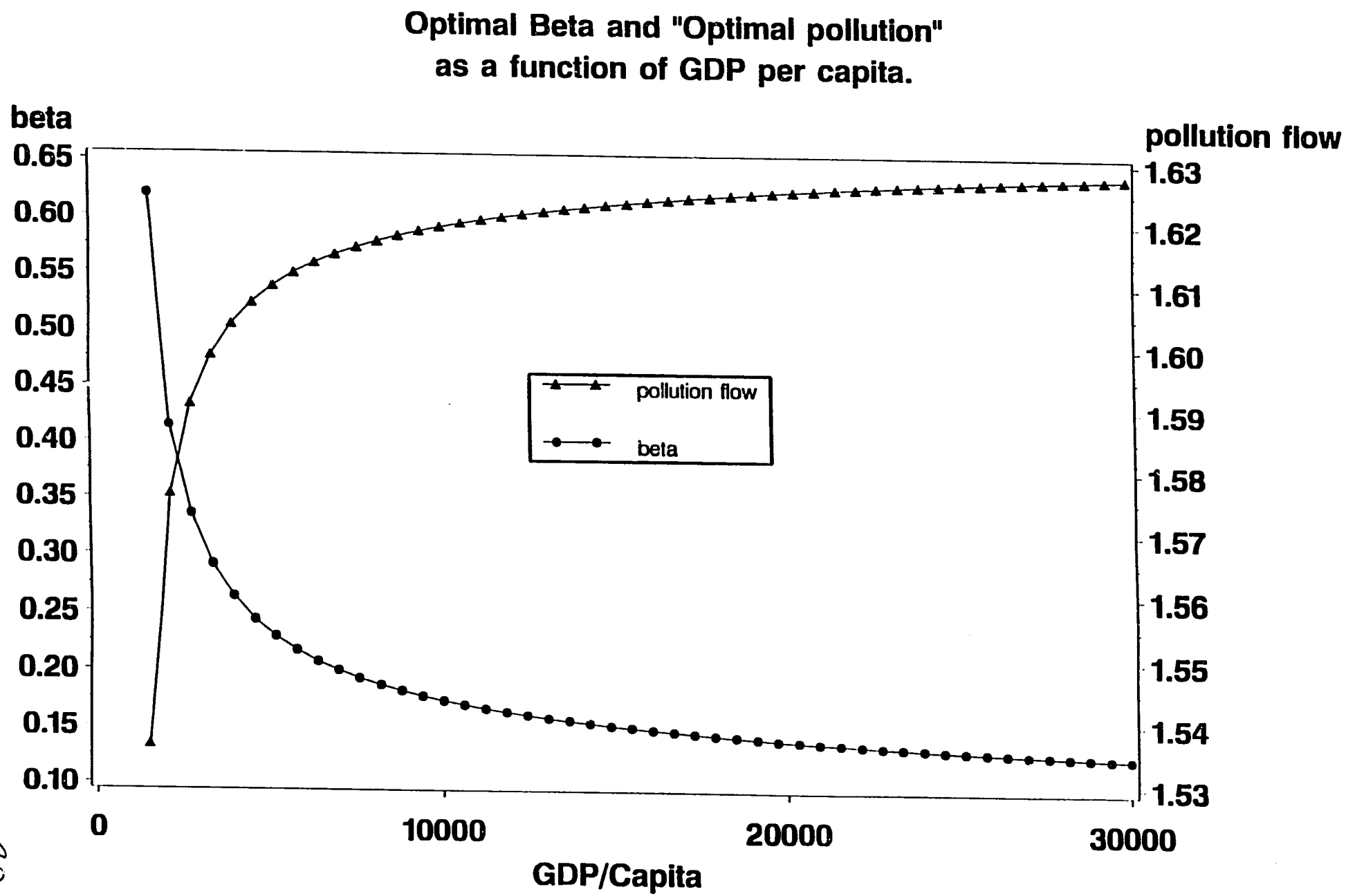
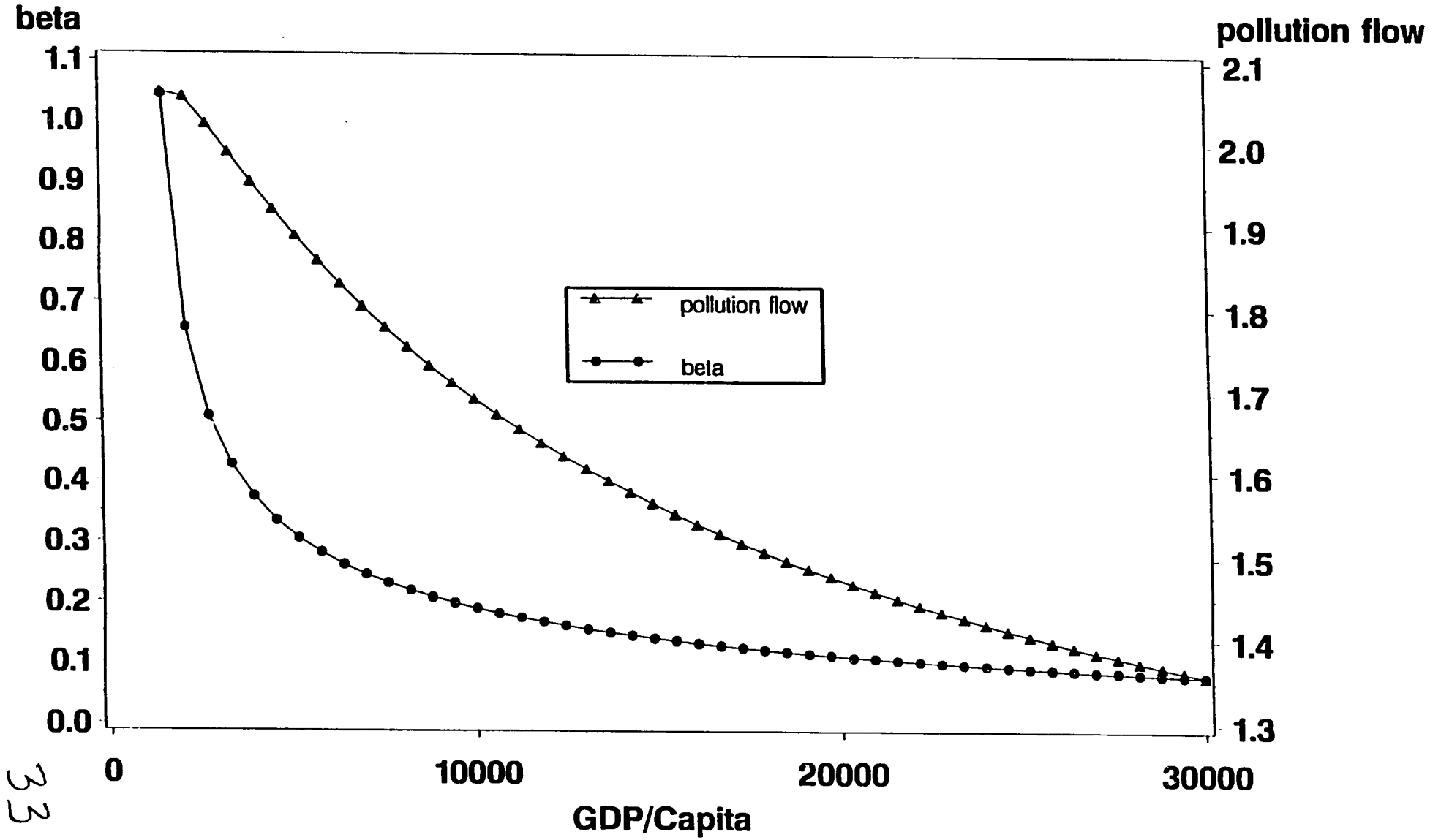
Fig 3



mu = 0.5

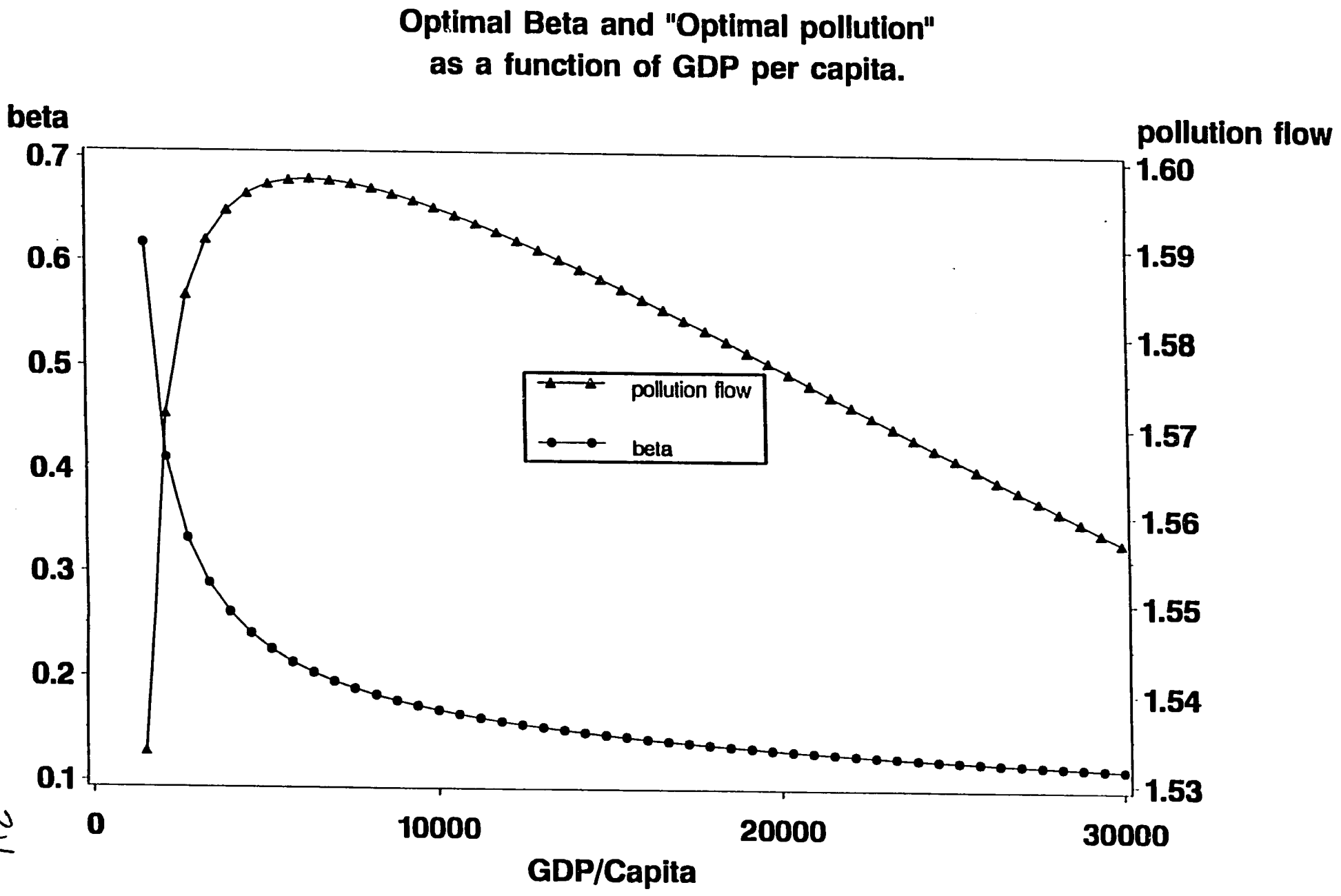
Figure 4

Optimal Beta and "Optimal pollution" as a function of GDP per capita.



mu = 0.3 + 0.01*K

Figure 5



mu = 0.5 + 0.001*K

Figure 6

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