The Environmental Kuznets Curve from Multiple Perspectives

William K. Jaeger and Van Kolpin

NOTA DI LAVORO 38.2008

APRIL 2008

CCMP – Climate Change Modelling and Policy

William K. Jaeger, *Department of Agricultural and Resource Economics, Oregon State University*
Van Kolpin, *Department of Economics, University of Oregon*

The Environmental Kuznets Curve from Multiple Perspectives

Summary

The analysis finds that in addition to U-shaped paths of environmental quality arising for growth in income per capita, growth in population can also produce socially efficient patterns that are U-shaped. Sufficient conditions for both types of paths are identified for a range of models and parameters, including symmetrical models with homothetic, constant-returns functions such as with CES functions. Similar results are also shown to arise in decentralized economies under either homogeneous or heterogeneous income levels.

Keywords: Environmental Kuznets Curve, Economic Growth, Environmental Quality

JEL Classification: Q2, D61, O13

The authors are professors in the Department of Agricultural and Resource Economics, Oregon State University and the Department of Economics, University of Oregon, respectively.

We are grateful to the participants in a FEEM seminar in Milan, Italy in November 2007 for their comments and suggestions.

Address for correspondence:

William K. Jaeger
Department of Agricultural and Resource Economics
Oregon State University
213 Ballard Extension Hall
Corvallis, OR 97331-3601
USA
E-mail: wjaeger@oregonstate.edu

I. Introduction

The relationship between economic growth, natural resources, and environmental quality has been the subject of debate for centuries. The contemporary view that, if the economy is growing then so must environmental degradation, was advanced by Boulding (1966) and formalized in the materials-balance model of Ayres and Kneese (1969). More recently the "neo-Malthusian" view has emphasized the fragility of the environment and the impact of economic and population growth on the natural capital stock. Beginning in the early 1990s, however, empirical evidence began to emerge suggesting a U-shaped relationship between environmental quality and per capita income. This so-called "environmental Kuznets curve" suggested that environmental quality might first decline, and then improve, with rising per capita income (Grossman and Krueger 1993; World Bank 1992; Copeland and Taylor 2003),[1] and evidence of a U-shaped pattern for growth in population was observed by Patel, Pinckney and Jaeger (1995).

The idea of an environmental Kuznets curve has elicited conflicting reactions. The strength of the empirical evidence has been studied extensively, but the results of those investigations have been inconclusive. Despite support for evidence of the relationship for some pollutants (Grossman and Krueger 1993; Panayotou 1993; Selden and Song 1994; Shafik and Bandyopadhyay 1992), others have reexamined the evidence and raised doubts about the findings (Stern and Common 2001; Harbaugh, Levinson and Wilson 2002; Millimet, List and Stengos 2003), while others question the generality of the pattern across different types of pollutants (Bradford, Schlieckert and Shore 2000; Chimeli 2007, Chimeli and Braden 2005) and the robustness of the empirical EKC relationships (Galeotti, Manera and Lanza, 2006; Deacon and Norman 2006; Perman and Stern 2003).

Among the issues raised are questions about the value of using reduced-form models that abstract from any underlying growth-environment relationships, and also whether conflicting empirical findings for different types of pollution caste doubts on the existence of the phenomenon generally. For overviews and surveys of the literature, see Stern, Common and Barbier (1996), de Bruyn (2002), Copeland and Taylor (2003) and a special issue of Ecological Economics (vol. 25, 1998).

Evidence of these U-shape patterns spawned considerable speculation as to its underlying causes, including the suggestion that it is an artifact of structural changes in an economy as it passes through "stages of development" from agrarian to industrial where there is often a reliance on heavy, highly-polluting industries, and subsequently to high-income service and information economies which are inherently less polluting (e.g., Panayotou (1993)). A second explanation suggests that environmental quality is a "luxury good" emphasizing the role of a high income elasticity of demand for environmental amenities to lead countries to allow increased pollution as an acceptable side effect of economic growth (e.g., Arrow et al. (1995)). The implication of this second argument cautions against the interpretation that economic growth may be good for the environment, since the empirical evidence may simply reflect an international redistribution of pollution and polluting industries between relatively richer and relatively poorer nations, consistent with the so called 'pollution havens' hypothesis.

Beginning in the mid-1990s a number of explicit theoretical models have illustrated several possible underlying mechanisms that can give rise to a U-shaped pattern for rising per capita income. According to Copeland and Taylor (2003), each of these models involves some restriction on either preferences or technology in order to generate the desired shape of the income-pollution path. The mechanisms by which these U-shape paths emerge are classified by

Copeland and Taylor as involving either income effects, threshold effects or increasing returns to abatement.[2]

For example, in the case of income effects, Lopez (1994) has demonstrated that when preferences are non-homothetic, a U-shaped pattern can emerge with rising per capita income provided that the income elasticity of the environmental good is sufficiently large. This provides formal treatment of the idea that when the environment is a luxury good, demand will rise at high income levels. Lopez also demonstrates, however, that when preferences and production are homothetic that monotonically rising pollution can be expected.

The threshold effects class of models involves an initial range of income levels over which no abatement takes place. After some threshold has been breached, abatement begins to be implemented and pollution declines with rising income provided appropriate assumptions about technology and tastes. The models in John and Pecchino (1994), Seldon and Song (1995) and Stokey (1998) fit into this class. In Pfaff, Chaudhuri and Nye (2003) a similar result is developed under alternative assumptions about available 'clean' production techniques given Cobb-Douglas preferences.

The third class involves increasing returns to abatement, for which Andreoni and Levinson (2000) use a simple model with increasing returns in abatement. As income rises and the scale of the economy grows, the relative cost of abatement declines relative to the cost of goods production. This attribute of technology produces a reversal from rising pollution toward declining pollution.

Thus, for all three classes of models, then, there is a "built-in" asymmetry or curvature in preferences or in production which allows for a shift in outcomes away from pollution inputs or goods and toward non-polluting inputs or goods as growth proceeds, and this leads to the possibility of a U-shaped trajectory. These examples offer important insights, yet it remains unclear how prevalent it may be to expect U-shaped patterns in the real world given the apparent requirement of asymmetries which make this possible. In our analysis below, we demonstrate that such asymmetries are not necessary to produce a U-shaped path.

In addition, the existing literature has yet to evaluate the role of growing population as a component of economic growth and the environment, so that they offer a limiting characterization of observable contemporary growing economies which tend to exhibit both rising income per capita and rising population. Indeed, although a number of these papers include explicitly dynamic processes where growth in income is endogenous, none has incorporated population growth, whether deterministic or endogenous, into these dynamic relationships.[3]

The current analysis builds on these recent contributions by including changes in population along side changes in income per capita as potential determinants of the environmental path. Moreover, we appeal to a framework in which both preferences and production technologies of arbitrary generality may be considered when examining the effects of economic growth on environmental quality. With this approach we extend the insights gained in the existing literature by identifying general conditions under which economic growth attributable to changes in essentially any set of economic parameters may lead to the improvement of environmental quality or, alternatively, its decline. We go on to consider decentralized economies and income inequality.

Our analysis finds that a U-shaped pattern is possible with growth in population (holding income per capita constant), and for growth in income per capita (holding population constant) – although the conditions for a U-shaped path arise in the case of rising population is found generally to differ from the conditions found in the case of rising income per capita. These results are obtained for a range of parameter values in conventional models, including standard symmetrical models involving homothetic, constant-returns to scale functions, such as simple CES models. These results are found to arise in part because environmental resources are characterized as "endowments" which tend to be relatively abundant initially, but become relatively scarce as growth proceeds, a shift which creates the possibility of a U-shaped path – an observation also noted by Pfaff, Chaudhuri and Nye (2003). Moreover, these results indicate plausible U-shaped trajectories for decentralized economies under either homogeneous or heterogeneous income levels.

In the next section we develop our general model and results for growth, addressing increasing income per capita separately from rising population. In section III we consider decentralized economies (that is, ones where government controls, coordination or collective action are assumed to be impossible or prohibitive in cost), as well as for equal and unequal per capita income levels. In the last section the interpretations and implications of our results are discussed.

II. General Methods and Results

We begin by introducing a general framework for analyzing the tradeoffs made between environmental quality and consumption in contexts of evolving social parameters such as per capita income, population levels, and resource endowments. A simple static framework is employed to explore these relationships, where environmental damage is assumed to be short-lived and stock effects can be ignored. This simplifying assumption will be a reasonable one for some kinds of air and water pollution which dissipate relatively quickly, but will be less satisfactory for biological resources which regenerate slowly, or for long-lived stock pollutants as in the case of climate change. These results will also be relevant to situations in which government decision makers themselves only have short run objectives. In that case, the behavior of a myopic social planner with regard to long-lived stock pollutants would be similar to that of a farsighted planner with short lived pollutants, assuming the single period structure is indistinguishable.

The absence of environmental stock effects eliminates the need for a social planner to be forward-looking in terms of the environment. And we will abstract from the determinants of economic growth itself (including rising income and population) by assuming that there is an exogenous path of changes in "basic economic parameters" which in turn have a strictly monotonic impact on income and/or population. We further assume that agents have identical preferences and, as a starting point, equal incomes. With these assumptions, a representative household approach implies that we can ignore intergenerational conflicts as well.

Consider a population of identical consumers whose preferences over environmental quality e and private consumption c may be characterized by a strictly concave utility function; where e and c are assumed to be univariate for expository clarity. Letting $\boldsymbol{\sigma}$ represent the profile of social parameters relevant to production possibilities, we define $P(\boldsymbol{\sigma})$ to be the set of all (c, e) profiles that can feasibly be achieved for a representative consumer through some public policy, collective action, or other coordinating mechanism.[4] Note that that a central government is *not* assumed to be an all-powerful social planner. Indeed, the construction of $P(\boldsymbol{\sigma})$ simply incorporates whatever influence a government or other coordinating institution is capable of exerting. The framework can represent a range of situations from coordination within a household to international treaties. As such, $P(\boldsymbol{\sigma})$ can be thought of as a "per capita production possibilities" set. $P(\boldsymbol{\sigma})$ is assumed to be convex and exhibit free disposal, the latter implying that if $(c,e) \in P(\boldsymbol{\sigma})$ and $(c',e') \leq (c,e)$ then $(c',e') \in P(\boldsymbol{\sigma})$.

It is useful to introduce the concepts of production and consumption elasticities, where we define *production elasticity* at any point (c,e) on the production possibilities frontier as the frontier's slope (in absolute value) divided by the ratio c/e, i.e., the percentage change in c divided by the percentage change in e. Similarly, define we define *consumption elasticity* as the slope at this point on the corresponding indifference (in absolute value) divided by c/e. We introduce these elasticity concepts because they allow us to succinctly articulate an insightful characterization of the impact arbitrary parametric changes have on environmental quality.

THEOREM 1: A parametric change will increase optimal environmental quality if and only if the change increases production elasticity relative to consumption elasticity at the initially optimal environmental quality level.

Proof: Consider a shift from an initial profile of social parameters $\boldsymbol{\sigma}^0$ to a new profile $\boldsymbol{\sigma}^1$. Let (c^0,e^0) denote the optimal outcome in $P(\boldsymbol{\sigma}^0)$, i.e., that which maximizes utility of the representative consumer, and let (c^1,e^0) be the point on the frontier of $P(\boldsymbol{\sigma}^1)$ corresponding to the original level of environmental quality e^0. Convexity of $P(\boldsymbol{\sigma}^1)$ implies that if its frontier is steeper than the consumer's indifference curve at (c^1, e^0), then the optimal environmental quality given $\boldsymbol{\sigma}^1$ must exceed that given $\boldsymbol{\sigma}^0$, as demonstrated in Figure 1. The reverse must be true if the frontier is less steep. (Applying the definitions of production and consumption elasticity, it immediately follows that the change from σ^0 to σ^1 will increase optimal environmental quality if and only if it leads to production elasticity that exceeds consumption elasticity at the point (c^1,e^0). QED

Theorem 1 thus provides a straightforward methodology for establishing whether or not a change in economic fundamentals will lead to an increase or a decrease in environmental quality at the social optimum. Indeed, this result establishes that one need only examine the relative impact the change in fundamentals will have on production and consumption elasticities. If the production/consumption elasticity ratio increases (when evaluated at the original level of environmental quality), then the change in economic fundamentals will necessarily lead to an increase in socially optimal environmental quality, with the reverse being true if instead the production/consumption elasticity ratio decreases. This reasoning applies equally to cases where per capita production possibilities have contracted (as illustrated in Figure 2).

Economic environments in which consumers share Cobb-Douglas preferences provide a particularly transparent framework for examining "trajectories" of environmental quality as the corresponding consumption elasticities are everywhere constant. A direct implication of Theorem 1 is that parametric changes in such settings induce increased environmental quality if and only if production elasticity is increased, a result we summarize in the corollary below.

COROLLARY 1: If preferences are Cobb-Douglas, then a parametric change will increase optimal environmental quality if and only if production elasticity increases at the initially optimal environmental quality level.

We now turn to a series of general expository examples demonstrating the application of these results. It is interesting to note that in each of these model types, growth in either per capita income or in population, can eventually lead to improved environmental quality.

III. Expository Analysis

III A. Growth in income per capita

In this section we treat per capita income as a parameter of the economic environment, while holding population fixed. Of course one can equivalently consider exogenously changes to "more basic" economic parameters, which in turn determine income level. The purpose here is to highlight some of the parametric changes that can give rise to U-shaped environmental paths. Three expository examples follow. The first model can be thought of as characterizing choices in production between polluting and non-polluting inputs or technologies. The second-model describes a polluting production technology, but where a secondary abatement technology exists which may be employed to limit environmental harms. The third model represents a more specific version of model 1, where both production and utility are CES functions.

Model 1. We first consider a model in which there are two inputs to the production of a private consumption good, the first being more productive but also more harmful to the environment than the second input. Letting x_1 and x_2 represent employment levels of inputs 1 and 2, production technology is characterized by a differentiable, increasing, concave per capita production function $c=c(x_1,x_2)$. That is, $c(x_1,x_2)$ represents the quantity of private good each representative consumer can enjoy when each consumer contributes the input profile (x_1,x_2) towards production. (One can alternatively model aggregate production, which is then distributed amongst the population.) Environmental quality will be characterized by $e=E-\delta(nx_1)$, where E represents the initial endowment of environmental quality, n is the population size, and δ represents a differentiable, increasing, and convex environmental degradation function. As we do throughout this paper, we measure inputs on a scale for which each unit has a price of 1 so that each agent's budget constraint can be concisely represented by $x_1+x_2=y$; where y is per capita income. Given per capita income y and a point (c,e) on the production possibilities frontier corresponding to positive levels of x_1 and x_2, and letting c_i represents the partial derivative of c with respect to x_i, production elasticity can be expressed by:

$$\varepsilon = -\frac{de/dc}{e/c} = \frac{n\delta'/(c_1-c_2)}{e/c} = \frac{n\delta'}{e}\frac{c}{(c_1-c_2)} \qquad (1)$$

For instance, suppose that c is a concave function taking the form $c(x_1,x_2) = c(x_1+\beta x_2)$ for some $\beta<1$. It follows $c/(c_1-c_2)=c/(1-\beta)c'$. For each given level of e, ε is implicitly an increasing function of y. (Simply note that given n, the value of e determines the values of x_1 and δ'. Furthermore, if y is increasing, so too are x_2 and the ratio c/c'.) If one further assumes that preferences are Cobb-Douglas, an immediate implication of Corollary 1 is that the income trajectory of environmental quality is increasing in income for all income levels beyond which positive levels of input 2 are utilized. For "low" income levels, e is plentiful relative to feasible levels of c and the optimal production plan will utilize only input 1, the most productive and polluting input. Consequently, environmental quality is initially decreasing in income but eventually becomes forever increasing in income, i.e., the income trajectory of environmental quality is "u-shaped."

Model 2. Let us now suppose that output is an increasing, differentiable, concave function of input 1, i.e., the (per capita) production function is of the form $c = c(x_1)$. Assume that input 2 is used solely to abate environmental degradation cased by the production process. In particular, suppose that environmental quality is of the form $e = E-\delta(nc, nx_2)$, where n denotes the population size, E denotes the initial level of environmental quality, and δ denotes a differentiable, convex environmental degradation function that is increasing in its first argument and decreasing in its second. Given per capita income y, a point (c,e) on the production possibilities frontier corresponding to positive abatement efforts, and letting δ_1 and δ_2 denote partial derivatives of δ with respect to aggregate consumption and aggregate abatement, production elasticity can be expressed by:

$$\varepsilon = -\frac{de/dc}{e/c} = \frac{n(\delta_1 - \delta_2)/c'}{e/c} = \frac{n\delta_1 c}{e} - \frac{n\delta_2 c}{c'e} \qquad (2)$$

For instance, suppose that $c(x_1) = kx_1^b$ for constants k, b>0. Further assume that whenever aggregate abatement expenditure is at least "one dollar" ($nx_2 \geq 1$) then $\delta(nc,nx_2) = h(nc)^\alpha/(nx_2)^a$ for constants h, a, α>0. For nx_2<1 let $\delta(nc,nx_2) = h(nc)^\alpha$. The reader may note that the structural form $\delta(nc,nx_2) = h(nc)^\alpha/(nx_2)^a$ emerges from a Cobb-Douglas "technology" for environmental degradation.[5] Assuming nx_2 >1, the expression for ε provided in equation (2) can be reduced to $\varepsilon=(\delta/e)(\alpha+ar/b)$, where $r=\lambda/(1-\lambda)$ and $\lambda=x_1/y$. It follows that ε is increasing in y if and only if r is increasing in y, which in turn occurs if and only if λ is increasing in y. Implicitly differentiating the identity $\delta(nc,nx_2) = \frac{h\left(nk(\lambda y)^b\right)^\alpha}{\left(n(1-\lambda)y\right)^a}$ = constant (an identity which must hold if environmental quality is unchanged after the parametric shift in y) with respect to y and solving for $d\lambda/dy$ yields

$$d\lambda/dy = \frac{(a-b\alpha)\lambda(1-\lambda)}{b\alpha(1-\lambda)y + a\lambda y}$$

thus $d\lambda/dy>0$ if and only if $a>b\alpha$. If one further assumes that preferences are Cobb-Douglas, application of Corollary 1 implies that if $a/\alpha>b$, the income trajectory of environmental quality will be increasing in income for all income levels beyond which $nx_2>1$. In other words, unless abatement is ineffective relative to returns to scale in production of c, the income trajectory of environmental quality must be eventually increasing.

Model 3. In this model we assume that both the production and utility functions are of the constant elasticity of substitution (CES) form. Let $c(x_1,x_2) = (a_1x_1^\alpha + a_1x_2^\alpha)^{1/\alpha}$ and $u(c,e)= (b_1c^\beta + b_2e^\beta)^{1/\beta}$ denote production and utility functions, where $\alpha,\beta\le 1$, $\alpha,\beta\ne 0$, and $a_1,a_2,b_1,b_2>0$. Note that this model is symmetric in both production and utility; production is homothetic in x_1 and x_2, and utility is homothetic in c and e.

Assume environmental quality is of the form $e=E-\delta(nx_1)$ for some increasing function δ with bounded derivative. Production elasticity can be written as

$$\varepsilon = -\frac{de/dc}{e/c} = \frac{n\delta'}{\frac{1}{\alpha}\left(a_1 x_1^{\alpha} + a_2 x_2^{\alpha}\right)^{\frac{1}{\alpha}-1} \alpha \left(a_1 x_1^{\alpha-1} - a_2 x_2^{\alpha-1}\right)} \frac{c}{e} = \frac{\left(a_1 x_1^{\alpha} + a_2 x_2^{\alpha}\right) n\delta'}{\left(a_1 x_1^{\alpha-1} - a_2 x_2^{\alpha-1}\right) e} \tag{3}$$

where the final equality follows by the fact that $c = (a_1 x_1^{\alpha} + a_1 x_2^{\alpha})^{1/\alpha}$. Differentiating the identity $u(c,e) = (b_1 c^{\beta} + b_2 e^{\beta})^{1/\beta}$ = constant to identify the slope (*de/dc*) of a given indifference curve, consumption elasticity can thus be written as

$$\eta = -\frac{de/dc}{e/c} = \frac{b_1}{b_2}\left(\frac{c}{e}\right)^{\beta} \tag{4}$$

Letting $r = x_2/x_1$ and making use of equations (3) and (4), one can rearrange the inequality $\varepsilon \geq \eta$ to yield

$$\frac{b_1}{b_2} n\delta' x_1^{1-\beta} e^{\beta-1} \geq \left(a_1 + a_2 r^{\alpha}\right)^{\frac{\beta-\alpha}{\alpha}} \left(a_1 - a_2 r^{\alpha-1}\right) \tag{5}$$

Let $e(y)$ denote the income trajectory of environmental quality and let $e^* = \lim_{y\to\infty} e(y) \geq 0$. Consider any value e' which is on the income trajectory and "close" to e^*. Fix environmental quality at e', thus fixing the left hand side of inequality (5), and consider increasing y beyond the point at which $e(y)=e'$. Observe that as y diverges to infinity, so must r. For large r, the right hand side of (5) is on the order of $\left(a_1 + a_2 r^{\alpha}\right)^{\frac{\beta-\alpha}{\alpha}}$ which is decreasing in r and converging to zero if $\beta < \alpha$, implying production elasticity is eventually increasing relative to consumption elasticity.

By Theorem 1 we may thus conclude the income trajectory of e must be eventually increasing whenever $\beta < \alpha$, or equivalently, whenever the elasticity of substitution in the production function (i.e., $1/(1-\alpha)$) exceeds the corresponding elasticity of substitution in the utility function (i.e., $1/(1-\beta)$). To the extent that society's "essential," or most important environmental goods (e.g., breathable air) are characterized by preferences with low elasticities of substitution, then they may also be the most likely to exhibit a U-shaped path. Inessential environmental goods (relatively high β), by contrast, may be less likely to exhibit a U-shaped path.

For the case of rising levels of income per capita, the results from model 1 above are consistent with those found by Stokey (1998), and by Pfaff, Chaudhuri and Nye (2003), in which a threshold exists beyond which clean technologies inputs begins to substitute for polluting technologies or inputs. Model 2 results are similar to those found in Andreoni and Levinson (2000), indicating how increasing returns in abatement can produce a U-shaped trajectory.

In the context of the CES functions in model 3, however, we can observe that it is not necessary to assume non-homothetic preferences, increasing returns to scale, or threshold effects in order to produce a U-shaped environmental path. All that is required is that the elasticity of substitution in utility be lower than the elasticity of substitution in production.

III B. Growth in population

The relationship between population, environmental resources, and economic growth is arguably the earliest question to be carefully studied in economics, including the dire predictions of Thomas Malthus. Contemporary theoretical and empirical literatures on this topic have sometimes been categorized into pessimists such as the neo-Malthusians, optimists such as Julian Simon (1981), and revisionists who contend that the effect of population on growth and resource use varies with time, place, and circumstance (see Birdsall (1988)). Theoretical models have found that higher population growth will lead to lower environmental quality including models in which the natural resource has amenity value as well as productive value (see Robinson and Srinivasan 1997). Empirical studies in this area have generally asked whether there is evidence that population growth exacerbates environmental degradation in ways that are separate from the role of per capita income growth, implying that the sign of the effect is expected to be independent of income. In general, this literature has led to the suggestion that slowing population growth may be a way to halt the rate of environmental degradation (see, for example, Jha et al. 1993). In part due to the emphasis on growth in income per capita in the empirical literature on the environmental Kuznets curve, none of the corresponding theoretical literature has included rising population despite it being a ubiquitous component of contemporary economic growth.

With the present framework, we can readily examine the effects population growth may have on optimal environmental quality, which are not as obvious as they may superficially appear. Indeed, superficial intuition may suggest that increasing the "number of mouths to feed" can only lead to increased environmental degradation. The error in this superficial logic can be seen by noting that population growth will alter the (per capita) production possibilities and thus also alter production elasticities. (Recall that we define production elasticity as the elasticity of the per capita production possibility curve.) As such, Theorem 1 implies that the impact population growth has on the optimal level of environmental quality will depend on how much consumption elasticity changes relative to this increase in production elasticity: If production elasticity increases (decreases) relative to consumption elasticity then environmental quality must increase (decrease). For many models, as we demonstrate below, population growth can eventually lead to production elasticity increases that outpace consumption elasticity increases and thus lead to improved environmental quality.

Readers may also note the apparent similarity between increases in per capita income for a given population size and increases in population size for a given per capita income. Both lead to increased aggregate income for the overall economy. It is important to note, however, that despite this apparent similarity, the two paths of enhancing aggregate income have completely different effects on the per capita production possibilities curve – increased per capita income will expand the per capita production possibilities set while population growth will contract per capita production possibilities (excepting special forms of increasing returns to scale production). Consequently, the precise effect aggregate income growth has on optimal environmental quality will depend on the manner in which this income growth was realized.

Let us now return to our three expository models to examine how population growth may affect the environmental path in comparison to the results for income per capita.

Model 1 (continued). We now consider production elasticity as a function of n rather than y. (For notational convenience we treat n as a continuous variable throughout this analysis.) As demonstrated earlier, production elasticity can be expressed as $\varepsilon = \frac{n\delta'}{e}\frac{c}{(c_1 - c_2)}$. It immediately follows that, at a given level of e, ε is increasing in n if and only if $nc/(c_1\text{-}c_2)$ is increasing in n. For instance, suppose $c = (x_1+\beta x_2)^a$ for some $\beta \in (0,1)$ and $a>0$. It follows that

$$\frac{nc}{c_1 - c_2} = \frac{n(x_1 + \beta x_2)}{(1-\beta)a} = \frac{(1-\beta)nx_1 + n\beta y}{(1-\beta)a} \qquad (6)$$

which is increasing in n (recall nx_1 is fixed when e is fixed).

The impact of increasing population is especially transparent when preferences are Cobb-Douglas. Indeed, if per capita income is sufficiently low (i.e., feasible consumption is low relative to e) then optimality dictates that all income is strictly devoted to the most productive (and most polluting) input and the incremental social income induced by an incremental population increase will also be devoted to the polluting input, causing further environmental degradation. On the other hand, if per capita income is sufficiently high that some of the clean input is being employed (or is on the margin of being employed), then an incremental increase in population leads to an incremental increase in ε and Corollary 1 thus implies environmental quality must increase. It follows that population increases induce an income trajectory that bottoms out at lower income levels and rises above the initial trajectory prior to the initial trough. Thus, the population trajectory of environmental quality (holding per capita income fixed) will itself be U-shaped as environmental quality will decrease at low population levels where "environment" is relatively abundant, and then increase once the environmentally friendly input begins to be used.

Model 2 (continued). Recall that production elasticity in this model is increasing in $\lambda = x_1/y$, and let us continue the assumption of Cobb-Douglas preferences. Implicitly differentiating the identity $\delta(nc, nx_2) = \frac{h\left(nk(\lambda y)^b\right)^\alpha}{\left(n(1-\lambda)y\right)^a}$ = constant (which must hold if environmental quality is unchanged with the parametric shift in n) with respect to n and solving for $d\lambda/dn$ yields

$$d\lambda/dn = \frac{(a-\alpha)\lambda(1-\lambda)}{n\left(b\alpha(1-\lambda)+a\lambda\right)} \qquad (7)$$

implying λ is eventually increasing in n only if $a>\alpha$. We conclude that when $a<\alpha$, population increases will decrease λ and thus, by Corollary 1, will necessarily lower the income trajectory at all income levels. If $a>\alpha$ then population increases will lower the income trajectory initially (for those low levels of income at which no abatement investments are made), but once income is at a level where abatement investments are made (or on the margin of being made) then increasing n increases ε and thus Corollary 1 once again implies increasing environmental quality. As in the previous model, it follows that increasing population causes the income trajectory to bottom out at lower income levels and rise above the initial trajectory somewhere before the initial trough. Here again the population trajectory of e with rising population will be U-shaped for constant per capita income levels.

Model 3 (continued). Note that inequality (5) can be reorganized as

$$\frac{b_1}{b_2}\left(nx_1\right)^{1-\beta}\delta' e^{\beta-1} \geq \left(a_1 + a_2 r^{\alpha}\right)^{\frac{\beta-\alpha}{\alpha}}(a_1 - a_2 r^{\alpha-1})n^{-\beta} \tag{8}$$

Holding environmental quality fixed, it follows that nx_1 is fixed and the left hand side of this inequality must also be fixed. Given $P=nx_1$ and y fixed, the right hand side of the reorganized inequality can be written entirely as a function of n. Indeed, $r=x_2/x_1=(y-x_1)/x_1$ and $x_1=P/n$, implying $r=\frac{ny}{P}-1$. The precise relationship between population size and optimal environmental quality depends on the parameters a_1, a_2, α, β, as well as per capita income. Even so, the signs α and β can be used to determine the direction of environmental quality for large n.

In particular, it is straightforward to show that in every case except for α and β both being negative, the right hand side of inequality (8) necessarily converges to zero, implying that environmental quality must eventually be increasing.

If, on the other hand both functions reflect CES substitution possibilities that are inelastic, (i.e., α, β<0), then $\left(a_1 + a_2 r^{\alpha}\right)^{\frac{\beta-\alpha}{\alpha}} (a_1 - a_2 r^{\alpha-1})$ converges to $a_1^{\beta/\alpha}$ and $n^{-\beta}$ diverges to infinity as n increases without bound. As this implies consumption elasticity exceeds production elasticity in the limit, it follows environmental quality must be eventually decreasing.

To summarize, these general results illuminate conditions under which both income growth and population growth can produce a U-shaped path. In the case of income growth, a U-shaped pattern occurs if production was more flexible than utility in terms of the elasticity of substitution ($\beta<\alpha$). For rising population, however, the relative magnitude of α and β do not distinguish U-shaped paths from other paths. Rather, only if both production and utility functions are inelastic (β,α<0) will a U-shaped trajectory not occur. Underlying these results is the difference between commodity consumption which is a rival good and environmental quality which is non-rival. Because of this difference, economic growth derived from rising income per capita will expand the individuals' production possibilities set whereas growth derived from rising population will contract the individuals' production possibilities. Depending on how this expansion or contraction of the PPF interacts with indifference curves, a U-shaped path may arise.

These findings are consistent with some prior empirical evidence found in the literature. For example, Patel, Pinckney and Jaeger (1995) find a U-shaped relationship between forest cover and population density (holding income constant) for rural Kenya. In their study area, rural populations had long ago reduced tree cover densities relative to the initial endowment by clearing land and collecting fuel wood, and recent increases in population density have forced reductions in average farm size. However, these recent changes have been accompanied by increased tree plantings at the farm level, which in turn have resulted in higher numbers of trees per acre, or a U-shaped pattern between environmental quality (tree density) and population. In a second example, Cropper and Griffiths (1994) find evidence of an environmental Kuznets curve (inverted-U for rising income) for deforestation among non-OECD countries—although most of their observations fall to the left of the peak. Their analysis shows that an increase in rural population density shifts this curve up (greater deforestation) in the case of Africa, and they also find that the turning point occurs at a lower per capita income in Africa than in Latin America. Both of these results are consistent with our theoretical models of population growth.

III.C. Discussion

For all three model types that exhibit a U-shaped trajectory for rising income, we show that rising population can also produce a U-shaped pattern even if income per capita is held constant. Since contemporary economic growth generally involves increases in both population and income per capita, these results suggest the possibility of U-shaped trajectories in economies that are compatible with the parameters for either set of results.

In the case of model 1, the existence of a threshold effect for the introduction of non-polluting inputs or technologies implies that trajectories will show an eventual increase in environmental quality for rising income per capita or for rising population where preferences are Cobb-Douglas. In the case of model 2 and Cobb-Douglas preferences, increasing returns to scale in an absolute sense, and relative to production of *c*, will eventually result in increasing environmental quality for generalized growth involving rising income per capita, and also for rising population. (Of course, the assumption of Cobb-Douglas preferences simply makes for convenient expository examples and it is not a necessary condition for such results. The "threshold effect" exhibited in these examples is likewise an artifact of the simplistic expository framework adopted, as can be seen by considering the class of examples embodied in model 3.)

However, in the case of model 3 we observe that having environmental quality be eventually increasing with rising income per capita is not predicated on the existence of threshold effects, increasing returns, or asymmetric preferences. The same is found for rising population. Indeed, so long as substitutions between inputs in the CES production function are elastic (i.e., $1/(1-\alpha)>1$) in an absolute sense, and also relative to the (CES) substitution elasticity in the utility function (i.e., $1/(1-\alpha)>1/(1-\beta)$), we can expect a U-shaped trajectory (where here we are referring to the CES definition of "elasticity of substitution"). In the case of rising populations, only where both CES functions have inelastic substitution possibilities will a U-shaped path not arise.

One aspect of the intuition for these results may be seen with reference to Figure 3 where per capita production and consumption possibilities for the two goods, *c* and *e*, are represented for the case of rising income per capita, but where the expansion of production possibilities is anchored to the upper left corner rather than the origin due to the initial endowment of E. Rather than expecting a rise in income to produce an expansion path emanating from the origin, in this case the path emanates from the upper left, and we can see the distinct possibility of a decline, followed by a rise, in environmental quality with the expansion of production possibilities.

In the case of rising per capita income, as an economy moves from a situation where environmental quality is abundant relative to feasible levels of consumption to situations where environmental quality may be scarce relative to consumption opportunities. As a result, choices may also shift from ones that are relatively “environment-using” to ones that are relatively “environment-conserving” (depending on production and consumption elasticities). In the case of rising population while holding per capita income constant, however, per capita production possibilities will contract in terms of feasible commodity consumption. The manner in which this may produce an optimal U-shaped path is illustrated in Figure 4. As the range of feasible commodity consumption opportunities declines relative to feasible e, it may not be intuitive why the optimal allocation would shift toward higher e and lower c, as illustrated in Figure 4. As population increases, however, an increasingly predominant use of the clean input will in the limit have a negligible effect on consumption but a large positive impact on (non-rival) environmental quality.

These results and intuition differ to some degree from those contributions to the recent literature in which some kind of asymmetry in preferences or technology is relied upon to generate a U-shaped path. One source of the contrasting findings in some of the recent literature stems from the way in which the environment has been modeled in the utility function. In the current analysis, utility is assumed to be increasing in environmental quality; whereas in some of the recent literature utility has been modeled as decreasing in pollution. Assumptions such as homotheticity in the first of these two models carry with them different implications than their symmetric counterpart in the second of these two models.[6]

When preferences are defined to be homothetic and constant returns-to-scale in terms of goods and environmental quality (E), and a starting point that is not at the origin but where e is initially abundant relative to c, the intuition for curvature in the environmental path becomes apparent as in figure 2. Thus, a priori restrictions imposing asymmetries in preferences or production are not necessary to produce a U-shaped path. Rather an inherent asymmetry in the initial relative abundance of *e* versus *c*, when combined with standard, neutral assumptions about preferences, can generate a U-shaped path with rising income per capita or population.

IV. Decentralized Economies

We now consider the implications of a completely decentralized regime in which consumers need not be homogeneous. To establish a baseline, we consider as our point of departure, decentralization with income distributed uniformly.

IV A. Uniform Income Distribution

In this framework, the production possibilities of a given agent *i* depend not only on individual income, but also the production decisions of other agents. Letting the profile $\lambda_{-i}=(\lambda_j)_{j\neq i}$ characterize the production strategies employed by each agent $j\neq i$, $P(\lambda_{-i},\boldsymbol{\sigma})$ will represent the production possibilities set for a given agent *i* under decentralization. We shall assume that for each parameter profile $\boldsymbol{\sigma}$, there exists a unique symmetric equilibrium for the resulting non-cooperative game in which agent *i* is free to unilaterally choose its own production strategy λ_i.

Note that the production possibility sets in the centralized and decentralized settings are closely related. Each point (c,e) on the frontier of $P(\boldsymbol{\sigma})$ corresponds to some "production technology" λ which, if employed by all agents, results in an output of *c* units and an environmental quality level of *e*. Thus if λ_{-i} consists of a profile in which $\lambda_j=\lambda$ for each $j\neq i$, then the frontiers of $P(\lambda_{-i},\boldsymbol{\sigma})$ and $P(\boldsymbol{\sigma})$ will intersect at the point (c,e); where agent *i* is also choosing λ. Let us now further assume that for a given per capita income level, environmental degradation can be written as a function of $\Sigma_j \lambda_j$ and production by agent j is a function of λ_j. (This was the case for each of our previous models as the 'technology' choice λ can be represented by $\lambda = x_1/y$.) It follows that the production elasticity of $P(\lambda_{-i}, y)$ at the frontier point (c,e) is $1/n$ times the production elasticity of $P(y)$ at the same point. A direct implication of this proportionality is that for each of our specific classes of models 1, 2, and 3, the income trajectory of environmental quality shares the same qualitative shape in both centralized and decentralized regimes.

IV B. Income Inequality

We now consider how income inequality may affect these results. The relationship between income inequality and the provision of a public good has been considered in other contexts. Olson (1965) and others have shown that inequality can play a positive role whereby the greater the share of collective benefits for collective action for a single member, the greater the propensity of this 'large' member to bear the costs involved. However, when inequality is large, 'small' users may be encouraged to free ride on the contribution of the 'large' contributor in such a way as to produce an offsetting effect. More generally, in situations where the set of contributors to the public good may change, income inequality has an ambiguous effect on the provision of a public good (Baland and Platteau 1997).

In the context of the current model, the results above can be readily applied to income inequality and its implications for environmental stewardship. Consider an example of *Model 1* for which $c=(x_1+\beta x_2)^a$ and $\delta(nx_1)=bnx_1$ for some $a,b>0$ and where all agents share identical Cobb-Douglas preferences. Let y continue to denote average per capita income, but now some agents will receive less and some more than this average. Formally, the total population N (size n) is partitioned into the set of poor agents , N_p (size n_p), and the set of rich agents, N_r (size n_r).

Incomes of poor and rich are respectively represented by $y(1-\theta_p)$ and $y(1+\theta_r)$, where $\theta_r, \theta_p \in (0,1)$ and $n_p\theta_p = n_r\theta_r$, thus average income equals y as claimed.

The equilibrium income trajectory for decentralized choice in this setting is calculated in much the same way as previous models. When incomes are low, all agents exhaust all of their income on the most productive and most polluting input. As average income rises, the rich are first to reach a threshold at which they begin using the less productive but less polluting input. In this setting, income inequality will thus initially have a positive effect on environmental quality. Suppose that for a given average income and income differential parameters θ_r and θ_p, the rich are just barely willing to begin investing in the less polluting input. Then an increase in the income differential, but keeping average income unchanged (increase in θ_r and corresponding decrease in θ_p) will make the rich inclined to allocate more income in the less polluting input so that environmental quality must increase.

As average income increases, the rich continue to shift resources toward the environmentally benign input while the poor continue to exclusively utilize the most productive input until they reach a threshold where they too wish to begin directing resources elsewhere. Eventually an income level is reached where the rich will devote all of their income solely to the 'clean' input, and where this would also be the case if they were at the average income level. At this point the poor devote relatively more of their income to the polluting input compared to what would be the case at the average income level. Consequently, there necessarily comes a point where the income trajectory for equal incomes and that for unequal incomes will cross, after which the unequal income trajectory drops below that of equal income.

As an overall summary of this model, income inequality is initially beneficial to environmental quality, but at 'high' average income levels it eventually becomes detrimental.

This result is germane to discussions of social policy. For example, the suggestion has sometimes been made that environmental and equity goals may reinforce one another. Our findings suggest that this may only be true at high income levels, in which case economic growth may represent a means to strengthening the desirable complementarity between these two social goals.

V. Concluding comments

We have shown that economic growth characterized by increases in either population or income per capita can often produce a U-shaped pattern. In the case of rising income per capita, this result is due in part to the fact that an initial endowment of environmental resources will tend to be abundant relative to consumer goods during early stages of growth, but become scarce relative to consumer goods as growth proceeds. Rising population, by contrast, causes per capita production possibilities to contract in terms of feasible commodity consumption. In this situation, an increasingly predominant use of the clean (or cleansing) input will, in the limit, have a negligible effect on consumption but a large positive impact on (non-rival) environmental quality.

Thus, our analysis finds that for broad classes of theoretical models, and in Pareto efficient as well as unregulated economies, environmental quality will follow a U-shaped trajectory. These results reinforce and build on a recent literature that has emphasized rising income per capita as a possible determinant of a U-shaped trajectory. We find also that the likelihood of a U-shaped pattern with growth does not require any particular predisposing assumption such as increasing returns, non-homothetic preferences, or income elastic consumption.

To the extent that environmental doomsayers have based their pessimistic forecasts on a linear extrapolation of past trends, the analyses here offer a more hopeful rendering. In a fashion similar to life-cycle working hours where rising labor supply during the early decades of life do not imply unending hours of labor late in life, increased environmental degradation during early- or middle-stages of growth may only represent the initial downward slope of a U-shaped trajectory, rather than a secular trend. These results do not, of course, suggest that economic growth necessarily contains any automatic, self-correcting mechanism for eliminating inefficient levels of environmental damage. Optimal environmental allocations can only be expected to occur in the presence of effective social, economic, and political institutions that correct for property rights failures and complex coordination problems. In decentralized economies the extent of free riding may make the path's nadir socially unacceptable or even lethal.

Although our static model does not permit explicit evaluation of dynamic questions, it is straightforward to consider, at least at a general level, how the presence of long-lived stock effects or, in the extreme, irreversible environmental damages represents a situation where failure to recognize the U-shaped-ness in the trajectory (i.e., the trajectory that would be possible in the absence of stock-effects or irreversibility) would lead to sub-optimal allocations. Similar to the failure to recognize the foreseeable rise in the "relative price" of environmental quality as incomes rise, a myopic policymaker who overlooks the inherent U-shaped-ness of an environmental trajectory will unwittingly exceed the optimal level of degradation by not recognizing the future rise in the desired level of environmental quality. In the case of irreversible damage, this will constitute a permanent social loss. While there is little evidence that policies are generally made in anticipation of U-shaped trajectories or rising environmental values, counterexamples such as the early establishment of national and urban parks and wildernesses areas are often described as visionary. Such foresightedness, however, has not been part of economists' standard methodologies where current values have generally been assumed to be the best proxy for future values, and where U-shaped trajectories for rising incomes and population have not been taken into account. These concerns may be especially relevant in cases such as species extinction, ozone depletion, and climate change.

REFERENCES

Andreoni, J. and A. Levinson, The simple analytics of the environmental Kuznets curve. Journal of Public Economics, **80**(2): 269-86 (2001).

Arrow, K., B. Bolin, R. Costanza, P. Dasgupta, C. Folke, C.S. Holling, B. Janssan, S. Levin, K-G. Mäler, C. Perrings, D. Pimentel, Economic growth, carrying capacity, and the environment, *Science* **268**, 520-521 (1995).

Ayres, R.U. and A. V. Kneese, Production, consumption, and externalities, *American Economic Review* **59**, 282-97 (1969).

Baland, J-M. and J-P. Platteau, Wealth inequality and efficiency in the commons; part I: the unregulated case, *Oxford Economic Papers,* **49**, 451-82 (1997).

Birdsall, N., Economic approaches to population growth, *in* "Handbook of Development Economics," Vol. 1(H. Chenery and T.N. Srinivasan, eds.), Elsevier Science Publishers B.V., Amsterdam (1988).

Boulding, K.E., The economics of the coming spaceship earth, *in* "Environmental Quality in a Growing Economy," (H. Jarrett, ed), Johns Hopkins Press, Baltimore (1966).

de Bruyn, S.M., "Economic growth and the environment: an empirical analysis." Kluwer Academic Press: Dordrecht (2002).

Bradford, D.F., R. Schlieckert and S.H. Shore, The environemental Kuznets curve: exploring a fresh specification. National Bureau of Economic Research Working Paper 8001. (November 2002).

Chimeli, A.B., 2007. Growth and the environment: Are we looking at the right data? Economics Letters 96 (2007) 89–96.

Chimeli, A.B., Braden, J.B., 2005. Total factor productivity and the environmental Kuznets curve. Journal of Environmental Economics and Management 49 (2), 366–380.

Copeland, B.R. and M. S. Taylor, Trade and the Environment: Theory and Evidence, Princeton University Press, 2003.

Cropper, M. and C. Griffiths, The interaction of population growth and environmental quality, *American Economic Review,* **84**, 250-254 (1994).

Dasgupta, P., An inquiry into well-being and destitution, Oxford University Press (1993).

Deacon, R.T., and C.S. Norman, 2006. Does the Environmental Kuznets Curve describe how individual countries behave? Land Economics, 82 (2): 291–315.

Galeotti, M., M. Manera and A. Lanza, 2006. On the Robustness of Robustness Checks of the Environmental Kuznets Curve. FEEM (Fondazione Eni Enrico Mattei). Working Paper 22.2006.

Grossman, G.M. and A.B. Krueger, Environmental impacts of a North American Free Trade Agreement, *in* “The Mexico-US Free Trade Agreement” (Garber, P.M., ed.), MIT Press, Cambridge, MA (1993).

Grossman, G.M., Pollution and Growth: What Do We Know? In *Economics of Sustainable Development* (I.Goldin and L.A. Winters, eds), Cambridge U. Press, New York (1995).

Jha, S.C., A. B. Deolalikar and E.M. Pernia, Population growth and economic development revisited with reference to Asia, *Asian Development Review* **11**, No. 2 (1993).

Johansson, P. and B. Kriström, 2007. On a clear day you might see an environmental Kuznets curve. Environ Resource Econ (2007) 37:77–90

John, A. and R. Pecchenino, An overlapping generations model of growth and the environment, *Economic Journal* **104**, 1393-1410 (1994).

Harbaugh, W.T., A. Levinson and D.M. Wilson, Reexamining the Empirical Evidence for an Environmental Kuznets Curve, *Rev. of Econ. and Statistics* 84(3):541-551 (2002)

List, J.A., Kunce, M., 2000. Environmental protection and economic growth: what do the residuals tell us? Land Economics 76(2), 267–282.

Lopez, R., The environment as a factor of production: the effects of economic growth and trade liberalization, *J. Environ. Econom. Management*, 27: 163-184 (1994).

Millimet, D.L., List, J.A., Stengos, T., 2003. The environmental Kuznets curve: real progress or misspecified models? The Review of Economics and Statistics 85 (4), 1038–1047.

Olson, M., The Logic of Collective Action. Harvard Univ. Press, Cambridge, MA (1965).

Panayotou, T., Empirical tests and policy analysis of environmental degradation at different stages of economic development, Working paper WP238. Technology and Employment Programme. Geneva: International Labor Office (1993).

Patel, S., T.C. Pinckney and W.K. Jaeger, Smallholder wood production and population pressure in East Africa: evidence of an environmental Kuznets curve? *Land Economics*, **71**, No. 4, 516-30 (1995).

Perman, R. and D. Stern 2003. Evidence from panel unit root and cointegration tests that the environmental Kuznets curve does not exist. Australian Journal of Agric. Resource Economics, 47(3): 325–347.

Pfaff, Alexander S.P, Shubham Chaudhuri, and Howard L.M. Nye, 2003. Household production and environmental Kuznets curves: examining the desirability and feasibility of substitution. Columbia University; processed.

Robinson, J.A. and T.N. Srinivasan, Long-term consequences of population growth: technological change, natural resources, and the environment, *in* "Handbook of Population and Family Economics," (M.R. Rosenzweig and O. Stark, eds), Elsevier Science B.V., Amsterdam (1997).

Selden, T.M. and D. Song, Environmental quality and development: is there a Kuznets curve for air pollution emissions? *J. Environ. Econom. Management*, 27, 147-162 (1994).

__________, Neoclassical growth, the J curve for abatement, and the inverted U curve for pollution, *J. Environ. Econom. Management*, 29, 162-168 (1995).

Simon, J.L., The Ultimate Resource. Martin Robertson, Oxford University Press (1981).

Stern, D.I. , M.S. Common, and E.B. Barbier, Economic growth and environmental degradation: the environmental Kuznets curve and sustainable development. *World Development* **24**, 1151-1160 (1996).

Shafik, N., and S. Bandyopadhyay, Economic growth and environmental quality: time series and cross-country evidence. Background paper for World Development Report, World Bank, Washington, D.C. (1992).

Stern, D.I., Common, M.S., 2001. Is there an environmental Kuznets curve for sulfur? Journal of Environmental Economics and Management 41, 162–178.

Stokey, N.L., Are there limits to growth. *International Economic Review*, **39**, No. 1 (1998).

World Bank, "World Development Report 1992: Development and Environment," World Bank, Washington, D.C. (1992).

Figure 1. PPF expansion: Indifference curve I_2 is less steep than $P(y^1)$ at the level of environmental quality e^0.

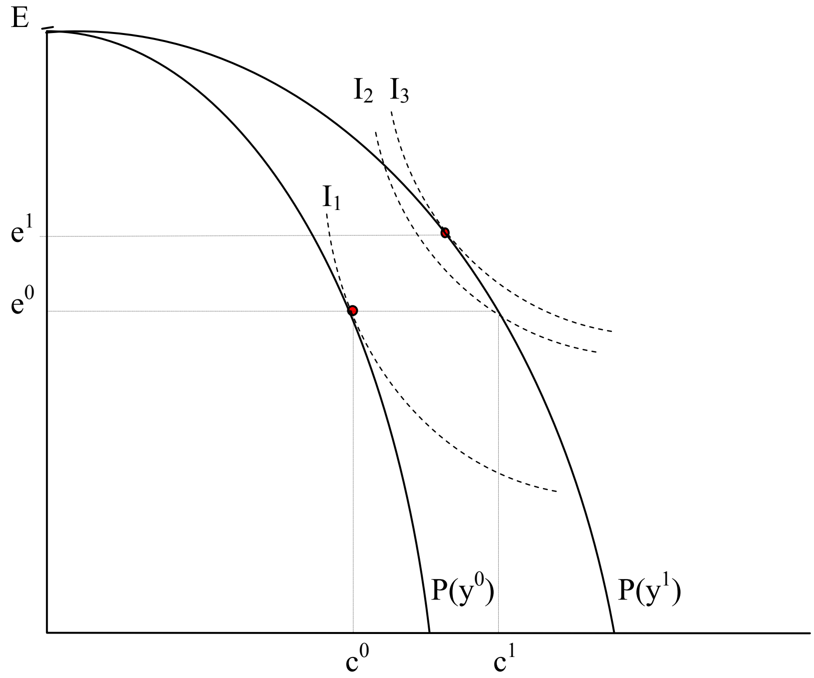


Figure 2. PPF Contraction: Indifference curve I_2 is less steep than $P(y^1)$ at the level of environmental quality e^0.

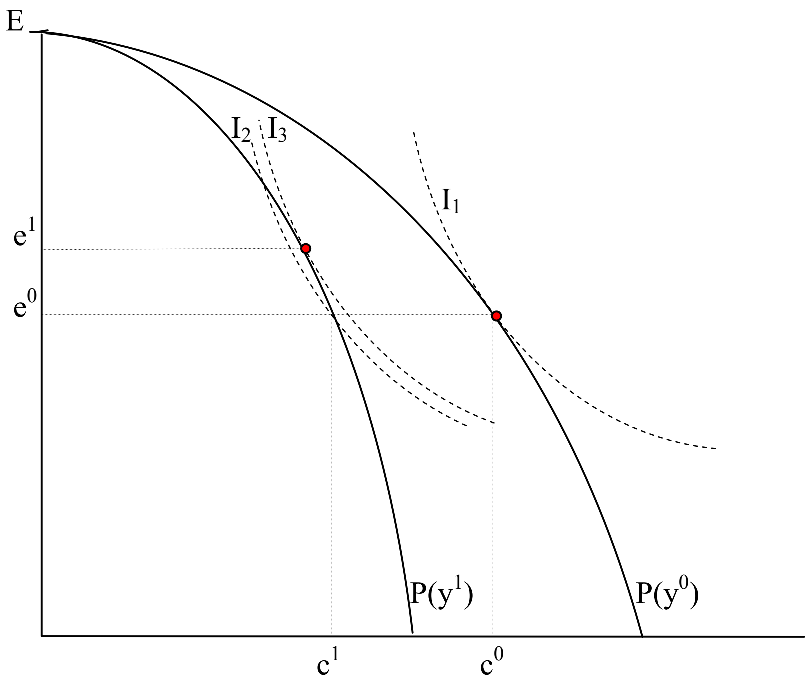


Figure 3. Efficient allocation of an environmental endowment at various income levels

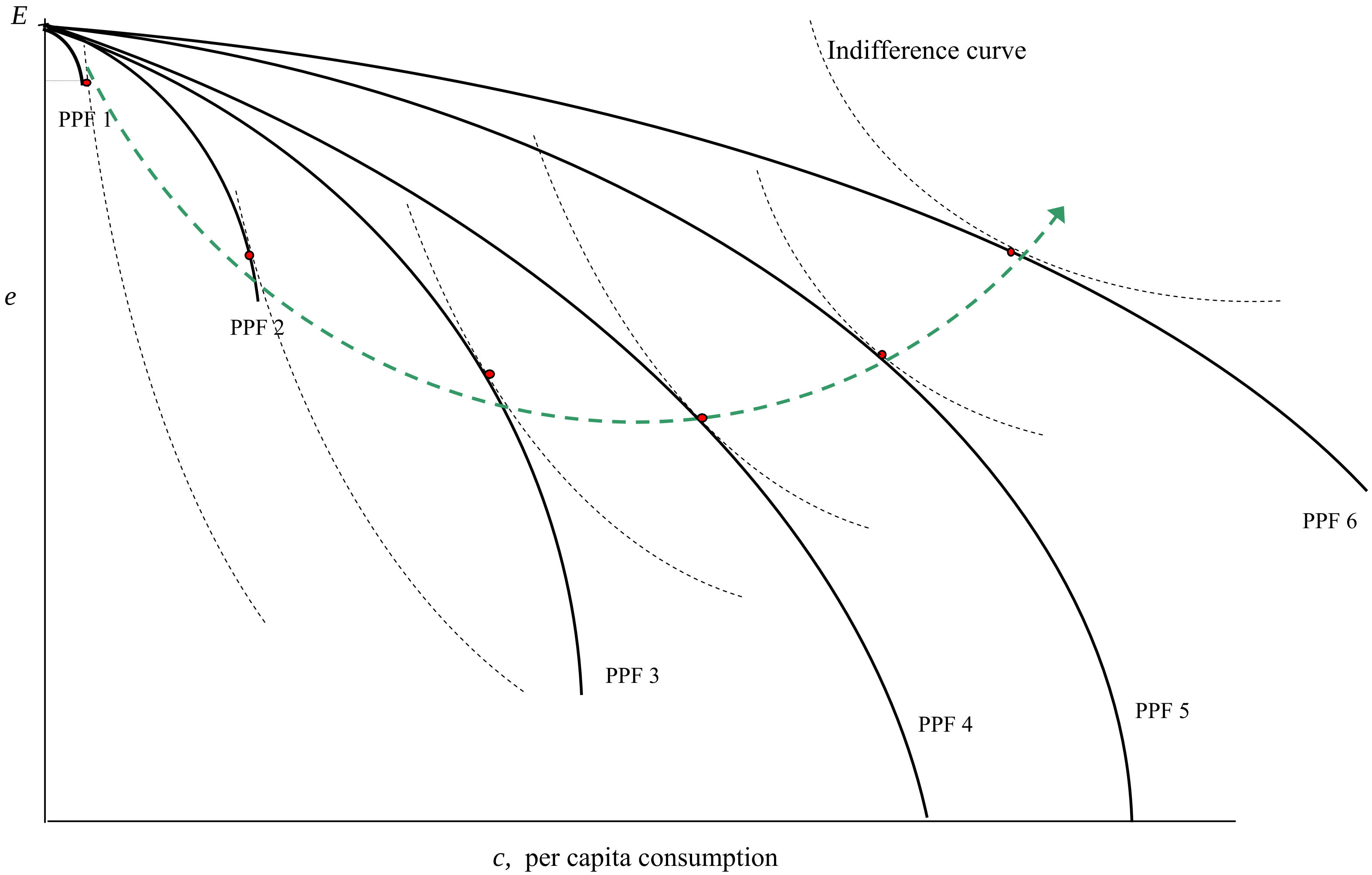
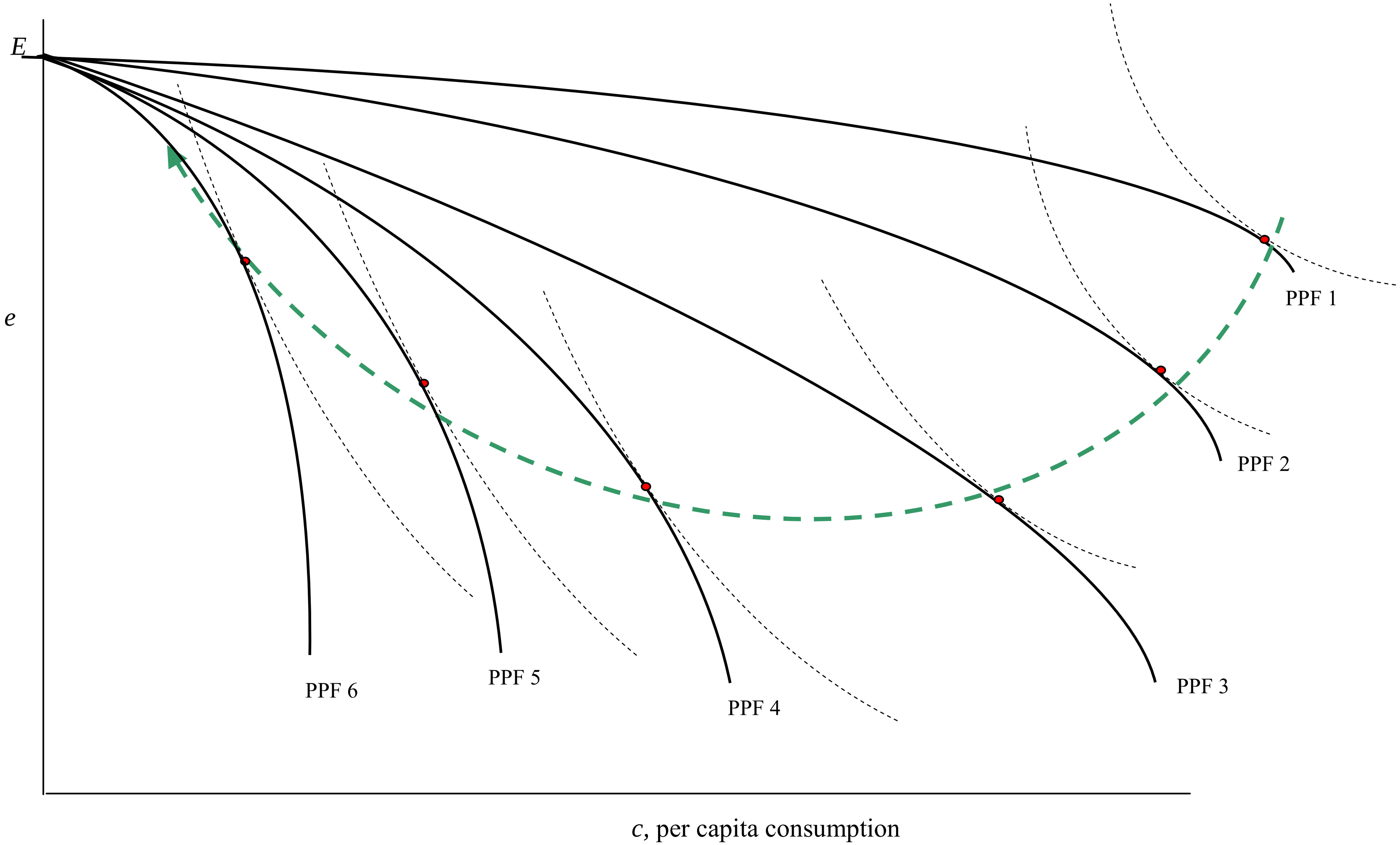


Figure 4. Efficient allocation of an environmental endowment at various population levels



[1] See also Seldon and Song 1994, Shafik 1994, Holtz-Eakin and Selden 1995, Grossman 1995, and Cropper and Griffiths 1994.

[2] In addition, Copeland and Taylor (2003) consider a fourth "sources of growth" explanation involving a shift from polluting to non-polluting industries.

[3] Moreover, identifying the impacts of poverty on population growth and the environment has been a complex and contentious task given their joint endogeneity and inconclusive empirical basis (see Robinson and Srinivasan 1997, Dasgupta 1993, and Birdsall 1988).

[4] We assume that public policy will induce identical consumers to behave identically. Later in this paper we consider economies with nonhomogeneous consumers.

[5] To see this, take *nc* to represent "potential pollution" which must be accounted for either through abatement efforts or actual pollution. The substitution possibilities between abatement and environmental waste disposal can be constructed in Cobb-Douglas form so that this relationship is expressed as $nc=h'(nx_2)^{a'}\delta^{\alpha'}$ for positive constants h', α', and a'. Letting $a= a'/\alpha'$, $\alpha=1/\alpha'$, and $h=(1/h')^{\alpha}$, then solving for δ yields $\delta = h(nc)^{\alpha}/(nx_2)^{a}$ as claimed.

[6] Like most prior studies, Lopez defines utility as decreasing in pollution rather than increasing in environmental quality. Assuming preferences are homothetic under this configuration, he finds that growth will necessarily lead to more pollution. However, the assumption of homotheticity in terms of pollution is implicitly contradicted by Lopez's own claims that pollution has "maximum tolerable limits." Indeed, no such limits can exist if doubling output and pollution will always increase welfare, as would be the case if homotheticity prevails. The present analysis avoids such inherent inconsistencies and in addition finds that a U-shaped path is quite possible in models

with homothetic preferences, but where preferences and homotheticity have been defined in terms of goods (environmental quality) rather than bads (pollution).

NOTE DI LAVORO DELLA FONDAZIONE ENI ENRICO MATTEI

Fondazione Eni Enrico Mattei Working Paper Series

Our Note di Lavoro are available on the Internet at the following addresses:

http://www.feem.it/Feem/Pub/Publications/WPapers/default.htm
http://www.ssrn.com/link/feem.html
http://www.repec.org
http://agecon.lib.umn.edu
http://www.bepress.com/feem/

NOTE DI LAVORO PUBLISHED IN 2008

CCMP	1.2008	*Valentina Bosetti, Carlo Carraro and Emanuele Massetti*: Banking Permits: Economic Efficiency and Distributional Effects
CCMP	2.2008	*Ruslana Palatnik and Mordechai Shechter*: Can Climate Change Mitigation Policy Benefit the Israeli Economy? A Computable General Equilibrium Analysis
KTHC	3.2008	*Lorenzo Casaburi, Valeria Gattai and G. Alfredo Minerva*: Firms' International Status and Heterogeneity in Performance: Evidence From Italy
KTHC	4.2008	*Fabio Sabatini*: Does Social Capital Mitigate Precariousness?
SIEV	5.2008	*Wisdom Akpalu*: On the Economics of Rational Self-Medication
CCMP	6.2008	*Carlo Carraro and Alessandra Sgobbi*: Climate Change Impacts and Adaptation Strategies In Italy. An Economic Assessment
ETA	7.2008	*Elodie Rouvière and Raphaël Soubeyran*: Collective Reputation, Entry and Minimum Quality Standard
IEM	8.2008	*Cristina Cattaneo, Matteo Manera and Elisa Scarpa*: Industrial Coal Demand in China: A Provincial Analysis
IEM	9.2008	*Massimiliano Serati, Matteo Manera and Michele Plotegher*: Econometric Models for Electricity Prices: A Critical Survey
CCMP	10.2008	*Bob van der Zwaan and Reyer Gerlagh*: The Economics of Geological CO_2 Storage and Leakage
KTHC	11.2008	*Maria Francesca Cracolici and Teodora Erika Uberti*: Geographical Distribution of Crime in Italian Provinces: A Spatial Econometric Analysis
KTHC	12.2008	*Victor Ginsburgh, Shlomo Weber and Sheila Weyers*: Economics of Literary Translation. A Simple Theory and Evidence
NRM	13.2008	*Carlo Giupponi, Jaroslav Mysiak and Alessandra Sgobbi*: Participatory Modelling and Decision Support for Natural Resources Management in Climate Change Research
NRM	14.2008	*Yaella Depietri and Carlo Giupponi*: Science-Policy Communication for Improved Water Resources Management: Contributions of the Nostrum-DSS Project
CCMP	15.2008	*Valentina Bosetti, Alexander Golub, Anil Markandya, Emanuele Massetti and Massimo Tavoni*: Abatement Cost Uncertainty and Policy Instrument Selection under a Stringent Climate Policy. A Dynamic Analysis
KTHC	16.2008	*Francesco D'Amuri, Gianmarco I.P. Ottaviano and Giovanni Peri*: The Labor Market Impact of Immigration in Western Germany in the 1990's
KTHC	17.2008	*Jean Gabszewicz, Victor Ginsburgh and Shlomo Weber*: Bilingualism and Communicative Benefits
CCMP	18.2008	*Benno Torgler, María A.GarcíaValiñas and Alison Macintyre*: Differences in Preferences Towards the Environment: The Impact of a Gender, Age and Parental Effect
PRCG	19.2008	*Gian Luigi Albano and Berardino Cesi*: Past Performance Evaluation in Repeated Procurement: A Simple Model of Handicapping
CTN	20.2008	*Pedro Pintassilgo, Michael Finus, Marko Lindroos and Gordon Munro* (lxxxiv): Stability and Success of Regional Fisheries Management Organizations
CTN	21.2008	*Hubert Kempf and Leopold von Thadden* (lxxxiv): On Policy Interactions Among Nations: When Do Cooperation and Commitment Matter?
CTN	22.2008	*Markus Kinateder* (lxxxiv): Repeated Games Played in a Network
CTN	23.2008	*Taiji Furusawa and Hideo Konishi* (lxxxiv): Contributing or Free-Riding? A Theory of Endogenous Lobby Formation
CTN	24.2008	*Paolo Pin, Silvio Franz and Matteo Marsili* (lxxxiv): Opportunity and Choice in Social Networks
CTN	25.2008	*Vasileios Zikos* (lxxxiv): R&D Collaboration Networks in Mixed Oligopoly
CTN	26.2008	*Hans-Peter Weikard and Rob Dellink* (lxxxiv): Sticks and Carrots for the Design of International Climate Agreements with Renegotiations
CTN	27.2008	*Jingang Zhao* (lxxxiv): The Maximal Payoff and Coalition Formation in Coalitional Games
CTN	28.2008	*Giacomo Pasini, Paolo Pin and Simon Weidenholzer* (lxxxiv): A Network Model of Price Dispersion
CTN	29.2008	*Ana Mauleon, Vincent Vannetelbosch and Wouter Vergote* (lxxxiv): Von Neumann-Morgenstern Farsightedly Stable Sets in Two-Sided Matching
CTN	30.2008	*Rahmi İlkiliç* (lxxxiv): Network of Commons
CTN	31.2008	*Marco J. van der Leij and I. Sebastian Buhai* (lxxxiv): A Social Network Analysis of Occupational Segregation
CTN	32.2008	*Billand Pascal, Frachisse David and Massard Nadine* (lxxxiv): The Sixth Framework Program as an Affiliation Network: Representation and Analysis
CTN	33.2008	*Michèle Breton, Lucia Sbragia and Georges Zaccour* (lxxxiv): Dynamic Models for International Environmental Agreements

PRCG	34.2008	*Carmine Guerriero*: The Political Economy of Incentive Regulation: Theory and Evidence from US States
IEM	35.2008	*Irene Valsecchi*: Learning from Experts
PRCG	36.2008	*P. A. Ferrari and S. Salini*: Measuring Service Quality: The Opinion of Europeans about Utilities
ETA	37.2008	*Michele Moretto and Gianpaolo Rossini*: Vertical Integration and Operational Flexibility
CCMP	38.2008	*William K. Jaeger and Van Kolpin*: The Environmental Kuznets Curve from Multiple Perspectives

(lxxxiv) This paper was presented at the 13th Coalition Theory Network Workshop organised by the Fondazione Eni Enrico Mattei (FEEM), held in Venice, Italy on 24-25 January 2008.

2008 SERIES	
CCMP	*Climate Change Modelling and Policy* (Editor: Marzio Galeotti)
SIEV	*Sustainability Indicators and Environmental Valuation* (Editor: Anil Markandya)
NRM	*Natural Resources Management* (Editor: Carlo Giupponi)
KTHC	*Knowledge, Technology, Human Capital* (Editor: Gianmarco Ottaviano)
IEM	*International Energy Markets* (Editor: Matteo Manera)
CSRM	*Corporate Social Responsibility and Sustainable Management* (Editor: Giulio Sapelli)
PRCG	*Privatisation Regulation Corporate Governance* (Editor: Bernardo Bortolotti)
ETA	*Economic Theory and Applications* (Editor: Carlo Carraro)
CTN	*Coalition Theory Network*