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William K. Jaeger and Van Kolpin
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Research Paper No. 187
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RP-187

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March 22, 2001

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ABSTRACT

The simple fact that environmental resources are endowments is found to have profound effects on their patterns of allocation with changes in income, population, and income inequality. For broad classes of theoretical models, and in Pareto efficient as well as decentralized economies, environmental quality is found to follow a U-shaped pattern with rising income. We examine population changes and variations in income inequality, and also find U-shaped patterns of behavior. Importantly, the marginal rate of substitution between consumption and environmental quality can generally be expected to rise monotonically with rising income. These results are found to have important policy implications.

Key words: economic growth, environmental quality, environmental Kuznets curve, population growth

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 be environmental degradation, was advanced by Boulding [6] and formalized in the materials-balance model of Ayres and Kneese [3]. 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.

These views have been challenged recently by empirical evidence of a "U-shaped" pattern in which environmental quality declines, and then rises with increases in per-capita income. The empirical evidence in support of this relationship is strongest in the case of urban air pollutants such as ambient sulfur dioxide and suspended particulates, but more tentative for water pollution (dissolved oxygen) and deforestation.[1] Still, such evidence of an "environmental Kuznets curve"[2] has rekindled debate about whether environmental degradation is inevitable, or whether economic growth might provide its own self-correcting mechanisms for environmental degradation (see Arrow *et al.* [2]).

The cause of this U-shape phenomenon has been the subject of considerable speculation, 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 (Panayotou [17]). A second explanation suggests the role of a high income elasticity of demand for environmental amenities whereby poor countries allow increased pollution as an acceptable side effect of economic growth (Arrow et al.

[2]). The implication of this argument cautions against the interpretation that economic growth may be good for the environment, since the empirical relationship may simply reflect an international redistribution of pollution and polluting industries between relatively richer and relatively poorer nations—the 'pollution havens' hypothesis.

A number of explicit theoretical models have demonstrated that a U-shaped path may occur under a variety of conditions. These include models of the relationship between income growth and the environment include several overlapping generations models. For example, John and Pecchenino [14] show that when short-lived individuals make decisions concerning the accumulation of capital and the provision of a public good that there may be multiple steady states, Pareto inefficient equilibria and over-investment in the environment. Their results include a specification for which a U-shaped path will arise. Other studies have shown that with specific restrictions on preferences or technology, a U-shaped environmental path can be found to occur as well. These include non-homothetic utility in consumption and environmental quality (Lopez [15], and increasing returns-to-scale in abatement technology (Andreoni and Levinson [1]).

The theoretical literature for which the possibility of a U-shaped trajectory is most apparent includes Seldon and Song [21] and Stokey [24]. In the case of Seldon and Song, a variation of a simple model developed by Forster [9] is shown to include the possibility of "an inverted U curve for pollution." Stokey employs a model where a range of constant returns-to-scale technologies offer alternatives which yield more goods but also more pollution. She demonstrates that if the marginal utility of consumption is elastic, pollution declines with income at high-income levels and will produce a U-shaped pattern.

In both analyses, utility is defined as additively separable in consumption and pollution, with utility decreasing in pollution at an increasing rate. This stylized form of the utility function in these studies limits their ability to flesh out the relationship between technology and preferences in explaining the conditions for which a U-shaped path will occur. The current analysis diverges from this early work by deriving results under less restrictive assumptions about preferences. Moreover, we extend the analysis to consider growing populations, decentralized economies, and income inequality.

The current analysis emphasizes the fact that environmental resources represent endowments, and that this fact has a profound effect on the expected patterns of allocation over paths of rising income and population. A useful framework for characterizing environmental resources is to distinguish between two general types of services provided by environmental resources. The first of these services pertains to environmental amenities directly (i.e., air quality, recreation opportunities, habitats, aesthetics, and the indirect use and non-use values associated with ecosystem services); the second type of service involves either the extraction of resources or the use of waste disposal services (e.g., pollution, logging, irrigation diversions), and involves consequent degradation of the first type of service. The first type of service is frequently non-rival, and tends to be defined and measured as a latent or "potential good" (Førsund [10]) in terms of the what is passively available, and initially abundant. By contrast, the second of these services is measured only in terms of what is actively utilized—the quantity of emissions or volume of resources extracted. These services tend to be inputs into production, and are thus a function of derived demand. They are also rival goods with additive impacts on the first type of service, the non-rival environmental amenities.[3]

Given this intrinsic asymmetry, an economy that is initially at a low income levels (has limited production possibilities), but endowed with abundant environmental resources, will seek to maximize consumption of goods with little regard for the environmental impacts of production. Environmentally benign inputs, technologies, or abatement activities will be ignored to the extent that these are more costly. As per capita income rises, so too will the derived demand for waste disposal and extractive services, and this will give rise to further losses of environmental quality. With continued increases in income and consumption, and decreases in environmental quality, a point can be anticipated where the marginal social value of environmental improvement will outweigh the marginal value of additional commodity consumption. Whether a 'turning point' in the environmental path will occur may depend on factors such as preferences, technologies, income distribution and institutions.

The remainder of the paper is organized as follows. In section II some key assumptions underlying our overall approach are laid out along with a first look at the intuition for the results obtained. This is followed in section III with our general analytical results. Section IV investigates the decentralized or unregulated case, and section V concludes.

II. A First Look

In order to focus on the underlying causes of the U-shaped path, we abstract from other potential influences such as intergenerational conflicts, political institutions, returns-to-scale, or asymmetric preferences. A simple static framework is employed to explore these relationships where environmental damage is assumed to be short-lived, so that stock effects are ignored. This simplifying assumption will be a reasonable one for many 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 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 the same as for a farsighted planner with short lived pollutants, assuming the single period structure is indistinguishable. Nevertheless, the implications of relaxing this assumption are discussed below.

The absence of environmental stock effects eliminates the need for a social planner to be forward-looking in terms of the environment. And we can abstract from the sources of growth itself by assuming that changes in income are either exogenous or deterministic. We further assume homogeneity of preferences and, as a starting point, equal incomes. With these assumptions, a representative household approach implies that we can ignore intergenerational conflicts as well.

As a base case we assume that some form of centralized decision-making exists, such as a Lindahl equilibrium, to achieve a Pareto efficient allocation. This assumption is relaxed to consider the alternate extreme case, where household choices are entirely decentralized or unregulated. Homogeneous preferences are maintained throughout, although income inequality is introduced for the unregulated model to consider how the base case results are affected.

The intuition for our result can be conveyed with a simple model of two normal goods; commodity consumption, c, and environmental quality, e. Were it the case that both goods were either purchased or produced, then we would expect the income expansion path to extend out from the origin in figure 1—linearly in the case of homothetic preferences—as indicated by the dotted arrow. With an endowment of environmental resources, however, our starting point is not the origin; rather it is in the upper-left corner of the figure with E as the initial level of environmental quality corresponding the environmental resource endowment.

From this starting point, we expect e to decline over some range of income levels rather than having e increase with rising income. The intuition for this is that the optimal allocation may represent something of a corner solution where technical limits constrain the substitution of commodity consumption for environmental quality (although a corner solution is not required to produce the downward portion of the trajectory, or to obtain a U-shaped result as will be seen below). An increase in income is represented here as an expansion of the production possibilities frontier which enlarges the potential for degrading environmental quality (as an acceptable side effect of increased consumption). As depicted in figure 1, so long as e is large relative to c, inputs or technologies which conserve e will be ignored, and rising income will favor augmenting c at the expense of e. A level of income will be reached, however, where e is no longer abundant relative to c so that, with both c and e being normal goods, further increases in income will lead individuals to desire increases in both, and the optimal allocation will depend on production possibilities.

This basic result can be illustrated with a simple, stylized model with n identical agents where utility, u, is a function of consumption, c, and environmental quality, e. Consumption is a linear function of an environmentally damaging good, x_1, and an environmentally benign good, x_2 such that $c = x_1 + \beta x_2$, where $\beta<1$. Units are defined so that each good has a price of 1, and the budget constraint for an exogenously given level of income is $y = x_1 + x_2$. In this way, the environmentally benign good is assumed to afford less utility per unit of expenditure. Environmental quality is a function of the environmental endowment, E, and damage due to consumption of x_1, where $e=E-n\alpha x_1$. For sufficiently low levels of income, a corner solution to the optimization problem will occur so long as $\partial u/\partial c>\alpha n(\partial u/\partial e)/(1-\beta)$. Over the range where this condition holds, efficiency implies consumption of x_1 only, and pollution will necessarily increase with rising income. With rising income and consumption, and declining environmental quality, an interior solution will occur at y^* where optimality implies $\partial u/\partial c=\alpha n(\partial u/\partial e)/(1-\beta)$. This is the nadir for environmental quality. For income $y > y^*$, this condition implies a constant ratio of the marginal utilities of c and e until $x_1=0$ and $e=E$. Thus, e will be non-decreasing as y increases above y^*.

This stylized example serves to highlight the intuition for the basic results—derived for more general forms and models below. For a given utility function and production technology, y^* will be an increasing function of E, the environmental endowment (since $\partial u/\partial e$ declines with E), and a decreasing function of population, n. Indeed, if, at some initial income level and population, E is very low relative to y, it may be optimal to consume only the environmentally benign good and not damage the environmental at all. A similar situation may occur for a sufficiently high population. Thus this example demonstrates the environmental "endowment effect" in giving rise to the possibility of a U-shaped pattern, and in determining the point at which increasing income should switch from being associated with environmental degradation, to being associated with environmental improvement. Were the initial endowment zero, and if e could be produced, then the model becomes a standard public goods problem with the optimal provision likely to rise monotonically with income.

This example suggests that an observed pattern of environmental deterioration may not be evidence of a secular and deleterious trend, rather it may simply reflect the downward portion of a U-shaped path with a potentially predictable turnaround. Although pollution is the most obvious application of this model, it applies equally to extractive resources such as logging, irrigation, land development, and hydroelectric power generation, which may compete with forms of environmental quality such as biodiversity, ecosystem functions and stability, in-stream flows, unique natural sites and recreational opportunities, all of which tend to be a function of endowed *in situ* resources.

Intuitively, we can now see that the efficient trajectory for environmental quality may decline and then rise with rising income (or rising population)— results which were not contemplated in the classic literature. Moreover, these results are "neutral" in the sense that they do not require any particular assumptions such as increasing returns-to-scale, non-homothetic utility, intergenerational conflicts, or specific political institution. How generalizable is this result? We turn to this question in the next section.

III. General Analytical Results

We begin by presenting an abstract model which enables us to examine the tradeoffs between environmental quality and consumption in contexts of evolving income levels, population sizes, income distributions, etc. Let e represent environmental quality and let c denote the level of private consumption (for expository clarity, each is assumed to be univariate). Let P represent a concave "production possibilities set" which characterizes all feasible profiles of per capita consumption and environmental quality. The preferences of n identical consumers are assumed to be represented by a concave utility function u defined over (c,e) space. It follows that a social planner faces the following optimization problem:

$$\max u(c,e)$$

$$\text{s.t. } (c, e) \in P$$

Of course changes in per capita income (synonymous with productive capital) will affect production possibilities. Letting y denote per capita income, we express this dependence with the notation $P(y)$. One primary focus of this paper will be to examine the "income trajectory" of optimal environmental quality, i.e., the relationship between socially optimal levels of environmental quality and income. As a first step in our study of this income trajectory, let (c^0,e^0) denote the optimal per capita consumption and environmental quality profile given the per capita income of y^0. Let (c^1,e^0) be the point on the frontier of $P(y^1)$ at the original level of environmental quality e^0. Concavity of production possibilities immediately implies that if the frontier of $P(y^1)$ is steeper than the indifference curve at the point (c^1, e^0), then the optimal environmental quality at the new income y^1 must exceed that at the original income y^0. (See figure 2 for an example demonstrating this simple logic.) The reverse must be true if the frontier is less steep.

This insight can also be articulated in terms of relative production and consumption elasticities. Define *production elasticity* at any point (c,e) on the frontier of $P(y)$ 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 *consumption elasticity* as the corresponding indifference curve's slope (in absolute value) divided by c/e. Thus by definition, income changes lead to increased environmental quality if and only if they lead to increased production elasticity relative to consumption elasticity at the point on the new production possibilities frontier corresponding to the initial optimal level of environmental quality. (Indeed, this relative increase can occur only if the slope of the production possibility frontier increases relative to the slope of the corresponding indifference curve.)

Cobb-Douglas preferences provide a particularly transparent framework for examining these trajectories of environmental quality. Indeed, Cobb-Douglas consumption elasticities are everywhere constant, implying parametric changes induce increased environmental quality if and only if production elasticity is increased. The following theorem and its corollary highlight the results established above.

THEOREM 1: Parametric changes lead to increased ex post optimal environmental quality if and only if production elasticity increases relative to consumption elasticity at the initially optimal environmental quality level.

COROLLARY 1: If preferences are Cobb-Douglas, then a parametric change leads to increased ex post optimal environmental quality if and only if production elasticity is increased at the initially optimal environmental quality level.

Note that low levels of income may lead a social planner to produce as much output as income will allow. Indeed, if income is low relative to an abundance of endowed environmental resources, maximum affordable output may be realized at a point where environmental quality is still relatively high. In such a case increased output may only be possible with additional income, and not via further reductions in environmental quality. Such situations bind the planner's choice to a "corner' of the production possibilities set where production elasticity is effectively infinite. Increased income leads to finite production elasticity (at this level of *e*) as the 'corner' is pushed lower. Theorem 1 thus implies that optimal environmental quality must decrease.

When not at a binding production possibilities 'corner', it may often be that the average product of environmental degradation will be more responsive to income changes than will the marginal product of degradation. Said otherwise, one may expect income changes to have a small *proportional* impact on the marginal product of degradation at high levels of output relative to that experienced at lower levels of output. Increases in income must then lead to increases in production elasticity. To the extent that consumption elasticity can be expected to eventually decrease, Theorem 1 would imply an increase in environmental quality.

A 'U-shaped' income trajectory of environmental quality emerges from the discussion above. When income is low the social planner's choice reflects a 'corner' situation described in the first paragraph; when income is high the scenario described in the paragraph immediately above applies.

Thus far production possibilities have been taken as given. In order to make our discussion more concrete, let us now consider deriving production possibilities from specific structural models of technology and resource constraints. There are a variety of scenarios one may envision.

One possibility is that consumption output can be produced from intermediate inputs. As some inputs may be more productive than others and some inputs may be more environmentally benign than others, the realization of consumption/environmental quality will depend on the allocation of income across inputs. The union of the outcomes resulting from all such allocations will thus yield the production possibilities set.

A second possibility is that income can be used to abate (mitigate, remove, recycle or eliminate the residual byproducts of production) environmental damage caused by production.

Production possibilities are then obtained by taking the union of all outcomes that result from allocating income between production and abatement objectives.

An alternative possibility is that there may be a variety of technologies that can be adopted and production possibilities can be calculated by taking the union of the outcomes that result from employing income in these various technologies. While this model may appear inherently distinct from the other two models, it can be interpreted as a broad generalization capable of including both models. Indeed, the proportion of income spent on one input versus another, or spent on production versus abatement, can be thought of as a "technology" choice.

A. Income trajectories

We now consider three specific models as contexts for our analysis. We begin by examining the environmental trajectories for rising income; this is followed by an examination of how these environment-income trajectories are affected by a change in population, as well as the environment-population trajectories when income is held constant.

Model 1. We first consider a model in which there are two inputs, x_1 and x_2, both productive, but where only x_1 is harmful to the environment. Production technology is characterized by the function $c=c(x_1,x_2)$ while environmental quality is represented by the process $e=E-\delta(nx_1)$, where E represents the initial endowment of environmental quality, n is the population size, and δ represents the differentiable 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, production elasticity can be expressed by:

$$\varepsilon = -(de/dc)/(e/c) = [n\delta' / (c_1 - c_2)]/(e/c)$$

It follows that ε is increasing in y, holding e fixed, if and only if $c/(c_1-c_2)$ is increasing in y; where c_i represents the partial derivative of c with respect to x_i. Suppose, for instance, that $c = c(x_1+\beta x_2)$ for some $\beta<1$, implying that x_2 is less productive than x_1. It follows $c/(c_1-c_2)=c/(1-\beta)c'$, which is increasing in y whenever the production function c is concave. Assuming Cobb-Douglas preferences, Corollary 1 can be applied to conclude that the income trajectory of environmental quality must be eventually increasing whenever c is concave. As environmental quality is clearly decreasing for low levels of income (environmental quality is high relative to consumption), we may conclude that the income trajectory is U-shaped.

Model 2. Let us now suppose that output is an increasing function of x_1 so that consumption output can be expressed as $c = c(x_1)$. Let x_2 denote individual abatement input and assume, once again, that inputs are measured on a scale such that $x_1 + x_2 = y$. Suppose that environmental quality is endowed at an initial level E and degrades increasingly with respect to aggregate consumption, but decreasingly so with respect to the aggregate abatement. To be precise, $e = E-\delta(nc, nx_2)$, where n denotes population size and δ represents the environmental degradation function which we assume is everywhere differentiable and equal to zero when c=0. Given the income level y, a functional relationship between c and e emerges from the equations $c = c(x_1)$, $e = E-\delta(nc, nx_2)$ and $x_1 + x_2 = y$.

Assuming Cobb-Douglas preferences, we consider the implications of Corollary 1. Let δ_1 and δ_2 denote partial derivatives of δ with respect to aggregate consumption and abatement, respectively. Given per capita income y and a point (c,e) on the production possibilities frontier corresponding to positive abatement efforts, production elasticity can be expressed by:

$$\varepsilon = -(de/dc)/(e/c) = -[-(n\delta_1 c' - n\delta_2)/c']/(e/c) = n\delta_1 c/e - n\delta_2 c/c'e$$

It follows that ε is increasing in y, holding e fixed, if and only if the right hand side of this equality is increasing in y. For instance, suppose that $c(x_1) = kx_1^b$ for constants k, $b>0$. We further assume that when $nx_2 \geq 1$ (aggregate abatement expenditure is at least "one dollar") then $\delta(nc,nx_2) = h(nc)^\alpha/(nx_2)^a$ for constants h, a, $\alpha>0$. If $nx_2<1$ then $\delta(nc,nx_2) = h(nc)^\alpha$. (Note that the two piece degradation function is merely an analytic convenience so that degradation does not become infinite when abatement expenditure is zero.) The structural form $\delta(nc,nx_2) = h(nc)^\alpha/(nx_2)^a$ emerges from a Cobb-Douglas "technology" for environmental degradation. 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 desired. Assuming abatement is non-negligible so that $(nx_2)^a >1$, ε reduces 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 λ is increasing in y. (Recall e and δ are held fixed in this calculation.) But if δ is constant, implicit differentiation of this relationship yields $d\lambda/dy=$

$(a-b\alpha)\lambda(1-\lambda)/[b\alpha y(1-\lambda)+a\lambda y]$, thus $d\lambda/dy>0$ if and only if $a>b\alpha$. In the context of Corollary 1, we see that environmental quality is initially decreasing in y (when y is low all income is exhausted on production), but eventually the social optimum is realized at a point where production elasticity is well defined. From that point on environmental quality will be increasing in y if $a/\alpha>b$. In other words, unless abatement is ineffective relative to returns to scale in production of c, the income trajectory of environmental quality must be U-shaped.

Model 3. In this model we want to relax our restriction that preferences are Cobb-Douglas, while at the same time introduce a similar functional form to production. We therefore assume that both the production and utility functions are of the constant elasticity of substitution (CES) form. Let $c(x_1,x_2) = (a_1x_1^{\alpha}+a_2x_2^{\alpha})^{1/\alpha}$ and $u(c,e)=(b_1c^{\beta}+b_2e^{\beta})^{1/\beta}$ denote production and utility functions, where $\alpha,\beta\leq 1$, $\alpha,\beta\neq 0$, and $a_1,a_2,b_1,b_2 > 0$. Assume environmental quality is of the form $e=E-\delta(nx_1)$ for some increasing function δ with bounded derivative. Production and consumption elasticities can be written as $\varepsilon = -(de/dc)/(e/c) = [a_1x_1^{\alpha}+a_2x_2^{\alpha}]n\delta'/[a_1x_1^{\alpha-1}-a_2x_2^{\alpha-1}]e$ and $\eta = -(de/dc)/(e/c)= (b_1/b_2)(c/e)^{\beta}$, respectively. Letting $r= x_2/x_1$, the inequality $\varepsilon\geq\eta$ is equivalent to:

$$(b_2/b_1)n\delta' x_1^{1-\beta}e^{\beta-1} \geq (a_1+a_2r^{\alpha})^{(\beta-\alpha)/\alpha}(a_1-a_2r^{\alpha-1}). \tag{1}$$

Let $e(y)$ denote the income trajectory of environmental quality and let $e^* =\lim_{y\to\infty}e(y)\geq 0$. Note that $e(y)$ is initially decreasing as $e(0)=E$ and this level of environmental quality can be maintained for higher levels of income only if consumption is held to zero. The income trajectory is "U-shaped" if $e(y)$ is eventually an increasing function. 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 (1), and consider increasing y beyond the point at which $e(y)=e'$. Observe that as y diverges to infinity, so does r. For large r, the right hand side is on the order of $(a_1+a_2r^{\alpha})^{(\beta-\alpha)/\alpha}$ which is decreasing in r if $\beta<\alpha$, implying production elasticity is increasing relative to consumption elasticity. By Theorem 1 we may thus conclude the income trajectory is "U-shaped." Should the reverse hold true, (i.e., $\beta>\alpha$), this trajectory cannot be U-shaped.

B. 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 [22], and revisionists who contend that the effect of population on growth and resource use varies with time, place, and circumstance (see Birdsall [5]). 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 [19]). 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. [13]).[4]

With the present framework, we can readily determine the effects population growth may have on the income trajectory of environmental quality using the insight developed above; one need only compare the relative impacts on production and consumption elasticity. If production elasticity increases (decreases) relative to consumption elasticity then environmental quality must increase (decrease). To evaluate this question in more specific terms, we turn again to the three models introduced above.

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, $\varepsilon = -(de/dc)/(e/c) = [n\delta'/(c_1-c_2)]/(e/c)$. It follows that ε is increasing in n, holding e fixed, if and only if $nc/(c_1-c_2)$ is increasing in n. For instance, suppose $c = (x_1+\beta x_2)^a$ for some $\beta<1$ and $a>0$. It follows that $nc/(c_1-c_2) = n(x_1+\beta x_2)/(1-\beta)a = [(1-\beta)nx_1+n\beta y]/(1-\beta)a$, which is increasing in n (recall nx_1 is fixed when e is fixed). We conclude that population increases will lower the income trajectory of environmental quality at sufficiently low levels of income (where all income is devoted to the most productive input) and increase environmental quality for higher levels of income. The trajectory will bottom out at lower income levels and will rise above the initial trajectory somewhere before the initial trough.

Model 2 (continued). Recall that production elasticity in this model is increasing in λ. Implicitly differentiating the identity $\delta(nc,n(1-\lambda)y)$=constant (which must hold if environmental quality is unchanging) yields $d\lambda/dn=(a-\alpha)\lambda/n(b\alpha(1-\lambda)+a\lambda)$, implying λ is eventually increasing in n only if $a>\alpha$. We conclude that when $a<\alpha$, population increases will decrease λ and thus 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, like the previous model, the trajectory will bottom out at lower income levels and will rise above the initial trajectory somewhere before the initial trough.

Model 3 (continued). Note that $(b_2/b_1)n^{1-\beta}\delta' x_1{}^{1-\beta}e^{\beta-1} \geq (a_1+a_2r^{\alpha})^{(\beta-\alpha)/\alpha}(a_1-a_2r^{\alpha-1})n^{-\beta}$ follows from reorganizing inequality (1). Holding environmental quality fixed, this implies that aggregate pollution $P=nx_1$ 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 $r=ny/P-1$. 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, in every case except for α and β both being negative, the right hand side of the reorganized inequality necessarily converges to zero, implying environmental quality must be eventually increasing. If, on the other hand $\alpha,\beta<0$, then $(a_1+a_2r^{\alpha})^{(\beta-\alpha)/\alpha}(a_1-a_2r^{\alpha-1})$ 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.

Thus for each model exhibiting a U-shaped trajectory for income, we also find broad ranges of parameter values for which higher population will have a negative effect on the environment at low levels of income, but a positive effect at higher income levels, and a movement of the turning-point toward a lower income level. Our results also imply that the relationship between environmental quality and population (holding income constant) may also follow a U-shaped path as Theorem 1 applies whether shifts in the production possibilities frontier are caused by changes in income, changes in population, or changes in any other parameter.

These possibilities, that the environmental effects of an increase in population may be positive, or that the sign of the effect will vary with income, has not been considered in the literature. Nevertheless, these results are consistent with some evidence in the empirical literature. For example, Cropper and Griffiths [7] find evidence of an environmental Kuznets curve (inverted-U) 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 the model above: higher population density shifts the curve toward more environmental degradation on the left-hand side of the U-shape, and since rural population density is more than twice as high in Africa as in Latin America (based on FAO statistics), the model predicts a left-ward shift in the income-environment turning point.

In a second empirical study, Patel, Pinckney and Jaeger [18] 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.

C. The value of environmental quality

With rising income per capita, what can be said about the change in the marginal rate of substitution between environmental quality and consumption? This question may have important policy implications especially when policies have impacts over long time horizons spanning large changes in income. With an endowment of environmental quality that is initially large relative to consumption possibilities, the marginal value or "price" of environmental quality in terms of the numeraire c (the inverse of the marginal rate of substitution) will be very low initially, but will rise as c rises and e declines. For a case where e can be expected to decline monotonically, this result is unambiguous. The value of e rises monotonically provided that increasing c and decreasing e necessarily raise the marginal rate of substitution of c for e; that is, indifference curves flatten.

For models exhibiting a U-shaped trajectory, this result depends on the evolving shape of the production possibility frontier as it shifts outward. For cases where, for a given value of e, the production possibility frontier becomes flatter, the monotonic rise in the marginal value of e must hold. To examine this in specific terms, let us revisit model 3. On the downward sloping portion of the U-shaped trajectory, income increases cause consumption to increase but environmental quality to decrease at the social optimum. Given that preferences in this model are assumed to be CES, it necessarily follows that the incremental amount of environmental quality that consumers are willing to give up for incrementally more consumption is increasing. In regards to the upward sloping portion of the income trajectory, note that for any given level of environmental quality, the slope of the production possibilities frontier at this given level of e is strictly decreasing in y. (This fact is readily verified by calculating the slope of the production possibilities frontier and noting that its absolute value is strictly decreasing in x_2.) Concavity of the frontier implies that the slope of the frontier is even lower still at higher levels of environmental quality. As the marginal rate of substitution must equal the marginal rate of transformation (slope of the frontier), it immediately follows that the "price" of environmental quality is increasing relative to consumption goods.

Thus, the fact that environmental resources are endowments implies that the price of *e* in terms of *c* can be expected to rise monotonically. This result is at variance with standard practices in policy analysis including the use of benefit-cost analysis where current prices are conventionally used to reflect a neutral assumption regarding expected future prices. The results presented here suggest that these practices may introduce a systematic bias against environmental protection, one with potentially large effects when forecast over long time horizons and large increases in income.

IV. Decentralized Economies

We now consider the general implications of a decentralized, unregulated regime in which there is no social planner to jointly determine agent behavior. We first consider our ongoing model in which income per capita is uniform across individuals; then we relax this assumption to consider the effect of income inequality on the environmental trajectory.

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 $j \neq i$, $P(\lambda_{-i}, y)$ will represent the production possibilities set for a given agent *i* under decentralization. We shall assume that for each $y \geq 0$, there exists a unique symmetric equilibrium for the resulting non-cooperative game in which agent i is free to unilaterally choose its own production technology λ_i.

Note that the production possibility sets with and without a social planner are closely related. Each point (c,e) on the frontier of $P(y)$ 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 $P(\lambda_{-i},y)$ and $P(y)$ 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 the sum $\Sigma_j \lambda_j$ and production by agent j is a function of λ_j. (Note 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 exactly $1/n$ times the production elasticity of $P(y)$ at the same point. An immediate implication of this proportionality is that for each of our specific classes of models 1, 2, and 3, the income trajectory of environmental quality is U-shaped when social choice is decentralized, as long as a U-shape emerges when a social planner is present. The trajectory is, however, lower when production choices are decentralized.

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 [16] 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 [4]).

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/polluting input. As average income rises, the rich are first to reach a threshold at which they begin using the less productive/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

The recognition that environmental resources are endowments has a profound effect on our understanding of their expected patterns of allocation over paths of rising income and population. The current 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 whereby passively available and initially abundant environmental amenity are traded-off against the derived demand for waste disposal services or extractive resources. During an early phase of growth, environmental quality will decline with increases in the derived demand for waste disposal and extractive services. Consumption will increase and environmental quality will decline. Beyond some point, however, rising per capita income and the higher relative scarcity of environmental quality will often shift the allocation in such a way that environmental quality improves. This result does not require any particular assumptions such as increasing returns, non-homothetic preferences, or intergenerational conflicts.

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 which correct for property rights failures and complex coordination problems.

A striking result arising from the environmental endowment effect is the observation that the marginal value of environmental quality in terms of consumption can often be expected to rise monotonically with growth. This observation carries with it fundamental implications for policymaking involving long time-horizons. Indeed, this result suggests that standard methods in benefit-cost analyses that use current prices as a proxy for expected future prices will introduce a myopic bias against the environment that may be significant in magnitude. With average global per capita incomes expected to rise five to ten fold over the 100 year time horizon relevant to climate change policy, the assumption that environmental values will be unchanged relative to goods prices could introduce large errors in these calculations.

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.

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Figure 1. Efficient allocation of an environmental endowment at various income levels

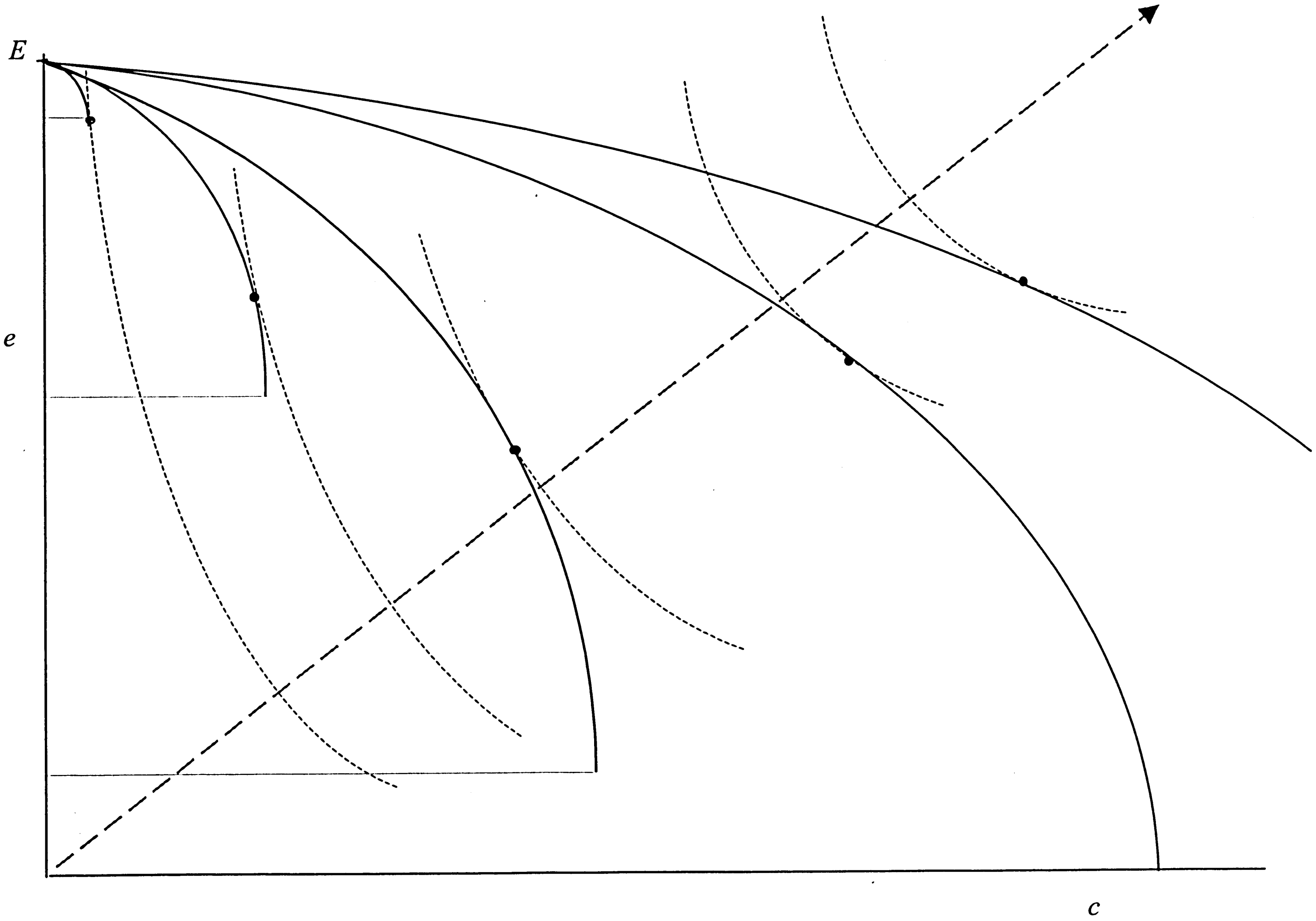
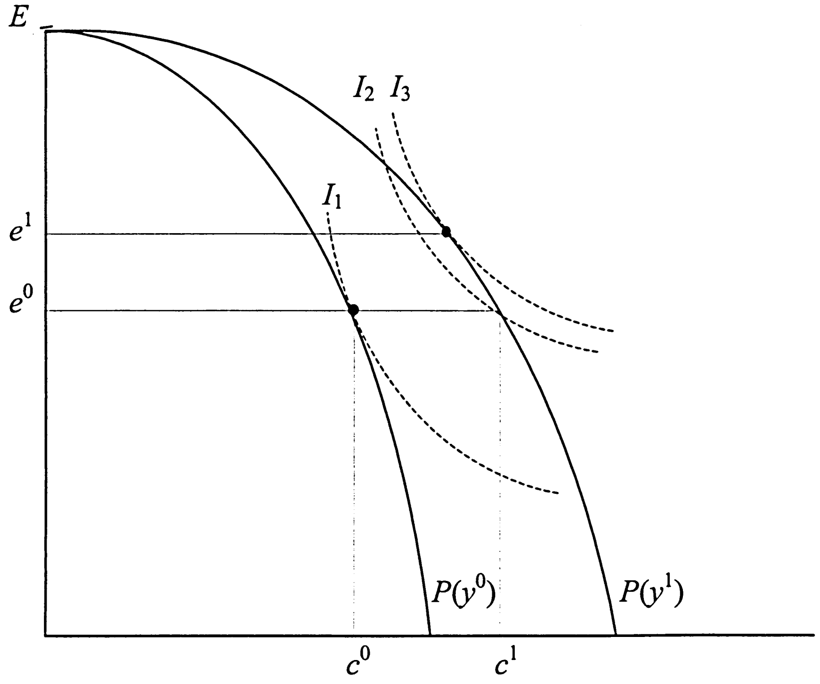


Figure 2. Indifference curve I_2 is less steep than $P(y^1)$ at the level of environmental quality e^0.



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[1] The empirical literature includes Grossman and Krueger [11], Grossman [12], World Bank [25], Seldon and Song [20], Panayotou [17], Cropper and Griffiths [7], Patel, Pinckney and Jaeger [18]. See Stern, Common and Barbier [23] for a survey.

[2] The term "environmental Kuznets curve" refers to an "inverted-U" shape where environmental damage, rather than environmental quality, is taken to be the dependent variable. Here we have 'upended' the inverted-U to consider positive quantities of a environmental goods rather than modeling the disutility of reductions in these goods from potentially arbitrary starting points.

[3] Isolated resources involving only 'reciprocal externalities,' where all individuals using the resource impose congestion externalities on all other users represent a special case of the current framework where only the extractive rival service is considered (e.g., fish harvest), but where the non-rival or amenity service (e.g., existence value of the fishery) is zero or negligible.

[4] Moreover, identifying the impacts of poverty on population growth and environmental degradation has been a complex and contentious task given both their joint endogeneity and inconclusive empirical basis (see Robinson and Srinivasan [19], Dasgupta [8] and Birdsall [5]).