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Why Might One Expect Environmental Kuznets Curves? Examining the Desirability and Feasibility of Substitution

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Why might one expect environmental Kuznets curves? Examining the desirability and feasibility of substitution*

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Abstract

This paper provides simple, transparent intuition for the perhaps surprising and certainly widely debated empirical findings of "environmental Kuznets curves", i.e. U-shaped relationships between per-capita income and indicators of environmental quality. We consider one possible component of such relationships: the linkage between income and household choices that impact upon the environment. Our explicit model emphasizes two features. First, degradation of the environmental endowment is a by-product of household activities. We present a household production model in which consumption of marketed commodities generates both a "good", desired non-environmental services, and a "bad", degradation of the environment. Second, while households can not directly purchase environmental quality, they can reorganize their activities so less degradation results. If environmental quality is a normal good, one expects substitution towards less degrading commodities, so that increases in income will increase environmental quality. We show that natural constraints on the desirability and feasibility of such substitution can produce non-monotonic relationships between household income and environmental quality, and in particular can produce household-level environmental Kuznets curves.

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1. Introduction

A number of papers have spurred both debate and additional study by suggesting the existence of U-shaped relationships between per-capita income and various indicators of environmental quality (e.g., air or water quality) at the aggregate level.[1] This finding—termed the environmental Kuznets curve—suggests that while economic growth may initially be associated with degradation of the environment, continued growth may reverse initial adverse effects. The ongoing attempts to confirm or refute this finding, and continuing debate about its policy implications, indicate a need for clear thinking about why such a relationship might arise.

An existing literature in the neoclassical growth tradition provides one way of thinking about pollution and growth; it makes use of a representative agent framework to explore optimal intertemporal tradeoffs between current consumption, investment in capital, and pollution control.[2] A good example is Gruver (1976), which extends the standard neoclassical growth model by incorporating the portfolio choice between investments in productive capital and pollution-control capital. A key result is that under certain parameter configurations it is possible for the optimal growth path to be unbalanced. The emphasis in the initial stages of growth is on the accumulation of productive capital, which results in increasing levels of output and pollution, but once a target stock of productive capital is reached, savings are shifted towards pollution-control capital, leading to reductions in pollution.

Such analysis is certainly suggestive. However, the representative agent framework used for such dynamic analysis of growth paths lacks a political economic or other explicit mechanism through which the environmental effects of economic growth might in reality be reversed. Further, the mechanisms underlying such a non-monotonic *aggregate* relationship may be relatively complex. For instance, even if all households valued the environment, given externalities it is not clear how such preferences would be aggregated to yield pollution control policies. Also, the factors underlying aggregate relationships may include economy-wide shifts in consumption, involving differential growth rates among economic sectors along a development path. Finally, underlying aggregate mechanisms might also involve trade. For instance, as a country grows richer it might cease to produce goods featuring "dirty" production processes, and instead simply import the finished goods.[3]

To develop simple and transparent intuitions, we step back from these aggregate complications to explicitly consider one building block of aggregate relationships: the way that households change the quality of their environments in response to changes in income when they have a high degree of control over that quality.[4] While we acknowledge the complications of moving to the aggregate level, if our results hold for each household, they are intrinsic to an economy. Also, once we have better understood the household dynamic, we can explicitly add complications.

While particular preferences for the environment could drive results, we assume only that environmental quality is a normally valued good.[5] Our household production model emphasizes two features.[6] First, degradation of the environmental endowment is a by-product of household activities. We present a model in which households consume marketed commodities that bundle a "good", desired non-environmental services, with a "bad", degradation of the environment. Second, while households can not directly purchase environmental quality, they can reorganize their activities so that less degradation results.

In this context, the theoretical puzzle of the existence of environmental Kuznets curves concerns how *non-monotonic* Engel curves for environmental quality can arise. If environmental quality is a normal good, the Engel curves for environment ought to be positively sloped at all incomes. That is, one expects household substitution towards more expensive but less environmentally degrading marketed commodities, so that rising income increases environmental quality monotonically.[7]

We show that the possibility of a non-monotonic relationship between household income and environmental quality can still arise quite naturally.[8] Consider that rising income also increases demand for the non-environmental services produced by environmentally-degrading marketed commodities. Thus, substitution towards more environmentally-friendly commodities is necessary for environmental quality to rise. We show that natural constraints on the desirability and feasibility of such substitution will generate ranges of income in which substitution does not occur. When these are preceded or followed by ranges of incomes in which substitution occurs and dominates, a non-monotonic household environmental Engel curve will result. In particular, a household-level environmental Kuznets curve may arise.

Three situations lead to a lack of substitution. First, poorer households consuming little and having degraded the environment only a little are not willing to pay higher prices for less degrading commodities. Second, when an increase in income leads a household to transition from a cheaper mix of commodities to a more expensive but less environmentally degrading one, the household will use only the transitional commodity for a time because of the discrete rise in price for the more expensive mix. And third, when richer households have fully substituted to the least degrading commodity, there no longer exists scope for further substitution.

Below, Section 2 outlines a simple household-production framework and illustrates how the competing demands, for non-environmental services and the substitution that increases environmental quality, can yield a non-monotonic environmental Engel curve (even when the environment is normally valued). Section 3 then provides analytical results, starting with a two-good case in which the choice of "how much" versus "how clean" illustrates the first and third reasons above for why substitution does not occur, and then for a three-good case in which the optimal purchases of marketed goods illustrate the second reason above for an absence of substitution. Section 4 concludes with a brief discussion and implications for further research.

2. Household production model

We begin with the observation that many environmental services cannot be directly purchased. Rather, households start with endowments of environmental amenities, which are degraded through the consumption of marketed commodities. For instance, in many poor, developing economies, the consumption of marketed fuels such as firewood or kerosene results in the joint production of services that households value (e.g., heat) and reductions in existing indoor air quality. We formalize this observation within a household production/characteristics framework. We use the simplest possible model to demonstrate that non-monotonic environmental Engel curves, such as household-level environmental Kuznets curves, may arise.

Let s denote a household's consumption of a generic non-environmental service, and let a denote the level of the environmental amenity enjoyed by the household. Neither s nor a can be directly purchased. Instead, they are jointly produced (in the case of a, degraded from the endowed level) through the consumption of marketed commodities. Consider a situation in which households have a choice between two marketed goods, a "dirty" (more environmentally destructive) good d and a "clean" good c. Assuming that s is generated linearly from the use of these goods, we can, without further loss of generality, redefine the units in which the two goods are measured so that the total volume of valued services s is given by:

$$s(\vec{q}) = q_d + q_c \tag{2.1}$$

where $\vec{q} = (\ q_d, q_c)$ are quantities of the dirty and clean goods respectively. Without losing any of the basic intuitions, we can also assume that the degradation of the environmental amenity a is fully linear in the marketed commodities. We assume both that the total emissions level e is linear in the purchased goods:

$$e(\vec{q}) = \alpha q_d + \beta q_c \tag{2.2}$$

where $\alpha > \beta > 0$, and that the environmental amenity is linear in total emissions, where A is the initial environmental endowment and $A > 0$:

$$a(e) = A - e \tag{2.3}$$

The household chooses the marketed $\vec{q}$ to maximize (2.4) subject to (2.5):

$$U(s, a) \tag{2.4}$$

$$p_d q_d + p_c q_c = y \tag{2.5}$$

where y is household income and p_d and p_c are, respectively, the per-unit (of services) prices of the dirty and clean goods (we also assume that $p_d < p_c$).

In this two-good case, it is instructive to recast the problem as a household choice of: i) the level of services s; and ii) how those services are produced. Let:

$$\pi \equiv \frac{q_c}{q_d + q_c} \tag{2.6}$$

be the share of the clean good in the overall service consumption of the household. The $s(\vec{q})$, $a(\vec{q})$ technologies then imply a function $a(s, \pi)$ such that:

$$a_s \equiv \frac{\partial a}{\partial s} < 0 \text{ and } a_\pi \equiv \frac{\partial a}{\partial \pi} > 0 \tag{2.7}$$

In other words, holding constant the share of clean goods, increased service consumption leads to a deterioration in environmental quality, and holding constant overall services, substitution to the clean good improves environmental quality.

Households then choose s and π to maximize (2.8) subject to (2.9):

$$U(s, a(s, \pi)) \tag{2.8}$$

$$\begin{aligned} p_d(1-\pi)s + p_c \pi s &= y \\ 0 \leq \pi &\leq 1 \end{aligned} \tag{2.9}$$

We assume that $U(.)$ is increasing and concave in both arguments, and that preferences are such that the demands for s and a would be normal were households able to directly purchase them. With these assumptions, it is straightforward to show that the household's optimal choices of both s and π will be weakly increasing in y, household income. That immediately raises the possibility that the relationship between household income and environmental quality may be non-monotonic, since:

$$\frac{da(s(y),\pi(y))}{dy} = \frac{\partial a}{\partial s}(.)\frac{ds}{dy}(y) + \frac{\partial a}{\partial \pi}(.)\frac{d\pi}{dy}(y) \tag{2.10}$$

For example, it could be that the demand for services s would rise rapidly from lower to middle incomes and then flatten, while that for "being cleaner", i.e. for π, would rise only at higher levels of household income. This could produce a U-shaped Engel curve.[9] The intuition here is that the ability to substitute between marketed goods allows a separation of two decisions: how much service to consume, and how to produce that service. The fact that these two decisions may move independently with respect to income allows for their combined effect to be non-monotonic.

3. Analysis

3.1. Two Goods – "how much" versus "how clean"

To derive analytical results, we now specify (2.4) further, in order to use the example of homothetic, Cobb-Douglas preferences for non-environmental services and environmental quality (the latter is simply normally valued, not a luxury good):

$$U(s,a) = s^m a^n, m+n=1 \tag{3.1}$$

and maximize (3.1) subject to (2.9) through the choice of s and π. This gives rise to a non-linear programming problem, the first-order Kuhn-Tucker conditions of which lead one to consider the following three cases: $\pi^* = 0$; $0 < \pi^* < 1$; and $\pi^* = 1$. These correspond to using only the dirty good, using a mix of marketed goods, and using only the clean good. As developed further below, it is clear that when the first or third cases are optimal, rising income will cause environmental quality to fall. This is because the share of the clean good is fixed (at zero or one), i.e. no substitution is occurring as income rises, such that the last term in (2.10) is zero. In the second case, substitution occurs and environmental quality rises with income.

3.1.1. Not Clean & Environment Degraded

In this model, $\pi^* = 0$ ("not clean") is optimal for poorer households, i.e.:

$$y \leq \frac{Amp_d(p_c - p_d)}{p_d(1-m)(\alpha-\beta) + \alpha(p_c - p_d)} \tag{3.2}$$

For these households, service demanded (or "how much") will rise with income, while environmental quality must fall, as seen in the following:

$$s^* = \frac{y}{p_d}; a^* = A - \frac{\alpha y}{p_d}; \frac{da^*}{dy} = -\frac{\alpha}{p_d} \tag{3.3}$$

Recall, at zero income the household receives zero services but a positive endowment of environmental quality. This asymmetry makes it likely that the marginal utility of services is higher than that of environment. Thus, a poor household could use the cleaner good, but desires not to, preferring to obtain services as rapidly as possible. Note that for larger m and A, even higher income households use only the dirty good. This makes sense: the greater the weight the household places on services, and the greater the environmental endowment, the more the household must consume the dirty good to provide services and degrade the environment before being willing to substitute to more expensive but less degrading goods.

Figure 1 helps to develop this intuition. The endowment is at the upper left ($s = 0$, $a > 0$). The dashed rays are the combinations of a and s attainable through exclusive use of one good. The solid lines connecting the rays are budget constraints for different levels of income; larger budgets are further from the endowment. The budget slopes indicate the relative shadow price of environment and services—i.e., the rate at which households can trade off environment and services given the underlying technologies and the prices of the marketed goods being consumed. The negative slope reflects our assumption that dirtier goods are cheaper than cleaner goods per unit of service produced. The shape of the indifference curves comes from the concavity of the utility function, into which both a and s enter positively.

This figure shows the optimal consumption points of the household at six different levels of income. The two income transitions from point A to point C involve degradation of environmental quality. Juxtaposing the indifference curves with the budget sets shows why in the lowest income transition from A to B, while the household could substitute it does not desire any of the clean good. Because the endowment is so skewed towards environmental quality, moving as rapidly as possible to greater balance of s and a is preferable, and this dictates using only the dirty good. Thus no substitution to less degrading commodities occurs.

Note that in transitions such as from B to C, during which the household starts to substitute, rising income can lower environmental quality. The reason is that over much of this income range no substitution to cleaner goods is preferred. For this transition, Figure 1 highlights that given the asymmetric endowment the household would like to substitute in the other direction, to a cheaper, dirtier good.[10] At the income at which B is chosen, the household would have preferred B' (note that from this unconstrained point, environmental quality would have increased in the shift to C). In sum, then, at low incomes the asymmetric endowment discourages substitution to cleaner goods, and thus rising income degrades the environment.

3.1.2. Partially Clean & Environment Improved

The $0 < \pi^* < 1$ ("partially clean") case is optimal for middle incomes:

$$\frac{Amp_d(p_c - p_d)}{p_d(1-m)(\alpha-\beta) + \alpha(p_c - p_d)} < y < \frac{Amp_c(p_c - p_d)}{p_c(1-m)(\alpha-\beta) + \beta(p_c - p_d)} \tag{3.4}$$

For these households, as suggested above, since environmental quality is a normally valued good, "how clean" (or π^*) will rise enough with income to offset the fact that "how much" service is demanded (or s^*) will also rise with income. The end result is that environmental quality increases with income:

$$s^* = \frac{m[A(p_c - p_d) + y(\alpha - \beta)]}{(\alpha p_c - \beta p_d)} \tag{3.5}$$

$$\frac{da^*}{dy} = \frac{(\alpha-\beta)^2 p_d(1-m) + (\alpha-\beta)\alpha(pc-pd)(1-m)}{(\alpha p_c - \beta p_d)(p_c-p_d)} > 0 \tag{3.6}$$

In Figure 1, from C to D environmental quality improves. The reason is that substitution is both desirable and feasible, so that the household's choices can raise its consumption of both normal goods s and a. Thus, the transitions from A to D trace out a non-monotonic and in fact a U-shaped relationship between y and a, i.e. a household-level environmental Kuznets curve over this range of incomes.

3.1.3. Completely Clean & Environment Degraded

The $\pi^* = 1$ ("completely clean") corner solution is optimal for richer households:

$$y \geq \frac{Amp_c(p_c-p_d)}{p_c(1-m)(\alpha-\beta)+\beta(p_c-p_d)} \tag{3.7}$$

For these households, still "how much" service is demanded rises with income, and again environmental quality must fall, as seen in the following:

$$s^* = \frac{y}{p_c}; a^* = A - \frac{\beta y}{p_c}; \frac{da^*}{dy} = -\frac{\beta}{p_c} \tag{3.8}$$

The intuition here is that the household can no longer substitute. While substitution remains desirable, it is no longer feasible since the household is using only the cleanest good.[11] Again, the values of m and A affect the income range.[12] Figure 1 confirms that environmental improvement is infeasible once the household is at point E, using only the clean good. Thus, the full set of transitions traces out an "inverted N" relationship of air quality to income, as in the top half of Figure 3.[13]

3.2. Three Goods – quantity choice

To illustrate an additional reason for the *absence* of the substitution that lies behind the increasing environmental quality in (3.6), we introduce a third marketed commodity, which we call the "transitional" good (denoted q_t). This good is cleaner than the dirty good but dirtier than the clean good. Now the household's problem is to choose $\vec{q}$ to maximize (3.1) subject to non-negativity constraints on $\vec{q}$ and to (3.9) and (3.10) below (in which $\alpha > \gamma > \beta > 0$ and $p_d < p_t < p_c$):

$$s(\vec{q}) = q_d + q_t + q_c; a(\vec{q}) = A - (\alpha q_d + \gamma q_t + \beta q_c) \tag{3.9}$$

$$p_d q_d + p_t q_t + p_c q_c = y \tag{3.10}$$

We must consider five cases: 1) $q_d > 0, q_t = 0, q_c = 0$; 2) $q_d > 0, q_t > 0, q_c = 0$; 3) $q_d = 0, q_t > 0, q_c = 0$; 4) $q_d = 0, q_t > 0, q_c > 0$; and 5) $q_d = 0, q_t = 0, q_c > 0$. The first and fifth cases are analogous to the low and high income cases for π above, in which environmental quality must fall with income. This is because there is no substitution when either only the dirty or only the clean good is used, although in the first case substitution is not desirable, while in the fifth case it is not feasible. The second and fourth cases are analogous to the middle income case for π, where substitution is desirable and feasible and permits rising environmental quality.

The case that introduces a new feature is the third one, in which only the transitional good is consumed. This case is optimal for the following income range:

$$\frac{Amp_t(p_t - p_d)}{(1-m)(\alpha p_t - \gamma p_d) + m\gamma(p_t - p_d)} \leq y \leq \frac{Amp_t(p_c - p_t)}{(1-m)(\gamma p_c - \beta p_t) + m\gamma(p_c - p_t)} \tag{3.11}$$

For these households, again "how much" service is demanded rises with income, and again environmental quality must fall, as seen in the following:

$$a^* = A - \frac{\gamma y}{p_t}; \frac{da^*}{dy} = -\frac{\gamma}{p_t} \tag{3.12}$$

While as in the first case substitution is feasible but not desirable, the reasoning has changed. In the first case, the asymmetric endowment makes environmental quality of little marginal value, but at incomes lower than in (3.11), the household has already been willing to pay for the transitional good to lessen environmental degradation. Substitution is not desirable because as the household comes to the point of consuming only the transitional good, it faces a discrete shift in the price faced for further substitution, because such substitution would involve replacing the dirty good with the clean good in the mix with the transitional good. For a range of incomes, this jump in the "cost of clean" discourages further substitution. Thus, only the transitional fuel is used, and environmental quality must fall with income.

Figure 2 helps to develop this intuition. It adds the transitional good to Figure 1, and depicts optimal consumption at six levels of income. As in Figure 1, lower income transitions (A to C) trace out a U-shaped income-environmental quality relationship. However, low and middle incomes (A to D or E) trace out a inverted–N-shaped relationship even before the clean good is used. Figure 2 shows that when an increase in income leads to a shift in the goods mix, as in the shift from C to E, the relative price of s and a will change. In particular, the relative price of environmental quality will rise, resulting in the household choosing a reduced level of environmental quality as income rises past the transition point.[14]

Finally, rising income given this new mix of goods again permits substitution and increasing environmental quality (from E to F), as in this linear characteristics case the relative price of s and a is constant while the household consumes the same mix of goods. Then as in Figure 1, environmental quality will of course fall when only the clean good is used. Thus, the existence of the transitional good permits multiple income ranges in which environmental quality decreases, increases, and then decreases again as income rises (see the bottom half of Figure 3). This would continue if additional transitional goods existed, or if cleaner ones were invented.

4. Conclusion

This paper has provided a simple, transparent perspective that helps to clarify whether the "environmental Kuznets curve" is an aggregate pollution-income relationship that one should expect based on the household choices that may underlie it. Our approach is distinguished by explicit modeling of a situation in which the household can control environmental quality (this makes it interpretable as a social planning problem as well). We emphasize that: (1) degradation of the environmental endowment is a by-product of household activities; and (2) a household can reorganize its activities such that less degradation results. If environmental quality is a normally valued good, as we have assumed, one might expect household substitution towards less degrading marketed commodities, such that rising income increases environmental quality monotonically. However, we show that natural constraints on the desirability and feasibility of this type of substitution can produce a non-monotonic relationship, such as a household-level environmental Kuznets curve.

Study of the household-level pollution-income relationship has value for positive work on the aggregate relationship. It suggests hypotheses whose testing may illuminate underlying mechanisms. For instance, Chaudhuri and Pfaff (1999) pursue the implications of this model by examining Pakistani households' shifts between fuels as household income rises, to get a sense for how households are in fact making the sorts of tradeoffs described above regarding indoor air quality. Also, our focus on substitution leads to the testable prediction that when most services are produced using transitional or the cleanest techniques, increases in income will lower environmental quality, potentially yielding "inverted-N-shaped" (not "U-shaped") relationships between income and environmental quality, or even ongoing sinusoidal relationships if innovation leads to ever cleaner new goods and techniques.

Once the household problem and its implications are better understood, we can start to add back the complications that arise when many agents interact to produce the environmental outcome. For instance, our household production framework suggests the possibility of endogenously increasing (environmental) product variety and quality during the process of income growth. With incomes rising, as more households are willing to substitute towards cleaner and potentially more expensive inputs, firms will have more incentive to provide newer, cleaner inputs. To our knowledge, this has not been explored, and we plan to pursue this in future research. In addition, with respect to pollution policies, representative agent-based optimal growth models necessarily assume away free-rider problems and other household-level externalities that may be important in practice. In contrast, while in this paper we have not emphasized the common property characteristics of many environmental amenities, nor performed the explicit aggregation that would provide a direct link between our household-level analysis and aggregate phenomena, the framework presented here provides the building blocks for a more explicit treatment of aggregation and free-rider issues. For instance, within politico-economic models that emphasize a regulatory channel through which an environmental Kuznets curve might come about, our framework should permit a more detailed characterization of why and how environmental voting behavior might change with income.

References

[1] Andreoni, J. and A. Levinson (2001). "The simple analytics of the environmental Kuznets curve". Journal of Public Economics 80:269-286.

[2] Asako, K. (1980). "Economic Growth and Environmental Pollution under the Max-Min Principle". *Journal of Environmental Economics and Management* 7:157-183.

[3] Becker, G. (1965), "A theory of the allocation of time," *Economic Journal*, Vol. 75, pp.493-517.

[4] Becker, R.A. (1982). "Intergenerational Equity: The Capital-Environment Trade-Off". *Journal of Environmental Economics and Management* 9:165-185.

[5] Chaudhuri, S. and A.S.P. Pfaff (1999), "Does Indoor Air Quality Fall or Rise as Household Incomes Increase?," SIPA Working Paper #1, Columbia University.

[6] Chimeli, A.B. and J.B. Braden (2001). "Economic Growth and the Dynamics of Environmental Quality". *Mimeo*, Department of Economics, University of Illinois at Urbana-Champaign.

[7] Chimeli, A.B.(2001). "Optimal Dynamics of Environmental Quality in Economies in Transition". *Mimeo*, Department of Economics, University of Illinois at Urbana-Champaign.

[8] Copeland, B.R. and M.S. Taylor (1995). "Trade and Transboundary Pollution". *American Economic Review* 85(4):716-737.

[9] D'Arge, R.C. and K.C. Kogiku (1973), "Economic growth and the environment," *Review of Economic Studies*, Vol. 40, pp. 61-77.

[10] Deaton, A. and J. Muelbauer (1980). *Economics and Consumer Behavior,* Cambridge University Press, Cambridge.

[11] Forster, B.A. (1973), "Optimal capital accumulation in a polluted environment," *Southern Economic Journal*, Vol. 39, pp.544-547.

[12] Gorman, W.M. (reprinted 1980), "A possible procedure for analysing quality differentials in the egg market," *Review of Economic Studies*, Vol. 47.

[13] Grossman, G. and A. Krueger (1995), "Economic Growth and the Environment," *Quarterly Journal of Economics* 110(2):353-377.

[14] Gruver, G.W. (1976), "Optimal investment in pollution control in a neoclassical growth context," *Journal of Environmental Economics and Management*, Vol. 3, pp.165-177.

[15] Hilton, F. G. H. and A. Levinson (1998), "Factoring the environmental Kuznets curve: evidence from automotive lead emissions," *Journal of Environmental Economics and Management*, Vol. 35, No. 2 (March).

[16] Holtz-Eakin, D. and T. Selden (1995). "Stoking the fires? CO_2 emissions and economic growth. *Journal of Public Economics* 57(1):85-101.

[17] Jaeger, William K. (1998). "Growth and Environmental Resources: A Theoretical Basis for the U-shaped Path". *mimeo* 10/14/98, Williams College, and presentation at an AERE/ASSA session, New York, January 1999.

[18] Kahn, M.E.(1998), "A Household Level Environmental Kuznets Curve," *Economics Letters*

[19] Keeler, E., M. Spence and R. Zeckhauser (1972), "The optimal control of pollution," *Journal of Economic Theory*, Vol. 4, pp.19-34.

[20] Kuznets, S. (1955). "Economic growth and income inequality," *American Economic Review*, Vol. 65, pp. 1-28.

[21] Lancaster, K.J. (1966a), "A new approach to consumer theory," Journal of Political Economy, Vol. 74, pp. 132-157.

[22] _______(1966b), "Change and innovation in the technology of consumption," *American Economic Review*, Vol. 56, pp. 14-23.

[23] Lopez, Ramon (1994). "The Environment as a Factor of Production: The Effects of Economic Growth and Trade Liberalization". *Journal of Environmental Economics and Management* 27:163-184.

[24] Lipsey, R.G. and G. Rosenbluth (1971), "A contribution to the new theory of demand: a rehabilitation of the Giffen good," *Canadian Journal of Economics*, Vol. 4, pp. 131-163.

[25] Plourde, C.G. (1972). "A Model of Waste Accumulation and Disposal". *Canadian Journal of Economics* 5(1):119-125.

[26] Saint-Paul, G. (1995). "Discussion", in Goldin, Ian and L. Alan Winters, eds., *The Economics of Sustainable Development*. Cambridge University Press for the OECD and Centre for Economic Policy Research. pp.47-50.

[27] Seldon and Song (1995), "Neoclassical growth, the J curve for abatement and the inverted U curve for pollution," *Journal of Environmental Economics and Management,* 29(2), pp. 162-168.

[28] Seldon and Song (1994), "Environmental quality and development: is there a U for air pollution emissions?," *Journal of Environmental Economics and Management,* 27(2):147-162.

[29] Shafik, N. (1994). "Economic development and environmental quality: an econometric analysis," *Oxford Economic Papers*, v.46.

[30] Stephens, J.K. (1976). "A Relatively Optimistic Analysis of Growth and Pollution in a Neoclassical Framework". *Journal of Environmental Economics and Management* 3:85-96.

[31] Stokey, Nancy L. (1998). "Are There Limits to Growth?". *International Economic Review* 39(1):1-31.

[32] Tahvonen, O. and J. Kuuluvainen (1993). "Economic Growth, Pollution, and Renewable Resources". *Journal of Environmental Economics and Management* 24:101–118.

[33] World Bank (1992). *World Development Report 1992: Development and the Environment*. Oxford University Press for the World Bank, Oxford, 308p.

ENDNOTES

1. See, for instance, World Bank (1992), Selden & Song (1994), Shafik (1994), Holtz-Eakin & Selden (1995), and Grossman & Krueger (1995).

2. See, for instance, Plourde (1972), Keeler et al. (1972), D'Arge and Kogiku (1973), Forster (1973), Gruver (1976), Stevens (1976), Asako (1980), Becker (1982), Tahvonen and Kuuluvainen (1993), Selden & Song (1995), Chimeli and Braden (2001), Chimeli (2001), and Stokey (1998).

3. Effects of trade in the context of income growth have been discussed by, among others, Saint-Paul (1995) and Jaeger (1998). Copeland and Taylor (1995) include the effect of trade on national incomes in considering the effects of trade on the environment within a general equilibrium setting.

4. Further, as our household fully internalizes its environmental effects, our results are consistent with efficient choice by a social planner.

5. Lopez (1994) and Selden and Song (1995) describe roles for preferences, while Andreoni and Levinson (2001) posit a particular mechanism involving increasing returns to abatement to explain the environmental Kuznets curve.

6. Classic early references in the household production literature include Gorman (1980), Becker (1965), Lancaster (1966a, 1966b).

7. While the example we mention on occasion below is household fuel switching in a developing country context (e.g., substitution from dung and wood to kerosene to liquid propone to natural gas as income rises), other examples of this kind of household substitution include: paying more for wind-powered electricity generation, or for more fuel efficient air conditioners; purchasing more expensive but biodegradable garbage bags; and buying a costlier but higher mileage automobile. These raise the issue of household voting and regulation, since they may not feature the same degree of internalization as fuels and indoor air quality. However, still people do these things of their own accord.

8. The household-level relationship between income and environmental quality might in fact take on any number of shapes, including a monotic rise in quality. This indeterminacy is an attractive property, as despite the attention given to evidence of U-shaped relationships, a more robust empirical finding is that the relationship is potentially non-monotonic. Also, some investigations find that there does not appear to be any significant aggregate empirical relationship at all.

9. For a more general but perhaps less illustrative intuition, ignore for the moment the fact that the input demand functions may not be differentiable at all incomes because of binding non-negativity constraints on input use, and represent the slope of the Engel curve linking a to y as:

$$\frac{da(\vec{q}(y))}{dy} = \sum_j \left(\frac{\partial a(\vec{q})}{\partial q_j}\right)\frac{\partial q_j}{\partial y}(y) \tag{4.1}$$

The key point to note here is that the demand for the marketed inputs is *derived* from the household's preferences for s and a. Thus, there can be no presumption that the demand for a marketed good will be normal. In fact, within a characteristics/household production framework, inferior marketed goods can be quite common (Deaton and Muellbauer (1980), Lipsey and Rosenbluth (1971)). If, therefore, dirty inputs are inferior (after a certain income) while clean inputs are normal, it is quite possible that the Engel curve for the environmental amenity will be U-shaped.

10. In the analytical results, this is suggested by the optimal π^* in this income range being negative in the absence of non-negativity constraints on π.

11. In Figure 1, that substitution remains desirable is conveyed by point E' being preferred to point E (analogous to the low-income case of B' preferred to B).

12. It is also worth noting that adding a fixed cost to the clean fuel leaves the ideas discussed above intact, although not surprisingly the value of the parameter representing the fixed cost also affects the income ranges.

13. Here it should be noted that Stokey (1998) also finds corner solutions as part of an environmental Kuznets curve, although only for poorer households.

14. Note that while relative shadow prices of non-marketed goods shifting with income characterizes household-production models in general, only when marketed goods bundle a "good" with a "bad" could the relative price shift accompanying an increase in income outweigh the direct effect of income. For instance, in the classic household production model in which marketed foods are purchased to provide a set of non-marketed "good" nutrients, an increase in income cannot lead to a decrease in the consumption of any nutrient (unless a non-marketed nutrient is a Giffen good, which is rare – a statement which should not be confused with our earlier assertion that within a household production framework, inferior or Giffen goods can be quite common among *marketed* commodities). Or, consider the case of homothetic preferences. In the nutrients case, the mix of marketed foods and relative shadow price of nutrients faced never change as income rises (in the analytical results, income does not appear in the nutrient share). In contrast, as Figure 2 indicates, when marketed commodities bundle a good with a bad, even with homothetic preferences a household must eventually change its mix of goods, and the relative shadow price of the environmental amenity must eventually rise.

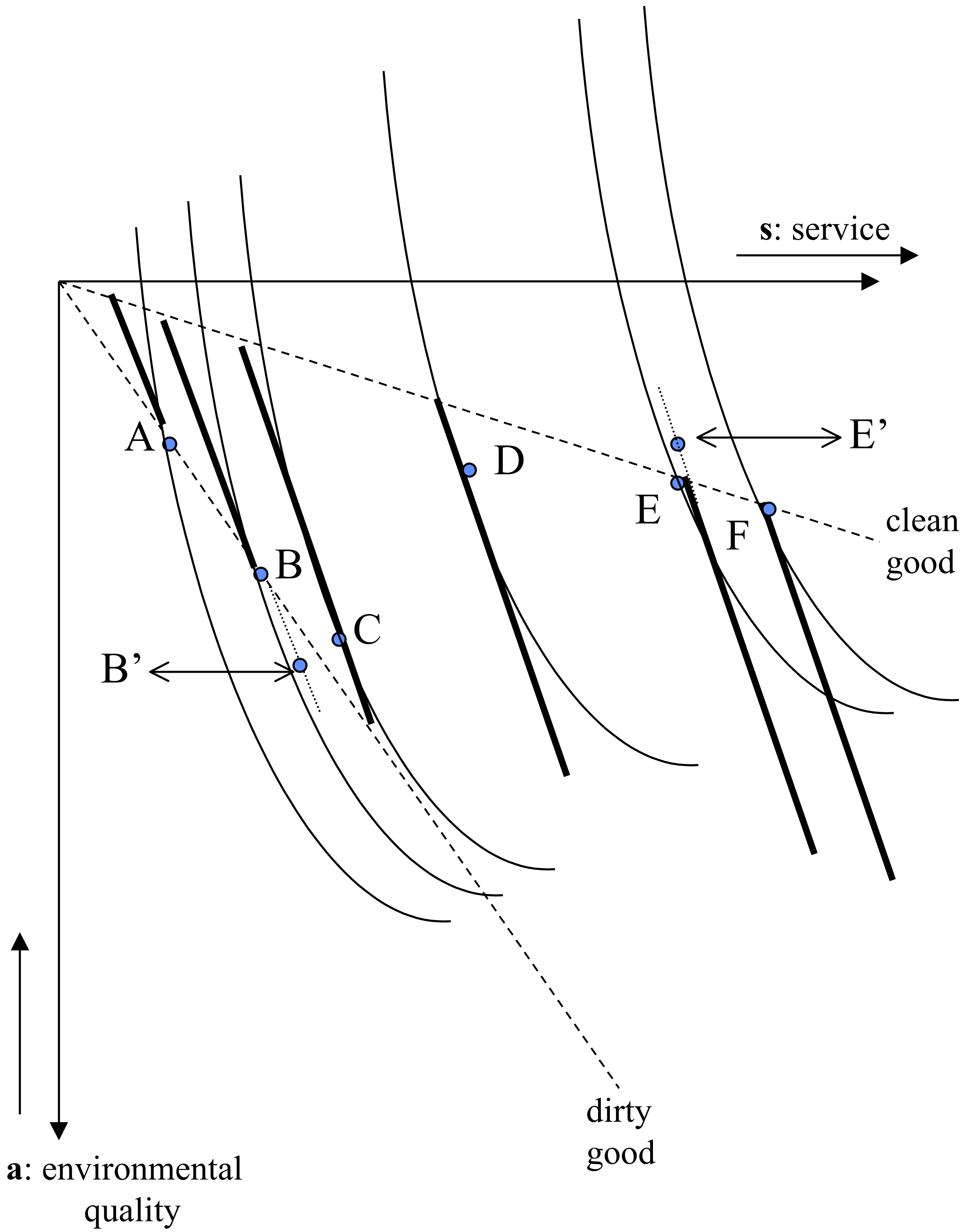

FIGURE 1

two goods

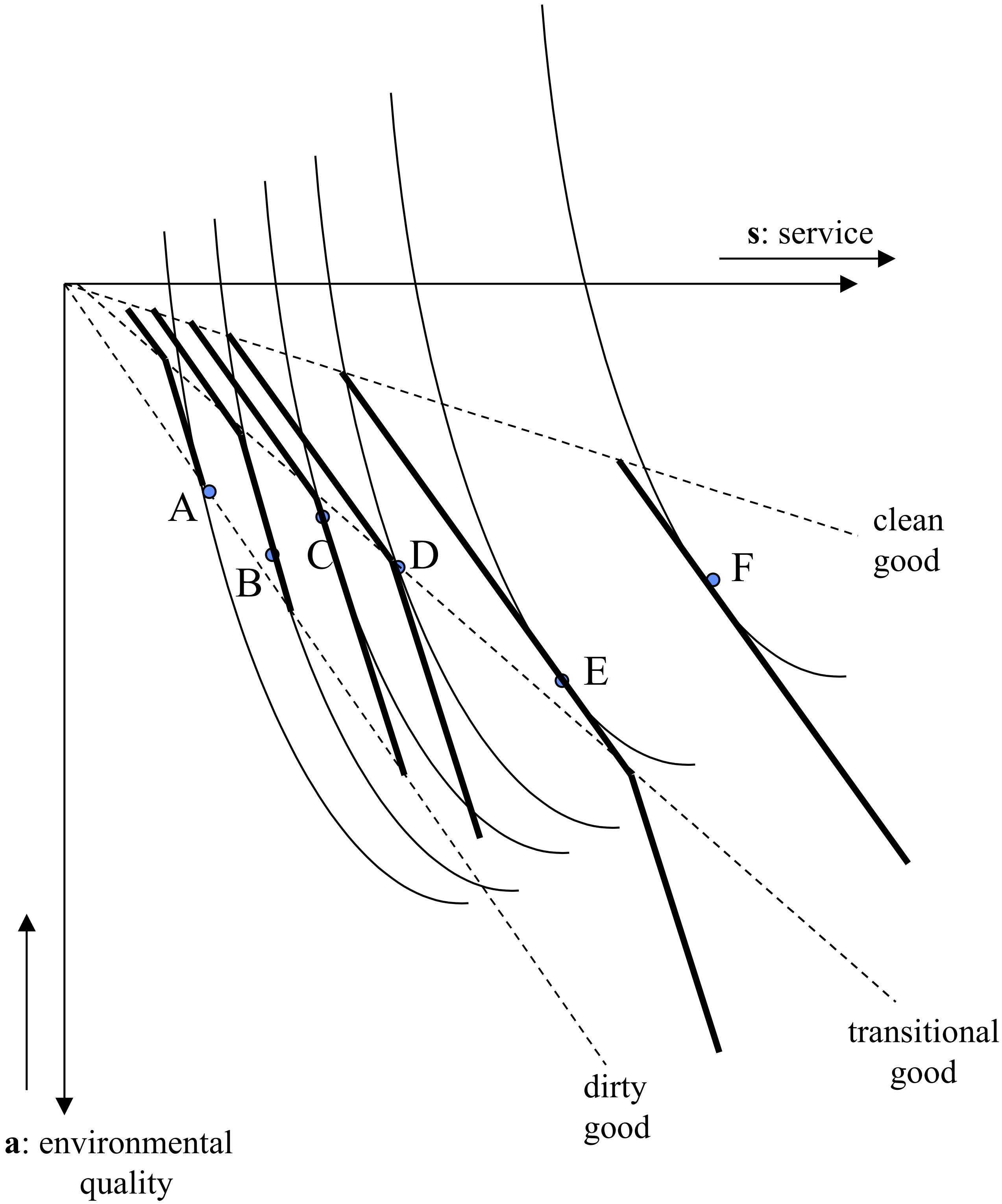

FIGURE 2

three goods

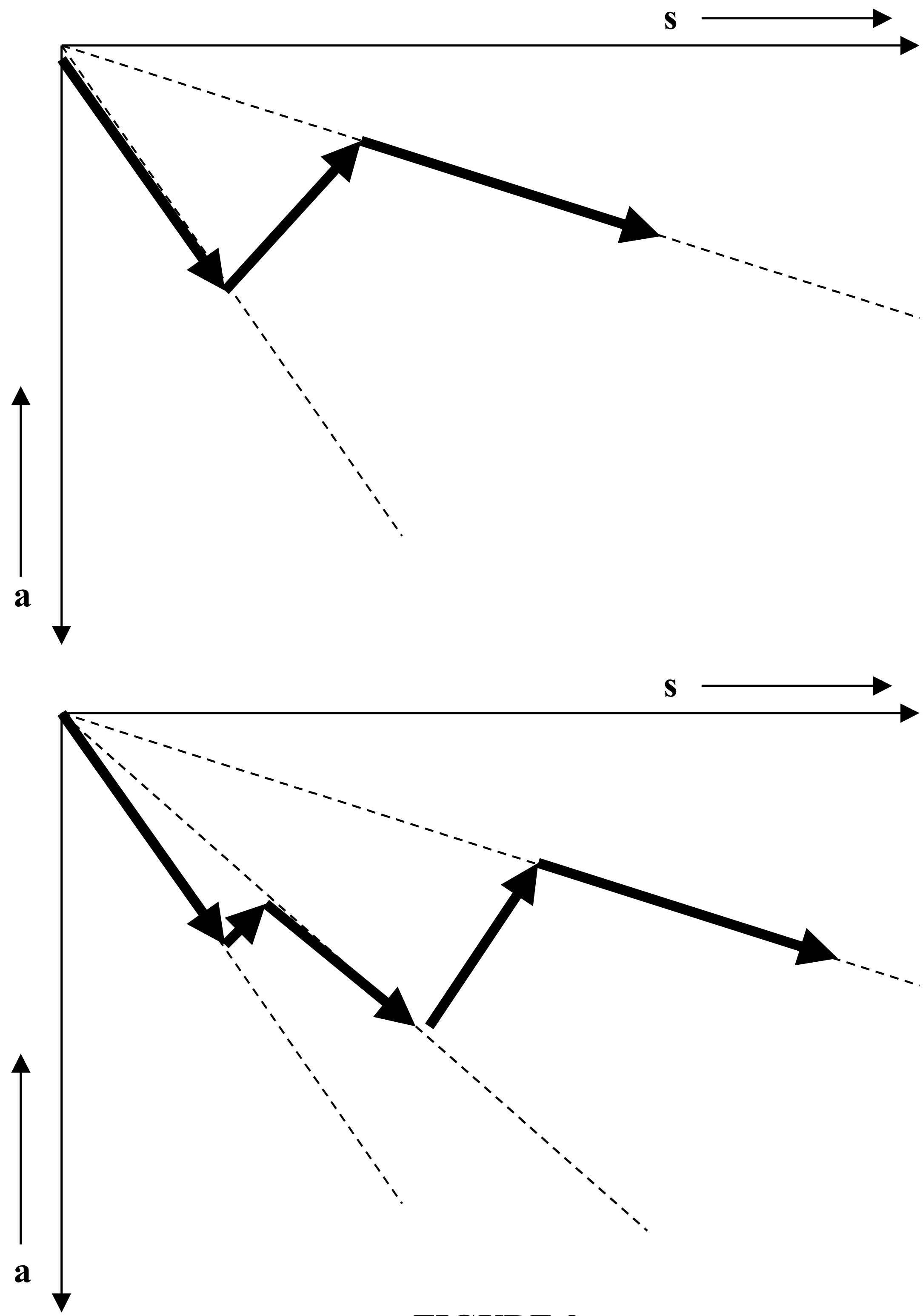

FIGURE 3

paths as income rises