Endowments, preferences, technologies and abatement: growth-environment microfoundations

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Abstract: Will economic growth inevitably degrade the environment, throughout development? We present a household-level framework emphasising the trade-off between consumption that causes pollution and pollution-reducing abatement. Our model provides a simple explanation for upward-turning, non-monotonic paths of environmental quality during economic growth. Its innovation yields sufficient conditions that simultaneously address preferences and technologies. With standard preferences, an asymmetric endowment (i.e., at zero income, consumption is also zero but environmental quality is positive) leads low-income households not to abate, and further this condition is sufficient for an environmental Kuznets curve (EKC) for a wide range of abatement technologies. Without such an endowment, however, even strong economies of scale in abatement are, on their own, insufficient for an EKC.

Keywords: environment; pollution; development; growth; abatement.

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1 Introduction

The question of whether environmental quality will inevitably fall during economic development has spurred empirical, theoretical and policy debate. Early empirical analyses that used countries as units of analysis suggested the so-called environmental Kuznets curves (EKCs), i.e. non-monotonic U-shaped relationships between per-capita income and environmental quality. Thus, environmental quality would rise during later stages of development[1]. To caricature the early literature, such relationships seemed empirically robust, at a national level, but theoretically puzzling. The lack of a predictive framework helped to fuel ongoing tension concerning the appropriate interpretation of empirical relationships of this type: do we believe and expect them, i.e. are they and should they be robust? And, are they in any way evidence that regulation is unnecessary, or simply an implication of increasing regulation as incomes rise?

Any modelling framework must take a stand on whether external effects among households are internalised. If regulations do not exist and households do not fully internalise their effects, it is not surprising that environment can fall with rising income[2]. But what is not as easy to explain in this setting is how environmental quality could rise with increasing income. For that to happen, households would have to care enough about the environment to coordinate and aggregate preferences, such as through voting. Thus, modelling of increasing regulation as incomes rise, which many feel is central to explaining observed EKCs, requires an understanding of the evolution of household choices during economic growth[3].

This paper provides a household-level framework to explore a simple, powerful reason why environmental quality may fall and then rise as incomes rise. It is relevant as a background for voting models, but also relevant when degradation features a significant private component[4]. In addition to clarity and transparency, this model in particular yields sufficient conditions for non-monotonic paths of environmental quality. These permit easy evaluation of whether a given combination of preferences and abatement technologies gives rise to such a path. While existing literature has tended to focus either on preferences or on abatement technologies[5], we allow the effect of a given technology to depend upon the preferences, and vice versa.

For each household, our model focuses upon the asymmetric endowment of consumption and environment, i.e. positive environmental quality but zero consumption at zero income. This is so natural an assumption as to appear obvious. We show that it is nonetheless crucial. Given standard preferences for consumption and environment, such that if households could purchase them separately and independently both would be normal goods, an endowment is sufficient for an EKC given a wide range of abatement technologies encompassing fixed costs and decreasing returns[6]. Thus, the model can account for the initial decrease in environmental quality as income rises and for increasing environmental quality as income continues to grow.

The key intuition is that, given an endowment of environmental quality that is degraded by consumption, and given convex preferences for consumption and environment, at low incomes the marginal rate of substitution implies that the household prefers not to spend to abate the effects of consumption. This results in a corner solution where no resources are expended on abatement, but consumption will rise with income. This causes environmental quality to fall with income.

However as income continues to rise, and the environment is degraded, the marginal rate of substitution between environmental quality and consumption increases in favour of the environment, until it is desirable to abate. This moves the household to an interior solution, in which it both consumes and abates, and for a wide range of abatement technologies environmental quality will increase with income because both goods are normal. We provide a condition, which determines whether environmental quality will rise with income as the income gets high enough. This compares the change in the marginal rate of substitution as incomes rise to the change in the marginal rate of transformation implied by the abatement technology[7]. As noted, such a general condition simplifies consideration of the implications for EKCs of combinations of whatever preferences and abatement technologies are of interest.

Finally consider that while with externalities a fall in environmental quality is the default and a rise is harder to explain, without externalities rising environmental quality is the default, and why it might fall with income is unclear. For most technologies, if the environment is a normal good then without further assumptions the Engel curves for environment ought to be, *a priori*, positively sloped at all incomes.

The need for an *explicit* explanation of a fall in environmental quality in this setting of internalisation is easy to overlook. The main theorem in Andreoni and Levinson (2001), for instance, simply assumes a fall: (paraphrasing – assuming consumption and environment are normal goods, and a particular increasing returns abatement technology) 'for any combination of utility and abatement technology that yields positive pollution for some level of income, optimal pollution will eventually decline back to zero for some sufficiently large income.' In contrast to this assumption of initially falling environmental quality, we show that for standard convex preferences *without* an asymmetric endowment, neither the abatement technologies we consider nor the increasing returns technology in Andreoni and Levinson (2001) accounts for a range of income in which environmental quality in fact falls. Hence, these abatement technologies alone cannot generate EKCs.

Section 2 below presents our simple model and, retaining its generality, works to our sufficient conditions for an EKC. Section 3 adds intuition through specific cases showing that our endowment-based is robust for a range of abatement technologies. It also explores abatement technologies without an environmental endowment, finding that even increasing returns is not sufficient for an EKC. Section 4 concludes with a brief discussion and implications for further research.

2 Household income and environmental quality

2.1 Preferences, abatement technology and environmental quality

A household gets utility from two goods, a marketed consumption good, denoted by c, and environmental quality, denoted q, so that utility can be written as:

$$U = U(c, q) \tag{2.1}$$

where $U_c > 0$, $U_q > 0$ and U is concave in c and q. Households enjoy an initial endowment of environmental quality ($q_0 \geq 0$) that is degraded by pollution, which as a byproduct of consumption rises with c. However, the household can choose to expend resources to 'abate' the effects of pollution on the environment, i.e. to make consumption less damaging, for instance by using cleaner but more expensive inputs or by cleaning up pollution already generated. Denoting such expenditures on environmental investment as e, we write environmental quality as:

$$q = q(c, e) \tag{2.2}$$

where $q_c < 0$ –environmental quality falls with rising consumption–and $q_e > 0$.

The general household problem, then, is to choose c and e to maximise (2.3) subject to the budget constraint (2.4) and, since a household can choose to expend zero resources on either c or e, also the non-negativity constraints (2.5):

$$U = U(c, q(c, e)) \tag{2.3}$$

$$p_c c + p_e e = y \tag{2.4}$$

$$c \geq 0, e \geq 0 \tag{2.5}$$

where y is household income, and p_c and p_e are, respectively, the prices of c and e.

2.2 Sufficient conditions for an EKC

Before providing specific results for particularly interesting cases (see Section 3), we derive general conditions for the two parts of an EKC, i.e. environmental quality falling with income at low incomes, and rising with income at higher incomes. For these general results, we start with a few assumptions about preferences:

$$U_c > 0, U_{cc} < 0, U_q > 0, U_{qq} < 0, \tag{2.6}$$

$$U_{qq} U_{cc} - U_{cq}^2 \geq 0, \quad \lim_{c \to 0} U_c(c, q) = +\infty, \quad \lim_{q \to 0} U_q(c, q) = +\infty.$$

We assume further that preferences are such that the demand for both of these goods, c and q, would be normal if these goods could both be purchased separately and independently:

$$U_c U_{cq} - U_q U_{cc} > 0, \; U_q U_{cq} - U_c U_{qq} > 0. \tag{2.7}$$

We also make the following assumptions about the relationships between consumption, environmental degradation and the abatement technology:

$$q_e > 0,\ q_{ee} \le 0,\ q_c < 0,\ q_{cc} \le 0$$

$$q_{ce} \ge 0,\ \lim_{e \to 0} q_e(c,e) = m < +\infty,\ q(0,0) = q_0 > 0. \tag{2.8}$$

To simplify the notation, we set $p_c = p_e = 1$.

Given these conditions, we ask whether an asymmetric endowment ($q_0 > 0$) leads to a low-income range in which nothing is spent on abatement but consumption occurs, such that environmental quality falls. Also, we examine whether such a range is followed by one in which consumption *and* abatement occur, and both rise with income such that environmental quality also rises, yielding an EKC. Here we do so for the general model, while in Section 3 we provide specific results (for instance income ranges for environmental quality falling and rising) for some cases of interest.

2.2.1 No abatement at low incomes

From (2.6, sixth), we know the non-negativity constraint on c will never bind, and from (2.8, first) we know the budget constraint will always bind. Hence we can write the first-order condition for maximisation of (2.3) subject to (2.5) and the budget as:

$$\begin{aligned} &U_c(c, q(c, y-c)) + U_q(c, q(c, y-c))q_c(c, y-c) \\ &\ge U_q(c, q(c, y-c))q_e(c, y-c) \end{aligned} \tag{2.9}$$

which holds with equality only if $e = y - c > 0$. On the left is the net marginal utility from additional consumption, including the marginal disutility from the loss of environmental quality brought about by additional consumption. The term on the right represents the marginal utility from additional abatement expenditures.

Let $c^*(y)$ and $e^*(y)$ denote the optimal choices of c and e from the maximisation problem above. Given the above assumptions regarding preferences and technology, we will show here that there exists $\hat{y} > 0$ such that for all $y < \hat{y}$:

$$c^*(y) = ye^*(y) = 0 \frac{dq}{dy} = q_c \frac{dc^*}{dy} + q_e \frac{de^*}{dy} = q_c < 0.$$

To see this, we can by start by defining:

$$g(y) \equiv U_c(y, q(y,0)) + U_q(y, q(y,0))q_c(y,0)$$

$$l(y) \equiv U_q(y, q(y,0))q_e(y,0). \tag{2.10}$$

For income y, $g(y)$ is the net marginal gain from devoting all income to consumption, whereas $l(y)$ is the marginal loss from doing so. Differentiation of g and l shows that

(2.6), (2.7) and (2.8) imply that $g(y)$ declines but $l(y)$ increases with y. Further, since from (2.6, sixth) along with (2.8, sixth and seventh) we know that:

$$\lim_{y\to 0} g(y) = +\infty \quad \lim_{y\to 0} l(y) = K < +\infty.$$

It follows that there exists $\hat{y} > 0$ such that:

$$\begin{aligned} &g(y)>i(y) \ \forall y<\hat{y} \\ &g(y)=i(\hat{y}) \\ &g(y)<i(y) \ \forall y>\hat{y}. \end{aligned} \tag{2.11}$$

The result follows from (2.11) given (2.9). Note the crucial role here of the assumption that $q_0 > 0$ – without the environmental endowment the three ranges in (2.11) may not exist. Given the endowment, when $y < \hat{y}$ the household will not spend on abatement because the net marginal utility of consumption, taking into account environmental degradation, is greater than the gain from abatement spending. This dictates the corner solution in which environmental quality must fall with income.

2.2.2 *Rising consumption and abatement at higher incomes*

Here we will show that under assumptions (2.6), (2.7) and (2.8), for all $y > \hat{y}$:

$$0 < c^*(y) < y 0 < \frac{dc^*}{dy} < 1 0 < e^*(y) < y 0 < \frac{de^*}{dy} < 1.$$

By totally differentiating (9) and rearranging terms, we can see that:

$$\frac{dc^*}{dy} = \frac{\Omega_c}{\Omega_e + \Omega_c}$$

where:

$$\Omega_c = U_q(q_{ee} - q_{ce}) - U_{cq}q_e - U_{qq}q_e(q_c - q_e) < 0 \tag{2.12}$$

$$\Omega_e = U_{cc} + U_{cq}q_c + U_{qc}(q_c - q_e) + U_{qq}q_c(q_c - q_e) + U_q(q_{cc} - q_{ce}) < 0.$$

Hence we can immediately see that:

$$0 < \frac{dc^*}{dy} < 1$$

$$0 < \frac{de^*}{dy} = \left(1 - \frac{dc^*}{dy}\right) = \frac{\Omega_e}{\Omega_e + \Omega_c} < 1.$$

These expressions indicate that, with rising income, eventually the household will want to spend on both consumption and environment. Further, we can see that the expenditures on each will rise with income. The question, then, is whether the simultaneous increases in pollution-causing consumption and pollution-reducing abatement expenditures will permit environmental quality to rise with income.

2.2.3 Falling then rising environmental quality

That the abatement expenditures will rise with income once $y > \hat{y}$ does not by itself guarantee that environmental quality will rise with income beyond the threshold $\hat{y}$. Because consumption is rising as well, the increase in e has to be large enough to offset the additional pollution caused by increased consumption. Under what combinations of preferences and abatement technologies is that likely to occur?

Note that the assumptions we have made thus far are *not* sufficient to ensure environmental quality rising with income. To see that this is the case, by way of contrast consider first the familiar case from basic consumer theory, in which the marginal rate of transformation (MRT) the consumer faces–i.e., the rate at which the consumer is able to exchange one marketed commodity for another–is fixed by exogenously given market prices and hence is independent of the consumer's income. In that case simple restrictions on preferences, e.g. of the sort we have imposed, do suffice to guarantee that the demand for these *marketed* commodities is normal.

We require further assumptions because environment is a *non-marketed* commodity. This implies that the relative shadow price of environmental quality, i.e. the MRT along the $c-q$ consumption possibility frontier, will generally (though not always) depend on the household's income. Whether non-marketed environmental quality falls or rises with income will, therefore, depend not just on preferences, i.e. how the marginal rate of substitution (MRS) of c for q changes, but instead on how both the MRS and the MRT change as we move between optima as income rises. The assumptions we have made so far pin down the changes in the MRS both along an indifference curve and in moving between indifference curves within a shift to a new optimum. They also pin down the change in MRT along a given consumption possibility frontier. The proposition below determines what we need to assume in addition, for EKCs to arise, about the change in the MRT in moving from one consumption possibility frontier to another within shifts to new optima, conditional on and specifically relative to the change in the MRS.

Proposition 2.1: Let

$$MRS(c,q) \equiv \frac{U_c}{U_q}$$

$$MRT(c,q) \equiv q_e - q_c.$$

If assumptions (2.6), (2.7) and (2.8) hold and there exists $\tilde{y}$ such that for all $y > \tilde{y}$:

$$\left.\frac{\partial MRS(c^*(y), q^*(y))}{\partial c}\right|_{q=q^*} - \left.\frac{\partial MRT(c^*(y), q^*(y))}{\partial c}\right|_{q=q^*} < 0 \qquad (2.13)$$

then:

$$\frac{dq^*}{dy} < 0 \text{ for all } y < \hat{y} \text{ where } \hat{y} \text{ is implicitly defined by } g(\hat{y}) = l(\hat{y})$$

$$\frac{dq^*}{dy} > 0 \text{ for all } y > \max\{\hat{y}, \tilde{y}\}.$$

Proof: That environment decreases with rising income until $\hat{y}$, given $q_0 > 0$, follows from Section 2.2.1. To see that adding (2.13) is sufficient for there to exist an income level beyond which environmental quality increases with income, note that for income above $\hat{y}$, when the non-negativity constraint on e is no longer binding:

$$\frac{dq(c^*(y), e^*(y))}{dy} = q_c \frac{dc^*}{dy} + q_e \frac{de^*}{dy}$$

$$= q_c \frac{\Omega_c}{\Omega_e + \Omega_c} + q_e \frac{\Omega_e}{\Omega_e + \Omega_c} = \frac{q_c\Omega_c + q_e\Omega_e}{\Omega_e + \Omega_c}$$

where Ω_e and Ω_c are defined as in (2.12). Since $(\Omega_e + \Omega_c) < 0$, we have that $\frac{dq^*}{dy} > 0$ if and only if $(q_e\Omega_e + q_c\Omega_c) < 0$. Substituting (2.9) and (2.12) above and rearranging:

$$q_e\Omega_e + q_c\Omega_c = U_q\left[\left(\frac{U_{cc}}{U_q} - \frac{U_{qc}U_c}{U_q^2}\right) + \frac{1}{q_e}(q_e(q_{cc} - q_{ce}) + q_c(q_{ee} - q_{ce}))\right].$$

But we also know that:

$$\left.\frac{\partial MRS(c^*(y), q^*(y))}{\partial c}\right|_{q=q^*} = \frac{U_{cc}}{U_q} - \frac{U_{qc}U_c}{U_q^2}$$

$$\left.\frac{\partial MRT(c^*(y), q^*(y))}{\partial c}\right|_{q=q^*} = \frac{1}{q_e}(q_e(q_{ce} - q_{cc}) + q_c(q_{ce} - q_{ee}))$$

and thus we can see directly that:

$$q_e\Omega_e + q_c\Omega_c = U_q\left[\left.\frac{\partial MRS(c^*(y), q^*(y))}{\partial c}\right|_{q=q^*} - \left.\frac{\partial MRT(c^*(y), q^*(y))}{\partial c}\right|_{q=q^*}\right].$$

Clearly then, $\frac{dq^*}{dy} > 0$ if and only if $\left[\frac{\partial MRS(c^*(y), q^*(y))}{\partial c} - \frac{\partial MRT(c^*(y), q^*(y))}{\partial c}\right] < 0$,

as the sufficient condition in the proposition suggests. If $\tilde{y} < \hat{y}$, then $\frac{dq^*}{dy} > 0$ from the moment that abatement expenditures are positive. If on the other hand $\tilde{y} > \hat{y}$, then even after households start to spend on abatement, environmental quality may fall with rising income, although only up to the threshold level of income $\tilde{y}$. Beyond that income level, environmental quality will improve with increases in income.

This result completes the intuition for sufficiency of an asymmetric endowment for an EKC (since Section 2.2.1 showed falling environment at low incomes, i.e. the first part of an EKC). In light of (2.13), see that an endowment yields a falling MRS as the scale of income and consumption rises, because with convex preferences the marginal gain from consumption falls as consumption rises. Thus, even were the MRT not to change with scale, given an endowment the conditions would exist for rising $q^*(y)$ once y is high enough, i.e. for the second part of the EKC. In fact, for a wide set of technologies the endowment will be sufficient for an EKC.

This result also permits the direct evaluation of whether a particular combination of preferences and abatement technologies can be expected to generate an EKC. Constant returns (unchanging MRT) leaves matters to the preferences, such that an asymmetric endowment yields an EKC. Increasing returns to abatement spending (e.g. $q_{ee} > 0$, $q_{cc} = q_{ce} = 0$) should help the second part of the EKC, i.e. rising environment, because raising q through abatement is easier as scale rises with income. In the light of (2.13), note that this makes the change in MRT as scale rises positive. Thus, as per Proposition 2.1 even if the MRS were unchanged with scale eventually environmental quality would rise with income, i.e. increasing returns abatement technologies do help generate the second part of the EKC, rising environment.

As noted earlier, though, without an asymmetric endowment we lack an explicit story for why environment falls in the low-income range, i.e. for the first part of an EKC. Thus, despite its role in raising environmental quality at higher incomes, increasing returns shifting the abatement MRT is not sufficient for an EKC.

3 Robustness and sufficiency

We now work through several illustrative examples in some detail, for two purposes: first, to demonstrate that an environmental endowment is sufficient for an EKC under a broad range of abatement technologies; and second, to show that even increasing returns to abatement is not sufficient, as without externalities an additional explicit story is necessary for why environmental quality falls with income.

3.1 The sufficiency of asymmetric endowments

3.1.1 Constant returns to abatement

For a first simple but in many ways quite representative general example, we assume Cobb–Douglas preferences for consumption and environmental quality:

$$U(c,q) = c^{\alpha} q^{\beta} \alpha + \beta = 1 \tag{3.1}$$

We assume an asymmetric endowment $q_0 > 0$, i.e. positive environmental quality but zero consumption at zero income. This is a natural assumption (again, below we argue that it is hard to see when it is *not* reasonable, for people who are able to stay alive and thus face this optimisation problem). For simplicity and transparency, we specify in (3.2) a class of simple constant-returns abatement functions[8]:

$$q = q_0 - \gamma c + \delta e \gamma, \delta > 0. \tag{3.2}$$

Given this expression for q, the household chooses c and e to maximise (3.1) subject to the budget constraint (2.4) and the non-negativity constraints (2.5). This gives rise to a non-linear programming problem, the first-order Kuhn Tucker conditions of which lead one to consider the following two cases: $c > 0, e = 0$ and $c > 0, e > 0$ [9]. The first case corresponds to a corner solution in which the household chooses not to abate, but does consume, and thus environment falls with income.

The $e^* = 0$ result is optimal for poorer households, i.e. those satisfying:

$$y \le \frac{q_0 \alpha p_c p_e}{\gamma p_e + \beta \delta p_c}. \tag{3.3}$$

For a household in this income range, the optimal level of consumption will rise with income (so that pollution will rise with income as well). Since nothing is spent on abatement, the optimal level of environmental quality must fall with income:

$$c^* = \frac{y}{p_c} \quad e^* = 0 \quad q^* = q_0 - \frac{\gamma y}{p_c} \quad \frac{\mathrm{d}q^*}{\mathrm{d}y} = -\frac{\gamma}{p_c} < 0. \tag{3.4}$$

While abatement is feasible, at low incomes it is not desirable. The household devotes all of its resources to consumption (expenditure on consumption, $p_c c^*$, equals y). If there were no environmental endowment ($q_0 = 0$), though, there would be no income range in which abatement is zero. It is the asymmetric endowment that leads to the boundary solution in which environmental quality falls with income.

The case where $e^* > 0$ is optimal for richer households, those satisfying:

$$y > \frac{q_0 \alpha p_c p_e}{\gamma p_e + \beta \delta p_c}. \tag{3.5}$$

Under the linear technology in (3.2), the MRT faced by the household does not vary with income. From Proposition 2.1, we know then that all that matters is whether the MRS falls with increases in income (and consumption). But with Cobb–Douglas preferences, which ensure that q is a normal good, this is guaranteed. Hence, even though consumption (and pollution) will rise with income, the household spends enough on abatement to ensure that environmental quality also increases:

$$c^* = \frac{y\alpha\delta + q_0\alpha p_e}{\delta p_c + \gamma p_e} \quad e^* = \frac{y(\gamma p_e + \beta\delta p_c) - q_0\alpha p_c p_e}{p_e(\gamma p_e + \delta p_c)} \quad \frac{\mathrm{d}q^*}{\mathrm{d}y} = \frac{\delta\beta}{p_e} > 0. \tag{3.6}$$

The derivative of optimal environmental quality with respect to income in these results conveys that the weight on the environment within the preferences matters. These results (see 3.5) also confirm that the asymmetric endowment is crucial. Were $q_0 = 0$ (i.e., the standard, zero-endowments case in which normal goods are defined), the solution in (3.6) would always obtain. Thus, as normal goods, both consumption and environmental quality would increase with income at *all* income levels.

3.1.2 Decreasing returns

Since increasing returns to abatement spending was seen above (see discussion of Proposition 2.1) to support the second part of an EKC (environmental quality rising with income at higher incomes), and since constant returns to abatement leaves things to the preferences, it is worth considering whether decreasing returns to abatement prevents an environmental endowment from leading to an EKC. With the preferences in (3.11), we know from Section 2.2.1 that the endowment will be sufficient for the fall in environmental quality within the low-income range. Thus, the question is whether, with an endowment but also decreasing returns to abatement, the quality of the environment can still rise with income at higher incomes.

Demonstrating the utility of Proposition 2.1, we can simply check whether a particular combination of preferences and an abatement technology satisfy the conditions provided there for environmental quality rising with income, once income is above a given level. Consider, then, (3.1)'s preferences and (3.7)'s technology:

$$q = q_0 + (1 - \exp[\gamma c]) + (1 - \exp[-\delta e])\gamma > \delta > 0. \tag{3.7}$$

For these specifics, all of (2.6), (2.7) and (2.8) hold. In terms of (2.13), we have:

$$MRS(c,q) \equiv \frac{\alpha}{(1-\alpha)}\frac{q}{c}$$

$$MRT(c,q) \equiv \delta\exp[-\delta e] + \gamma\exp[\gamma c]$$

$$\frac{\partial MRS}{\partial c} - \frac{\partial MRT}{\partial c} = \frac{-\alpha}{(1-\alpha)}\frac{q}{c^2} - \gamma\exp[\gamma c](\gamma - \delta) < 0. \tag{3.8}$$

Thus, given (3.1), the asymmetric environmental endowment remains sufficient for an EKC even for the decreasing returns to abatement technologies in (3.7).

3.1.3 Extreme decreasing returns to abatement

Consider again the constant-returns abatement function (3.2), except now add an extreme diminishing returns component, such that actual abatement, denoted a, rises with abatement expenditures e only up to $e_{\max}$. After that point, actual abatement a equals $e_{\max}$ no matter how high the abatement expenditures e:

$$a(e) = \begin{cases} e & \text{if } e \le e_{\max} \\ e_{\max} & \text{if } e > e_{\max} \end{cases}. \quad (3.9)$$

Going from a level of abatement spending that is below $e_{\max}$ to one above it, the marginal abatement per unit of spending decreases discretely from 1 to 0.

The household then maximises (3.1) subject to (2.4) and (2.5), given the technology $q = q_0 - c + a(e)$, where $a(e)$ is as defined in (3.9) (and the γ and δ from (3.2) are dropped to avoid unnecessary clutter). The optimisation problem yields three active cases: $c > 0, e = 0$; $c > 0, 0 < e < e_{\max}$ and $c > 0, e = e_{\max}$.

The first two cases are essentially identical to the two cases in Section 3.1.1, with households in the low-income range (as in (3.3)) spending nothing on environmental investment and lowering the quality of the environment as income rises. Those with higher incomes (as in (3.5), though in this case also bounded above by the expression in (3.10)) spend on both consumption and environmental investment, and improve the quality of the environment as income rises. Thus, the basic EKC result from Section 3.1.1 is seen to hold with this decreasing returns abatement technology.

The new feature is case 3), which is optimal for the richest households:

$$y \ge \frac{e_{\max} p_e (p_e + p_c) + q_0 \alpha p_c p_e}{p_e + \beta p_c}. \quad (3.10)$$

Although environmental quality is still normal, households cease investing in the environment through abatement spending because the marginal abatement from environmental investment is zero after e exceeds $e_{\max}$. However, consumption continues to increase with income, such that pollution increases and environmental quality must fall with income, as seen in the following optimal values for this income range:

$$c^* = \frac{y - p_e e_{\max}}{p_c} \quad e^* = e_{\max} \quad q^* = q_0 - \frac{y}{p_c} + \frac{(p_c + p_e)}{p_c} e_{\max} \quad \frac{dq^*}{dy} = -\frac{1}{p_c} < 0. \quad (3.11)$$

Thus with decreasing returns to abatement, both poor and rich households can arrive at corner solutions where environmental quality falls with income because of a lack of additional abatement effort to offset rising consumption. The relationship between income and environmental quality can then become an 'inverted N' or 'sideways S', as quality decreases, increases, and then decreases again with income.

This is an interesting result at the least because of related findings in the empirical literature on EKCs, where some fitted aggregate relationships take this shape[10]. Also, such an empirical finding might even be expected, given a finite set of feasible abatement technologies to choose from (as opposed to a technology within which one can invest continuously in abatement without limit), such that the rich, upon using only the 'cleanest' technology, may not have further scope for abatement[11].

3.2 The insufficiency of increasing returns

3.2.1 Fixed costs of abatement

Now we modify (3.2) again, but instead of facing decreasing productivity of abatement spending on the margin as in (3.9) now a household can choose from two types of environmental investment: e_1, with no fixed cost but a relatively high marginal cost p_1; and e_2, with a fixed cost, $f > 0$, but a relatively lower marginal cost p_2 [12]. Together, these abatement choices $\vec{e} = (e_1, e_2)$ form the simple increasing returns abatement technology in (3.12), the last part of a $q = q_0 - c + a(e)$ technology:

$$a(\vec{e}) = e_1 + e_2 \tag{3.12}$$

where the household is faced with the piecewise defined budget constraint,

$$y = \begin{cases} p_c c + p_1 e_1 & \text{if } e_2 = 0 \\ p_c c + p_1 e_1 + p_2 e_2 + f & \text{if } e_2 > 0 \end{cases}. \tag{3.13}$$

where $p_2 < p_1$. The household is also faced with the non-negativity constraints:

$$c \geq 0, e_1 \geq 0, e_2 \geq 0 \tag{3.14}$$

and picks c and $\vec{e}$ to maximise (3.1) subject to (3.13), (3.14) and (3.15):

$$q = q_0 - c + e_1 + e_2. \tag{3.15}$$

Assuming that the first type of abatement investment (i.e., e_1) is not dominated[13], the optimisation problem leads one to consider three cases[14]:

$$c > 0, e_1 = e_2 = 0 \quad c > 0, e_1 > 0, e_2 = 0 \quad c > 0, e_1 = 0, e_2 > 0. \tag{3.16}$$

The $c > 0, e_1 = e_2 = 0$ result is optimal for the poorest households:

$$y \leq \frac{q_0 \alpha p_c p_1}{p_1 + \beta p_c} \tag{3.17}$$

For these households, the optimal values c^* and q^* are like those for the poorer households in Section 3.1.1, and so $\frac{\mathrm{d}q^*}{\mathrm{d}y}$ here is equal to $-\frac{1}{p_c} < 0$. Thus, this is again an income range in which environmental quality falls with increasing income (and, as above, this is an income range which does not exist if $q_0 = 0$).

The $c > 0, e_1 > 0, e_2 = 0$ result is optimal for middle incomes[15]:

$$\frac{q_0 \alpha p_c p_1}{p_1 + \beta p_c} < y \leq \frac{q_0 \alpha p_c p_2}{p_2 + \beta p_c} + f. \tag{3.18}$$

The optimal values c^*, q^*, and e_1^* for households in this income range are like those for the richer households in Section 3.1.1 (substituting e_1 for e and p_1 for p_e). Thus, much as in that setting, $\frac{dq^*}{\mathrm{d}y} = \frac{\beta}{p_1} > 0$, i.e. environmental quality rises with income.

Lastly, the $c > 0, e_1 = 0, e_2 > 0$ result is optimal for the richest households:

$$y > \frac{q_0 \alpha p_c p_2}{p_2 + \beta p_c} + f. \tag{3.19}$$

This is much like just above (but now substitute e_2 and p_2 for e and p_e in Section 3.1.1). Thus, $\frac{\mathrm{d}q^*}{\mathrm{d}y} = \frac{\beta}{p_2} > 0$, and environmental quality rises with income. While q rises in both the middle and the highest income ranges, because $p_2 < p_1$ the derivative of environmental quality with respect to income is greater for the higher income range. Note, then, that the transition between environmental investments, which raises the fixed costs but lowers the marginal cost of abatement, discretely increases the rate at which environmental quality rises with income.

In any case, these results further demonstrate the robustness of the endowment-based EKC result, for an increasing returns technology. More importantly, though, they show the insufficiency of the increasing returns abatement technology on its own. If $q_0 = 0$, the income range in (3.17) vanishes, and environmental quality always rises with income, as the middle income range in (3.18) becomes simply $y < f$, and the high-income range in (3.19) becomes $y \geq f$. As $\frac{eq^*}{\mathrm{d}y} > 0$ for both ranges, we can see that without the asymmetric endowment the quality of the environment will rise with income for *all* incomes, i.e. there will not be an EKC.

To consider the validity of the asymmetric endowment, note the results when even e_1 has a fixed cost, but there is no endowment. If a household is rich enough (given this fixed cost) to both consume and abate, then outcomes are as just described: the income range in (3.17) vanishes and environmental quality rises with income. However, until that point, the household *neither abates nor consumes.* Thus, a starving household will choose not to consume because of the implications for the environment. In our minds this is so generally unrealistic, when thinking of actual low-income households, as to lead us to seek the source of the lack of relevance of the result. Our conclusion is that households would be dead at $q=0$. Thus, the almost-starving household (low c due to low y) in which people can stay alive and consume (given that many die of, e.g., lack of potable water) clearly has an endowment of environmental quality, e.g. water to drink and air to breathe.

3.2.2 'Explosive' increasing returns to abatement

Andreoni and Levinson, 2001 posit a particular increasing returns abatement technology which depends upon consumption directly. Their specification of the technology $q = q_0 - c + a$ assumes $q_0 = 0$ and an $a(c,e)$ where $a_c > 0, a_e > 0$, and a is homogenous of degree k where $k > 1$. We call this 'explosive' increasing returns because as the scale of income and consumption rise, the returns to abatement investments in e increase *ad infinitum*. Their motivating example, however, is small-scale: a broom can for the same level of effort accomplish more abatement when sweeping up a quarter inch of dust, e.g., than when sweeping up an eighth of an inch. It may not be appropriate to generalise from this small scale to unlimited scale[16].

The point here is that this technological assumption cannot by itself generate an EKC. It implies that as income and c rise, marginal productivity of e also rises. A given investment in e yields more a. That supports the upward-sloping part of an EKC, as per Proposition 2.1, but does not substitute for the asymmetric endowment in explaining (as in Section 2.2.1) the downward-sloping part of an EKC.

Consider $a(c,e) = ce$. Here $a_c > 0, a_e > 0$, and a is homogenous of degree k where $k > 1$. The household's problem is to pick c and e to maximise (3.1) subject to (2.4), (2.5) and, of course, this specification of $a(c,e)$ and thus also of $q(c,e)$. As in some of the problems above, the cases to consider are: $c > 0, e = 0$ and $c > 0, e > 0$. The $e^* = 0$ result is optimal for poorer households, satisfying:

$$y \le \frac{\sqrt{p_e^2 + 4\beta q_0 \alpha p_c p_e} - p_e}{2\beta}. \tag{3.20}$$

The key point here can already be made, with reference to this expression: with no environmental endowment ($q_0 = 0$), this income range in which environmental quality will fall with income (as in (3.4) and (3.11)) simply vanishes. Since elsewhere environmental quality rises with income (as discussed above, increasing returns makes this more likely), lacking an endowment this technology does not generate an EKC. Formally, the $e^* > 0$ case is optimal for richer households:

$$y > \frac{\sqrt{p_e^2 + 4\beta q_0 \alpha p_c p_e} - p_e}{2\beta} \tag{3.21}$$

so that if environmental quality is in fact rising with income within this range, then for the $q_0 = 0$ case it will always rise with income. And in fact[17]:

$$e^* = \frac{2yp_e\beta + p_e y + p_e^2 - \sqrt{p_e^2(y-p_e)^2 + q_0\alpha p_e^3 p_c[\beta + p_e^2]}}{2(2-\alpha)p_e^2}$$

$$\frac{\mathrm{d}q^*}{\mathrm{d}y} = \frac{\sqrt{\Phi + D}\left[4yp_e(2-\alpha)\beta + 2yp_e\beta + yp_e + p_e^2\right] + p_e^2\beta(y-2p_e)^2 + D}{2(2-\alpha)p_c\sqrt{\Phi + D}} > 0$$

where $\Phi = p_e^2(y-p_e)^2$ and $D = q_0\alpha p_e^3 p_c[\beta + p_e^2]$ are used to simplify. Without an environmental endowment, even this 'explosive' increasing returns to scale technology explains only environmental quality increasing with income, not an EKC.

4 Conclusion

Using a household-choice framework, this paper provided a simple explanation for non-monotonic, upward-turning paths of environmental quality during economic growth. The very natural assumption of an asymmetric endowment (i.e., positive environmental quality but zero consumption at zero income) is sufficient. The intuition is that, given the endowment, the MRS between consumption and environment at low incomes makes abatement undesirable. As income and consumption increase, though, and the endowment is degraded by consumption, this corner solution gives way to interior solutions in which both consumption and abatement expenditures rise with income. We provide sufficient conditions, involving the details of both preferences and abatement technologies, that ensure for this interior solution that environmental quality also rises with income, i.e. that the abatement increase is large enough to offset the effect of the increased consumption on pollution.

This endowment-based result is robust to a wide range of abatement technologies, including fixed costs of and decreasing returns to abatement. Our decreasing-returns case stimulates further empirical examination (national level or more disaggregate) of the growth-environment relationship for results other than 'U shapes'. We also show that even relatively extreme abatement technologies do not generate such 'EKC-like' paths of environmental quality on their own. The reason is that they do not generate an income range in which environmental quality falls with income.

This work suggests more formalised analysis of microfoundations of national-level EKCs, i.e. adding formal aggregation of heterogeneous household preferences (given relevant abatement technologies) to the literature on dynamic optimisation by national social planners. Our household approach could be applied in a setting of externalities and multiple agents whose voting for taxation and environmental spending evolves with income if they care about environmental outcomes (as assumed here, and see micro-level empirical evidence in Chaudhuri and Pfaff, 1998). We plan to pursue this application in future research.

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Notes

1 See, for instance, World Bank, 1992; Selden and Song, 1994; Shafik, 1994; Holtz-Eakin and Selden, 1995; Grossman and Krueger, 1995 and more recently, special issues of both *Environment and Development Economics*, in November 1997, and *Ecological Economics*, in May 1998.

2 Environmental economics textbooks feature environmentally damaging external emissions that rise with the scale of production of the polluting good. If regulations or Coasian bargaining do not lead to internalisation, these emissions will surely lower environmental quality as incomes rise.

3 Neoclassical growth models that consider pollution and growth have provided one approach when externalities are assumed to be internalised, and can provide results similar to ours (see Plourde, 1972; Keeler, Spence and Zeckhauser, 1972; D'Arge and Kogiku, 1973; Forster, 1973; Gruver, 1976; Stephens, 1976; Asako, 1980; Becker, 1982; Tahvonen and Kuuluvainen, 1993; John and Pecchenino, 1994; Selden and Song, 1995; Jones and Manuelli, 1995; Stokey, 1998 and Chimeli, 2001). But they will not easily explain regulatory choice given heterogeneous voters (note that while Jones and Manuelli (1995) features a representative agent at each point in time, the paper considers the problem of intertemporal collective decision-making). The dynamic representative agent framework lacks a realistic political economic mechanism through which degradation might in reality be reversed. In contrast, household models can yield insights within a setting of internalisation and, as they can be applied in a multi-agent setting in the presence of externalities, can permit explicit modelling of how environmental preferences might be aggregated through voting in order to produce regulation.

4 For example, Chaudhuri and Pfaff (1998; 2003) consider empirically how household fuel choice in Pakistan changes with income, in the light of the effects of fuels on indoor air quality, a private good. While stove emissions have external effects as well, private environmental quality is significantly degraded. More generally, other forms of degradation of the environment also feature private components, and there exists significant private provision of environmental abatement in the absence of regulations.

5 For instance, Stokey (1998) emphasises the role of elasticity of preferences, while Andreoni and Levinson (2001) focuses upon a role for a very particular type of increasing returns to abatement.

6 Such an endowment assumption (which we argue is hard to refute) is implicit in some existing papers (e.g., John and Pecchenino, 1994). However, its truly central role has not been highlighted. Further, such endowments can be thought of more broadly if we consider not only preferences and the MRS but also technologies and the MRT (again, our framework easily permits their comparison). For instance, Chimeli (2001) suggests that an off-equilibrium-path 'endowment' of capital may exist for economies in transition and, given that, traces the optimal path of the MRT as income rises.

7 This part of the paper significantly generalises our related work in Pfaff, Chaudhuri and Nye (2004). The theoretical analyses they present develop in detail the case of input substitution as an abatement technology. That case, in turn, corresponds to the empirical work on 'household EKCs' for indoor air quality in Chaudhuri and Pfaff (1998; 2003).

8 Note that the input-substitution technology in Pfaff, Chaudhuri and Nye (2004) is constant returns. As that paper argues, there are many cases in which input substitution is the relevant abatement technology. Note also, including as motivation for Section 3.1.3, that the existence of a cleanest input may imply that at highest incomes environmental quality will again fall with income. At the highest incomes only the cleanest input is used, and its use rises with income.

9 In all, the Kuhn–Tucker conditions allow for four cases: $c > 0, e = 0$; $c > 0, e > 0$; $c = e = 0$ and $c = 0, e > 0$. Given our assumption on preferences (2.7, sixth), as long as $y > 0$ the non-negativity constraint on c will never be binding, ruling out in the third and fourth conditions.

10 See, for example, Grossman and Krueger (19950 (p.361, Figures 1, 3 and 4, and p.369), Torras and Boyce (1998) (pp.152–153, 157) and Hill and Magnani (2001) (Table 1).

11 See Pfaff, Chaudhuri and Nye, 2004 for a formalised theoretical result. One example they mention is switching among a finite set of fuels in order to shift the consumption - air quality MRT. Note also the discussion in Jones and Manuelli (1995) and Torras and Boyce (1998).

12 Fixed costs may well exist. Further, lower-marginal-cost options may have higher fixed costs. Andreoni and Levinson (2001) provide useful evidence that abatement technologies with higher fixed costs may have lower marginal costs. They cite EPA studies of the emission control from large coal-fired burners, and they also regress pollution abatement operating costs by industry and by US state on a measure of the size of the industry's contribution to gross state product.

13 Specifically, this is the assumption that: $f > \dfrac{q_0 \alpha p_c{}^2 \beta (p_1 - p_2)}{p_1 + \beta p_c}$.

14 Consider two non-linear programming problems, one for $e_2 = 0$ and one for $e_2 > 0$. The $e_2 = 0$ problem yields four cases: $c > 0, e_1 = e_2 = 0$; $c > 0, e_1 > 0, e_2 = 0$; $c = e_1 = e_2 = 0$; $c = 0, e_1 > 0, e_2 = 0$. However, given (2.7, sixth), such that when $y > 0$ the non-negativity constraint on c will not be binding, third and fourth conditions are ruled out. The $e_2 > 0$ problem also yields four cases: $c = e_1 = 0, e_2 > 0$; $c = 0, e_1 > 0, e_2 > 0$; $c > 0, e_1 = 0, e_2 > 0$; $c > 0, e_1 > 0, e_2 > 0$. As above, first and second conditions are ruled out by (2.7, sixth) when $y > 0$. Also, it is easily shown that once $e_2 > 0$, i.e. if the fixed cost has been incurred, given $p_1 > p_2$ case four is ruled out. From both problems together, then, we are left with the three cases considered in the text.

15 The assumption of the conditions under which e_1 is not dominated, specified earlier, ensures that this income range exists, i.e. that: $\dfrac{q_0 \alpha p_c p_1}{p_1 + \beta p_c} < \dfrac{q_0 \alpha p_c p_2}{p_2 + \beta p_c} + f$.

16 As in the broom example, it may often be the case that rising c increases $\frac{da}{de}$ near $c = 0$: no matter how hard you try ($e > 0$), vacuuming a clean ($c = 0$) rug accomplishes nothing ($a = 0$). However, often a capacity constraint (given e) may arise well within the relevant scale of c. Consider a single broom, thought of as a single unit of e spending. A sweep of a clean floor accomplishes nothing, while a sweep of a floor with a half-inch of dirt accomplishes more than a sweep of a floor with a quarter-inch. But then consider a floor with two feet of dirt, a scale likely to be beyond the capacity of a single sweep of the broom. At four inches per sweep, e.g., simple division suggests that it will take six sweeps to eliminate the dirt. But simple division is precisely a statement of capacity and, by implication, constant returns over large scales. Thus, for a scale of c well beyond the capacity of the e in question, abatement will become effectively constant returns to scale.

17 This is one of two roots of a quadratic equation. It is the one in which a higher environmental endowment implies lower optimal abatement expenditures (as makes intuitive sense, given the effect of 'free' environment on the MRS and given our previous results, e.g. in Section 3.1.1).