Environment and Development Economics 11: 697–707 © 2006 Cambridge University Press
doi:10.1017/S1355770X06003226 Printed in the United Kingdom

A note on 'the simple analytics of the Environmental Kuznets Curve'

FLORENZ PLASSMANN
Department of Economics, State University of New York at Binghamton, PO Box 6000, Binghamton, NY 13902-6000. Tel: 607-777-4304. Fax: 607-777-2681. Email: fplass@binghamton.edu

NEHA KHANNA*
Department of Economics & Environmental Studies Program, State University of New York at Binghamton, PO Box 6000, Binghamton, NY 13902-6000. Tel: 607-777-2689. Fax: 607-777-2681. Email: nkhanna@binghamton.edu

ABSTRACT. In a widely cited paper, Andreoni and Levinson (2001) argue that, under very mild restrictions on preferences, increasing returns to scale in pollution abatement are a sufficient condition for pollution to ultimately fall to zero with income growth. We show that the existence of an Environmental Kuznets Curve depends on the relative magnitudes of the returns to scale in abatement and in gross pollution, rather than on their absolute values. Increasing returns to scale in abatement by themselves are not sufficient for pollution to fall with income unless the returns to scale of abatement exceed the returns to the production of gross pollution.

1. Introduction

According to the Environmental Kuznets Curve (EKC) hypothesis, pollution initially increases as income increases, but eventually declines once income has crossed some threshold. Many authors (including Jones and Manuelli, 2001; Stokey, 1998; and Gawande *et al.*, 2001) have offered theoretical explanations for the EKC relationship between income and pollution. Andreoni and Levinson (2001) suggest that many of these explanations are based on economies of scale in pollution abatement and show that, under very mild restrictions on preferences, increasing returns to abatement are sufficient for pollution to ultimately fall to zero as income increases. Their paper has received considerable attention in the environmental economics literature; as of July 2006, the *Social Science Citation Index* shows 27 publications that cite Andreoni and Levinson (2001).

* Corresponding author

We thank the journal editor and three anonymous reviewers for their comments on an earlier draft. All errors are ours.

https://doi.org/10.1017/S1355770X06003226 Published online by Cambridge University Press

In this paper, we show that Andreoni and Levinson's result depends on their assumption that the 'production' of gross pollution has constant returns to scale (they assume that pollution is directly proportional to consumption). We generalize their model by allowing the gross pollution function to exhibit increasing, decreasing, or constant returns to scale, and show that the existence of an EKC depends on the relative magnitudes of the returns to scale in the production of abatement and gross pollution, rather than on their absolute values. This simple generalization implies that increasing returns to scale in abatement by themselves are not sufficient for pollution to eventually fall with income.

Andreoni and Levinson's assumption that gross pollution is a constant proportion of consumption is intuitive if we think of pollution in terms of emissions. However, emissions are not necessarily the most relevant measure of (subjective) environmental quality. In modeling environmental quality, it is often more useful to think of pollution defined in terms of ambient concentration (the amount of pollution a consumer is exposed to), rather than the quantity of emissions released into the environment, or in terms of damage, such as loss of habitat or species or human health impacts. Under these alternative definitions, the constant returns to scale formulation is not very appealing. The following two examples outline cases where the gross pollution function does not exhibit constant returns to scale.

Consider first the case of tropospheric (ground level) ozone (O_3) pollution. O_3 is not 'emitted' into the atmosphere but is formed by the chemical reaction between its precursors, primarily volatile organic compounds (VOCs) and nitrogen oxides (NO_x), in the presence of sunlight. The relationship between ambient O_3 concentrations and the emissions of its precursors is highly non-linear, and proportional changes in the emissions of VOCs and NO_x do not lead to an equiproportionate change in O_3 concentrations (see, for example, EPA, 1999, especially appendix C).

Another example where gross pollution does not exhibit constant returns to scale are dose- or concentration-response functions that link the ambient concentration of a pollutant to the probability of damage. Concentration-response functions show that for many pollutants the human body is able to withstand exposure to some level of ambient concentration without any perceptible adverse health impact. Indeed, this is how the United States Environmental Protection Agency (EPA) determined the National Ambient Air Quality Standards (NAAQS) for the criteria pollutants under the Clean Air Act. For example, the current NAAQS for O_3 is 0.08 ppm (eight hour standard) and air quality is considered 'satisfactory' if the ambient concentration of O_3 is below this threshold. It is only when the ambient concentration rises above 0.08 ppm that the presence of O_3 in the air is considered 'pollution', and the extent of that pollution is measured in terms of the rising probability of adverse health impacts, as determined by the concentration-response function for O_3. Concentration-response functions are typically shaped like a logistic function and include some sections that exhibit increasing and others that exhibit decreasing returns to scale with respect to the ambient concentration (see, for example, EPA, 1997). Thus, if subjective pollution is modeled as probability of damage, it is reasonable to expect the gross pollution function to have either

https://doi.org/10.1017/S1355770X06003226 Published online by Cambridge University Press

non-constant returns to scale throughout or even different returns to scale over different ranges of the function

Our result that returns to scale in abatement that exceed the returns to scale in gross pollution are sufficient for an EKC is intuitively appealing. As more and more pollution is generated as a result of additional resources being consumed, net pollution will decrease if some of the additional resources are also devoted to pollution abatement and the increase in abatement more than offsets the increase in the generation of pollution.

2. A sufficient condition for an EKC

The model

In Andreoni and Levinson's (2001) static model, a single, infinitely lived, representative consumer obtains utility from consuming a private good, C, and from living in an environment of quality Q. The consumer's utility function

$$U = U(C, Q) \tag{1}$$

is quasi-concave in C and Q with positive marginal utilities from consumption and environmental quality so that $\partial U/\partial C = U_C > 0$ and $\partial U/\partial Q = U_Q > 0$. Environmental quality is the difference between the quality of an environment without anthropogenic pollution, O, and the amount of net pollution, P. To simplify the notation, we set $O = 0$ so that $Q = -P$, and we use the terms 'improvement in environmental quality' and 'reduction in net pollution' synonymously.

Net pollution is the level of pollution that the consumer is exposed to, and we define it as the difference between gross pollution, $P^G(C)$, which is a byproduct of consumption and abatement, A. It is intuitive to assume that gross pollution increases monotonically with consumption so that $\partial P^G(C)/\partial C = P^G_C > 0$. The consumer can produce abatement by spending part of his resources on environmental effort, E, where the abatement function $A = \tilde{A}(P^G(C), E)$ describes the effectiveness of environmental effort in improving environmental quality. Because C and E are both taken from the endowment, M, we chose their units so that their relative price equals 1 and the consumer's resource constraint is $M = C + E$.

Consumption is the only argument of the gross pollution function, and we express the abatement function as

$$A = \tilde{A}(P^G(C), E) = A(C, E) \tag{2}$$

so that the net pollution function is given by

$$P(C, E) = P^G(C) - A(C, E) \tag{3}$$

We follow Andreoni and Levinson (2001) in assuming that $\partial A/\partial C = AC > 0$, $\partial A/\partial E = A_E > 0$, and that abatement is zero if either $C = 0$ or $E = 0$ (that is, $A(0, x) = A(x, 0) = 0 \,\forall\, x$). We assume that net pollution increases with consumption so that $\partial P/\partial C = P_c = P^G_C - A_C > 0$; the assumption $A_E > 0$ implies that net pollution decreases with environmental effort so that $\partial P/\partial E = P_E = -A_E < 0$.

https://doi.org/10.1017/S1355770X06003226 Published online by Cambridge University Press

Andreoni and Levinson (2001) assume that gross pollution is directly proportional to consumption and write equation (3) as[1]

$$P_{AL}(C, E) = C - A(C, E) \tag{3a}$$

They assume that the abatement function $A(C, E)$ is continuous, concave, and homogeneous of degree k. They show that, under very mild restrictions on preferences, increasing returns to scale in abatement are sufficient for net pollution $P_{AL}(C, E)$ to ultimately become zero as the consumer's resources increase.

In the following section, we show that this sufficient condition holds only for the restricted pollution function (3a). We show that the corresponding sufficient condition for the general pollution function (3) is that the returns to scale in abatement exceed the returns to scale in the 'production' of gross pollution, which implies that increasing returns to scale in abatement by themselves are not sufficient for pollution to ultimately fall with income.

The sufficient condition

Assume that the abatement function $A(C, E)$ and the gross pollution function $P^G(C)$ are continuous and twice differentiable, that $A(C, E)$ is homogeneous of degree k, and $P^G(C)$ is homogeneous of degree δk.[2] These homogeneity assumptions imply that pollution function (3) is homogeneous of degree k if $\delta = 1$ and non-homogeneous if $\delta \neq 1$. If $\delta < 1$ ($\delta > 1$), then the returns to scale of abatement exceed (are less than) the returns to scale of gross pollution. Andreoni and Levinson's (2001) model is a special case with $\delta = 1/k$ and $k > 1$.

Using the homogeneity assumptions on $P^G(C)$ and $A(C, E)$, we prove:

Theorem 1. *Assume that the utility function $U(C, Q)$ is quasi-concave in C and Q, that C and Q are both normal goods, that the gross pollution function and the abatement function are both continuous, twice differentiable, and homogeneous, and that abatement is zero if either $C = 0$ or $E = 0$. Then net pollution will ultimately fall to zero as income increases if:*

- *(i) the consumer's marginal rate of substitution between the consumption share $c = C/M$ and the scaled environmental quality $q = Q/M^{\delta k}$, MRS_{cq}, evaluated at $q = 0$, is bounded by some $\theta > -\infty$, and*
- *(ii) the returns to scale of abatement exceed the returns to scale of gross pollution ($\delta < 1$).*

Our proof follows closely the setup of the proof in Andreoni and Levinson (2001). We show that $\delta < 1$ (but not $k > 1$) is a sufficient condition for pollution to fall to zero once income has become sufficiently high. The

[1] We follow Andreoni and Levinson and suppress the proportionality constant in the first term of equation (3a) because its magnitude is irrelevant for the analysis.

[2] This assumption only requires that the relationship between gross pollution and consumption can be expressed as a constant multiple of the returns-to-scale parameter of the abatement function. It neither requires nor implies that the relationship between gross pollution and consumption depends on the properties of the abatement function.

https://doi.org/10.1017/S1355770X06003226 Published online by Cambridge University Press

proof proceeds in five steps: first, define the consumption possibilities frontier (CPF) for the consumption share $c = C/M$ and environmental quality relative to $M^{\delta k}$. Second, show that the CPF crosses the zero pollution level from above at least once if $\delta < 1$. Third, describe consumer preferences in (c, q) space. Fourth, describe how the CPF shifts as M increases, depending on whether $\delta \gtreqless 1$. Finally, describe how the utility-maximizing bundle (c^*, q^*) changes as M increases. We use this to show that: (i) if the returns to scale in gross pollution are the same as the returns to scale in abatement, increasing returns to scale in abatement are not a sufficient condition for pollution to become zero as income increases; and (ii) if the returns to scale in gross pollution are less than the returns to scale in abatement, the CPF becomes vertical at the zero-pollution level as M becomes infinitely large, and, under our restriction that the consumer's indifference curve at the zero pollution level is not vertical, it is tangent to the CPF at zero pollution at some finite value of M.

The CPF

At the center of Andreoni and Levinson's proof is the CPF for consumption and environmental quality, defined relative to $M^{\delta k}$

$$\begin{aligned} q &= Q/M^{\delta k} = -P(C, M-C)/M^{\delta k} = -(P^G(C) - A(C, M-C))/M^{\delta k} \\ &= A(c, 1-c)M^{k-\delta k} - P^G(c) \\ &= a(c)M^{(1-\delta)k} - P^G(c) \end{aligned} \tag{4}$$

where $c = C/M$ is the consumption share and we set $a(c) = A(c, 1-c)$ following Andreoni and Levinson's notation. Scaling Q by $M^{\delta k}$ ensures that $P^G(c)$ is independent of M and thereby anchors the CPF at $(c = 0, q = 0)$ and $(c = 1, q = -P^G(1))$.[3] If $\delta = 1$, then net pollution is zero $(q = 0)$ if $a(c) = P^G(c)$, regardless of income. If $\delta \neq 1$, then for any $\hat{c}$ that leads to nonzero abatement, there is a corresponding level of income, $\hat{M} = (P^G(\hat{c})/a(\hat{c}))^{1/((1-\delta)k)}$, for which net pollution is zero. Let $\hat{c}$ represent the consumption share at which $q = 0$ for a given $\hat{M}$.

The derivative of equation (4) with respect to c yields the slope of the CPF

$$\frac{\partial q}{\partial c} = \frac{\partial a(c)}{\partial c} M^{(1-\delta)k} - \frac{\partial P^G(c)}{\partial c} \tag{5}$$

whose sign depends on the sign of $\partial a(c)/\partial c$ as well as on the relative magnitude of the two terms. If gross pollution has non-decreasing returns to scale ($\delta k \geq 1$), then the second-order derivative

$$\frac{\partial^2 q}{\partial c^2} = \frac{\partial^2 a(c)}{\partial c^2} M^{(1-\delta)k} - \frac{\partial^2 P^G(c)}{\partial c^2} \tag{6}$$

[3] The assumption that $A(0, x) = A(x, 0) = 0 \,\forall\, x$ implies that $a(0) = a(1) = 0$. Together with $A_C > 0$ and $A_E > 0$, this assumption also implies that the abatement function is strictly concave in c. Note that q is not an expenditure share, and that it is irrelevant at which values of q the CPF is anchored. Also note that gross pollution is $P^G(c)M^{\delta k}$ and not $P^G(c)$.

https://doi.org/10.1017/S1355770X06003226 Published online by Cambridge University Press

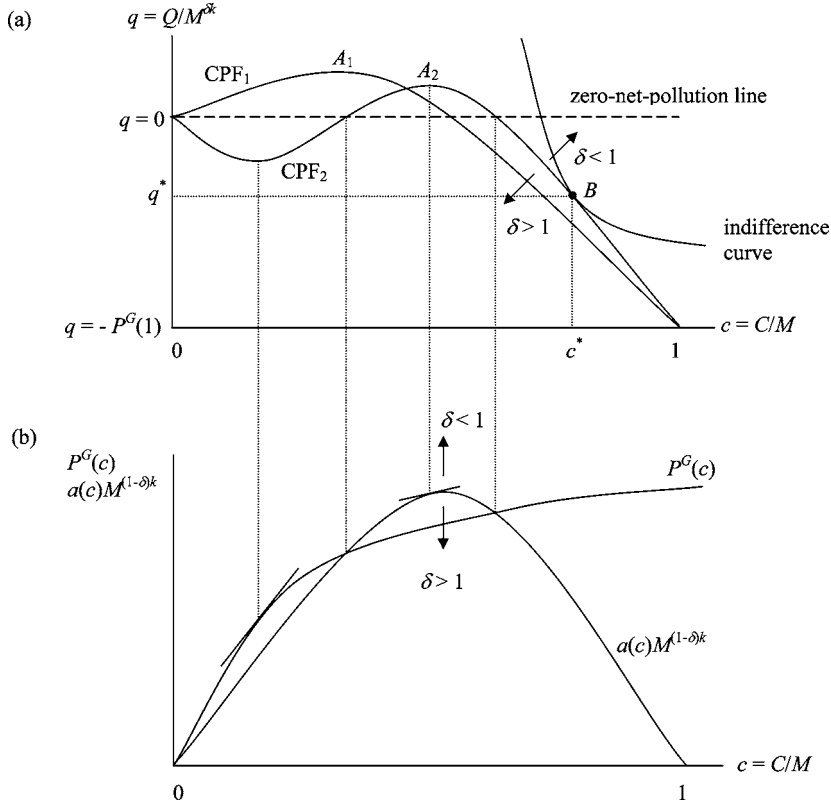


Figure 1. *The relationship between the CPF and the two components of scaled environmental quality. The arrows indicate how the curves shift as M increases*

is non-positive, which implies that the CPF is concave and that it will intersect the zero-net-pollution line at most once with $c > 0$.[4] Figure 1a shows such a CPF with $\delta k \geq 1$ as curve CPF$_1$.

If gross pollution has decreasing returns to scale ($\delta k < 1$), then the second derivative of the CPF may be positive for some c and the CPF can intersect the zero-net-pollution line more than once.[5] For example, figure 1b shows a scaled gross pollution and a scaled abatement function that intersect twice at positive consumption shares, and figure 1a shows the corresponding

[4] Concavity of the abatement function implies $\partial^2 a(c)/\partial c^2 \leq 0$ and non-decreasing returns to scale in gross pollution ($\delta k \geq 1$) imply $\partial^2 P^G(c)/\partial c^2 \geq 0$. We follow Andreoni and Levinson (2001) in assuming concavity instead of strict concavity, which makes it possible that gross pollution and abatement initially increase at the same rate. In this case net pollution is zero for some small c (that is, the CPF coincides with the zero-net-pollution line), but the assumptions $\partial P^G(c)/\partial c > 0$ and $a(1) = 0$ ensure that net pollution is positive for sufficiently large c.

[5] If $\delta k < 1$, then $\partial^2 P^G(c)/\partial c^2 < 0$ and equation (6) may be positive.

https://doi.org/10.1017/S1355770X06003226 Published online by Cambridge University Press

CPF (the vertical difference between $a(c)M^{(1-\delta)k}$ and $P^G(c)$) as curve CPF_2.[6] This CPF describes a situation where several consumption shares lead to the same level of net pollution. The assumption of non-satiation ensures that the utility-maximizing consumer always chooses the highest possible consumption share c for any given level of environmental quality. It follows that no part of the CPF to the left of its global maximum (points A_1 and A_2 in Figure 1a) can represent a utility-maximizing combination of q and c.

Zero net pollution
At the intersection(s) of the CPF and the zero-net-pollution line, the slope of the CPF is

$$\left.\frac{\partial q}{\partial c}\right|_{c=\hat{c}} = \frac{\partial a(\hat{c})}{\partial c}\frac{P^G(\hat{c})}{a(\hat{c})} - \frac{\partial P^G(\hat{c})}{\partial c} \tag{7}$$

The assumptions that $a(1) = 0$ and $\partial P^G(c)/\partial c > 0$ ensure that net pollution is positive at $c = 1$. Because we assume that the abatement function is continuous and $P^G(0) = 0$, positive net pollution at $c = 1$ implies that equation (7) is negative at the highest consumption expenditure share $\hat{c}$ for which net pollution is zero (that is, the CPF crosses the zero-net-pollution line from above).

Consumer preferences in (c, q) space
Define $W(c, q; M) \equiv U(cM, qM^{\delta k})$ as a representation of preferences in (c, q) space. The consumer maximizes W by choosing the combination of q and c at which his marginal rate of substitution, $MRS_{cq} = (\partial W(c, q; M)/\partial c)/(\partial W(c, q; M)/\partial q)$, equals the marginal rate of transformation, dq/dc (the point of tangency of the highest indifference curve and the CPF). Figure 1a shows this optimal combination (c^*, q^*) for CPF_2 as point B. The assumption that the utility function is quasi-concave ensures that the marginal rate of substitution is always non-positive, which means that the indifference curve cannot be tangent to the CPF at any c for which the CPF slopes upward. We follow Andreoni and Levinson in assuming that the combination $(0 < c^* < 1, q^* < 0)$ maximizes the consumer's utility for a given M, so that net pollution is positive.

The effect of changes in M on the CPF
An increase in M changes q and thereby the CPF according to

$$\frac{\partial q}{\partial M} = (1-\delta)ka(c)M^{(1-\delta)k-1} \tag{8}$$

which is zero if $\delta = 1$, positive $\forall c \in (0, 1)$ if $\delta < 1$, and negative $\forall c \in (0, 1)$ if $\delta > 1$ (recall that $a(0) = a(1) = 0$). Recall that the scaled gross pollution function, $P^G(c)$, is independent of M, so any movement of the CPF is due to a movement of the scaled abatement function only. Furthermore, our

[6] Equation (4) indicates that for any $\hat{c}$ that leads to non-zero abatement, there is a $(\hat{c}, \hat{M})$ combination for which net pollution is zero if $\delta \neq 1$, which implies that the gross pollution and abatement functions must intersect at least once.

https://doi.org/10.1017/S1355770X06003226 Published online by Cambridge University Press

assumption that $A(0,x) = A(x,0) = 0 \,\forall\, x$ implies that the CPF is anchored at its two endpoints.

Consider first the case where the gross pollution function and the abatement function have the same returns to scale ($\delta = 1$). In this case, the CPF becomes $q = a(c) - P^G(c)$ with $\partial q / \partial M = 0$ and remains unchanged as M changes: neither the scaled gross pollution function, nor the scaled abatement function move as M increases. Consider next the case of $\delta < 1$ when the returns to scale in abatement exceed the returns to scale of gross pollution and equation (8) is positive. An increase in income stretches the scaled abatement function $a(c)M^{(1-\delta)k}$ upward, thereby stretching the CPF upward as well for all c for which $a(c) > 0$. The third possible case is $\delta > 1$ when the returns to scale in gross pollution exceed the returns to scale in abatement. Because the first term $a(c)M^{(1-\delta)k}$ in equation (4) converges to zero as M increases towards infinity, the CPF converges to $-P^G(c)$ in the limit. In terms of figure 1b, the scaled abatement curve contracts downward and the CPF moves downward, approximating $P^G(c)$ in the limit.[7]

The income–pollution path

Finally, we describe how the utility maximizing bundle (c^*, q^*) changes as M increases. Consider first the case when the gross pollution function and the abatement function have the same returns to scale ($\delta = 1$). We use this case to illustrate that increasing returns to scale in abatement ($k > 1$) do not constitute a sufficient condition for an EKC. If preferences are such that the utility maximizing C/E ratio is constant, then the optimal consumption share c^* remains unchanged as M changes. If neither the CPF nor the indifference curve moves in response to a change in M, then an increase in income does not change the combination (c^*, q^*) at which the CPF is tangent to the highest indifference curve. Because this result holds for all k, it follows that increasing returns to abatement are not sufficient for pollution to ultimately fall with income.

Consider now the case of $\delta < 1$ when the returns to scale in abatement exceed the returns to scale of gross pollution. An increase in M stretches the CPF upwards for all $c \in (0,1)$ so that the highest consumption share $\hat{c}$ at which net pollution is zero increases. The key to determining the relationship between income and pollution is the change in the slope of the CPF at $(c,q) = (\hat{c},0)$, which we obtain by differentiating equation (7) with respect to c

$$\left.\frac{\partial^2 q}{\partial c^2}\right|_{c=\hat{c}} = \frac{\partial^2 a(\hat{c})}{\partial c^2}\frac{P^G(\hat{c})}{a(\hat{c})} + \frac{\partial a(\hat{c})}{\delta c}\left(\frac{a(\hat{c})\frac{\partial P^G(\hat{c})}{\partial c} - \frac{\partial a(\hat{c})}{\partial c}P^G(\hat{c})}{(a(\hat{c}))^2}\right) - \frac{\partial^2 P^G(\hat{c})}{\partial c^2}$$

$$= \frac{\partial^2 a(\hat{c})}{\partial c^2}\frac{P^G(\hat{c})}{a(\hat{c})} + \frac{\partial a(\hat{c})}{\partial c}\frac{-\left.\frac{\partial q}{\partial c}\right|_{c=\hat{c}}}{a(\hat{c})} - \frac{\partial^2 P^G(\hat{c})}{\partial c^2} \qquad (9)$$

[7] If the gross pollution function has increasing returns to scale ($\delta k > 1$), the CPF will remain concave. If $\delta k = 1$, the CPF will eventually approach a straight line, whereas if $\delta k < 1$, the CPF may initially be convex over a certain range of c (as shown in Figure 1a) and but will eventually become convex throughout, as the scaled abatement function shifts downward and lies below $P^G(c) \,\forall\, c > 0$.

https://doi.org/10.1017/S1355770X06003226 Published online by Cambridge University Press

The first term is always non-positive because of the assumption that $a(c)$ is concave, so the sign of equation (9) depends on the sign of $\partial a(\hat{c})/\partial c$ (second term) and the magnitude of δk (third term). We follow Andreoni and Levinson (2001) in assuming that $a(c)$ has its unique maximum at $0 < \bar{c} < 1$, which implies that $\partial a(c)/\partial c < 0$ for every $c > \bar{c}$. The homogeneity of $a(c)$ ensures that $\bar{c}$ is independent of M. Because $\hat{c}$ increases with M when $\delta < 1, \partial a(\hat{c})/\partial c < 0$ for sufficiently large M. As long as the change in the growth rate of gross pollution (the last term in equation (9)) is finite, the assumption that $a(\hat{c})$ converges to 0 as $\bar{c}$ converges to 1 ensures that

$$\lim_{c \to l} \frac{\partial^2 q}{\partial c^2}\bigg|_{c=\hat{c}} = -\infty \tag{10}$$

In terms of figure 1, equation (10) implies that as the CPF stretches upwards, it eventually becomes vertical at $(c, q) = (1, 0)$ because the CPF is still anchored at $(c, q) = (1, P^G(1))$. As long as MRS_{cq} at $q = 0$ is bounded by some $\theta > -\infty$, the highest indifference curve cannot become vertical and will become tangent to the CPF at $(q = 0, c < 1)$ as M increases towards infinity.[8] That is, net pollution will ultimately fall to zero. This proves theorem 1.

The intuition is straightforward. If the returns to scale of abatement exceed the returns to scale of gross pollution, then less and less environmental effort is necessary to abate the additional gross pollution caused by additional consumption. At the limit, as $M \to \infty$, an infinitesimal amount of environmental effort can abate all additional gross pollution that is caused by additional consumption. The assumption $\lim_{M \to \infty} MRS_{cq} > -\infty$ ensures that the consumer spends at least such an infinitesimal amount of environmental effort in the limit.[9]

For the sake of completeness, consider the case when the returns to scale of gross pollution exceed the returns to scale of abatement ($\delta > 1$). An increase in M stretches the CPF downwards for all $c \in (0, 1)$ so that the highest consumption share $\hat{c}$ at which net pollution is zero decreases. The assumption $P^G_C > 0$ ensures that gross pollution is positive $\forall\, c > 0$, which

[8] Note that the restriction on preferences refers to the marginal rate of substitution between c and q at $q = 0$, and not to the marginal rate of substitution between C and Q. Although $q = 0$ implies $Q = 0, c = 1$ does not imply $C = 1$, and the consumption possibilities frontier in (C, Q) space

$$\begin{aligned} Q &= -P(C, M - C) = A(C, M - C) - P^G(C) \\ &= a(c)M^k - P^G(c)M^{\partial k} \end{aligned}$$

that corresponds to the set of indifference curves derived from $U(C, Q)$ does not become vertical at $Q = 0$ as M increases towards infinity and $\delta < 1$.

[9] Because an increase in M increases $\hat{c}$, the consumer must increase his consumption share if he does not want to reduce pollution. If $\lim_{M \to \infty} MRS_{cq} = -\infty$, then the consumer is unwilling to reduce his consumption share even if doing so permitted him to reduce pollution by an infinite amount. But if $\lim_{M \to \infty} MRS_{cq} > -\infty$, then the consumer accepts some tradeoff between consumption and a finite reduction in pollution, and is willing to spend the necessary amount on environmental effort to reduce pollution to zero once its marginal effectiveness has become sufficiently high.

https://doi.org/10.1017/S1355770X06003226 Published online by Cambridge University Press

implies that $\hat{c} = 0$ once the scaled abatement curve has become so flat that it is below $P^G(c) \forall dc > 0$ (that is, the CPF will intersect the zero-pollution line only at $c = 0$). Pollution will only fall to zero if consumption is zero. There is no guarantee that pollution will ultimately fall with income as this depends entirely on the consumer's decision to reduce his consumption share.

3. Conclusion

Andreoni and Levinson (2001: 271) argue that various theoretical explanations of the EKC hypothesis can be modeled as increasing returns to scale in the abatement technology and suggest that increasing returns to scale in abatement are sufficient for pollution to eventually decline to zero as income increases. We show that this conclusion depends on the assumption of constant returns to scale in gross pollution. For nonconstant returns to scale in gross pollution, a sufficient condition for pollution to decline is rather that the returns to scale in abatement exceed the returns to scale in gross pollution.

What is the practical relevance of extending Andreoni and Levinson's model to accommodate non-constant returns to scale in pollution? The answer depends to some extent on the practical relevance of the original model. Andreoni and Levinson (2001) provide empirical evidence for increasing returns to scale in abatement on the plant, at the national, and at the international level. In the context of their model, this suggests that pollution *will* ultimately fall even without any environmental policies, at least as long as the increasing returns to scale in abatement prevail. Andreoni and Levinson emphasize that their finding does not support laissez-faire attitudes towards pollution because their model does not indicate the level of income at which pollution will begin to decline, and this level may simply be too high to be of practical relevance. But the position of the turning point is indeterminate only because they assume general functional forms for the utility and abatement functions. Restricting the properties of these functions simplifies the task of identifying the income level beyond which pollution declines. Andreoni and Levinson provide an example with a Cobb–Douglas abatement function and a Cobb–Douglas utility function defined over consumption and environmental effort for which it is straightforward to determine the position of the turning point.[10] Whether pollution begins to fall at a reasonable level of income therefore depends on how much we either know or are willing to assume about consumer preferences. With respect to abatement technologies, however, Andreoni and Levinson's empirical results suggest that the conditions for pollution to fall eventually are favorable.

Our model extension implies that any empirical evidence of increasing returns to scale in abatement by itself is not sufficient to draw this conclusion, and thereby lends additional support to the warning voiced by Andreoni and Levinson, and many others before them, that economic growth alone will not solve all pollution problems. Our result suggests that it is necessary to examine the channels that generate gross pollution in

[10] Set their equation (7) (p. 273) equal to zero and solve for M.

https://doi.org/10.1017/S1355770X06003226 Published online by Cambridge University Press

the first place in addition to analyzing abatement technologies. If gross pollution increases more than proportionally with consumption, as it does in the convex range of a concentration-response function, then the knowledge that abatement technologies have increasing returns to scale does not imply anything about the income-pollution path. Conversely, if gross pollution exhibits decreasing returns to scale – for example, in the concave range of a concentration-response function – net pollution may decline even if the abatement technology exhibits decreasing returns to scale.

References

Andreoni, J. and A. Levinson (2001), 'The simple analytics of the Environmental Kuznets Curve', *Journal of Public Economics* **80**: 269–286.

Environmental Protection Agency (EPA) (1997), 'The benefits and costs of the Clean Air Act 1970–1990', EPA Report to the Congress, EPA- 410-R-97-002, Office of Air and Radiation, October.

EPA (1999), 'The benefits and costs of the Clean Air Act 1990–2010', EPA Report to Congress, EPA-410-R-99-001. Office of Air and Radiation, Office of Policy, November.

Gawande, K., R.P. Berrens, and A.K. Bohara (2001), 'A consumption–based theory of the Environmental Kuznets Curve', *Ecological Economics* **37**: 101–112.

Jones, L.E. and R.E. Manuelli (2001), 'Endogenous policy choice: the case of pollution and growth', *Review of Economic Dynamics* **4**: 369–405.

Stokey, N.L. (1998), 'Are there limits to growth?', *International Economic Review* **39**: 1–31.

https://doi.org/10.1017/S1355770X06003226 Published online by Cambridge University Press