Environment and Development Economics 7: 429–448 © 2002 Cambridge University Press
DOI:10.1017/S1355770X02000268 Printed in the United Kingdom

The environmental Kuznets curve and satiation: a simple static model

CHRISTOPH M. LIEB
Interdisciplinary Institute for Environmental Economics, University of Heidelberg, Bergheimerstr.20, D–69115 Heidelberg, Germany.
Tel: ++49 6221 54 80 11. fax: ++49 6221 54 80 20.
Email: lieb@mail.eco.uni-heidelberg.de

ABSTRACT. The environmental Kuznets curve (EKC) is a hypothesis stating that pollution rises with income at low income levels but falls at higher ones. We analyse the EKC in a representative consumer model in which pollution is generated by consumption and can be abated. We show that at low income levels no abatement is optimal and pollution increases with income. Once abatement expenditures are positive, we demonstrate that satiation in consumption is not only sufficient to find an EKC, but a tendency to satiation—or in other words the condition that environmental quality is a normal good—is even necessary if we assume a standard functional form for the pollution function. Finally, we reconsider the results of two related models of the literature: We verify that the relationship between the income elasticity of demand for environmental quality and the EKC is ambiguous.

(JEL: D62, O40, Q20)

Keywords: Environmental Kuznets curve, satiation, pollution, abatement, normal goods.

1. Introduction

In 1991 Grossman and Krueger found evidence that some pollutants are rising with income at low income levels, but at a higher income level a turning point is reached and further growth subsequently leads to lower pollution. This inverted U-shaped pattern of behaviour of the pollution–income relationship (PIR) has come to be known as the environmental Kuznets curve (EKC). Since then several researchers analysed different aspects of the EKC. On the one hand, there is growing empirical evidence that the EKC is a real world phenomenon, at least for some pollutants with mainly local and immediate (health) effects.[1] On the other

I am grateful to Till Requate, Bouwe Dijkstra, Clive Bell, Sander de Bruyn and three anonymous referees for extremely helpful comments on earlier drafts of this paper. I also thank the 'Graduiertenkolleg Environmental and Resource Economics' which is sponsored by the 'Deutsche Forschungsgemeinschaft' for financial support.

[1] For two excellent reviews of the empirical literature on the EKC see Ekins (1997) and Stern (1998). A more recent survey can be found in Lieb (2001: Chapter 2).

hand, there were efforts to understand the underlying causes for the inverted U-shaped PIR (for a survey of this literature see Lieb, 2001: Chapter 3): technological progress can cause the EKC (Smulders and Bretschger, 2000). Moreover, Andreoni and Levinson (2001) claim that increasing returns to scale in abatement allow rich countries to abate at lower average costs than poor countries. However the EKC for one pollutant can also emerge because this pollutant is substituted for by another pollutant (de Bruyn, 2000: 87). Similarly, Saint-Paul (1995) proposes that the migration of dirty industries from rich to poor countries contributes to high pollution in middle-income countries and to low pollution in high-income countries. Finally, most authors give environmental policy a major role in causing the EKC.

The downturn of the EKC might also emerge because demand for environmental quality increases with income. So, it was often argued that environmental quality is a luxury good, that is, that the income elasticity of demand for environmental quality is greater than one. However, McConnell (1997: 394) shows that 'there is no special significance of an income elasticity equal to one' for the shape of the PIR. Nevertheless, McConnell (1997: 394) claims that 'higher income elasticities [of demand for environmental quality] result in slower increases or faster declines in pollutants'.[2] We show, however, that this is not correct. Instead the relationship between the income elasticity and the PIR is ambiguous.

Reconsidering McConnell's (1997) model we find two other explanations why demand for environmental quality increases with income and thus why there is an EKC: First, because environmental quality is a normal good. Hence, what really matters is not that the income elasticity of demand for environmental quality is greater than one (that is, that environmental quality is a luxury good), but that it is greater than zero (that is, that environmental quality is a normal good). As we will demonstrate this can also be called a tendency to satiation in consumption, that is, a tendency to zero marginal utility of consumption at a high, possibly infinite consumption level. There exist other models in the literature which show that a tendency to satiation is one possible cause of the EKC although the words 'satiation' and 'normal good' have never been used (see López, 1994; John and Pecchenino, 1994; Selden and Song, 1995; and Stokey, 1998). The second cause of the EKC is an increasing marginal rate of transformation between pollution and consumption. This condition, however, is not satisfied for standard functional forms for the pollution function. Hence, we contribute to the literature by showing that in a representative consumer model with pollution generated by consumption the tendency to satiation (that is, the normality of environmental quality) is even *necessary* to find an EKC (assuming standard functional forms for the pollution function). Not surprisingly, outright satiation at a finite consumption level is always sufficient to generate an EKC.

To derive our results we study a simple static model adapted from McConnell (1997). However, we offer a graphical interpretation of the

---

[2] A similar result is found by Magnani (2000). But she uses a simplistic utility function which is linear in consumption and environmental quality.

results and our model rests on weaker assumptions: first, by stating that both consumption and environmental quality are normal goods we apply only ordinal, not cardinal assumptions about the utility function. Second, we assume that abatement is more efficient when emissions are high or, in other words, we do not require that the cross-derivative of the pollution function is zero. This allows us to derive two conditions on the pollution function which are of prime importance for the behaviour of pollution.

We also prove that the model of Stokey (1998)—which at first glance seems rather different from our model—is actually an interesting special case of it. Her model is an ideal example to illustrate our findings. Moreover, we offer a new interpretation of Stokey's (1998) result: with asymptotic satiation there is an EKC, but without satiation pollution is monotonically rising. Thus in her model the shape of the PIR exactly depends on whether or not there is satiation.

Satiation is not a very popular concept with economists although there is some evidence in favour of it: a tendency to satiation for agricultural and industrial goods was already observed in the 1950s in the richer countries (Fourastié, 1954: 86). Zinn (1987: 277) even claims to have seen evidence of satiation for certain services. Furthermore, a tendency to satiation is equivalent to the normality of environmental quality. That environmental quality is a normal good, however, is an assumption that most economists would subscribe to.

In the model analysed in this paper we abstract from several explanations of the EKC made in earlier contributions to the literature: an improvement of political institutions which would allow a better internalization of external costs is not possible as we look at the first-best solution. A pollutant cannot be substituted for by another one because there is only one pollutant in the model. Moreover, technological progress is excluded from the model. Furthermore, migration of dirty industries cannot be analysed because there is only one country. Hence, the tendency to satiation or the normality of environmental quality is only a necessary condition for an EKC if we abstract from these possibilities.

We must also be cautious because the model is only valid if the consumer—or the benevolent government—is aware of the causal links between consumption and pollution which in reality is not always the case (Stigliani *et al*., 1991; Opschoor, 2000: 364; and Huesemann, 2001). Hence, the results we will derive are valid for those types of pollutants which are generated by consumption: for example, exhaust components are generated by the consumption of car kilometres. Moreover, consumption often results in waste. Similarly, the consumption of washing powder leads to waste water. Furthermore, energy—often gained from fossil fuels—is needed for the consumption of services from household appliances such as fridges, stoves, washing machines, lawnmowers, and many more. Finally, until recently the use of spray cans resulted in CFC emissions.

The paper is organized as follows. In section 2 we introduce the basic assumptions of the model which is solved in section 3 where we analyse under what conditions an EKC emerges. Then the results are compared to the literature in section 4: We comment on the models of McConnell (1997) and Stokey (1998). Section 5 concludes.

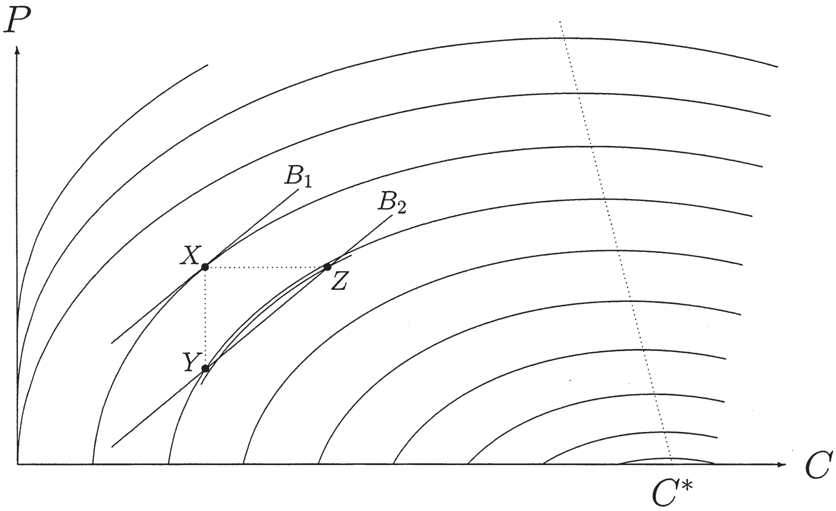

Figure 1. *Graphical illustration of the normal good assumption*

2. The model

The simple static model of McConnell (1997) is used and extended in this paper. We assume a representative consumer with given preferences which depend on consumption C and pollution P. An example of some indifference curves is shown in figure 1. There might (but need not) be a satiation level of consumption which for zero pollution is at C^*. The preferences are well behaved so that they can be represented by a monotonic quasiconcave utility function U. In particular, we assume $U_C > 0$ (below the possible satiation level) and $U_P < 0$. Moreover, C and $-P$ are normal goods:[3] if the consumer could trade consumption goods and pollution at a fixed relative 'price' and if his income increased, he would choose more consumption and less pollution. Starting at the optimal point X on the budget line B_1 in figure 1 the new optimal point must lie between Y and Z on B_2. In other words, the slope of the indifference curve at Y must be steeper than at X, but flatter at Z than at X. The slope of the indifference curve, that is, the *marginal rate of substitution* (MRS), is given by $MRS = -U_C/U_P$. Taking the derivative with respect to C and P the normal good assumption means[4]

$$MRS_C = \frac{\partial MRS}{\partial C} = \frac{-U_{CC}U_P + U_{PC}U_C}{U_P^2} < 0 \qquad (1)$$

---

[3] Empirical evidence that environmental improvements are normal goods can be found in Kriström and Riera (1996).

[4] Note that these two assumptions also ensure that the utility function is quasiconcave: moving along an indifference curve to the right, C and P increase such that—according to (1) and (2)—the slope of the indifference curve becomes flatter. Hence, the indifference curves are concave.

$$MRS_P = \frac{\partial MRS}{\partial P} = \frac{-U_{CP}U_P + U_{PP}U_C}{U_P^2} < 0 \tag{2}$$

Finally, we assume $\lim_{C\to 0} MRS = \infty$ for all P. Hence, we make only ordinal assumptions about the utility function.[5] Note that if environmental quality is a normal good, MRS_C is negative, and the slope of the indifference curve becomes increasingly flatter when we move to the right in figure 1. Therefore we can also call this a tendency to satiation in consumption because at the satiation level the indifference curve becomes horizontal. Hence, we can use the terms 'normality of environmental quality' and 'tendency to satiation' interchangeably.

Next, pollution P depends on consumption C and abatement expenditures A (in terms of the consumption good), that is, $P = P(C, A)$. We assume that $P_C > 0, P_{CC} \geq 0, P_A < 0, P_{AA} > 0, P_{AC} = P_{CA} \leq 0$, and $\lim_{A\to 0}|P_A| < \infty$.[6] Abatement expenditures become increasingly less efficient as the cheapest abatement opportunities are first exploited ($P_{AA} > 0$, for empirical evidence see Faber *et al*., 1996: 272). Contrary to the bulk of literature which for simplicity assumes $P_{AC} = 0$,[7] we assume $P_{AC} \leq 0$ (or $P_{CA} \leq 0$) which is more general and plausible: The higher the level of emissions caused by consumption, the more efficient are the abatement expenditures (or the higher the abatement expenditures, the less polluting is consumption: For example with a more efficient end-of-pipe technology (higher A) emissions caused by consumption result in less pollution).

To derive our results it is convenient to introduce two further conditions. To visualize these conditions consider the iso-pollution lines in

---

[5] All additional assumptions about second derivatives are cardinal. Nevertheless, several authors assume $U_{CC} < 0$, $U_{PP} < 0$, and often also $U_{CP} \leq 0$ or even $U_{CP} = 0$ to simplify the calculations: while McConnell (1997) realizes that U_{CP} might be positive or negative and John and Pecchenino (1994) and Ansuategi (2000: Chapter 4) both assume $U_{CP} \leq 0$, the majority of researchers assume $U_{CP} = 0$, in particular Stokey (1998) whose model will be analysed in Section 4 below, as well as Forster (1973), Gruver (1976), López (1994), John *et al.* (1995), Jones and Manuelli (1995), Saint-Paul (1995), Selden and Song (1995), Ansuategi, Barbier, and Perrings (1998), Ansuategi and Perrings (2000), Cassou and Hamilton (2000), and Smulders and Bretschger (2000) where we have only considered papers dealing with the EKC. Whereas $U_{CC} < 0$ and $U_{PP} < 0$ are relatively plausible, $U_{CP} = 0$ is a restriction on allowed preferences (for example, if $U_{CP} = 0$, the satiation level must be at C^* for all pollution levels which excludes preferences as in Figure 1). Furthermore, with a monotonic transformation we can change a cardinal utility function with $U_{CC} < 0$ (or $U_{PP} < 0$) into another cardinal utility function—still representing the same preferences—with $U_{CC} > 0$ (or $U_{PP} > 0$) and thus $U_{CP} < 0$ according to (1) (or (2)). Keeler, Spence, and Zeckhauser (1971) come closest to our assumptions. They retain $U_{CC} < 0$ and $U_{PP} < 0$ (which we do not need), but use the normal good assumption for U_{CP}.

[6] As we will see $P_C = 0$, $P_A = 0$, and $P_{AA} = 0$ are also possible when C and A go to infinity.

[7] This assumption can be found in McConnell (1997), as well as in Forster (1973), Gruver (1976), John and Pecchenino (1994), John *et al.* (1995), Selden and Song (1995), Ansuategi, Barbier, and Perrings (1998), Ansuategi and Perrings (2000), and Ansuategi (2000: Chapter 4).

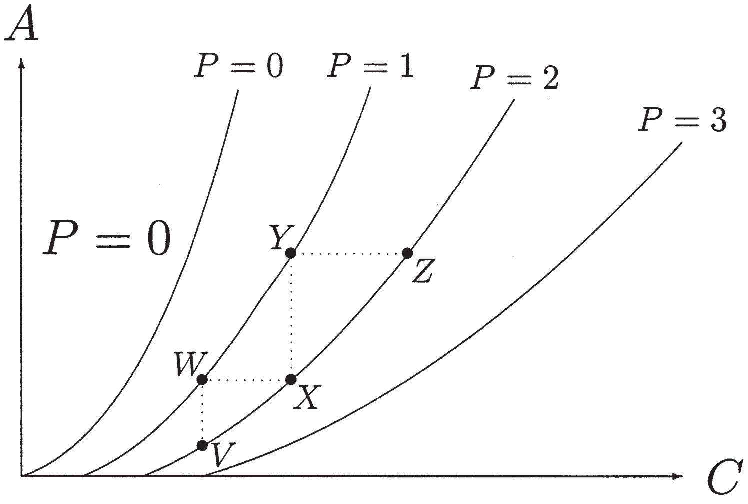

Figure 2. *The iso-pollution lines*

figure 2.[8] Pollution must always be non-negative. Thus there are no iso-pollution lines above the $P = 0$ line. From $dP = 0 = P_C dC + P_A dA$ we see that the slope of the iso-pollution lines is $dA/dC = -P_C/P_A > 0$. The two conditions are

$$V := \left.\frac{dP_C}{dC}\right|_{P\,=\,\text{constant}} = P_{CC} + P_{CA}\left.\frac{dA}{dC}\right|_{P\,=\,\text{constant}} = \frac{-P_{CC}P_A + P_{AC}P_C}{-P_A} < 0 \quad (3)$$

$$W := \left.\frac{dP_A}{dC}\right|_{P\,=\,\text{constant}} = P_{AC} + P_{AA}\left.\frac{dA}{dC}\right|_{P\,=\,\text{constant}} = \frac{-P_{AC}P_A + P_{AA}P_C}{-P_A} > 0 \quad (4)$$

The first condition states that P_C falls when we move along the iso-pollution lines to the right. Since the horizontal distance between two iso-pollution lines is determined by P_C, (3) also means that the horizontal distance increases with consumption ($\overline{YZ} > \overline{WX}$ in figure 2). In other words, consumption becomes less polluting with rising income if we allocate additional income to consumption and abatement such that pollution stays constant. Condition (4) states that $|P_A|$ falls when we move along the iso-pollution lines to the right. Since the vertical distance between two iso-pollution lines is determined by P_A, (4) also means that the vertical distance increases with abatement ($\overline{XY} > \overline{VW}$). Put differently, abatement becomes more expensive with rising income if pollution is again held constant. Both conditions might or might not hold. Standard functional forms fulfil conditions (3) and (4).[9] Note that if we assumed $P_{AC} = 0$, as is

---

[8] The iso-pollution lines cannot only be convex as in figure 2 but they might also be concave.

[9] Conditions (3) and (4) both hold for the following two examples: for $P = C^{\beta}(C + A)^{1-\beta} - x$ where $\beta > 1$ and $x \geq 0$ which will be further analysed in section 4 (see (16) and (17)) and for $P = fC^g/(kA + 1)^h - x$ where $g \geq 1$, $x \geq 0$, and $f, h, k > 0$.

common in the literature, we would implicitly assume that (4) is satisfied, but (3) is not.

To complete the model, we assume that the exogenously given income Y is split up into consumption C and abatement expenditures A, that is, $Y = C + A$.

3. Solution of the model

The representative consumer or the social planer maximizes

$$\max_{C,A} U(C, P(C, A)) + \lambda (Y - C - A) + \gamma A + \mu P(C, A)$$

where λ, γ, and μ are the multipliers with respect to $Y = C + A$ and the nonnegativity constraints $A \geq 0$ and $P \geq 0$, respectively.[10] The first-order conditions are

$$U_C + (U_P + \mu) P_C - \lambda = 0 \tag{5}$$

$$(U_P + \mu) P_A - \lambda + \gamma = 0 \tag{6}$$

$$Y - C - A = 0 \tag{7}$$

The *consumption possibilities curve* (*CPC*) shows all feasible combinations of consumption and pollution for a given income level Y: it is defined by $P(C, Y - C)$ and is depicted in figure 3. The slope of the *CPC* is the *marginal rate of transformation* (*MRT*) between pollution and consumption, that is, $MRT = P_C - P_A > 0$. The *CPC* is convex as $P_{CC} - 2P_{AC} + P_{AA} > 0$. If income increases, the *CPC* moves downwards since more abatement is possible for the same level of consumption. The endpoints of the *CPC*s lie on the convex $P(C, 0)$ line (points above the $P(C, 0)$ line would imply negative

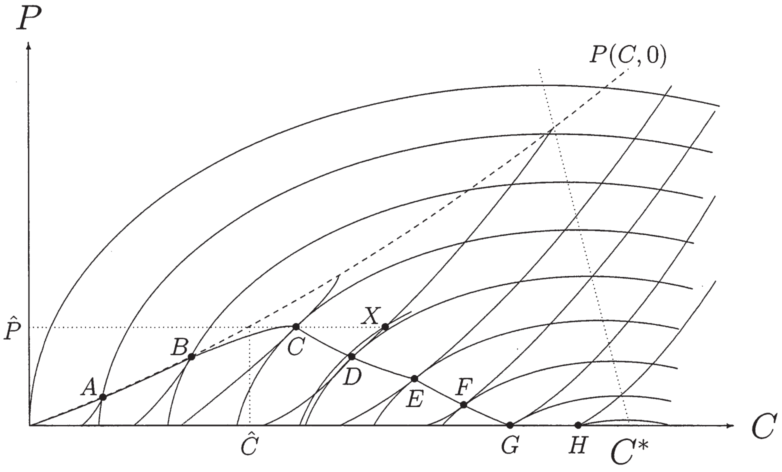

Figure 3. *Indifference curves, CPCs, and the optimal path of the economy*

---

[10] McConnell (1997) assumes an interior solution for A and wholly neglects that $P \geq 0$ must hold.

abatement expenditures and are thus not feasible). Combining (5) and (6) and dividing by $-U_P$ we derive

$$MRS = -\frac{U_C}{U_P} = (P_C - P_A)\frac{U_P + \mu}{U_P} - \frac{\gamma}{U_P} = MRT\frac{U_P + \mu}{U_P} - \frac{\gamma}{U_P} \tag{8}$$

or $MRS = MRT$ at an interior solution where $\mu = \gamma = 0$. Hence, at an interior solution, as at points C, D, E and F in figure 3, the concave indifference curve is tangent to the convex CPC.

3.1. Zero abatement expenditures

If on the $P(C, 0)$ line the slope of the indifference curve is steeper than the slope of the CPC as at point A in figure 3, then the point of the CPC on the $P(C, 0)$ line is optimal. Thus abatement expenditures are zero. In other words, if on the $P(C, 0)$ line

$$MRS(C, P(C, 0)) \geq MRT(C, 0) = P_C(C, 0) - P_A(C, 0) \tag{9}$$

holds, (8) shows that $A = 0$ since $\gamma \geq 0$ (where $P > 0$ ($\mu = 0$) on the $P(C, 0)$ line).

Proposition 1

At low income levels abatement expenditures are zero and pollution increases with exogenously growing income. At a higher level of income, however, abatement expenditures become positive.

Proof Since $\lim_{C\to 0} MRS = \infty$ whereas $(P_C - P_A)$ is bounded for small Y ($\lim_{A\to 0} |P_A| < \infty$), (9) holds for small Y. Hence, if Y rises and $A = \mu = 0$, pollution grows ($dP/dY = P_C dC/dY + P_A dA/dY = P_C > 0$ as $dC/dY = 1$ and $dA/dY = 0$), and (8) changes according to

$$MRS_C + MRS_P P_C = P_{CC} - P_{AC} - d(\gamma/U_P)/dY$$

Because the terms on the left-hand side are negative (see (1) and (2)) and the first two terms on the right-hand side are positive, $-d(\gamma/U_P)/dY$ must be negative or $|\gamma/U_P|$ must decline. As soon as $\gamma = 0 = \gamma/U_P$, A becomes positive (at point B in figure 3).

At low income levels the economy is so poor or suffers from so little pollution that it is optimal not to abate. If income then rises, all additional income is spent on consumption as long as abatement is zero. Then pollution rises along the $P(C, 0)$ line. Abatement expenditures become positive at a low income level if the indifference curves are flat and the CPCs are steep (see (9)). The MRS is small if consumption is relatively satiated (U_C small) or if preferences are 'green' ($|U_P|$ high): a rise in pollution decreases utility by a greater amount if the environment is highly valued. This finding also explains why local pollutants or pollutants with severe health effects (for which $|U_P|$ is high) are abated at lower income levels than transboundary and global pollutants or less health damaging pollutants (see Ansuategi and Perrings, 2000). Abatement expenditure also become positive at a small income level, if they can be abated at low costs ($|P_A|$ high, for example CFCs, see Cole, Rayner, and Bates, 1997) or if consumption is highly pollution-intensive (P_C high).

3.2. The behaviour of pollution at an interior solution

Let us analyse the behaviour of pollution once abatement expenditures are positive.

Proposition 2

At an interior solution, consumption and abatement expenditures increase with exogenously rising income, and pollution declines with income if

$$-MRS_C > \frac{P_{CC}P_A - P_{AC}P_C - P_{AC}P_A + P_{AA}P_C}{-P_A} = W - V \qquad (10)$$

where V and W are defined in (3) and (4). Pollution rises if the inequality sign in (10) is reversed.

Proof Totally differentiating (8) and (7) at an interior solution with positive abatement expenditures and positive pollution ($\gamma = \mu = 0$) yields

$$\begin{bmatrix} MRS_C + MRS_P P_C - P_{CC} + P_{AC} & MRS_P P_A - P_{AC} + P_{AA} \\ -1 & -1 \end{bmatrix} \begin{bmatrix} dC \\ dA \end{bmatrix} = \begin{bmatrix} 0 \\ -dY \end{bmatrix}$$

Denote the entries in the first row of the 2 × 2 matrix by $b_1 < 0$ and $b_2 > 0$. The determinant of this matrix is $b_2 - b_1 > 0$. By Cramer's rule we obtain

$$\frac{dC}{dY} = \frac{b_2}{b_2 - b_1} > 0 \qquad \text{and} \qquad \frac{dA}{dY} = \frac{-b_1}{b_2 - b_1} > 0$$

where $dC/dY + dA/dY = 1$. Using $dP/dY = P_C dC/dY + P_A dA/dY$ we derive[11]

$$\frac{dP}{dY} = \frac{P_{CC}P_A - P_{AC}P_C - P_{AC}P_A + P_{AA}P_C - MRS_C P_A}{P_{AA} - 2P_{AC} + P_{CC} + MRS_P(P_A - P_C) - MRS_C} \qquad (11)$$

from which (10) follows immediately.

Rising income increases consumption and abatement expenditures as was to be expected since consumption and abated pollution are normal goods. To grasp the intuition behind (10), we derive it graphically, following figure 3. We start at an optimal point like *C* where the indifference curve is tangent to the *CPC*. Consider point *X* which lies on the new *CPC* (for the higher income) at the same level of pollution as before. Pollution falls (rises) with growing income if the indifference curve is flatter (steeper) than the *CPC* at point *X*. The new optimal point is *D*. The slope of the *CPC*, that is, the *MRT*, changes on a horizontal ray on which pollution is constant according to $\left.\frac{d(P_C - P_A)}{dC}\right|_{P\,=\,\text{constant}} = V - W$. The slope of the indifference curve, that is, the *MRS*, falls along a horizontal ray ($\text{MRS}_C < 0$, see (1)). Pollution declines if the MRS falls more than the *MRT*, that is, if $-MRS_C > W - V$ which is (10). A corollary follows immediately:

---

[11] For $P_{AC} = 0$ (11) is identical with (4) in McConnell (1997: 391): expanding (11) with $-U_P$ and inserting (1) we find $\{-U_P(P_C P_{AA} + P_A P_{CC}) - P_A U_{CC} + P_A U_{PC} U_C/U_P\}/\{-U_P(b_2 - b_1)\}$ where according to (8) at an interior solution U_C/U_P equals $P_A - P_C$.

Corollary 1
Pollution falls with income at an interior solution if the MRT increases when we move to the right in figure 3, that is, if $V - W \geq 0$. *This is the case if conditions (3) and (4) are both violated.*

For example if $P_{AA} = P_{AC} = 0$, that is if there are constant returns to scale in abatement, we obtain $V > 0$ and $W = 0$. Thus pollution falls with income.[12] However, as mentioned in section 2 there is empirical evidence for $P_{AA} > 0$. Furthermore, for standard functional forms (3) and (4) are both satisfied (see footnote 9) such that $V - W < 0$. Then the slope of the indifference curve and the slope of the *CPC* are both smaller at point *X* than at point *C* in figure 3. In general, it follows from (10) that pollution falls

- if the slope of the indifference curves, that is, the *MRS*, falls fast with consumption holding pollution constant ($|MRS_C|$ high). This is the case:

  if there is a tendency to satiation (U_C falls fast with consumption) and

  if preferences quickly become 'greener' with rising consumption: Then starting at the same level of pollution, the marginal disutility of a rise in pollution, that is, $|U_P|$, grows fast with consumption.

- if the slope of the *CPC*, that is, the *MRT*, becomes slowly flatter or even steepens when we move horizontally to the right in figure 3. This is the case:

  if the environmental impact of consumption declines only slowly or even rises with income holding pollution constant (*V* slightly negative or positive) and

  if abatement costs grow only slowly or even shrink when we move along the iso-pollution lines to the right (see figure 2, *W* slightly positive or negative).

Thus the behaviour of pollution depends on the relationship between preferences and the pollution function (for an example see section 4). Since pollution rises as long as abatement expenditures are zero, we find an EKC if pollution falls at the interior solution.

It follows that if the *MRT* declines ($V - W < 0$) as it does for standard functional forms, the *MRS* must fall even faster to cause an EKC. Hence, a corollary ensues:

Corollary 2
Assuming standard functional forms for the pollution function we find that a sufficiently strong tendency to satiation is necessary for an EKC to exist or in other words it is necessary that environmental quality is a normal good.

3.3. Zero pollution and satiation

Corollary 1 tells us that there is an EKC if the *MRT* increases ($V - W \geq 0$). From now on, however, we concentrate on a declining *MRT* ($V - W < 0$).

---

[12] The fact that constant returns cause the EKC is also derived by Selden and Song (1995) and it resembles the result of Andreoni and Levinson (2001) which we discuss in section 4.

To find weaker conditions for an EKC, we study under what conditions zero pollution is reached. The assumption that zero pollution is technically feasible will be relaxed in sub-section 3.4.

Pollution is zero whenever the slope of the indifference curve is smaller than the slope of the *CPC* on the *C* axis in figure 3 (see points *G* and *H*). In other words, pollution is zero, that is $\mu \geq 0$, whenever

$$MRS(C, 0) \leq MRT\,(C, A) = P_C(C, A) - P_A(C, A) \tag{12}$$

holds at the point of the *CPC* where pollution is zero (see (8)).[13] If for every point of the *C* axis there is a *CPC* starting at this point, we say that zero pollution is technically feasible. Then the point of the *CPC* where pollution is zero moves to higher consumption levels as income rises.

Proposition 3

Pollution is zero at high income levels if zero pollution is technically feasible and if for $C^* \leq \infty$

$$\lim_{C\to C^*} MRS(C, 0) < \lim_{C\to C^*} MRT(C, A) \tag{13}$$

holds at the point of the CPC where pollution is zero. Inequality (13) is satisfied if at least one of the following three conditions holds:

(a) *Condition (3) is violated and* $\lim_{C\to\infty} MRS(C, 0) = 0$.
(b) *Condition (4) is violated and* $\lim_{C\to\infty} MRS(C, 0) = 0$.
(c) *There is a finite satiation level of consumption.*

Proof Since zero pollution is technically feasible, the point of the *CPC* on the *C* axis moves to higher consumption levels when income rises. Therefore it follows immediately from (12) that pollution is zero at high income levels if (13) holds. Inequality (13) is satisfied if $\lim_{C\to\infty} MRS(C, 0) = 0$ and if either P_C or $-P_A$ increases or stays constant, that is if either condition (3) or (4) is violated. If P_A became zero, the *CPC* would not move downwards any more with rising income and zero pollution would not be technically feasible. Thus $P_A < 0$ for finite *A* and *C*. Hence, at C^*, that is at the satiation level of consumption, $MRS(C^*, 0) = 0$ while $MRT = P_C - P_A > 0$. Thus (13) holds.

Corollary 3

If pollution is zero at high income levels, the PIR is an EKC.

Proof This follows immediately from proposition 1: pollution rises at low income levels but is zero at high income levels.

However, if (3) and (4) are not both violated, it is conceivable (see proposition 2) that before turning down, the PIR continues to rise when *A* becomes positive (as in figure 3) and that there are rising parts in the falling branch of the EKC.

Let us examine the intuition behind condition (a), (b), and (c) of proposition 3 in turn. Assume that (a) or (b) holds. Then consumption becomes

---

[13] Cancelling $-P_A$ (12) can also be written as $U_C \leq -U_P P_C$. Thus if the marginal utility of consumption is smaller than the marginal disutility of pollution caused by consumption, pollution is zero.

less attractive since the *MRS* falls and approaches zero, that is since there is a tendency to satiation or in other words since environmental quality is a normal good. Note that $\lim_{C\to\infty} MRS(C, 0) = 0$ is the usual Inada condition. Furthermore, most of the additional income is devoted to abatement because the environmental impact of consumption is rising ((3) violated) or because abatement has a large effect since its costs are falling ((4) violated). Pollution accordingly falls all the way down to zero. If P_{AC} was zero as in the model of McConnell (1997), (3) would be violated and pollution would become zero (if this is feasible and if $\lim_{C\to\infty} MRS(C, 0) = 0$). However, standard functional forms fulfil conditions (3) and (4) (see footnote 9).

Hence, the result that satiation (condition (c)) causes zero pollution and thus induces an EKC is more important. Intuitively, at the satiation level we can easily dispose of some consumption almost without lowering utility. If the same income used for abatement instead of consumption can decrease pollution, it is better used for abatement. Decreasing pollution is no longer possible when pollution is zero. Thus the satiation level can only be reached if pollution is zero. Pollution already becomes zero before the satiation level is reached (at point *G* in figure 3).

Finally, consider (13). In general, if conditions (3) and (4) hold and if there is no satiation, the slope of the indifference curves, that is, the *MRS*, and the slope of the *CPC*, that is, the *MRT*, both fall when we move along a horizontal ray to the right in figure 3, and anything goes (see (10) or figure 3): if the *MRS* falls slower than the *MRT*, pollution rises monotonically. If both slopes fall at the same speed, pollution becomes constant at a positive level of pollution (this happens for $\sigma = 1$ in Stokey's (1998) model discussed in section 4). Finally, if the *MRS* falls faster than the *MRT*, pollution is falling. Analysing the behaviour of the two slopes on the *C* axis in figure 3, we see that pollution becomes zero (at $\bar{C}$ in figure 4a) if (13) holds.[14] However, if the inequality sign in (13) is reversed as in figure 4b, zero pollution is not attainable implying that the falling pollution asymptotically approaches some positive level from above. In the borderline case of $\lim_{C\to\infty} MRS = \lim_{C\to\infty} MRT$ the relative speed, with which the common limit is approached, determines whether or not zero pollution is attainable.

Therefore to bring about zero pollution, it is necessary and sufficient that the *MRS* becomes smaller than the *MRT* (see (13)). So we again find that *the normality of environmental quality (or a tendency to satiation, that is,* $|MRS_C| < 0$*) is necessary for zero pollution and the EKC if the MRT declines along the C axis in figure 3 as it does for standard functional forms.* Conditions (a), (b), and (c) in proposition 3 are sufficient for zero pollution, but not necessary. However, pollution becomes zero at a lower consumption level if one or several of the three conditions is satisfied: according to figure 4 zero pollution will be reached at a lower consumption level if the $MRT = P_C - P_A$ is rising at zero pollution ((a) and (b)) and if the $MRS(C, 0)$ is low ((c), assuming that satiation causes the *MRS* to be smaller everywhere).

---

[14] Note that the *MRS* falls always faster than the *MRT* in figures 4a and 4b. Conditions (a), (b), and (c) of proposition 3 are violated in figure 4 since $\lim_{C\to\infty} MRS(C, 0) > 0$ and if both (a) and (b) held, the *MRT* would rise.

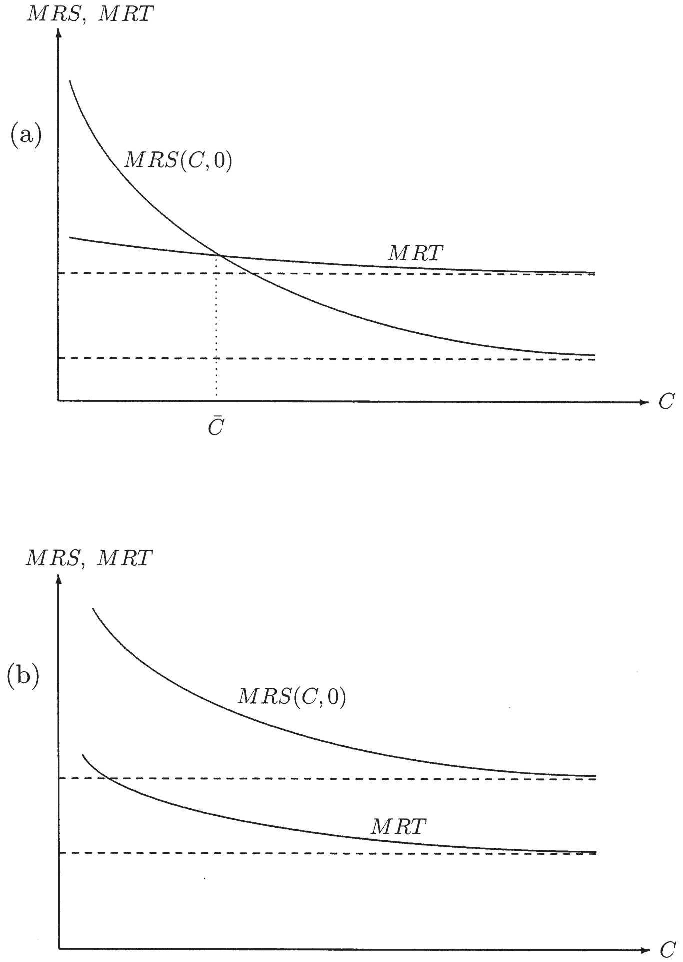

Figure 4. *The MRS and the MRT at zero pollution if (a), (b), and (c) are violated*

Remember that a low *MRS* and a high *MRT* (on the *P*(*C*, 0) line) also let abatement expenditures become positive at a lower income level (see (9)).

3.4. The solution if zero pollution is technically infeasible

Up to now we have assumed that zero pollution is technically feasible. This need not be the case. It is often assumed that zero pollution requires infinite abatement expenditures. Then the $P = 0$ iso-pollution line in figure 2 is identical with the *A* axis and all the *CPCs* in figure 3 start at the origin. For rising income the *CPC* moves downwards but becomes identical with the *C* axis only for infinite income. Hence, for all $C > 0$ zero pollution is technically not feasible since there is no *CPC* starting at point (*C*, 0) in figure 3. However, for all positive levels of pollution—for example for

$\hat{P} > 0$ in figure 3—it is technically feasible to reach $\hat{P}$ which we define to mean that for all C[15] there is a *CPC* going through the point $(C, \hat{P})$. With rising income the *CPC* moves to the right on a horizontal line at $\hat{P}$. Note that we can choose $\hat{P}$ arbitrarily close to zero.[16] We can now state the analogue to proposition 3 for an interior solution.

Corollary 4

Suppose that $\hat{P} > 0$ is technically feasible. Then if

$$MRS(C, \hat{P}) < MRT(C, A) \tag{14}$$

holds at the point of the CPC where $P = \hat{P}$, pollution is smaller than $\hat{P}$. (14) is satisfied at high income levels if at least one of the following three conditions holds:

(a) *Condition (3) is violated and* $\lim_{C\to\infty} MRS(C, \hat{P}) = 0$.
(b) *Condition (4) is violated and* $\lim_{C\to\infty} MRS(C, \hat{P}) = 0$.
(c) *There is a finite satiation level of consumption.*

Proof Decreasing consumption and holding income constant (which implies $dA = -dC$) we find that the left-hand side of (14) increases ($MRS_C dC + MRS_P\,(P_C - P_A)dC > 0$ for $dC < 0$) and the right-hand side decreases ($(P_{CC} - 2P_{AC} + P_{AA})dC < 0$) until $MRS = MRT$ which holds at an interior solution (see (8)). Thus with less consumption and more abatement pollution is smaller. The proof that conditions (a), (b), and (c) imply that (14) holds is exactly analogous to the proof of proposition 3.

That pollution is smaller than $\hat{P}$ if (14) holds, can immediately be seen from point X in figure 3. As mentioned, if zero pollution requires infinite abatement expenditures, we can choose $\hat{P}$ arbitrarily close to zero. Therefore pollution approaches zero as consumption goes to infinity or to the satiation level. Hence, *we also find an EKC if zero pollution requires infinite abatement expenditures* and if corollary 4 holds. Note that if (4) is violated, $|P_A|$ increases with income when pollution is held constant. Thus zero pollution is feasible in this case. If zero pollution is not feasible, (4) holds. If $P_{AC} = 0$ holds, (3) is violated. In this case we find an EKC (if $\hat{P}$ is feasible for all $\hat{P} > 0$ and if the Inada condition $\lim_{C\to\infty} MRS(C, \hat{P}) = 0$ holds). Hence, *it is crucial to allow for $P_{AC} < 0$ to make a monotonically rising PIR a possible outcome of the model*. Furthermore, the assumption that zero pollution requires infinite abatement expenditures makes only sense in a model with $P_{AC} < 0$. It again follows from (14) that if the *MRT* declines when we move to the right, the tendency to satiation or to 'green' preferences must be strong enough to cause an EKC.

[15] More precisely, for all $C > \hat{C}$ where $\hat{C}$ is defined by $\hat{P} = P(\hat{C}, 0)$ and is shown in figure 3.

[16] Consider the two examples in footnote 9, $P = C^{\beta}\,(C + A)^{1-\beta} - x$ where $\beta > 1$ and $P = fC^{g}/(kA + 1)^{h} - x$. In both examples zero pollution is technically not feasible if $x = 0$ (only for $A = \infty$ pollution becomes zero). However, in both examples an ever-so small $\hat{P} > 0$ is technically feasible for every (finite) level of consumption if abatement and thus income is only high enough.

4. Relationship to the literature

There are two other authors whose models are closely connected to the model of this paper. The first is McConnell (1997). Although his intuition is similar, his interpretation is different: McConnell (1997: 391) claims that 'the higher the income elasticity of demand for environmental quality, the slower the growth in pollution when positive or the faster the decline in pollution when negative.' This, however, is not correct as shown by a counterexample in the appendix. Rather the relationship between the income elasticity of demand for environmental quality and the PIR is ambiguous in our model.

The second author is Stokey (1998). Her model, seeming quite different at first glance, boils down to a special case of our general model with specific functional forms for $U(C, P)$ and $P(C, A)$. It is therefore an ideal example to illustrate our results. Stokey (1998) analyses the EKC in a model in which $C = zY$ where $z \, \varepsilon \, [0, 1]$ is an index for the technology used in production. A higher z allows more consumption, but also causes more pollution as $P = \max\{Yz^{\beta} - x, 0\}$, where $\beta > 1$ and $x \geq 0$ (Stokey uses $x = 0$ which makes zero pollution technically infeasible). Assuming $P > 0$ and using $z = C/Y$ we derive

$$P = C^{\beta}Y^{1-\beta} - x = C^{\beta}(C + A)^{1-\beta} - x$$

It is easy to check that this pollution function satisfies all our assumptions, that is, $P_C > 0$, $P_A < 0$, $P_{CC} \geq 0$, $P_{AA} > 0$, $P_{AC} \leq 0$, and $\lim_{A\to 0} |P_A| = \beta - 1 < \infty$ ($P_{CC} = 0$ and $P_{AC} = 0$ hold only for $A = 0$). Another formulation of the model is $C = (P + x)^{1/\beta}Y^{1-1/\beta}$, a Cobb–Douglas production function (Stokey, 1998: 8). The utility function is given by

$$U(C, P) = V(C) - H(P) = \frac{C^{1-\sigma} - 1}{1 - \sigma} - \frac{B(P + \varepsilon)^{\gamma}}{\gamma} \tag{15}$$

where B, $\sigma > 0$ and $\gamma > 1$. Note that we have extended *Stokey*'s (1998) model by $\epsilon \geq 0$ to allow for zero pollution.[17] This utility function fulfils all our assumptions (see (1), (2), and $\lim_{C\to 0} MRS = \infty$).

At low levels of income we again find that pollution rises with income as long as there is no abatement. For an interior solution we derive:

Corollary 5

In Stokey's (1998) model (10) is equivalent to $\sigma > 1$. Thus, at an interior solution, pollution falls with income if $\sigma > 1$, and it rises if $\sigma < 1$.

Proof Both P_C and $|P_A|$ fall when we move along the iso-pollution lines to the right since it is straightforward to show that the numerators in (3) and (4) simplify to

---

[17] For $\epsilon = 0$ we have $U_p(C, 0) = 0$ and $MRS\,(C, 0) = \infty$ for all C. Then (12) is never satisfied except at the satiation level where $0 = U_C(C^*, 0) = -U_p(C^*, 0)\, MRT = 0$. So if $U_p(C, 0) = 0$, only satiation causes zero pollution. In the literature utility functions with $U_p(C, 0) = 0$ are often used to simplify the calculations. At least for high consumption levels, however, it is not implausible that the marginal disutility at zero pollution ($U_p(C, 0)$) is negative: The first speck of pollution does diminish our utility.

$$-P_{CC}P_A + P_{AC}P_C = C^{2\beta-2}Y^{-2\beta}(C - Y)\beta(\beta - 1) < 0 \quad \text{for } A > 0 \tag{16}$$

$$-P_{AC}P_A + P_{AA}P_C = C^{2\beta-1}Y^{-2\beta}\beta(\beta - 1) > 0 \tag{17}$$

Inserting (15) into (1) and dividing (17) − (16) by $-P_A = (\beta - 1)C^{\beta}Y^{-\beta}$ we find that (10) simplifies to

$$\frac{\sigma C^{-\sigma-1}}{B(P + \epsilon)^{\gamma-1}} > \beta C^{\beta-2}Y^{1-\beta} \tag{18}$$

From (8) we know that $U_C = -U_P(P_C - P_A)$ at an interior solution. So inserting (15) and $P_C - P_A$ we obtain

$$C^{-\sigma} = B(P + \epsilon)^{\gamma-1}\beta C^{\beta-1}Y^{1-\beta} \quad \text{or} \quad \frac{C^{-\sigma-1}}{B(P + \epsilon)^{\gamma-1}} = \beta C^{\beta-2}Y^{1-\beta}$$

Inserting this result into (18) we immediately see that it reduces to $\sigma > 1$.

Since in Stokey's model conditions (3) and (4) hold (see (16) and (17)), $\sigma \gtrless 1$ determines whether or not the *MRS* falls faster than the *MRT* along a horizontal ray in figure 3 at an interior solution (see (10)), that is, whether or not the tendency to satiation is sufficiently strong. As seen from the proof both the assumptions about $U(P, C)$ and $P(C, A)$ are crucial for obtaining an EKC if the elasticity of marginal utility of consumption σ is greater than one. Stokey (1998, 3 and 23) stops with this finding. However, looking at the definition of $V(C)$ in (15) we realize the following: on the one hand, if $\sigma < 1$, $V(C)$ is positive, and as C goes to infinity, $V(C)$ goes to infinity too. On the other hand, if $\sigma > 1$, $V(C)$ is negative, and as C goes to infinity, $V(C)$ asymptotically approaches $1/(\sigma - 1)$ from below. This means that utility of consumption is bounded above by $1/(\sigma - 1)$. Thus there is an EKC if utility of consumption is bounded above because then further consumption becomes less attractive. If utility of consumption is unbounded, however, pollution increases monotonically as consumption is more appealing.[18] This result is very intuitive. Note that assuming utility of consumption to be bounded above rests on cardinal utility. Thus this result cannot be generalized to ordinal utility. However, it is very similar to satiation. Therefore we conclude:

Corollary 6
If there is asymptotic satiation in Stokey's (1998) model, the PIR is an EKC. If there is no satiation, the PIR is monotonically rising.

In Stokey's (1998) model the satiation level C^* is ∞. So even when the consumption level is still much smaller than C^*, the tendency to satiation is so strong if $\sigma > 1$ that pollution declines already at very low levels of consumption (as soon as $A > 0$).

In a similar model as presented in section 3, Andreoni and Levinson (2001) find yet another reason for pollution to become zero at high levels

---

[18] For $\sigma_1 > 1 > \sigma_2$ and for every point with $C > 1$ in figure 3 the $MRS = -U_C/U_P$ is higher for the smaller σ_2 because $C^{-\sigma_2} > C^{-\sigma_1}$.

of income: they assume $P = \alpha C - R(C, A)$ where $\alpha > 0$.[19] Here αC denote emissions and $R(C, A)$ is the reduction in emissions due to abatement where $R(C, A)$ is an increasing, concave function with increasing returns to scale and $R(C, 0) = R(0, A) = 0$. Then pollution becomes zero at some income level due to the increasing returns in abatement if $U_P(C, 0) < 0$. However, this income level may be high indeed as the proof rests on a limit argument when income goes to infinity.

5. Conclusion

The main result of this paper is that in a representative agent model with pollution generated by consumption, satiation in consumption is always a sufficient condition for the downturn of the EKC and that a tendency to satiation—or in other words the normality of environmental quality—is even a necessary condition if we assume a standard functional form for the pollution function. The intuition is that if there is a tendency to satiation, growth in consumption does not increase utility by much and therefore additional income is devoted to abatement such that pollution falls. We have shown that Stokey's (1998) model is a special case of our model. With her specification of functional forms satiation is even all-decisive: with asymptotic satiation there is an EKC and without satiation pollution increases monotonically. This specification also shows that satiation can already cause pollution to fall at levels of consumption which are far below the satiation level.

This result has been derived using only an ordinal, not a cardinal utility function and with a more general pollution function than in previous studies. This allowed us to state two important conditions for the behaviour of pollution: whether or not consumption becomes increasingly less polluting and abatement increasingly more expensive with rising income while holding pollution constant. We have shown that at low income levels pollution rises with exogenously growing income because abatement expenditures are zero. At a higher income level, however, abatement expenditures become positive.

For further growing income the behaviour of pollution depends on satiation and the two conditions mentioned above. Pollution declines if the marginal rate of transformation (*MRT*) between pollution and consumption increases with income, for example if both conditions are violated. If zero pollution is technically feasible, pollution finally becomes zero (negative pollution is infeasible). If exactly one of the two conditions holds (for example if the cross derivative of the pollution function is zero as in previous models) and if there is a tendency to satiation, the pollution level also becomes small (or zero) at a sufficiently high income level. Thus we again find an EKC. Satiation, however, leads to an EKC independent of the two conditions and the *MRT*. Without satiation and if the two conditions hold, pollution can rise monotonically, it can become constant at some positive pollution level, or it can fall asymptotically approaching some

---

[19] Andreoni and Levinson (2001) restrict themselves to $\alpha = 1$ although their proof goes through for any $\alpha > 0$. Note that $P_C = \alpha - R_C < 0$ is possible in this model as $R_C > 0$.

level of pollution from above. The latter is the case if the marginal rate of substitution falls faster than the *MRT* (if we hold pollution constant), that is, if there is a sufficiently strong tendency to satiation. Hence, only if the *MRT* increases with income, the tendency to satiation—or the normality of environmental quality—is not necessary to obtain an EKC. However, for standard functional forms the *MRT* decreases. All these results are independent of whether or not zero pollution is technically feasible.

It has been claimed by McConnell (1997) and other researchers that a high income elasticity of demand for environmental quality works in favour of falling pollution. We have shown, however, that a higher income elasticity can cause a more positive or a more negative slope of the PIR. Hence, there is no simple relationship between the income elasticity of demand for environmental quality and the PIR.

Building on the literature we presented a static model. This is unsatisfactory since the EKC is an inherently dynamic phenomenon in the course of economic growth and since the level of income needed to reach zero (or a low level of) pollution might be high. Thus it is not clear whether such a high income level is attained in a growth model. Lieb (2001: chapter 6) shows that all the results derived in this paper are also valid in a dynamic extension of the model and he analyses under what conditions zero pollution is attainable.

Appendix: Counterexample to McConnell's claim

To determine the influence of the income elasticity of demand for environmental quality on the EKC, McConnell (1997) uses a counterfactual model in which the representative consumer can buy consumer goods at a price of one and environmental quality Q at a price of π, that is, $Y = C + \pi Q$. Since pollution is the difference between the best environmental quality, Q_{max}, and the actual environmental quality, Q, the consumer maximizes[20]

$$\max_C U(C, P) = \max_C U(C, Q_{max} - Q) = \max_C U(C, Q_{max} - (Y - C)/\pi$$

Calculating the first-order condition we find $MRS = -U_C/U_P = 1/\pi$. This implies $MRS_C dC + MRS_P 1/\pi dC - MRS_P 1/\pi dY = 0$. Using $dC = dY - \pi dQ$ we derive[21]

$$\frac{dQ}{dY} = \frac{MRS_C}{\pi MRS_C + MRS_P} > 0 \tag{19}$$

The income elasticity of demand for environmental quality is given by $\eta = Y/Q\ dQ/dY$.

McConnell's (1997: 391) claims that a higher η causes the slope of the PIR to become more negative (that is if the slope is positive, it becomes flatter

---

[20] Note that the consumer does not internalize the external effect he causes with his consumption.

[21] Equation (19) is identical with equation (3) in McConnell (1997: 391): inserting (1) and (2) into (19) we obtain $\{-U_{CC} + U_{PC}U_C/U_P\}/\{-\pi U_{CC} + \pi U_{PC}U_C/U_P - U_{CP} + U_{PP}U_C/U_P\}$. Replacing U_C/U_P by $-1/\pi$ and multiplying through by $-\pi$ we find the identity. McConnell (1997: 391) claims that dQ/dY can also be negative. As equation (19) shows this is only possible if either C or $-P$ is not a normal good.

and if it is negative, it becomes steeper). The slope of the PIR, dP/dY, is given by (11). We now present a counterexample to show that this claim is not correct. Taking the utility function (15) with $\epsilon = 0$ we derive $MRS = C^{-\sigma}/BP^{\gamma-1}$ and thus

$$MRS_C = -\frac{\sigma}{C}\,MRS, \qquad MRS_P = -\frac{\gamma-1}{P}\,MRS,$$

$$\text{and } \frac{dQ}{dY} = \frac{\sigma/C}{\pi\sigma/C + (\gamma-1)/P}$$

Now we consider an optimal point, such as point X in figure 1, where the indifference curve is tangent to the budget line, and we examine a change in preferences. Assume that γ falls and that B changes such that the $MRS = 1/\pi$ stays constant at the optimal point X.[22] It follows that MRS_C stays constant, but $|MRS_P|$ falls and dQ/dY rises. Since Q and Y remain unchanged, η increases too. Furthermore, the denominator of (11) decreases whereas the numerator stays constant. Thus if the slope of the PIR is positive, it becomes steeper. Hence, McConnell's (1997) claim that the slope becomes more negative when η rises is violated.

References

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

Ansuategi, A. (2000), 'Economic growth and environmental quality: a critical assessment of the environmental Kuznets curve hypothesis', Thesis, Environment Department, University of York.

Ansuategi, A., E.B. Barbier, and C. Perrings (1998), 'The environmental Kuznets curve', in J.C.J.M. van den Berg and M.W. Hofkes (eds), *Economic Modelling of Sustainable Development: Between Theory and Practice*, Dordrecht: Kluwer Academic Publisher, pp. 139–164.

Ansuategi, A. and C. Perrings (2000), 'Transboundary externalities in the environmental transition hypothesis', *Environmental and Resource Economics* **17**(4): 353–373.

Cassou, S.P. and S.F. Hamilton (2000), 'The transition from dirty to clean industries: optimal fiscal policy in a two-sector model of endogenous growth', mimeo, Kansas State University.

Cole, M.A., A.J. Rayner, and J.M. Bates (1997), 'The environmental Kuznets curve: an empirical analysis', *Environment and Development Economics* **2**: 401–416.

de Bruyn, S.M. (2000), 'Economic growth and the environment: an empirical analysis', *Economy and Environment*, Vol. 18, Dordrecht, Boston, and London: Kluwer Academic Publishers.

Ekins, P. (1997), 'The Kuznets curve for the environment and economic growth: examining the evidence', *Environment and Planning* **A29**: 805–830.

Faber, M., F. Jöst, R. Manstetten, G. Müller-Fürstenberger, and J.L.R. Proops (1996), 'Linking ecology and economy: joint production in the chemical industry', in M. Faber, R. Manstetten, and J.L.R. Proops (eds), *Ecological Economics – Concepts and Methods*, Cheltenham, UK and Brookfield, US: Edward Elgar, Chapter 13, pp. 263–278.

---

[22] In general a change in preferences also changes the optimal point and thus Q, C, and P.

Forster, B.A. (1973), ‘Optimal capital accumulation in a polluted environment’, *Southern Economic Journal* **39**: 544–547.

Fourastié, J. (1954), *Die grosse Hoffnung des zwanzigsten Jahrhunderts*, Köln-Deutz: Bund-Verlag.

Grossman, G.M. and A.B. Krueger (1991), ‘Environmental impacts of a North American Free Trade Agreement’, Discussion Paper No. 158, Woodrow Wilson School, Princeton University. Also published in 1993 in P.M. Garber (ed.), *The Mexico–US Free Trade Agreement*, Cambridge, MA and London: The MIT Press, pp. 13–57.

Gruver, G.W. (1976), ‘Optimal investment in pollution control capital in a neoclassical growth context’, *Journal of Environmental Economics and Management* **3**: 165–177.

Huesemann, M.H. (2001), ‘Can pollution problems be effectively solved by environmental science and technology? An analysis of critical limitations’, *Ecological Economics* **37**: 271–287.

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

John, A., R. Pecchenino, D. Schimmelpfennig, and S. Schreft (1995), ‘Short-lived agents and the long-lived environment’, *Journal of Public Economics* **58**: 127–141.

Jones, L.E. and R.E. Manuelli (1995), ‘A positive model of growth and pollution control’, NBER Working Paper No. 5205.

Keeler, E., M. Spence, and R. Zeckhauser (1971), ‘The optimal control of pollution’, *Journal of Economic Theory* **4**: 19–34.

Kriström, B. and P. Riera (1996), ‘Is the income elasticity of environmental improvements less than one?’, *Environmental and Resource Economics* **7**: 45–55.

Lieb, C.M. (2001), ‘Possible causes of the environmental Kuznets curve: a theoretical analysis’, Thesis, Department of Economics, University of Heidelberg.

López, R. (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.

Magnani, E. (2000), ‘The environmental Kuznets curve, environmental protection policy and income distribution’, *Ecological Economics* **32**: 431–443.

McConnell, K.E. (1997), ‘Income and the demand for environmental quality’, *Environment and Development Economics* **2**: 383–399.

Opschoor, H. (2000), ‘The ecological footprint: measuring rod or metaphor?’ *Ecological Economics* **32**: 363–365.

Saint-Paul, G. (1995), ‘Discussion of “Pollution and growth: what do we know?”’, in I. Goldin and L.A. Winters (eds), *The Economics of Sustainable Development*, New York: Cambridge University Press, pp. 47–50.

Selden, T.M. and D. Song (1995), ‘Neoclassical growth, the J curve for abatement, and the inverted U curve for pollution’, *Journal of Environmental Economics and Management* **29**: 162–168.

Smulders, S. and L. Bretschger (2000), ‘Explaining environmental Kuznets curves: how pollution induces policy and new technologies’, Discussion Paper No. 2000–95, Center for Economic Research, Tilburg.

Stern, D.I. (1998), ‘Progress on the environmental Kuznets curve?’, *Environment and Development Economics* **3**: 173–196.

Stigliani, W.M., P. Doelman, W. Salomons, R. Schulin, G.R.B. Smidt, and S.E.A.T.M. Van der Zee (1991), ‘Chemical time bombs: predicting the unpredictable’, *Environment* **33**(4): 4–9 and 26–30.

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

Zinn, K.G. (1987), ‘Fourastié versus Neoklassik. Nochmal: Die aktuelle Strukturdiskussion im Licht der Dreisektorenthese’, *Wirtschaft und Gesellschaft* **13**: 271–280.