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The Environmental Kuznets Curve – A Survey of the Empirical Evidence and of Possible Causes

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Abstract

Many environmentalists believe that economic growth necessarily harms the environment, i.e. they believe that the pollution-income relationship (PIR) is monotonically rising. In the last decade, however, some studies have found an environmental Kuznets curve (EKC), i.e. an inverted U-shaped PIR. Accordingly, economic growth has been promoted as a method of improving the environment. This interpretation, however, is not tenable. To show this, we survey the empirical evidence and its possible explanations. We find an EKC for flow and local pollutants, but a monotonically rising PIR both for stock and global pollutants and for aggregate measures of pollution. Critically analysing the estimation technique we show *inter alia* that time series analyses are more appropriate than cross country analyses. Migration of dirty industries can explain an EKC obtained in a cross country analysis, but not in a time series analysis. Four causes of a time series EKC are empirically validated: rising demand for environmental quality, substitution between pollutants, technological progress, and increasing returns to scale in abatement. We argue that all these causes stem from policy measures. Hence, an EKC exists for a certain pollutant when policy measures are taken, but the PIR is monotonically rising if the government remains inactive.
(JEL: D62, O00, Q20)

Keywords: environmental Kuznets curve, economic growth, pollution, environmental policy, environmental quality, abatement.

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1 Introduction

In 1991 Grossman and Krueger found evidence that while some pollutants rise with income at low income levels, at a higher income level a turning point is reached and further income growth subsequently leads to lower pollution (see figure 1). Panayotou (1995, first published 1993) called this inverted U-shaped pattern an environmental Kuznets curve (EKC) after the original Kuznets curve, which describes an inverted U-shaped relationship between income inequality and income (Kuznets 1955). Both the EKC and the original Kuznets curve are based on the idea that in the course of economic growth some measure of the quality of life - environmental quality or an equal income distribution - will initially deteriorate before improving again (Pearson 1994, 201 and Munasinghe 1999, 95). More generally, the behaviour of pollution when income rises can be called a pollution-income relationship (PIR). Thus the EKC is a special case of the PIR - namely an inverted-U shaped PIR.

Many environmentalists believe that economic growth necessarily involves a degradation of environmental quality (Cole 1999, 87), i.e. they believe that the PIR is monotonically rising. If this is the case, growth must sooner or later come to a halt since the world's capacity to absorb pollution is only limited (López 1994) - unless there is pollution-saving technological progress that allows production to increase without causing additional pollution (Stokey 1998). From this perspective solving the pollution problem is one of the main challenges of the 21st century (Homburg and Matthies 1998, 13).

However, the EKC found by Grossman and Krueger (1991) and subsequently by many other authors has given rise to a completely different opinion:[1] pollution is considered as only a transitional phenomenon in the course of economic growth. If this is the case, then 'in the longer run, the surest way to improve your environment is to become rich' (Beckerman 1992, 491). Hence, 'most governments and global institutions [...] see no conflict between economic growth [and environmental degradation]' because they 'typically argue that only economic growth can provide the resources with which to tackle environmental problems' (Cole 1999, 91 and 87). Beckerman (1992, 482) even concludes that 'the best - and probably the only - way to attain a decent environment [...] is to become rich'.

This article has two main purposes. First, we critically survey the empirical literature on the PIR to see whether or not an EKC actually exists or for which pollutants it exists. This literature survey - given in the first part of the article - improves upon previous work because it also deals with several conflicting results published in the last few years. This implies that we arrive at different conclusions. After analysing the estimation technique, the results derived with this method are presented: an EKC arises for flow and local pollutants, but the PIR is monotonically rising both for stock and global pollutants and

[1] Before the first EKC studies appeared, there was hardly any evidence concerning the relationship between economic growth and the environment. Therefore we will not discuss the frequently surveyed literature on growth and the environment published before the EKC studies materialized. Surveys of this literature can, for instance, be found in Cole (2000b, chapter 4) or de Bruyn (2000, part I).

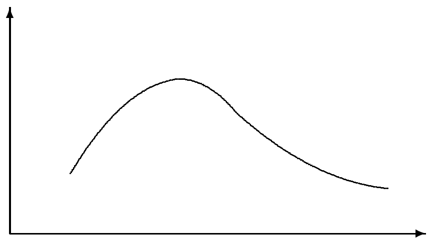

Figure 1: The environmental Kuznets curve.

for aggregate measures of pollution. We also critically examine the estimation technique used to derive these results. We show that pollution data are of poor quality, that data are even missing for many types of pollution, that the use of a time trend can be problematic, that multicollinearity may impair the results - a fact that has been neglected by the literature to date - that different countries have different PIRs, and that shocks may have permanent effects on the PIR. Finally, some emission forecasts show that emissions will continue to rise fast. The main conclusion from the first part of the article is that the EKC exists, but only for some pollutants and not in all countries alike. The recent EKC evidence has been derived with reduced form models. These models only show what shape the PIR has, but they do not allow any conclusions about why it should have that shape.

Therefore the second main purpose of this article is to find possible causes of the EKC. In other words, we are looking for explanations why there is an EKC for some pollutants, but not for others. Thus in the second part of the article we gather all the different possible causes of the EKC that have been proposed in the theoretical literature. We discuss various theoretical models and arguments put forward to explain the EKC. Moreover, we review some further empirical evidence to see whether or not these explanations are supported by the data. All literature surveys to date concentrate on the empirical literature, as we do in the first part of this article. Hence, such a detailed survey of all possible causes of the EKC and in particular of their empirical validity has never been given before.

The rising branch of the EKC can be explained by the fact that *ceteris paribus* more production causes more pollution. The downturn of the EKC occurs because the *ceteris paribus* condition is violated. Pollution declines for one of the following reasons: because demand for environmental quality rises with income (possibly from fear of incurring irreversible damage) and this induces stricter environmental policies; because one pollutant is reduced by replacing it by another pollutant; because technological progress makes it possible to produce more while causing less pollution; or because increasing returns to scale in abatement allow richer countries to abate at lower average costs. These causes are supported by the empirical evidence. Only partly empirically validated is the hypothesis that the EKC arises because dirty industries migrate out of developed countries into developing countries. Finally, the effects of structural change and income distribution on the EKC are only small, not to say insignificant. We also show that a falling EKC does not necessarily imply that environmental quality is improving because irreversible damage may have happened. The main conclusion of the second part of the article is that the downturn of the EKC emerges when policy measures are taken, but that the PIR can be expected to be monotonically rising when the government remains inactive.

Hence, the EKC does not occur automatically in the course of economic growth. So the optimistic interpretation of the EKC - which led 'policy makers such as the World Bank and the General Agreement on Tariffs and Trade (GATT) [to] use the results as evidence that economic growth should be promoted as a method of improving the environment' (Kelly 2000, 2) - is not tenable. Indeed, Ayres (1995, 97) goes so far as to say that this interpretation is 'false and pernicious nonsense'.

This article is organized as follows. In the first part - consisting of sections 2-6 - we survey the empirical literature. In section 2 we describe the data situation and the pollutants for which the PIR has been estimated. In section 3 we review the traditional empirical EKC studies, which all employ a cross country analysis. First, the traditional cross country estimation technique is discussed in subsection 3.1, then the results for a number of pollutants and for some aggregate measures of pollution are presented in subsection 3.2, and finally the traditional technique is criticized in subsection 3.3. This criticism leads to the conclusion that time series analysis is more appropriate. Accordingly, results from time series analyses are surveyed in section 4. In section 5 we give an overview of some emission forecasts. Section 6 summarizes the results from empirical studies.

In the second part - consisting of sections 7-16 - we review the theoretical literature for possible causes of the downturn of the EKC. In section 7 we argue that increasing demand for environmental quality can be responsible for the downturn. In subsection 7.1 we discuss several models which all predict an EKC because of the internalization of external effects by the government. In section 8 we show that the EKC for a certain pollutant may emerge because this pollutant is substituted for by another pollutant. In section 9 we argue that technological progress can cause the EKC. In section 10 we introduce the idea that increasing returns to scale in abatement could play a key role. In section 11 we consider the view that structural change - the rise and fall of the industrial sector - explains the EKC. In section 12 we present the consequences for the EKC when it is caused by the migration of dirty industries from developed into developing countries. In section 13 we analyse whether or not income distribution influences the EKC. In section 14 we demonstrate that shocks - mostly caused by the government - could also be important for the EKC. In section 15 we state that a falling EKC does not imply that environmental quality rises with income when irreversibilities are involved. We therefore argue in subsection 15.1 that the fear of overstepping a threshold may cause the downturn of the EKC. Since it is important whether the turning point lies above or below a threshold level, we discuss in subsection 15.2 some theoretical results concerning the location of the turning point of the EKC. In section 16 we summarize the possible causes of the EKC and in section 17 we draw some conclusions.

Part I: The Empirical Literature

2 Data and pollutants

One of the main problems in estimating the PIR is finding reliable and comparable data for pollution (Ansuategi 2000, 31). In different countries data are often measured by different methods and possibly at unrepresentative locations (Shafik 1994). Furthermore, sufficiently long time series are missing because collection of environmental data started in the 1960s at the earliest, for many countries and pollutants much later still. Data from developing countries are even more rare and 'often considered unreliable' (Auffhammer et al. 2001a, 3). Moreover, for many dimensions of environmental quality data are missing, so that the PIR cannot be estimated for these dimensions. Hence, most studies focus on those pollutants for which data are available, i.e. on air and water pollutants.

We now give an overview of the pollutants that have been analysed in the empirical literature and of some data-related issues concerning these pollutants. For a survey of the exact data sources for all the pollutants discussed below, we refer the reader to Ansuategi (2000, 32-35). Air pollutants such as sulphur dioxide (SO_2), suspended particulate matter (SPM), oxides of nitrogen (NO_x), carbon monoxide (CO), lead, and volatile organic compounds (VOC) are all connected with important health hazards (Selden and Song 1994, 150, Grossman 1995, 29, and Carson et al. 1997, 438). Because of non-comparable measurement methods some researchers estimate two regressions for SPM: one method indicates dark material in the air (dark matter), the other measures the total weight of SPM (heavy particles) (Grossman and Krueger 1991, 10). The data situation for the most prominent greenhouse gas, carbon dioxide (CO_2), is the best of any pollutant as relatively long time series are available for many developed and developing countries (Roberts and Grimes 1997, 192). However, for CO_2 only emission data are available.

For the other indicators of air pollution there has been a discussion over the advantages and disadvantages of emission per capita and concentration data. Emissions are directly connected with current economic activity, but they are independent of the area in which they are released and therefore of the damage they cause. Concentrations, by contrast, measure the local impact on the environment, but they are not directly related to local, current economic activity - especially when the pollutant is transboundary and long-lived (Ansuategi 2000, 82).[2]

We may ask whether the income level at the turning point of the EKC should be expected to be higher for emissions or for concentrations. Note first that concentration data are mostly gathered in cities (Stern 1998, 182) while emission data are nation-wide. Selden and Song (1994, 148) argue that the turning point of the EKC should lie at a

[2] Ansuategi (2000, chapter 5) therefore proposes to use emissions per area, which measure the potential damage irrespective of where it occurs. He obtains similar results as other authors with emissions per capita or concentrations.

higher income level for national emissions than for urban concentrations because urban concentrations can easily be reduced by using higher smoke stacks or by moving dirty industries out of urban areas and because urban air quality has an immediate impact on human health. Another effect has been overlooked in the EKC literature: though falling, emissions may still lie above the assimilative capacity of nature. Then the concentration continues to increase (cf. figure 7 below). Only when emissions fall below the assimilative capacity, does the concentration also start to decline. In this case the turning point for concentrations lies at a higher income level than for emissions.[3] The evidence tends to support the first argument - that the turning point for national emissions lies at a higher income level - (Cavlovic et al. 2000), but the evidence is ambiguous.

Furthermore, emission and concentration data both have their measurement problems. Emission data are not measured, but calculated from estimates of fuel use and emission coefficients for different fuel types (de Bruyn, 2000, 100). Concentrations vary widely over time and space. Moreover, the monitoring stations are often located at sites where pollution is considered an actual or potential problem (Grossman 1995, 24). Due to this site selection bias we tend to overestimate concentrations (Borghesi 1999). More seriously still, the setting up of a monitoring station shows that there is some political will to combat pollution. This may bias the results towards the EKC: when the monitoring station is set up, concentrations may be high and rising. Thus pollution is tackled and concentrations subsequently fall. So as neither emissions nor concentrations are clearly superior, it is advisable to estimate the PIR with both data sets.

In addition to the estimations for air pollutants, the PIR has also been studied for three groups of river-water quality indicators measured as concentrations: first, the state of the oxygen regime (dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), and nitrates), which is crucial for the fish population, second, the concentration of pathogens (fecal and total coliform (FCOL and TCOL)), which cause a variety of sometimes fatal diseases, and, third, the concentration of heavy metals (lead, cadmium, arsenic, mercury, and nickel), which bioaccumulate in fish and - when eaten by man - involve many health risks (Grossman and Krueger 1995, 357-359).

The relationships between the lack of clean drinking water and income and between the lack of urban sanitation and income have also been analysed. Strictly speaking, however, these are not pollution indicators, but measures of the absence of basic services (Ekins 1997, 811). Moreover, the PIR has also been estimated for municipal waste and for deforestation. Deforestation data are notoriously unreliable for three reasons: first, because they are often estimated from population growth rates, second, because countries that have already cut down most of their original forests seem to have undergone an improvement (Shafik and Bandyopadhyay 1992), and, third, because there are important differences in biodiversity between primeval forests and monocultural plantations and

[3] Kelly (2000, figures 6 and 7) finds this result in his model, but he does not point it out.

these differences are lost in the data. Finally, there are also studies examining the PIR for some aggregate measures of pollution. These measures will be considered in paragraph 3.2.1 below.

We thus see that the PIR has been estimated for many pollutants. Many other indicators of pollution, however, are difficult to measure, in particular soil erosion (van Kooten and Bulte 2000, 387), desertification, pollution and depletion of groundwater aquifers, biodiversity loss (Cole 1999, 95), acidification (Neumayer 1998, 168), extinction of animal and plant species, climate change, the ozone hole, and the risks of nuclear power stations. Karr and Thomas (1996) argue that EKC results obtained for the human-health-related environmental indicators discussed above should not be considered representative for overall environmental quality or ecological health. Similarly, Arrow et al. (1995) state that our main interest should lie in ecosystem resilience. Resilience is a measure of the magnitude of shocks an ecosystem can accommodate and still return to the same equilibrium as before. However, if pollution oversteps a certain threshold level, the ecosystem flips into another, possibly environmentally disastrous equilibrium. So we should measure pollution relative to this threshold. Furthermore, environmental quality is also threatened by so-called chemical time bombs, chemicals that first accumulate without causing any harm, but are then suddenly released and damage the environment (Stigliani et al. 1991). However, neither resilience (Ayres 1995, Schindler 1996 and Orians 1996) nor chemical time bombs are measurable.

Summarizing, we conclude that the data quality is poor and that data are only available for recognized, potentially highly damaging, and easily measurable pollutants. In fact, the choice of a pollution indicator is often determined by data availability (de Bruyn, 2000, 73). Hence, even if we found that there is an EKC for all the pollutants which have been analysed, we could not conclude that there is an EKC for overall pollution.

To estimate the PIR we need not only pollution data but also income data. Almost all studies use gross domestic product (GDP) in purchasing power parity dollars (PPP$). Only a few researchers employ GDP measured in market exchange rates, which understates the income of poor countries. Hill and Magnani (2000) argue that we should use net domestic product defined as GDP minus depreciation. This makes sense, but gives similar results. The use of 'green GDP', which Hill and Magnani (2000) also propose, is less advisable since we are interested in the relationship between pollution and economic activity and this is best measured by GDP. Finally, Perrings and Ansuategi (2000) also estimate the PIR with consumption and with the human development index (HDI). However, the results for these indicators are largely the same as for GDP and they even have lower explanatory power, i.e. lower adjusted R^2. Hence, the almost exclusive use of GDP in PPP$ is reasonable.

3 Traditional studies: Cross country analyses

3.1 Estimation technique

The traditional and still dominant technique in the EKC literature is to estimate

$$P_{it} = \alpha + \beta_1 Y_{it} + \beta_2 Y_{it}^2 + \beta_3 Y_{it}^3 + \beta_4 X_{it} + \epsilon_{it} \tag{1}$$

where P is pollution measured in emissions per capita or in the concentration of a certain pollutant, Y is GDP per capita mostly measured in PPP$, i is an index for the country or for the measuring station, t is an index for time, X is a vector of additional explanatory variables, and ϵ is the error term. The vector X typically consists of the population density[4] and - for concentration data - of variables describing the site of the monitoring station (dummies for central city or suburban and for industrial, commercial, or residential land use nearby, and the like). Sometimes (1) is also estimated without any additional explanatory variables, i.e. without $\beta_4 X_{it}$.

To have a reasonably large data set, (1) is estimated using panel data from as many countries and years as possible. Some data sets are only available for one year so that pure cross country analysis is applied. Panel data, however, are preferable as they allow for higher efficiency of the econometric estimates (Ansuategi 2000, 32). While many studies use ordinary least squares (OLS) to estimate (1), others employ generalized least squares (GLS), which is more appropriate as it corrects for heteroscedasticity and autocorrelation.

Some researchers estimate (1) without the cubic term $\beta_3 Y_{it}^3$. This technique, however, is too favourable to the EKC hypothesis. The cubic formulation, by contrast, allows for both an inverted U-shaped and a monotonically rising PIR. Additionally, it has the advantage that the EKC does not have to be symmetric as in the quadratic formulation: the cubic function may rise faster than it declines, or vice versa. If the cubic term is not significant, it can be skipped.[5] This procedure - proposed by Shafik and Bandyopadhyay (1992) - has been adopted by most researchers. If β_2 is also insignificant in the quadratic estimation, even the linear formulation - with both $\beta_2 Y_{it}^2$ and $\beta_3 Y_{it}^3$ dropped - makes sense. Therefore the estimation of (1) will produce one of the following seven results: a monotonically falling or rising PIR, an inverted U-shape (i.e. the EKC), a U-shape, an N-shape (first rising, then falling, and finally rising again), an inverted N-shape, or an insignificant, i.e flat PIR.

Estimations of (1) have not only been run with levels data but also with logarithms ($\ln P$ and $\ln Y$ instead of P and Y). Although most researchers estimate (1) in levels only or in logarithms only, it is actually an empirical question which functional form fits the data better. We should therefore estimate both versions - and also semi-logarithmic

[4] The population density can have a positive or negative sign and is often insignificant.

[5] It is possible that β_1, β_2, and β_3 are all insignificant in the cubic estimation, but that β_1 and β_2 are highly significant in the quadratic estimation (see table 1 in Shafik and Bandyopadhyay 1992).

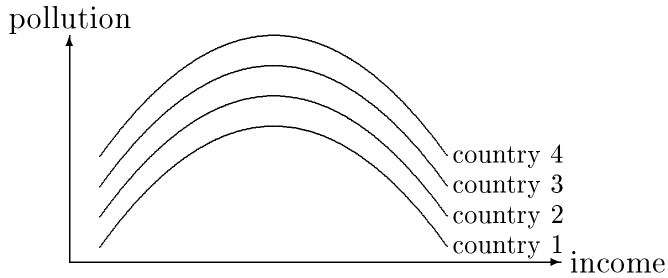

Figure 2: Estimation with fixed effects.

versions with only pollution or only income in logarithms - and pick the one that has the highest explanatory power. For a quadratic formulation the use of logarithms is theoretically preferable because as income goes to infinity, the estimation in levels predicts that pollution goes to minus infinity, whereas when the logarithm of pollution goes to minus infinity, pollution approaches zero (Cole et al. 1997). This is an important theoretical point as emissions and concentrations cannot be negative. However, what really matters in practice is which functional form has the higher explanatory power inside the data range. This can be the estimation in levels or in logarithms (see table 4 in Cole et al. 1997). Furthermore, as long as the trough (i.e. the local minimum) of the N-shape is outside the data range, a slowly declining PIR can also be estimated in levels. Note also that the turning point estimate depends on the choice of the functional form (Hilton and Levinson 1998). Hence, we should not have too much confidence in the turning point estimate - not least because the data quality is poor (Ekins 1997).

Often (1) is estimated with a time trend, i.e. with an additional term $\beta_5 t$. This time trend is added in order not to attribute environmentally beneficial or harmful effects to GDP growth which are in fact traceable to technological progress or to enhanced environmental awareness. However, as discussed in paragraph 3.3.3 below the introduction of a time trend is problematic.

Finally, (1) is often estimated using fixed effects, i.e. replacing the intercept α by a dummy variable α_i for each country or monitoring station. Hence, each country has its own intercept (see figure 2). This corrects for different climatic conditions (emissions by heating in the winter), different resource endowments (high stocks of fossil fuels or many possibilities for water power generation), and systematic measurement errors. Random effects are often calculated in addition to fixed effects. The assumption for random effects is that the α_i are drawn from a distribution with mean α. A Hausman test is then used to check whether fixed or random effects are preferable (Green 1997, 632-634).

Note that (1) is a reduced form (Panayotou 1997). Actually, the influence of income on environmental regulation, on technology, and on structural change should be estimated first. Then the relationship between these variables and pollution could be examined. However, due to data problems income is used as a catch-all variable in (1). Thus we cannot tell which underlying cause is the main driving force behind the EKC: the estimation is a black box. Accordingly, the results have given rise to widely varying interpretations. For instance, the results have been used to promote growth strategies as discussed in section 1, although, in fact, they are not suitable for policy recommendations.

3.2 Results

In this subsection we present the results which have been found using cross country analyses. Since we are considering man-made pollution, the PIR must begin at the origin: without any income (or production), there is no pollution. So man-made pollution must rise before it can fall. Therefore we interpret the finding of a monotonically falling PIR as evidence for the EKC, but the turning point of the EKC occurs at such a low income level that it could not be detected with the data at hand. Similarly, we interpret a U-shaped PIR as evidence of an N-shaped PIR. In this interpretation we follow some of the literature (see Kaufmann et al. 1998, Scruggs 1998, Dinda et al. 2000, Harbaugh et al. 2000, and Millimet and Stengos 2000). Furthermore, following Cole et al. (1997) and Stern and Common (2001), we consider the finding of an EKC with a turning point outside the sample range as evidence for a monotonically rising PIR.

Tables 1 - 5 summarize the estimation results. For each pollutant the first column shows our interpretation of the shape of the estimated PIR, which is either monotonically rising ($\nearrow$), an EKC ($\frown$), an N-shape ($\sim$), or an insignificant relationship (is). In tables 1 and 2 results for emissions are indexed by an ^{e}, while all other results represent concentrations. The second column gives either the income level at the turning point of the EKC (in thousands of mostly 1985 PPP$), the income range in which the turning points fall if several regressions have been run (for example in levels and logarithms, with and without fixed effects, or with and without additional regressors, i.e. X_{it} in (1)), the two turning points (peak and trough of the N-shape), or the actual estimation result (for example a monotonically falling PIR ($\searrow$) or a U-shape ($\smile$) and the turning point).

The main finding from tables 1 - 4 is that an EKC emerges for local and flow pollutants, whereas the PIR is monotonically rising for global and stock pollutants.

As can be seen from tables 1 and 2, most studies agree that there is an EKC for all air pollutants: SO_2, SPM, NO_x, CO, lead, and VOC. However, the turning point estimates vary widely. While some estimates lie at relatively low income levels, others are at the income level of the richest countries (or even beyond). So we cannot draw any definite conclusions concerning the income level at the turning point. The establishment of an EKC for these pollutants is not surprising because these pollutants cause severe local health risks and because abatement is relatively cheap (Selden and Song 1994, 155). It seems that the pollutants causing the highest health risks - SO_2 and SPM (Grossman 1995) - are addressed at the lowest income levels. Although all these pollutants are stock pollutants, they all have very short lifetimes in the atmosphere and can therefore be considered as flow pollutants from a long-run point of view. The lifetime of SO_2 is 1-4

Table 1: Empirical results for the PIR for several air pollutants.

	SO_2		SPM				NO_x	
			dark matter		heavy particles			
Grossman and Krueger 1991	$\sim$	4.5, 15.0	$\sim$	5.0, 10.0	$\frown$	$\searrow$		
	$\frown$	4.5	$\sim$	4.0, 10.0	$\nearrow$	$\nearrow$		
Shafik and Bandyopadhyay 1992	$\frown$	3.7		$\frown$	3.3			
Shukla and Parikh 1992[a]	is		is		$\frown$	11.0-12.5		
Grossman et al. 1994	$\frown$	13.9		$\nearrow$	$\frown$ 27.5		$\frown$	19.4
Selden and Song 1994	$\frown^e$	8.7-10.7		$\frown^e$	9.5-10.3		$\frown^e$	11.2-21.8
Grossman 1995	$\sim$	13.4, 24.0		$\frown$	15.9		$\frown$	18.5
Grossman and Krueger 1995	$\sim$	4.1, 13.5	$\frown$	6.2	$\frown$	$\searrow$		
Panayotou 1995	$\frown^e$	2.9		$\frown^e$	4.5		$\frown^e$	5.5
Carson et al. 1997	$\frown^e$	$\searrow$		$\frown^e$	$\searrow$		$\frown^e$	$\searrow$
Cole et al. 1997	$\frown^e$	5.7-6.9		$\frown^e$	7.3-8.1		$\frown^e$	14.7-15.1
Lim 1997	$\frown$	$\searrow$		$\frown$	$\searrow$		$\frown$	$\searrow$
Panayotou 1997	$\sim$	5.0, 17.5						
Vincent 1997				$\nearrow$	$\nearrow$			
Kaufmann et al. 1998	$\sim$	$\smile$ 12.5						
Scruggs 1998	$\frown$	$\searrow$		$\frown$	$\searrow$			
Torras and Boyce 1998	$\sim$	3.9, 15.4	$\sim$	4.4, 10.5	$\frown$	$\searrow$		
Wu 1998			$\frown$	$\searrow$	$\frown$	n.a.		
Gallet et al. 1999[b]	$\frown^e$	10.5					$\frown^e$	14.5
List and Gallet 1999	$\frown^e$	22.6					$\frown^e$	8.7
Ansuategi 2000, chapter 5	$\frown^e$	4.7-6.6						
Barrett and Graddy 2000[c]	$\sim$	5.2, 12.5	$\frown$	8.1	$\frown$	$\searrow$		
	$\sim$	1.8, 14.7	$\frown$	8.8	$\nearrow$	$\nearrow$		
Cavlovic et al. 2000	$\frown$	18.9	$\frown$	4.9	$\frown$	6.1	$\nearrow$	$\frown$ 30.8
Cole 2000b, 112	$\frown^e$	5.2					$\frown^e$	20.3
Dinda et al. 2000	$\frown$	$\searrow$		$\sim$	$\smile$ 12.5			
Hill and Magnani 2000	$\frown^e$	7.4-12.7					$\frown^e$	8.9-17.4
Hung and Shaw 2000	is			is			$\frown$	12.8
List and Gerking 2000	$\frown^e$	26.1					$\frown^e$	15.2
Millimet et al. 2000	$\frown^e$	8.0					$\frown^e$	12.0
Perrings and Ansuategi 2000	$\frown^e$	9.6						
Gangadharan and Valenzuela 2001	is			is			is	
Stern and Common 2001	$\frown^e$	9.2						
	$\nearrow^e$	$\frown$ 908.2						

[a] Own calculations from table 3 in Shukla and Parikh (1992). [b] Own calculations from table 2 in Gallet et al. (1999). [c] Own calculations from tables 2 and 7 in Barrett and Graddy (2000). [e] Emissions, all other estimates represent concentrations. $\frown$ = EKC. $\nearrow$ = Monotonically rising PIR. $\searrow$ = Monotonically falling PIR. $\sim$ = N-shaped PIR. is = insignificant PIR. n.a. = Turning point estimate not available. numbers = Income level at turning points in thousands of mostly 1985 PPP$.
Notes: The first column for each pollutant shows our interpretation of the estimated shape of the PIR. The second column gives the turning point, the peak and the trough of the N-shape, the actual estimation result, or the range in which the turning points fall if several regressions have been run.

days,[6] that of NO_x is 2-5 days, that of CO is 1-3 months, and that of hydrocarbons (VOCs are hydrocarbons, see Nentwig 1995, 451) ranges from hours to a few days (Liu

[6]Since all empirical EKC studies consider SO_2 and NO_x as air pollutants only, we also treat them as such. In so doing, we are neglecting the fact that they are also stock pollutants causing acidification of soils, fens, and lakes.

Table 2: Empirical results for the PIR for some further air pollutants and CO_2.

	CO		lead		VOC		CO_2 emissions	
Holtz-Eakin and Selden 1992							↗^{e}	⌒ 35.5-8000.0
Shafik and Bandyopadhyay 1992							↗^{e}	↗
Grossman et al. 1994	⌒	16.7	⌒	16.5				
Selden and Song 1994	is^e							
Grossman 1995	⌒	22.8	↗	↗				
Sengupta 1996							∼^{e}	8.7, 15.3
Carson et al. 1997	⌒^{e}	↘			⌒^{e}	↘	⌒^{e}	↘
Cole et al. 1997	⌒^{e}	9.9-10.1					↗^{e}	⌒ 25.1-62.7
Lim 1997							↗^{e}	↗
Moomaw and Unruh 1997							∼^{e}	12.8, 18.3
Roberts and Grimes 1997, 192							↗^{e}	↗
Hilton and Levinson 1998			⌒^{e}	4.0-11.0				
Schmalensee et al. 1998							⌒^{e}	9.8
Agras and Chapman 1999							↗^{e}	⌒ 101.0
							⌒^{e}	13.6
Galeotti and Lanza 1999a							⌒^{e}	17.1
Gallet et al. 1999[a]	⌒^{e}	13.8			⌒^{e}	15.0		
Borghesi 2000							↗^{e}	↗
Cavlovic et al. 2000	↗	⌒ 30.8					↗^{e}	⌒ 199.3
Hill and Magnani 2000							⌒^{e}	8.7-12.3
							↗^{e}	↗
Hung and Shaw 2000	⌒	6.8						
Perrings and Ansuategi 2000							↗^{e}	↗
Auffhammer et al. 2001b, 20							↗^{e}	⌒ n.a.
Azomahou and van Phu 2001							↗^{e}	↗
Bengochea-Morancho et al.2001							↗^{e}	↗
Carlsson and Lundström 2001							↗^{e}	↗
							⌒^{e}	24.6
Gangadharan and Valenzuela 2001							∼^{e}	5.8, 18.9
Heil and Selden 2001							↗^{e}	⌒ 36.0-2300.0

[a] Own calculations from table 2 in Gallet et al. (1999).

Note: For further explanations, see table 1.

and Lipták 2000, 32 and IPCC 1996, 92, for a definition of lifetime see IPCC 1996, 76). SPM is washed out by rain- and snowfall (Liu and Lipták 2000, 34) and thus also has a short lifetime.[7]

Some studies have found that air pollution starts to rise again at high income levels. For instance, Kaufmann et al. (1998, 216) find a U-shape for SO_2 with trough at 12500 PPP$. They interpret this result as follows. At low income levels (below 3000 PPP$, the lowest income level in their data set) SO_2 rises because of a shift from biomass fuels to coal. Then the SO_2 concentration falls as the economy moves away from fuels with high sulphur content, such as coal, toward fuels with low sulphur content, such as oil and natural gas. Beyond 12500 PPP$ the rising energy consumption and the increasing

[7] I have not found any data for the lifetime of lead.

Table 3: Empirical results for the PIR for the concentration of river water pollutants.

	oxygen regime			pathogens			heavy metals		
	pollu-tant			pollu-tant			pollu-tant		
Shafik and Bandyopadhyay 1992	−DO[a]	is		FCOL	∼	1.4, 11.4			
Grossman and Krueger 1995	−DO[a]	⌢	2.7	FCOL	⌢	8.0	lead	∼	1.9, 14.5
	BOD	is		TCOL	∼	3.0, 8.5	cadmium	⌢	11.6
	COD	is					arsenic	∼	4.9, 15.0
	nitrates	⌢	10.5				mercury	is	
							nickel	is	
Cole et al. 1997	nitrates	⌢	15.6-25.0						
Lim 1997	BOD	⌢	n.a.						
Vincent 1997	BOD	is							
	nitrogen	↗	↗						
Scruggs 1998	−DO[a]	⌢	↘	FCOL	↗	↗			
Torras and Boyce 1998	−DO[a]	⌢	↘	FCOL	is				
Barrett and Graddy 2000[b]	−DO[a]	⌢	3.0	FCOL	⌢	9.5	lead	is	
	BOD	is		TCOL	∼	3.1, 8.9	cadmium	⌢	11.1
	COD	is					arsenic	↗	↗
	nitrates	⌢	10.5				mercury	is	
							nickel	∼	⌣ 9.9
Cavlovic et al. 2000	aggregate	⌢	6.5				aggregate	⌢	16.4
Hettige et al. 2000	BOD	⌢[c]	7.0						

[a] Since more dissolved oxygen means less pollution, the results are for minus dissolved oxygen. [b] Own calculations from table 5 in Barrett and Graddy (2000). [c] This PIR rises until 7.0 and then stays constant. DO = dissolved oxygen. BOD = biological oxygen demand. COD = chemical oxygen demand. FCOL = fecal coliform. TCOL = total coliform.
Note: For further explanations, see table 1.

abatement costs outweigh the ongoing substitution of fuels, and the SO_2 concentration rises again.

For CO_2 emissions, however, the majority of studies finds a monotonically rising PIR (see table 2). Nevertheless, some studies find an EKC, while others obtain that the slope of the PIR becomes increasingly steeper (Shafik and Bandyopadhyay 1992, Borghesi 2000, and Perrings and Ansuategi 2000). The PIR tends to be rising because CO_2 is a global stock pollutant with a lifetime of about 125 years (Frey et al. 1991, 165).

Note that even if we find an EKC for emissions per capita, pollution can continue to rise for two reasons. First, the population is growing. Although population growth is one of the main driving forces behind environmental decay and stopping it is important (Sengupta 1996, Wackernagel and Rees 1997a, 168, and de Bruyn 2000, 11), we will not analyse this issue in this article.[8] Second, although emissions are falling, they may still lie above the assimilative capacity of nature so that concentrations continue to increase.

[8]For a study of the relationship between the PIR and population growth, see Baldwin (1995).

Table 4: Empirical results for the PIR for some further pollutants.

	lack of clean water		lack of sanitation		deforest-ation		municipal waste	
Shafik and Bandyopadhyay 1992	⌒	↘	⌒	↘	is		↗	↗
Cropper and Griffiths 1994					⌒	4.8-5.4		
					is			
Panayotou 1995					⌒	0.8		
					is			
Cole et al. 1997							↗	↗
Lim 1997					↗	↗	⌒[a]	n.a.
							↗[b]	↗
Torras and Boyce 1998	⌒	↘[c]	⌒	↘[c]				
Cavlovic et al. 2000					⌒	4.9		
Perrings and Ansuategi 2000	⌒	↘			⌒	1.9		
Gangadharan and Valenzuela 2001					is			
Minliang et al. 2001							↗	↗

[a] Estimate for domestic waste. [b] Estimate for industrial waste. [c] Actually an inverted N-shape with rising pollution in the range of 11.3-14.9 or 11.0-16.9, respectively.
Note: For further explanations, see table 1.

However, since for short-lived air pollutants the EKC is also found for concentrations (at least in urban areas), this does not seem to constitute a problem. But for the long-lived CO_2 the situation is different (cf. subsections 15.1 and 15.2).

For the river-water quality indicators in table 3 the evidence is weaker. While many EKCs (with widely varying turning point estimates) are found, several insignificant PIRs are also obtained. Again, some results indicate an N-shape. Shafik and Bandyopadhyay (1992) explain the final upturn of the N-shape for fecal coliform by the fact that people in high income countries no longer directly depend on river-water quality because of improvements in water supply systems. Since the monitoring stations are in rivers, the concentrations of these pollutants would quickly decline if emissions stopped: so river pollutants are short-lived. Thus they can also be viewed as flow pollutants.

Lack of clean drinking water and lack of urban sanitation are classic examples of strictly local problems. Furthermore, the health risks are high (survival is at stake) and the costs of provision are fairly low (Shafik 1994, 761). Hence, it is not surprising that the EKC has a very low turning point (see table 4). As soon as resources become available, these two problems are solved. However, Ekins (1997, 811) argues that these two indicators are measures of the absence of basic services, not of environmental quality.

The evidence is weakest for deforestation (see table 4). Whereas some studies find an insignificant PIR, others find an EKC, but the explanatory power is very low ($R^2 = 0.09$ in Perrings and Ansuategi 2000). So it seems that income is not an important determinant of deforestation. However, these weak results may also be a reflection of the poor data quality discussed in section 2.

Table 5: Empirical results for the PIR for some aggregate measures of pollution.

Cole et al. 1997	energy consumption	$\nearrow$	$\frown$ 22.5-34.7
Suri and Chapman 1998		$\nearrow$	$\frown$ 55.5
Agras and Chapman 1999		$\nearrow$	$\frown$ 62.0-195.0
Cole et al. 1997	traffic volume	$\nearrow$	$\frown$ 65.3-108.2
Hettige et al. 1992	air toxics emissions	$\nearrow$	$\nearrow$
Carson et al. 1997		$\frown$	$\searrow$
Millimet and Stengos 2000		$\sim$	$\smile$ 30.0
Wang et al. 1998	health risk of hazardous waste sites	$\frown$	22.6
De Bruyn and Opschoor 1997	throughput	$\sim$	n.a.
Rothman 1998	ecological footprint	$\nearrow$	$\nearrow$

Note: For explanations, see table 1.

The PIR for municipal waste, finally, is monotonically rising (see table 4). Municipal waste is a stock pollutant since it is deposited in waste disposal sites and accumulates there.[9] Furthermore, these disposal sites may be located at places where nobody lives or only poor people who have no political power (Shafik 1994). Thus since the waste problem can easily be externalized, waste generation is not reduced.

The main focus of all empirical studies is the income level at the turning point. The pollution level at the turning point is not even reported in most studies. What really matters, however, is the pollution level, since it determines what damage occurs and whether or not thresholds are overstepped (Agras and Chapman 1999, Borghesi 1999, and Perrings and Ansuategi 2000). We will analyse thresholds in section 15.

3.2.1 Results for aggregate measures of pollution

It has been argued that pollution as perceived by the general public is an aggregate measure (Wu 1998). Hence, to obtain an overall picture of the PIR, there have also been efforts to estimate the PIR for aggregate pollution. However, aggregation of different pollutants is ‘problematic’ (Magnani 2000a, 433). The weights of different pollutants in the aggregate are always somewhat arbitrary. Thus all aggregates can only be considered approximations (de Bruyn 2000, 67-70). Some researchers (Ekins 1997, Scruggs 1998, and Wu 1998) aggregate the pollutants for which they have data using simple weighting techniques. Not surprisingly, the results mirror the average of the PIR estimates for the single pollutants. Therefore we concentrate on aggregates that use different data sources from the studies analysed so far. The results for these aggregate indicators are shown in table 5.

The most frequently analysed aggregate indicator is energy consumption - the ‘chief source of a number of environmental problems’ (Suri and Chapman 1998, 196). Traffic volume can also be considered as the root of several types of pollution. Both indicators

[9] If waste is incinerated, about 30% of its original weight remains for disposal (Nentwig 1995, 347).

invariably rise with income. Hettige et al. (1992) find evidence that emissions of 320 toxic substances per unit of industrial output increase with income. This implies that the PIR for toxic substances is also monotonically rising because industrial output increases with income (Ekins 1997, 812). By contrast, Carson et al. (1997) obtain an EKC for air toxics emissions, while Millimet and Stengos (2000) estimate an N-shaped PIR for 650 toxic chemicals. Analysing subcategories of these chemicals, Millimet and Stengos (2000) also find weak evidence that subcategories with mainly local effects have turning points at smaller income levels than subcategories with more transboundary effects. For the health risk of hazardous waste sites, Wang et al. (1998) derive an EKC with a turning point at a high income level. De Bruyn and Opschoor (1997) construct a measure of the flow of material and energy. This throughput indicator is aggregated from the consumption of steel, energy, and cement and from weight of freight transport. The estimated form is an N-shape, but the turning points have not been calculated. The ecological footprint - developed by Wackernagel and Rees (1997a) - is a related, but more detailed indicator. It converts material and energy consumption flows into the area of land and water that is necessary to make these flows sustainable.[10] Rothman (1998) estimates a monotonically rising PIR for the ecological footprint per capita.

Moreover, Nentwig (1995, 547-551) observes that the list of endangered species - a crude measure of biodiversity loss - is growing steadily, and that the anthropogenic speed with which species become extinct is ten thousand times higher than the natural one, resulting in huge losses in biodiversity. Similarly, Skonhoft and Solem (2001) find that wilderness land - a crude measure of biodiversity - is declining steadily with income. Finally, Ekins (1997) summarizes two reports of the OECD and of the European Commission on the state of nature. These reports acknowledge that progress has been made with some urgent pollution problems - those problems for which an EKC has been found. However, there remain substantial problems 'across all areas of environmental concern' (Ekins 1997, 815). Furthermore, high-risk activities are increasing. In fact, OECD countries will 'have to face more intractable problems than those solved in previous decades' (Ekins 1997, 815). Thus environmental degradation is growing despite heavy investment in abatement. These reports clearly negate the existence of an EKC for overall pollution.

Summarizing, we find that the EKC has been observed for pollutants with mainly local and immediate effects such as short-lived air pollutants. It seems that those air pollutants causing the highest health risks are addressed at the lowest income levels. For water pollutants - which can also be considered flow pollutants - the EKC has also been found, although the evidence is less clear. For global and stock pollutants such as

[10] 'The ecological footprint [of an economy] can be represented as the aggregate area of land and water [...] that is claimed by participants in that economy to produce all the resources they consume, and to absorb all their wastes they generate on a continuous basis' (Wackernagel and Rees 1997b, 7). The area of land is an aggregate of various ecological categories: built-up area, arable land, pasture, forest, and land used to absorb CO_2 emissions caused by burning fossil fuels (Wackernagel et al. 1999, 381).

CO_2, however, the PIR for emissions seems to be monotonically rising.[11] Furthermore, most aggregate pollution indicators are monotonically rising. Hence, EKC studies have observed improvements in well-known problem areas, but they have missed out on more recent concerns (Ekins 1997, 816).

Many studies obtain N-shaped PIRs. Although some authors have argued that the final upturns are not important (Grossman and Krueger 1991 and 1995) or that they are merely a 'curiosity' (Ansuategi 2000, 41), they are not at all irrelevant (Torras and Boyce 1998, 157). The final upturns mean that in the end income growth is not sustainable. However, in the studies to date there is surprisingly little interest in the final upturn of the N-shaped PIR (Stern 1998, 192).

3.3 Critique of the traditional estimation technique

The traditional estimation technique with which these results have been derived has often been criticized. Estimations with (1) may suffer from the following weak points which we will discuss in turn: a simultaneity bias may impair the results; other functional forms than the polynomial may fit the data better; the use of a time trend may be problematic; the regression may suffer from multicollinearity; income may not have an immediate, but only a lagged effect on pollution; and a homogeneity test may reveal that the slope coefficients are not identical in all countries. Additional objections against the traditional estimation technique will be discussed in section 4.

3.3.1 Simultaneity bias

Not only does income influence pollution, pollution also has an effect on income. Labour productivity is reduced because some pollutants decrease the ability to concentrate and learn and because other pollutants cause work-day losses due to health problems (van Ewijk and van Wijnbergen 1995, 197). Moreover, pollution reduces harvests, forestry yields, and fish catches (McConnell 1997, 392). If pollution has an effect on income, there is a simultaneity bias in the regression and OLS produces biased and inconsistent results (Stern et al. 1996). However, only Hung and Shaw (2000) find simultaneity in two of their four regressions, while no simultaneity is detected by Holtz-Eakin and Selden (1992), Cole et al. (1997), List and Gallet (1999), and List and Gerking (2000). When Hung and Shaw (2000) estimate a simultaneity model, they obtain similar results as with the traditional model. Hence, although pollution surely influences income, this effect is mostly so small that it is not significant when tested for. Thus it appears that the results do not suffer from a simultaneity bias.

[11] Cavlovic et al. (2000) draw a similar conclusion from a meta-analysis of EKC studies. A meta-analysis is a method of statistically summarizing the findings of different studies with conflicting results. However, Cavlovic et al. (2000) do not distinguish between estimations in levels and in logarithms (cf. subsection 3.1) and between estimations with and without a time trend (cf. paragraph 3.3.3).

3.3.2 Other functional forms

While most studies use a quadratic or cubic polynomial to estimate the PIR, some studies try to find better functional forms. Schmalensee et al. (1998) use a spline function which is piecewise linear: they split up the data into ten income groups of equal size and estimate a linear function for each group where these functions are restricted such that the ensuing PIR is continuous. A spline function with only four income groups is estimated by Hilton and Levinson (1998). Both studies derive similar results with the spline function and with the traditional polynomial.

Galeotti and Lanza (1999a) propose using the functional form of the Gamma or Weibull distribution. These two distributions can be monotonically falling or inverted U-shaped, where the inverted U-shape is more or less asymmetric (rising fast and falling slowly). But they cannot be monotonically rising or N-shaped. Thus with this specification, we surely find falling pollution at high income levels. This biases the results in favour of the EKC hypothesis. Although Galeotti and Lanza (1999a, 1) state that Gamma and Weibull are unambiguously better than the traditional technique, their table 7 reveals that this is not always the case, and that the differences are small. Since the Gamma and Weibull distribution favour the EKC hypothesis too heavily, it seems preferable to use the traditional functional form.

It is clear that in reality the PIR of a country is not exactly a cubic function. The polynomial is only an approximation to the actual path. Hence, given that they allow for a very flexible functional form, it is not surprising that Millimet and Stengos (2000), Millimet et al. (2000), and Azomahou and van Phu (2001) find that this yields significantly better results than the traditional polynomial. These authors use nonparametric approaches, in which the value of pollution P_0 for a given income level Y_0 is given by[12]

$$P_0 = \sum_{i=1}^{n} \frac{K[(Y_i - Y_0)/s]}{\sum_{j=1}^{n} K[(Y_j - Y_0)/s]} \; P_i$$

where $K[\cdot]$ is the standard normal density function, s is a smoothing parameter, and n is the sample size. Hence, P_0 is a weighted average of all observed P_i where the weight is smaller when the corresponding income level Y_i is farther away from Y_0. In most cases the results from nonparametric regressions are similar to those from the traditional polynomial, although there are exceptions.[13] While Millimet and Stengos (2000) state that the polynomial tends to overestimate the income level at the turning point, Millimet et al. (2000) derive the opposite result. Hence, the approximation by a polynomial is often sufficiently exact for it to show the general shape of the PIR. Moreover, although the nonparametric approach allows significant improvements, it can also be 'overly computationally burdensome' (Millimet 2000, 5).

[12]This equation is taken from Azomahou and van Phu (2001, 8) and corrected according to Härdle (1990, 25).

[13]The differences in Azomahou and van Phu (2001), however, are probably due to outliers in the data.

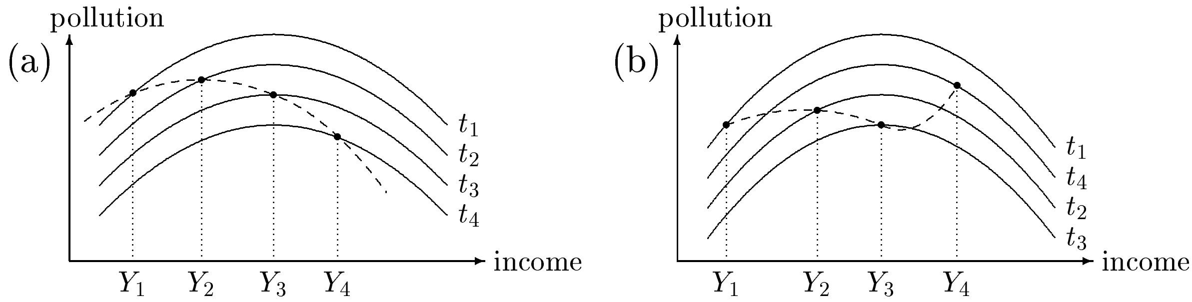

Figure 3: The estimated EKC and the PIR of a growing country over time when the time trend is (a) negative or (b) insignificant. (Source: de Bruyn et al. 1998)

3.3.3 Time trend

The time trend is introduced into the estimation to account for changes in technology and environmental awareness that are not related to income. However, as de Bruyn et al. (1998, 165-167) show, the use of a time trend has important effects. Suppose we estimate (1) including $\beta_5 t$ and the time trend is negative. Then the estimated EKC with a turning point at Y_3 shifts downward over time, as shown in figure 3a. However, a single country growing over time follows the dashed path in figure 3a: the country does not move along the estimated EKC. Hence, the turning point for this country will occur at the smaller income level Y_2. More seriously, if the time trend is insignificant, the EKC may first shift downward and then upward, as in figure 3b. Then the country follows an N-shaped path, although an EKC has been estimated. If the time trend is positive, we may even estimate an EKC although the true PIR is monotonically increasing. Hence, *to conclude that pollution is falling at high income levels, it is crucial that the time trend be significantly negative.* However, as the estimation results reveal, the time trend is not always negative. It can be insignificant or even significantly positive. Thus the use of a time trend calls the EKC results into question, making it advisable to reestimate the PIR without the time trend.

Cole (2000b, 79-85) argues that whenever a time trend is used in the estimation, the average income growth rate and the estimated time trend should be used to calculate the true income turning point (Y_2 in figure 3a). Except for Cole (2000b), however, all researchers using a time trend calculate the turning point while neglecting the time trend, i.e. they derive Y_3 in figure 3a. It turns out that while Y_2 is often similar to the turning point estimate when the time trend is omitted, Y_2 and Y_3 can be significantly different (Cole 2000b, table 5.5). Hence, the turning point estimates of many studies are biased upward if the time trend is negative or biased downward if it is positive.

3.3.4 Multicollinearity

The problem of multicollinearity is completely disregarded by almost all EKC studies and the very few of them that calculate test statistics do not discuss the implications. In my opinion, however, multicollinearity should be a major concern. When the explanatory variables are highly correlated, small changes in the data can have 'dramatic' effects on the results (Green 1997, 420). This gives cause for concern because pollution data are unreliable. Thus - if multicollinearity is present - even slight measurement errors can cause wide swings in the estimated turning point and may even change the estimated shape of the PIR. Furthermore, since GDP, squared GDP, and cubed GDP enter the regression function, there is reason to believe that multicollinearity may actually be present. In fact, Stern (1999, 13) finds evidence for multicollinearity in three of his six estimations, although he only uses a quadratic function. By contrast, in Ansuategi's (2000, 94) regression multicollinearity does not constitute a problem.

Grossman and Krueger (1995) have made the following estimation technique popular:

$$P_{it} = \alpha + \beta_1 Y_{it} + \beta_2 Y_{it}^2 + \beta_3 Y_{it}^3 + \beta_4 \bar{Y}_{it-} + \beta_5 \bar{Y}_{it-}^2 + \beta_6 \bar{Y}_{it-}^3 + \beta_7 X_{it} + \epsilon_{it} \tag{2}$$

where $\bar{Y}_{it-}$ is the average of GDP per capita over the prior three years and the other variables are defined as in (1). Grossman and Krueger (1995, 361) include $\bar{Y}_{it-}$ to capture the effect of permanent income and because past income levels influence current environmental standards. This estimation technique has been subsequently used by several researchers (Grossman et al. 1994, Islam 1997, Barrett and Graddy 2000, and Harbaugh et al. 2000). Since current GDP, Y_{it}, and lagged GDP, $\bar{Y}_{it-}$, are 'highly correlated' (Grossman and Krueger 1995, 361) and since both are used as cubic functions, it seems very probable that multicollinearity is present. This is in fact the case: most β_j, $j = 1, \ldots, 6$, are not significant, but jointly they are highly significant.[14] Furthermore, the turning point for dark matter in Grossman and Krueger (1995) is 6151 PPP$, but merely by dropping one country (Hong Kong) from the sample, Barrett and Graddy (2000) obtain a turning point of 7286 PPP$ - which lies more than two standard deviations away from 6151 PPP$. These are both clear signs of multicollinearity (Green 1997, 420). Hence, the main result of Harbaugh et al. (2000, 2) - namely that the turning points and indeed the shape of the PIR are both 'sensitive to slight variations in the data and to reasonable permutations in the econometric specification' - does not invalidate the EKC hypothesis as they interpret it, but only demonstrates that (2) is impaired by severe multicollinearity problems. Islam (1997) derives the same main result - that the PIR differs widely - but also misses the most plausible explanation: multicollinearity.

Hence, when estimating the PIR, we should not use (2) and we should check whether or not multicollinearity is present. Furthermore, since Stern (1999) finds multicollinearity

[14] See Grossman and Krueger (1995, 373-376), Grossman et al. (1994, tables 2a-7b), Barrett and Graddy (2000, tables 2-7), and Harbaugh et al. (2000, table 3 and appendix tables 1-2). Islam's (1997) tables are not printed out.

in his data although he uses only a quadratic specification, multicollinearity may even explain the large differences in the turning points estimated by different studies.

3.3.5 Lagged effects

Most researchers argue that environmental policy is a major driving force behind the EKC (see part II). When income rises, environmental regulations become stricter. However, this process needs some time. First, the regulations are worked out and debated over in parliament. Then it takes some time before the effects of the new regulations become measurable. For example, firms need time to adjust their technology (Auffhammer et al. 2001b). Furthermore, there are often temporary arrangements before the new regulations come into force. Nevertheless, the EKC is always estimated with current GDP. Only Grossman and Krueger (1995) and those authors using (2) have introduced lagged GDP. Actually, lagged GDP has a higher explanatory power than current GDP (Grossman and Krueger 1995, 366). We may expect the lag to be longer than three years. Hence, Harbaugh et al. (2000) also used the average GDP of the last ten years in their estimations. Since these estimations are all impaired by multicollinearity, it could be interesting to estimate the EKC with a polynomial of lagged GDP only and see whether or not the explanatory power is really higher than with current GDP. However, to my knowledge this has not yet been done.

Another technique to account for lagged effects is to include lagged pollution, P_{it-1}, as an additional regressor in (1). Then an increase in current income has a direct effect on current pollution and, through the lagged pollution regressor, on pollution in the next period and all future periods as well. This technique - used by Agras and Chapman (1999) and by Auffhammer et al. (2001b) - assumes that the largest effect of current income is on current, not future pollution levels. This is not the case, however, when using lagged GDP regressors. Moreover, a regression with a lagged pollution regressor may be impaired by unit roots, as explained in section 4 below.

3.3.6 Homogeneity test

There has been criticism of the fact that PIR estimations assume that all countries follow the same path. While an estimation with fixed or random effects allows for different levels of pollution, it is still assumed that the slope coefficients are identical, i.e that all countries reach the turning point at the same income level (see figure 2). Instead of merely imposing such a strong restriction, we should use a homogeneity test to check whether or not this assumption is justified. If it is not, the estimates of cross country studies are biased and inconsistent (List and Gallet 1999, 411). Several researchers have carried out such a test (Koop and Tole 1999, List and Gallet 1999, and de Bruyn 2000, 105-106). They all derive highly significant evidence that the PIRs do not have the same slope coefficients in different countries. Using different techniques, the same result is also found by Dijkgraaf and Vollebergh (1998), Perman and Stern (1999), Millimet (2000), Millimet et al. (2000), and Auffhammer et al. (2001b). Hence, *every country has its own PIR*. As the results of Dijkgraaf and Vollebergh (1998), Koop and Tole (1999), List and Gallet (1999), Millimet (2000), and Millimet et al. (2000) show, these PIRs do not only have different turning points, they also exhibit different shapes. This explains the vast variation in results that cross country studies come up with: the estimated PIR is different depending on the countries in the sample.

It also follows that developing countries do not have to grow along the path that developed nations have taken. The same result is also derived with a different technique by Roberts and Grimes (1997), Hilton and Levinson (1998), Gallet et al. (1999), and List and Gerking (2000). They show that the cross country PIR changes over time. Hence, a country starting its development later will follow a different PIR.

However, when estimating the PIR of each country separately, we are actually considering a time series model. Hence, new problems arise which we discuss in the next section.

4 Time series analysis

One of the main shortcomings of time series EKC studies is that the time series are short. Environmental data are simply not available over long time periods. The only relative exception is emission data where relatively long time series exist because emissions are estimated from fuel-use data gathered before environmental data collection started. The absence of long time series is the main reason why most EKC studies use cross country analysis. However, as the homogeneity tests revealed, different countries have different PIRs, so pooling is not possible.

The possible presence of unit roots, however, makes the statistical analysis more complicated. A time series x is not stationary if it contains a unit root, i.e. if $\alpha = 1$ in

$$x_t = \alpha x_{t-1} + \epsilon_t$$

where ϵ is the error term. When x is not stationary, shocks (represented by ϵ) have permanent effects and do not evaporate over time (Green 1997, 847). Including a non-stationary variable in a regression implies that standard t-tests are invalid. It can then lead us to conclude that there is a significant relationship although in fact there is none. ‘Pretesting variables for unit roots is therefore a necessary routine to prevent the occurrence of spurious results’ (de Bruyn 2000, 107). In fact, de Bruyn (2000) finds that GDP and emissions of SO_2, NO_x, and CO_2 in 4 OECD countries all contain unit roots, except for SO_2 in the United States. Liski and Toppinen (2001) obtain unit roots for CO_2 emissions in 10 of 17 OECD countries. Moreover, Perman and Stern (1999) find that SO_2 emissions and GDP have a unit root in almost all of 74 countries. Using more sophisticated panel unit root tests, Perman and Stern (1999) come to the same conclusion, whereas Heil and Selden (2001) do not find unit roots in CO_2 emissions and GDP. So the evidence is ambiguous,[15] and more research is needed to determine whether or not unit roots are present. Without unit roots, estimation results from (1) - for each country separately - are valid. But if there are unit roots, the results may be spurious.

If all variables contain unit roots, there are two possible ways out of this problem. First, there may be cointegration: pollution and income may move together so that shocks only cause deviations from a long-run equilibrium and have no permanent effects. This long-run equilibrium can be estimated with (1). If there is cointegration, the residuals of (1) are stationary. Testing the residuals of (1) for unit roots, de Bruyn (2000, 115) finds that only CO_2 in the Netherlands and in West Germany is cointegrated with income, but the PIR is monotonically rising. For the ten other estimations, however, there is no cointegration. Then shocks have permanent effects on the PIR. Hence, de Bruyn (2000) finds no evidence for the EKC. Perman and Stern (1999, 34) find evidence for cointegration between SO_2 emissions and income in only 7-39 of 74 cases (for different estimation methods). However, individual country cointegration tests suffer from 'very low power' due to the moderate length of the time series (Perman and Stern 1999, 17). Hence, the probability is high that cointegration is rejected although it is in fact present. Several different panel cointegration tests give mixed results, but Perman and Stern (1999, 23) conclude that there is weak evidence for cointegration in the panel as a whole. They also obtain that each country has its own cointegration vector, i.e. its own PIR. This implies that the traditional technique may be valid as long as we allow the PIR to differ between countries. However, if there is no cointegration, results estimated with the traditional technique are spurious. More research is needed to find out whether or not there is cointegration.

When both variables contain unit roots the second possibility is to estimate the PIR in growth rates that are stationary. De Bruyn (2000, 111) estimates

$$\Delta P_{it} = \alpha + \beta \Delta Y_{it} + \epsilon_{it} \tag{3}$$

where $\Delta x_{it} = lnx_{it} - lnx_{it-1}$. He has removed the quadratic term ΔY_{it}^2 because it is almost perfectly collinear with ΔY_{it}. The results of de Bruyn (2000, 112) show that economic growth increases emissions of SO_2, NO_x, and CO_2 as β is significantly positive in most cases. So growth is bad for the environment. Without growth, however, pollution would decline, as α is negative. Asking why pollution declines, de Bruyn (2000, 122-133) reestimates (3) with an additional regressor $\beta_2 \ln Y_{t-1}$. He finds that β_2 is always negative and mostly significant. Therefore economic growth directly increases pollution, but it also increases income and thus decreases pollution in all subsequent periods. But only after 53-381 years are the initial costs of economic growth compensated for by long-term benefits (de Bruyn 2000, 128). Hence, reductions in pollution occur not because of growth, but in

[15] There is a 'considerable debate' in the macroeconomic literature whether or not GDP contains a unit root (see de Bruyn 2000, 109-110 and the citations therein).

spite of growth. If there is cointegration, however, (3) gives only the short-run dynamics, whereas (1) gives the long-run relationship (Green 1997, 852).

5 Emission forecasts

Some studies predict the future path of global emissions. First, population and GDP forecasts are taken from the existing literature or estimated. These are then used to predict emissions in each country based on EKC results derived with the traditional technique. Subsequently, emissions are aggregated to world emission levels. All studies conclude that world emissions of SO_2, SPM, NO_x, CO, and CO_2 are rising fast up to the endpoint of the forecast which is 2020, 2025, 2050, or 2100 (see Holtz-Eakin and Selden 1992, Selden and Song 1994, Stern et al. 1996, Schmalensee et al. 1998, Cole 1999, Galeotti and Lanza 1999b, Auffhammer et al. 2001b (only for China), and Heil and Selden 2001). One of the main driving forces behind this result is that the income distribution is skewed towards zero (Selden and Song 1994, 156): most people's income is below the world mean income level. If we considered only world mean income, SO_2 emissions per capita would decline from 55 to 38 kg between 1990 and 2025, and total emissions would increase by ten percent due to population growth. If we take the actual skewed income distribution into account, however, emissions per capita double (from 73 to 142 kg), while total emissions triple (Stern et al. 1996, 1157). Hence, emissions rise sharply although Stern et al. (1996) use Panayotou's (1995) SO_2 result with a turning point at 2900 $ - the third lowest turning point of all studies (see table 1). An additional factor causing emissions to grow is the assumption that income and population are growing faster in poor countries than in rich ones. So CO_2 emissions rise with an average growth rate of 1.8% up to 2100 (Holtz-Eakin and Selden 1992) and thus triple or even quadruple up to 2100 (Heil and Selden 2001). CO_2 emissions also grow fast because the EKC rises steeply but falls slowly (Galeotti and Lanza 1999b).

However, such forecasts are not unproblematic. If there are unit roots without cointegration, shocks have permanent effects and forecasts are not feasible (Labson and Crompton 1993). Technological breakthroughs or new regulations may radically change the PIR we have observed in the data of the past. In fact, there is evidence that the PIR changes over time (Roberts and Grimes 1997, Hilton and Levinson 1998, Gallet et al. 1999, and List and Gerking 2000). Furthermore, we have established that every country has its own PIR. Hence, forecasts based on cross country evidence are 'unwise' (Stern and Common 2001, 175). These shortcomings show that emission forecasts should not be taken too literally. But the predictions still serve as a warning against over-optimistic conclusions. Even if there is an EKC with a low turning point (for example 2900 $), emissions are likely to increase for many years to come. Hence, if we really want to reduce emissions, drastic measures must be taken going far beyond what has been done so far to combat pollution. The only alternative is to hope for a technological revolution (Holtz-Eakin and Selden 1992).

6 Summary of the empirical evidence

Reviewing the empirical evidence for the EKC we find that the EKC is only observed for flow and local pollutants, but not for stock and global pollutants. Although the EKC is not found for all pollutants, the EKC has been interpreted to mean that pollution is only a temporary problem in the course of economic growth. However, even for the pollutants for which an EKC has been observed this is a 'dangerous' conclusion because the forecasts show that 'temporary may entail a time scale of 100 years or more' and because 'certain types of environmental damage are irreversible' (Hill and Magnani 2000, 17). Irreversible damage will be analysed in section 15 below. Moreover, sometimes an N-shape is obtained. The final upturn means that in the end income growth is not sustainable. Nevertheless, most researchers do not attach any significance to this finding.

Furthermore, the EKC has been estimated for a few pollutants only. For many other types of pollution data are not available. Data tend to be collected for human-health-related indicators only. Besides, most aggregate measures of pollution show a monotonically rising PIR. Therefore growth does not improve overall environmental quality and the conclusion that growth is necessary (Asafu-Adjaye 1998, 69) - or even sufficient (Azomahou and van Phu 2001, 3) - to ensure a drop in pollution is not tenable. Indeed, in the opinion of Ayres (1995, 97) it is 'false and pernicious nonsense'.

The empirical results show that the turning points and even the shape of the EKC vary widely between studies. This has led several researchers to relatively pessimistic conclusions concerning the EKC hypothesis: 'Empirical evidence is weak' (Stern 1998, 174); 'Unequivocal evidence for an EKC relationship is very scant' (Ekins 1997, 805); 'The EKC is only an empirical regularity that at best has proved to be a rule with too many exceptions' (Ansuategi 2000, 24); 'Whether economic growth will be beneficial or harmful to the environment in the long run remains a matter of belief' (Neumayer 1998, 172); 'The EKC hypothesis can be deemed invalid' (Ekins 1997, 813).

However, the vast variety of results can most probably be explained by weak points in the econometric analysis of the PIR, meaning that the above conclusions are based on uncertain foundations. First, including a time trend in the regression, but then neglecting that time trend when calculating the turning point can bias the turning point estimate. Second, if there is multicollinearity, slight variations in the data can have dramatic effects on the results. Since the data sources are unreliable and the regressors are correlated, multicollinearity may account for the wide variation in results. Third, homogeneity tests reveal that different countries follow different PIRs. Hence, depending on the countries included in a cross country analysis, the turning point of the EKC or even the shape of the PIR will differ.

We therefore need to conduct a time series analysis for each country separately. In the absence of unit roots this is unproblematic. However, some - though not all - researchers find that pollution and GDP both contain unit roots. If so, shocks have permanent effects on the PIR and previous results are spurious, unless pollution and income are cointegrated. Whether or not pollution and income are cointegrated is still open to debate, although there is some weak evidence that they are. In this case, the country specific results are valid. There is also some evidence that economic growth is bad for the environment unless these effects are corrected by other means.

The main finding is therefore that the EKC is a real-world phenomenon, but only for a few pollutants and not in all countries alike. Two natural questions arise. Why is pollution rising at low income levels, but falling at higher ones? And why is there an EKC for some pollutants, but not for others? The reduced form models analysed so far are not able to give an answer. We address these questions in the rest of this article.

Part II: Possible Causes of the Environmental Kuznets Curve: The Theoretical Literature

In part II of this article, we review the literature for possible causes of the inverted U-shaped PIR. We discuss several theoretical models and arguments that predict an EKC. Furthermore, we consider the empirical relevance of these causes. One of the main questions we have to address is whether the EKC occurs automatically in the course of economic growth or whether environmental policy plays a crucial role in causing the downturn of the EKC. The survey also gives some clues as to why there is an EKC for some pollutants, but not for others.

Theoretical models make many simplifying assumptions about the ecosystem. One of the main assumptions is that different types of pollution can be considered separately. In reality, however, there are many interconnections between them (Beltratti 1996, 2 and Moslener and Requate 2001). Nevertheless, this assumption is often necessary in order to make the models tractable. Moreover, in many models dealing with economic growth and the environment the EKC is excluded by assumption: it is assumed that the economy follows a balanced growth path on which pollution stays constant (see, for instance, Bovenberg and Smulders 1995 and 1996, Smulders 1995a and 1995b, van Ewijk and van Wijnbergen 1995, and Smulders and Gradus 1996). We will not discuss these models because they are not related to the EKC and because, as we have seen, the evidence rejects the assumption of balanced growth.

All other things being equal, economic growth is bad for the environment. This is due to the first law of thermodynamics, which states that no material can be destroyed. Hence, when economic activities increase, more material is 'transformed into other goods (bound to become waste some time), into waste, and pollution' (Neumayer 1998, 162). This so-called *scale effect* explains why pollution increases with income at low income levels. In the rest of this article we will discuss several counteracting forces that may cause pollution to decline at higher income levels.

7 Demand for environmental quality

A first possible cause of the downturn of the EKC is that demand for environmental quality increases with income, i.e. that environmental quality is a normal good. There are several reasons in favour of this argument. First, only when basic needs have been met will additional resources be devoted to combating pollution. Rising income makes these resources available. Second, with rising income, immaterial goods such as environmental quality become more important (Eglin 1995 and Vogel 1999, 32). Third, average education increases with rising income. Thus environmental awareness (Selden and Song 1994), the fear of environmental health hazards, and the concern for the reduced life expectancy grow accordingly (Gruhl 1992, 119). Finally, the opportunity costs of lost work-days due to health problems increase with income because wages rise (Shafik 1994). Lieb (2002) shows that, in a simple model with pollution generated by consumption, it is even necessary for the downturn of the EKC that environmental quality is a normal good. This means - so Lieb (2002) argues - that there is a tendency to satiation in consumption.

It is often argued that environmental quality is a luxury good, i.e. that the income elasticity of demand for environmental quality is greater than one (Ansuategi et al. 1998, Neumayer 1998, Vogel 1999, 76, Cole 2000b, 27, and de Bruyn 2000, 89). However, the empirical evidence shows that the income elasticity, though positive, is smaller than one, i.e., that environmental quality is a normal, not a luxury good (Kriström and Riera 1996). Furthermore, as mentioned before, Lieb (2002) shows in a theoretical model that what really matters is not that environmental quality is a luxury good, but that it is a normal good: when income grows by one percent environmental quality must increase (or pollution must decline) for the downturn of the EKC - but not necessarily by more than one percent. Hence, the luxury good argument is not tenable.

Since abatement is a public good, the government must ensure that the increased demand for environmental quality can be met. With rising income, people increase their support for environmental policies in elections and referenda. They may also join an environmental lobbying group to put the government under pressure - an effective way of bringing down pollution (Hettige et al. 1996, 1898). Relatively advanced political institutions are necessary to internalize externalities and to enforce regulations and thus to cause the downturn of the EKC. However, advanced social, legal, and fiscal institutions may only be feasible in rich democratic countries (Baldwin, 1995, 61, de Bruyn 1997, 487, and Andreoni and Levinson 2001, 270). There is evidence that higher GDP makes policy-decisions more environmentally friendly (Congleton 1992, Ringquist 1993, and de Bruyn 1997), that democratic countries have lower pollution levels (Torras and Boyce 1998, Harbaugh et al. 2000, and Carlsson and Lundström 2001), and that democracies are more likely to sign international environmental agreements (Congleton 1992 and Fredriksson and Gaston 2000). Further evidence shows that political and civil freedoms only significantly decrease concentrations of those pollutants that have direct health effects

(Barrett and Graddy 2000, 455). Public pressure tends to be at its highest in connection with those pollutants.

Hence, increasing demand for environmental quality and the ensuing policy measures may actually cause the EKC - at least for pollutants involving major health hazards.

7.1 Internalization of external effects

Internalization of external effects as discussed above can also cause an N-shaped PIR. Based on a simplistic model Pezzey (1989, 25-29) predicts that, first, pollution is externalized such that pollution grows due to the scale effect. As pollution and income grow, however, the policy maker starts to internalize external effects. As internalization proceeds, pollution declines. When internalization is complete, pollution starts to increase again because of the scale effect.

In the rest of this subsection we discuss several interrelated models of the EKC. In all these models the EKC emerges because there is no abatement at low income levels, whereas at higher income levels abatement expenditures become positive because demand for environmental quality increases with income. Since abatement is a public good, policy is again of prime importance. Often, these models predict an inverted V-shaped PIR, rather than an inverted U-shaped PIR, because pollution suddenly starts to decline when abatement expenditures become positive. All these models assume that a utility function U is maximized depending on consumption C and pollution P, $U(C, P)$, where $U_C > 0$ and $U_P < 0$.

Selden and Song (1995) develop a dynamic model in which pollution is generated by production capital, whereas in Lieb's (2002) static model pollution is generated by consumption. In both models pollution can be abated and all external effects are internalized by the government. The models of McConnell (1997) and of Stokey (1998) are both special cases of Lieb's (2002) model. While Selden and Song (1995) and Lieb (2002) only consider flow pollutants, Stokey (1998) extends her model to stock pollutants and also analyses two dynamic extensions of her static model. She shows that the main result from the static model - that there is an EKC if there is asymptotic satiation in consumption, but that pollution is monotonically rising if there is no satiation (this interpretation stems from Lieb 2002) - also holds in these three extensions.

The main driving force behind the EKC in these models is a tendency to satiation in consumption, which causes demand for environmental quality to increase with income. Since it is assumed that all external effects are internalized, it follows that regulations tighten. Note that if pollution is high or if abatement is cheap, abatement expenditures become positive at a lower income level in these models.

In an overlapping generations model with a stock pollutant, John and Pecchenino (1994) derive similar results. In their model too, there is no abatement at low income levels because the country is poor and enjoys high environmental quality, i.e. a low pollution

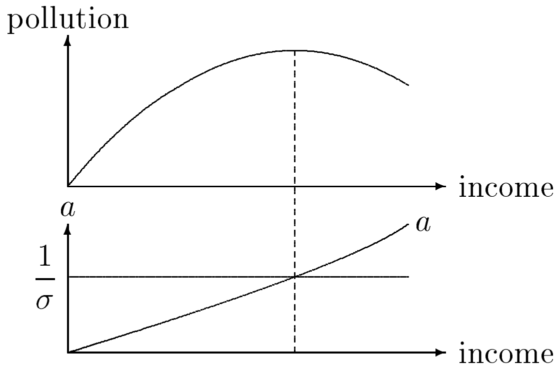

Figure 4: The EKC in the model of López (1994).

stock. At higher income levels abatement causes the downturn of the EKC.[16]

If there is no internalization, pollution rises monotonically with income in the static model of López (1994, 165-173). However, if the government adjusts the price of the environment as a factor of production, we find that the PIR is rising (falling) if $1/\sigma > (<)$ $a := -U_{CC}C/U_C$, where σ is the constant elasticity of substitution in production between conventional inputs (labour and capital) and pollution and where a is the elasticity of marginal utility of consumption, also called the coefficient of relative risk aversion (Mas-Colell et al. 1995, 195). Hence, the higher σ and a, the higher the probability that pollution declines with income. The intuition behind this result is as follows. Income growth increases the value of the environment to the consumers. Thus the government raises the price of pollution as an input in production. If the marginal utility of consumption falls fast (high a), a large price increase is necessary because demand for environmental quality rises fast. Furthermore, if substitution between conventional inputs in production and pollution is high (high σ), a given price increase will induce a major reduction of the polluting input because there are many possibilities to substitute away from the polluting input. Finally, López (1994) shows that under plausible conditions a increases with income, while σ is assumed to be constant as shown in figure 4. Since $a = 0$ for zero income, the PIR rises at first, but when a crosses the threshold level $1/\sigma$, pollution starts to decline: an inverted U-shaped EKC ensues. Hence, the EKC is again caused by the rising demand for environmental quality and the assumption that all externalities are internalized.

The models analysed so far consider only the influence of economic growth on environmental degradation, but they neglect the fact that pollution also affects growth. This may be because 'the effect of economic growth on environmental quality outweighs, both

[16] We should also make reference to the model of Jones and Manuelli (1995). However, their overlapping generations model with a flow pollutant gives unrealistic predictions. For myopic governments - a more realistic assumption than far-sighted ones (Jones and Manuelli 1995, 6) - they predict an N-shaped pollution path over time, but pollution is falling because consumption declines, which is not reasonable. Furthermore, they do not show how income behaves along this path. Actually, over time pollution and income suddenly drop at the trough of the N-shape. Moreover, the tax revenues are wasted, which is again unrealistic.

in magnitude and importance, the reversed effect' (de Bruyn 2000, 6). Remember also that we could not detect a simultaneity bias in the regression results. Nevertheless, these reversed effects do exist (cf. paragraph 3.3.1). Accordingly, McConnell (1997, 392-393) and López (1994, 173-179) extend their models assuming that higher pollution reduces output. They find that in this case an EKC - caused by zero and positive abatement expenditures and the internalization of external effects - is possible even if consumers do not suffer from pollution ($U_P = 0$), because lower pollution allows for increased output.

Internalization - caused by the rising demand for environmental quality - is central in all these models. Thus they help to explain why there is an EKC for air pollutants such as SO_2, whose external costs are at least partly internalized, while the PIR is monotonically rising for CO_2 and municipal waste, whose external effects are not yet internalized (Stern, 1998, 176). In fact, many empirical studies (see for example Grossman 1995, Cole et al. 1997, de Bruyn 1997, Lim 1997, Panayotou 1997, Hilton and Levinson 1998, Unruh and Moomaw 1998, Selden et al. 1999, Barrett and Graddy 2000, de Bruyn 2000, Hettige et al. 2000, and Minliang et al. 2001) conclude that environmental policy is of prime importance for the downturn of the EKC. Hence, the models discussed in this subsection may indeed capture an important part of the story behind the EKC. However, Selden and Song (1995) and Jaeger (1999) urge caution in interpreting these models. The similarity between observed EKCs and model predictions does not mean that we are following an optimal path. Actual pollution may well lie above or below the optimal level.

8 Substitution between pollutants

The downturn of the EKC for one pollutant may also occur because it is substituted for by another pollutant. A flow or local pollutant could be replaced by a stock, transboundary, or global pollutant. If the government only regulates some pollutants, the firms will substitute away from the regulated to the unregulated pollutants (Devlin and Grafton 1994). Possibly, the reason why firms substitute one pollutant for another is that they concentrate all their ingenuity and energy on tackling the regulated pollutant, and are thus unaware that they are emitting more of an unregulated pollutant. The internalization of a currently existing externality may also result in emissions of a new, hitherto not emitted chemical substance whose consequences for the environment may not yet be known (de Bruyn 2000, 87). The reason can be technological progress. Alternatively, firms may reduce the input of a certain substance due to internalization. If this substance is a joint product of another firm and if it has formerly been fully used as an input to the first firm, it is now released into the environment (Baumgärtner and Jöst 2000). Furthermore, energy gained from fossil fuels may also be replaced by nuclear power - an energy source with its own problems. This shifts the costs on to future generations. There is evidence that increased nuclear power generation has helped to reduce emissions of SO_2, SPM, and NO_x (Scruggs 1998, 271, Selden et al. 1999, 14 and Viguier 1999).

In an overlapping generations model, Lieb (2001) assumes that the flow pollutant only causes immediate damage, whereas the stock pollutant will only harm the environment in the future. Hence, myopic governments neglecting future damage internalize the external effects of the flow pollutant only, while the stock pollutant remains unregulated. In this model, Lieb (2001) shows that rising stock pollution may even cause the EKC for the flow pollutant: without the stock pollutant, the PIR for the flow pollutant can be monotonically rising. Note also that the result of the model - an EKC for the flow pollutant and a monotonically rising PIR for the stock pollutant - is consistent with the empirical evidence.

Finally, abatement technologies themselves cause some pollution while they are abating other pollutants (Huesemann 2001). This fact has been disregarded by the EKC literature to date,[17] although it is often observed in reality as the following two examples show. First, in the catalytic converter of a car, the exhaust components - CO, NO_x, and hydrocarbons - are all transformed into CO_2 (Holzbaur et al. 1996, 66). Furthermore, the catalytic converter increases fuel use and thus CO_2 emissions (Cole, 2000b, 76) and consists partly of platinum, which accumulates in the soil. Second, end-of-pipe technologies have been the most important determinant in causing the downturn of the EKC for SO_2 (de Bruyn 1997, 493 and Ekins 1997, 822). However, energy is needed to run an end-of-pipe technology. Since most energy is gained by burning fossil fuels, this causes higher CO_2 emissions. More generally, every end-of-pipe technology consumes energy and therefore increases CO_2 emissions (Faber et al. 1996, 272). This may explain why Stern (1998, 183-184) has noticed a shift from SO_2 and NO_x emissions to CO_2 emissions. Hence, substitution between pollutants may well be one of the main driving forces behind the EKC.

9 Technological progress

Technological progress is also important for the pollution path. Note that technological progress is linked to economic growth because with rapid economic growth, 'more modern capital is newly installed or replaces old capital' (Neumayer 1998, 164). However, it is not clear *a priori* whether technological progress reduces or enhances emissions. Since 'research and development (R&D) efforts by the private sector are still oriented more towards the development of conventional factors saving techniques than to environmental saving techniques', growth tends to increase pollution (López 1992, 154).

However, with appropriate policies, technological progress will move in an environmentally friendly direction. Nentwig (1995, 233) and Stern and Common (2001, 175) state that, in the case of SO_2, policy changes have induced significant environmentally friendly technological changes. Policy makers also enforced the use of end-of-pipe technologies

[17] Only Lieb (2001) assumes that abatement of flow pollution can increase stock pollution.

that have been 'most important' in the reduction of heavy metals emissions (de Bruyn 2000, 227). Furthermore, income increases public environmental R&D expenditures (Komen et al. 1997), which in turn reduce pollution (Zaim and Taskin 2000, 33). Hence, policy is of the utmost importance for the direction of technological progress.

When a new cheap abatement technology is invented, this technology is implemented in many different countries at about the same time. Since these countries have different income levels, this may explain why the turning point of the EKC varies widely between countries.

Technological progress may also explain the N-shaped PIR. De Bruyn (2000, 4) argues that 'reductions in environmental pressure are a temporary phenomenon, that will cease once technological opportunities for further reductions have been exhausted or have become too expensive'. The final upturn of the PIR could therefore 'be explained by the difficulty of keeping up efficiency improvements (innovations) with the continuing growth of production' (de Bruyn 2000, 91). Hence, it may be hard to tighten environmental policy any further - especially when compliance costs become high. Furthermore, 'if there exists a thermodynamic lower bound on reductions in materials and energy use per unit of GDP, emissions may rise once these boundaries are approached' (de Bruyn, 2000, 91 and Huesemann 2001).

Smulders and Bretschger (2000) argue that policy-induced technology shifts explain the EKC. In their model, the rising branch of the EKC emerges because a labour-saving, but polluting technology spreads. The fact that the labour-saving technology is a source of pollution only becomes apparent after some time, however, due to growing evidence of damage found by natural scientists. Public concern increases accordingly and this culminates in the imposition of an emission tax. In the model, this causes pollution to drop immediately and to stay constant thereafter. However, at some point in time another technology will be invented, which is again environmentally clean. While firms adopt this technology, pollution will fall and become zero when all firms have adopted it. There are two crucial conditions for the downturn of the EKC. First, the clean technology has to be invented. Second, the tax must be sufficiently high, because otherwise it does not pay to adopt the new technology. If one of these conditions is violated for a certain pollutant, the model will not predict an EKC for this pollutant. Note, however, that the model of Smulders and Bretschger (2000) predicts an inverted U-shaped pollution path over time. It is not shown that income rises along this path. Nevertheless, it seems plausible that slowly accumulating information about damages and their underlying causes will lead to policy measures - but only after damages have become sufficiently obvious: Wackernagel and Rees (1997b, 9) argue that 'technological fixes limp behind the problems that industrialization causes'.

An extension of the model allows for cycles as shown in figure 5 (Smulders and Bretschger 2000). After some time, there may be evidence that a substance emitted by the 'clean' technology also harms the environment. So the first pollutant is merely replaced by ano-

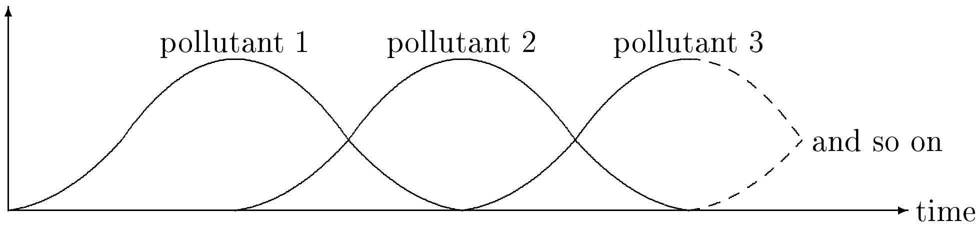

Figure 5: Cycles in the model of Smulders and Bretschger (2000).

ther. Again, public concern mounts until a new emission tax is imposed. This hopefully induces another technology such that the second pollutant also approaches zero. However, this new technology may emit a third pollutant, so that a third cycle of the model begins.

Empirical evidence of such cycles for the consumption of thirty important materials in the US is found by Labys and Waddell (1989). They find that each material follows a life cycle: consumption first rises and then falls again. However, as consumption of a certain material starts to decline, consumption of other materials begins to rise. Furthermore, due to technological progress we use more and more different materials. Therefore, 'newer materials have been replacing older ones' (Labys and Waddell 1989, 239). So progress in technological efficiency does not solve all environmental problems, as is often thought. Instead, it typically leads to higher consumption of natural resources since the gains are reinvested in other polluting activities according to Wackernagel and Rees (1997a, 173 and 1997b, 18-20). This is a case of indirect substitution between pollutants. For instance, despite increased energy efficiency, energy consumption increased in OECD countries between 1975 and 1989 (Wackernagel and Rees 1997b, 18).

Summarizing, we find that technological progress is important for the PIR. When abatement technologies or cleaner production technologies become available, growth is possible without increasing pollution. However, it takes appropriate market conditions set by policy makers to ensure that these technologies will actually be invented and used. There is overwhelming empirical evidence supporting the argument that technological progress is crucial for the EKC. This evidence will be discussed in section 11 below.

10 Increasing returns to scale in abatement

An explanation of the EKC which is also based on technology, though not on technological progress, is offered by Andreoni and Levinson (2001). They argue that increasing returns to scale in abatement can cause the EKC. With increasing returns, a larger economy can abate pollution at lower average costs. Hence, a growing economy is ultimately able to reduce its pollution. Andreoni and Levinson (2001) consider a simple static model. Income Y - which rises exogenously - must be split up between consumption C and abatement expenditures A, $Y = C + A$. Pollution P is generated by consumption and can be abated.

In particular, they assume $P = \alpha C - R(C, A)$, where αC with $\alpha > 0$[18] represents the emissions and R the abated emissions. Finally, utility U is given by $U(C, P)$, where $U_C > 0$ and $U_P < 0$. Andreoni and Levinson (2001) then prove that in this model an EKC results if the abatement technology $R(C, A)$ exhibits increasing returns to scale (some further conditions are also needed). For a simple example they also show that the PIR is linear and monotonically increasing when the abatement technology exhibits constant returns to scale. This result, however, is only valid if abatement is relatively unproductive. If, by contrast, abatement is relatively productive, pollution is always zero.[19]

Andreoni and Levinson (2001) also argue that increasing returns are plausible. If an abatement technology involves fixed costs of installment, it has increasing returns because, once these fixed costs are paid for, additional abatement expenditures can be used to actually reduce pollution. Furthermore, for a richer country it may be profitable to use another abatement technology with higher fixed costs and lower marginal costs. Looking at various data, Andreoni and Levinson (2001) also find some empirical evidence for increasing returns to scale in abatement. The EKC may also arise because although there is no initial abatement, as income grows, more and more industries 'reach the critical size at which the installation costs of abatement equipment can be borne with minimum impact on production costs and profits' (WTO 1999, 50).

Hence, in the model of Andreoni and Levinson (2001) policy does not play any role in causing the downturn of the EKC. The downturn occurs automatically in the course of economic growth due to the increasing returns to scale in abatement. Nevertheless, policy is important. The authors show that without any environmental policy, there is also an EKC, but at inefficiently high levels of pollution. So policy should still internalize

[18] Andreoni and Levinson (2001) assume $\alpha = 1$, although their proof is valid for any $\alpha > 0$.

[19] The example analysed by Andreoni and Levinson (2001) is $P = C - C^\alpha A^\beta$ and $U = C - P = C^\alpha A^\beta$. The standard Cobb-Douglas solution of $\max_{C,A} C^\alpha A^\beta$ subject to $Y = C + A$ is $C = Y\alpha/(\alpha+\beta)$ and $A = Y\beta/(\alpha+\beta)$. So when income grows exogenously, we find

$$\begin{aligned} P &= C - C^\alpha A^\beta = \frac{\alpha}{\alpha+\beta}Y - \left(\frac{\alpha}{\alpha+\beta}\right)^\alpha \left(\frac{\beta}{\alpha+\beta}\right)^\beta Y^{\alpha+\beta} \\ \frac{dP}{dY} &= \frac{\alpha}{\alpha+\beta} - (\alpha+\beta)\left(\frac{\alpha}{\alpha+\beta}\right)^\alpha \left(\frac{\beta}{\alpha+\beta}\right)^\beta Y^{\alpha+\beta-1} \\ \frac{d^2P}{dY^2} &= -(\alpha+\beta-1)(\alpha+\beta)\left(\frac{\alpha}{\alpha+\beta}\right)^\alpha \left(\frac{\beta}{\alpha+\beta}\right)^\beta Y^{\alpha+\beta-2}. \end{aligned}$$

If the abatement technology has increasing returns to scale ($\alpha+\beta > 1$), the PIR is concave ($d^2P/dY^2 < 0$): an EKC emerges. By contrast, if the abatement technology exhibits constant returns to scale ($\alpha+\beta = 1$), the PIR is linear ($d^2P/dY^2 = 0$). Accordingly, if abatement is relatively unproductive, i.e. if $\beta < 0.5$, then the PIR is monotonically rising: for $\alpha+\beta = 1$ the slope of the PIR simplifies to $dP/dY = \alpha - \alpha^\alpha(1-\alpha)^{1-\alpha}$, which is positive if $1 > \alpha^{\alpha-1}(1-\alpha)^{1-\alpha} = [(1-\alpha)/\alpha]^{1-\alpha}$ or if $1 > (1-\alpha)/\alpha$, which reduces to $\alpha > 0.5$ or $\beta < 0.5$. For $\alpha < 0.5$, the PIR is monotonically falling. However, since the PIR starts at the origin, this means that pollution would be negative. Since negative pollution is not feasible, we are at the corner solution of zero pollution for $\alpha \leq 0.5$ and for all Y. This is overlooked by Andreoni and Levinson (2001, 273), who write that the PIR is always rising for $\alpha + \beta = 1$.

all external effects. Moreover, in practice, there may not be any abatement at all without regulations.

Finally, since the abatement technologies for different pollutants are different, the model does not predict an EKC for all pollutants. For instance, 'if the abatement technology exhibits increasing returns to scale at low income levels, but decreasing returns to scale at high income levels, an N-shaped path may also result' (Millimet and Stengos 2000, 3).

11 Structural change

Another explanation of the EKC that has been used to justify growth strategies without environmental policies is structural change (Gangadharan and Valenzuela 2001, 514). People living at the subsistence level produce almost no pollution. However, as the country grows, agriculture intensifies and industry starts to develop causing increasingly greater pollution. By contrast, when the country becomes rich, the service sector expands quickly and pollution may fall again. Hence, the rise and fall of the industry sector could explain the EKC. Furthermore, the structure within the industry sector changes as well. First, 'as income rises, the composition of manufacturing shifts from light to heavy industry', i.e. from relatively clean industries such as food and textiles to polluting industries such as chemicals, minerals, metals, and machinery (Syrquin 1988, 242-243 and Panayotou 1995). At higher income levels, high-tech industries which are far less polluting (Dinda et al. 2000, 410) and research activities expand (Panayotou 1995).

Under plausible conditions, however, de Groot (1999) concludes from his model that while structural change helps to reduce emissions, it is not sufficient to cause the downturn of the EKC. So emissions-saving technological progress is crucial for the downturn. Without technological progress, the EKC only emerges if policy ensures that polluting inputs become increasingly more expensive.

Similarly, in the model of Cassou and Hamilton (2000) structural change - caused by rising pollution taxes - explains the EKC. They assume that there is a clean and a dirty good and that the dirty sector is larger at the outset. Therefore a high tax on the dirty good would reduce consumption considerably because human capital is sector-specific. So the government keeps taxes low and lets the dirty sector grow until the faster growing clean sector becomes sufficiently large. Then the government increases the tax rate faster so that the dirty sector declines again. Thus the dirty sector - and, accordingly, pollution - follows an inverted U-shaped development path. The main reason for the EKC is that the government wants to smooth the consumption path out. So structural change is policy-induced in the model of Cassou and Hamilton (2000). Without the optimal policy, the PIR would be monotonically rising.

To analyse empirically whether or not structural change is important, many researchers have used the estimation equation (1) and have added an additional regressor $\beta_5 M_{it}$ where

M is the manufacturing share in GDP. While some studies find that β_5 is positive (Rock 1996, Panayotou 1997, Borghesi 2000, and Cole 2000a), others conclude that the effect of structural change is only small or even insignificant (Grossman et al. 1994, Grossman 1995, Suri and Chapman 1998, and Auffhammer et al. 2001b). Moreover, Cole (2000a) and Millimet (2000) find that structural change alone cannot explain the EKC. Instead, as predicted by de Groot (1999), policy and technological progress are crucial for the downturn of the EKC.

Further evidence for structural change and for technological progress comes from decomposition analyses. Before we turn to the empirical results, we first discuss the theoretical underpinnings of decomposition analyses. The basic idea in every decomposition analysis is that emissions in period t, E_t, can be written as (de Bruyn 2000, 164)

$$E_t = \sum_{j=1}^{n} Y_t \, S_{j,t} \, I_{j,t} \tag{4}$$

where there are n sectors in the economy, Y is GDP, S_j is the share of sector j in GDP, and I_j is the emission intensity of sector j. Since $S_j = Y_j/Y$ where Y_j is output in sector j and since $I_j = E_j/Y_j$ where E_j are the emissions of sector j, (4) is an identity. Differentiating (4) with respect to time and dividing by E_t yields

$$\hat{E} = \hat{Y} + \sum_{j=1}^{n} e_j \hat{S}_j + \sum_{j=1}^{n} e_j \hat{I}_j \tag{5}$$

where a hat means the percentage change of the variable ($\hat{X} = (dX/dt)/X$) and where $e_j = E_j/E$ is the share of sector j in emissions. The first term on the right hand side of (5) is called the *scale effect*, the second term is the *composition effect*, and the third term is the *technique effect*. As already discussed, income growth leads *ceteris paribus* to higher emissions due to the scale effect. The composition effect shows how structural change influences emissions. The technique effect, finally, describes how changes in emission intensities caused by new technologies affect emissions. Some problems arise because (5) is in continuous time, while actual measurements are only available at discrete points in time. So (5) must be transformed into a discrete equivalent (de Bruyn 2000, 165). We will not discuss the many different discrete approximations that have been put forward (see Ang and Lee 1994, Ang 1994, and de Bruyn 2000, chapter 9).

Decomposition analyses have been applied to emissions of SO_2, CO_2, SPM, NO_x, CO, VOC, and heavy metals, as well as to energy and fuel consumption (see Howarth et al. 1991, Torvanger 1991, Ang and Lee 1994, de Bruyn, 1997, Sun 1998, Selden et al. 1999, Stern 1999, Viguier 1999, and de Bruyn 2000, chapter 11). All studies find that the composition effect is small and may even increase emissions, whereas the technique effect is large and always decreases emissions. Hence, decomposition analyses show that the technique effect is much more important for the downturn of the EKC than the composition effect. So we again find that structural change cannot explain the EKC (Selden et al. 1999). Instead, technological progress is crucial, which is likely to

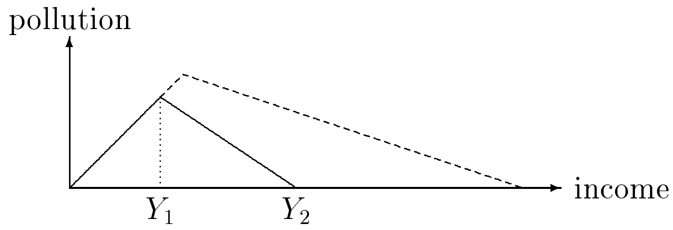

Figure 6: The shift of the cross country EKC when the price of the dirty good increases due to world income growth in the model of Saint-Paul (1995).

be policy-induced as Smulders and Bretschger (2000, 2) argue. However, these studies are mostly for rich countries. In poor countries structural change may be an important driving force behind the rise of pollution.

Finally, the fact is often neglected that structural change can only be responsible for the downturn of the EKC for one reason: the polluting sector must shrink *absolutely* (not only relative to growing GDP). This is only the case if this sector produces inferior goods whose consumption falls with income - which is 'unlikely' - or if the products of this sector are no longer produced but imported (Torras and Boyce 1998, 149). This will be discussed in the next section.

12 Migration of dirty industries

Dirty industries might migrate from rich countries into middle-income countries (where in contrast to poor countries the infrastructure is sufficiently developed). Migration thus leads to low pollution in high-income countries and to high pollution in middle-income counties. So migration could explain EKC findings obtained in cross country studies. This is alarming for developing countries. While middle-income countries may be able to relocate the dirty industries to even poorer countries, these countries have nowhere to go and will face the much more difficult task of abating emissions instead of moving them to other countries.

The consequences of migration for the EKC are analysed by Saint-Paul (1995). He assumes that there is a dirty and a clean good, that pollution is strictly local and tied to the production of the dirty good, and that the only reason for trade is pollution. He finds that poor countries (income smaller than Y_1 in figure 6) only produce the dirty good because its price is higher than the price of the clean good. The richer of two poor countries can produce more and will thus suffer from more pollution. A middle-income country produces both goods. The richer of two middle-income countries produces less of the dirty good because the demand for environmental quality rises with income. Finally, a high-income country (income greater than Y_2 in figure 6) fully specializes in the production of the clean good and imports its consumption of the dirty good. A cross country analysis thus produces an EKC with zero pollution at high income levels. When all countries grow, they would prefer more consumption of the dirty good, but less pollution. Therefore the price of the dirty good (relative to the clean one) rises. Due to this price increase, the falling branch of the EKC shifts upward and to the right (see dashed EKC in figure 6) and the rising branch of the EKC becomes longer so that the turning point moves to higher income and pollution levels. Extending the model of Saint-Paul (1995) it is immediately demonstrable that the poorest country may also be on the falling branch of the EKC. Furthermore, Saint-Paul (1995) shows that the PIR is monotonically rising in a closed economy. Since the world as a whole is closed, income growth must lead to higher world pollution. So at least some of the countries experience rising pollution - although they all are on the falling branch of the EKC! The reason is that the falling branch of the EKC moves upward when world income growth induces a price increase of the dirty good.

Migration can occur in two ways. On the one hand, firms may actually move their production site from developed in developing countries. Examples are industries with high toxic intensities (Birdsall and Wheeler 1992) and the leather tanning industry (Ayres 1997, 423). On the other hand, production sites may grow faster in developing countries than in developed ones. In fact, Low (1992) shows that dirty industries grow faster in developing than in developed countries, and Perrings and Ansuategi (2000, 23) find that 'developing countries account for a steadily increasing proportion of world output in many of the most highly polluting industries'. Similarly, Stern (1998, 185) observes that the poorest US states often host more polluting industries, while the richest states have large service sectors. Hence, the findings of Carson et al. (1997) - an EKC for seven different pollutants across US states (see tables 1, 2, and 5) - can possibly be explained by migration. Moreover, Cole (2000a) obtains that the ratio of dirty to clean manufacturing output rises at low income levels, but falls at higher ones with a turning point at 5300 PPP$.

Further evidence for migration is the fact that the consumption of dirty goods in developed countries rises faster than their production (Rothman 1998). This is possible due to imports from developing countries. The export share of dirty industries is growing in developing countries, but falling in the world as a whole (Low and Yeats, 1992). Furthermore, Suri and Chapman (1998) conclude from their empirical analysis that imports help to cause the downturn of the EKC. Most EKC studies analyse production-based measures of pollution. Rothman (1998) argues that consumption-based measures should be used instead. He analyses the ecological footprint - a consumption-based measure - and finds a monotonically rising PIR (cf. table 5). Hence, the EKC found for production-based measures may paint too optimistic a picture: economic growth may not solve environmental problems but only relocate them. Furthermore, trade itself is polluting. International trade is responsible for one eighth of world oil consumption (Cole 2000b, 28). 'Thus trade contributes substantially to energy-related environmental damage' (Ekins et al. 1994, 7-8).

Finally, it has been argued that migration is beneficial because countries with higher assimilative capacities should host more polluting firms (Dean, 1992, 16, WTO 1999, 50, and Ansuategi 2000, 47). However, this presupposes that all external effects are internalized in all countries. Since this is not the case, it is important to note that 'tropical resources such as forests, fisheries and soils [...] are known to be more fragile and less resilient than temperate resources' (Neumayer, 1998, 170). Hence, the relocation of pollution to developing countries may have serious effects on the environment there.

Since the evidence analysed in the section 11 suggests that structural change alone cannot explain the EKC, the migration of dirty industries is usually not so rapid that pollution levels in developed countries decline considerably. Nevertheless, dirty industries can grow fast in developing countries. Hence, *while the migration of dirty industries may explain the cross country EKC, it cannot explain the EKC of a single, growing developed country over time.* Moreover, the whole cross country EKC is likely to move upward when income grows. This implies that countries do not move along the EKC as estimated in cross country studies. Furthermore, developing countries will actually have to reduce pollution by abating it or by curtailing consumption, while developed countries could relocate the polluting production process without having to lower consumption.

13 Income distribution

It has been argued that income distribution may influence the PIR. Suppose that environmental policy is determined by the median voter[20] and that environmental quality is a normal good (as we argued in section 7). Then a more equal income distribution makes the median voter better off, so environmental regulation tightens and pollution falls. Accordingly, the EKC may be caused by the original Kuznets curve, which states that income inequality - not pollution - follows an inverted U-shaped path when income grows. However, for this to be true, the income of the median voter must actually decline at low income levels although average income rises. Due to deepening inequality this is possible, though hardly very plausible. Vogel (1999, 113) argues the likelihood of development in the industry sector causing both high income inequality and high pollution. Nevertheless, a more equal income distribution may help to cause the downturn of the EKC. Or, to put it differently, 'large distributive imbalances in high-income countries can prevent environmentally friendly policies from being adopted and pollution from declining' (Magnani 2000b, 14).

A similar conclusion is drawn by Torras and Boyce (1998). They state that if income distribution is highly unequal, the poor, who suffer from pollution, do not have much political power, whereas the wealthy, who derive profits from polluting activities, dominate the political process. Hence, a more equal income distribution again leads to stricter environmental policies. By contrast, Gangadharan and Valenzuela (2001, 524) argue that

[20] 'The median voter theorem is widely applied [...] to so-called general interest issues', such as the environment (Eriksson and Persson 2001, 6).

more equal standards of living mean that 'more people are able to afford the use of electricity, cars, and other luxuries - which leads to increased energy use' and thus to higher pollution.

The empirical evidence for income inequality is rather weak. The Gini coefficient often has the expected sign, but is frequently insignificant (Scruggs, 1998, Torras and Boyce 1998, Borghesi 2000, Magnani 2000a, and Gangadharan and Valenzuela 2001). This may be due to the poor quality of the data for the Gini coefficient (Torras and Boyce 1998). Results obtained from using political rights and civil liberties are more supportive to the hypothesis that higher inequality in political power - not in income - aggravates pollution (Torras and Boyce 1998, Barrett and Graddy 2000, Harbaugh et al. 2000, and Carlsson and Lundström 2001).

Summarizing, we conclude that in empirical terms the income distribution has only a minor effect on the PIR. Inequality in political power may be more important than income inequality. An equal distribution of political power may help to cause the downturn of the EKC.

14 Shocks

In section 4 we showed that shocks have permanent effects on the PIR if the income or pollution data contain unit roots and if they are not cointegrated. As we have seen, the empirical evidence is inconclusive. This leaves the possibility open that shocks are at the root of the EKC. Moomaw and Unruh (1997) argue that the oil price shock may have been more important for the turning point of the EKC for CO_2 than income: in 16 OECD countries, the turning point occurred in the 1970s at widely different income levels (8900-15400 PPP$). However, income is still important. The oil price shock only led to declining CO_2 emissions in the wealthy OECD countries. Unruh and Moomaw (1998, 227) state that shocks overcome political and economic inertia and cause changes that often occur within a single year. By contrast, de Bruyn (2000, 124) obtains that changes in energy prices do not have a significant effect on changes in pollution. Moreover, the time dummies in the estimation of Stern and Common (2001, 171) do not point to sudden declines caused by the oil price shock (or other shocks). Hence, if the oil price shock has an effect, it only gradually becomes visible.

De Bruyn (2000, 152) argues that shocks can also cause an N-shaped PIR. In equilibrium, the PIR is monotonically rising due to the scale effect. However, shocks can lead to reductions in pollution. Once the effects of the shock evaporate, the economy reaches a new equilibrium and pollution rises again with income. There is evidence of such behaviour for steel and energy consumption in four OECD countries (de Bruyn 2000, 152-156). Hence, when income grows, institutional and technological breakthroughs are required to keep pollution at reasonably low levels (de Bruyn 2000, 156).

The EKC might also be spurious because there is a structural break. Developing countries might follow a monotonically rising PIR, while the PIR of developed countries might be monotonically falling (Vincent 1997). Halkos and Tsionas (2001) try to estimate such behaviour. However, for CO_2 and deforestation they find that developing and developed countries follow almost the same PIR, i.e., there is no structural break. Furthermore, evidence has appeared for an EKC in a single developing country (China) for waste gas emissions (Auffhammer et al. 2001a and 2001b) and for waste water emissions (Minliang et al. 2001).

Since shocks may explain the EKC (see inconclusive evidence in section 4 and here), it is important to know the nature of these shocks. Shocks may result from price changes (oil price), from policy measures (Unruh and Moomaw 1998, 227), or from technological innovations (de Bruyn 2000, 151). The oil price shock was the result of a policy measure on the part of the OPEC (Organisation of the Petroleum Exporting Countries). Price changes also result from the internalization of external effects. Furthermore, technological innovations can also be influenced by policy measures. Hence, with the possible exception of technological innovations, all shocks are traceable to policy measures. Rising demand for environmental quality and rising scientific knowledge about the environmental consequences of production may lead to sudden changes in policy. Therefore, shocks are not a new explanation of the EKC. However, internalization is no longer considered a continuous process, but a succession of sudden jumps.

15 Irreversibilities

Before concluding this article we must discuss a crucial point which may lead to another cause of the EKC. Falling emissions or concentrations seem to imply that environmental quality improves. The EKC could be taken to signify that environmental quality is equal on the rising and on the falling branch of the EKC at the same level of emissions or concentrations. However, this need not be the case. As mentioned in subsection 3.2, even if emissions per capita fall, total emissions may rise because the population is growing. Furthermore, the most obvious (although extreme) counterexample is irreversible damage. When a certain threshold level of emissions or concentrations is crossed, irreversible damage may occur. Then falling emissions or concentrations do not mean that environmental quality is improving again. In fact, even zero emissions or concentrations are not sufficient to restore the pristine state of the environment (Vogel 1999, 22). So even if an EKC for soil erosion, desertification, extinction of animal and plant species, biodiversity loss, and nuclear waste generation exists, the damage involved is irreversible. For instance, when a piece of land is cleared of trees and then reafforested, we have the same area of forest, but biodiversity is much lower (Nentwig 1995, 550).

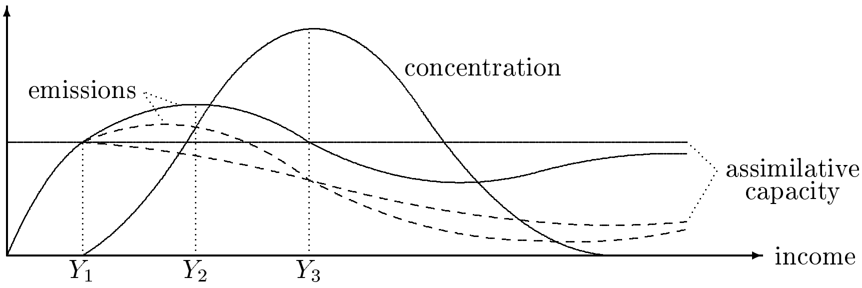

Figure 7: Emissions, the concentration, and the assimilative capacity.

A similar effect can also be found in a less extreme example. Suppose that nature can assimilate a certain amount of emissions. However, when emissions of a steadily growing economy exceed the assimilative capacity, the pollutant starts to accumulate (at income level Y_1 in figure 7). This concentration may, for example, affect human health. Only when emissions fall below the assimilative capacity again, will the concentration begin to decline and hopefully approach zero, as in figure 7 (Sprösser 1988, 77-83). For income levels between Y_2 and Y_3 emissions decline, but the concentration still grows and causes increasingly serious human health problems. The concentration may also reduce the assimilative capacity (see dashed line in figure 7). Then the concentration will only follow the same path if emissions are immediately reduced accordingly (dashed path). Again, if emissions fall below the (declining) assimilative capacity, the concentration will start to decrease, but the assimilative capacity will still decline, i.e., the state of nature deteriorates even further. Hence, we also find that falling concentrations along the EKC path are no guarantee that the state of the environment will improve. In this example, the damage may be reversible: when concentrations are back to zero, the assimilative capacity may recover and return to its original level. However, the costs of reversing the damage are high, since emissions must be reduced drastically if they are to fall below the declining assimilative capacity.

15.1 Tunneling through the environmental Kuznets curve

The argument that derives from this is that policy makers in countries on the rising branch of the EKC should ensure that thresholds are not overstepped and irreversibilities are prevented - or, as Munasinghe (1995 and 1999) and Panayotou (1997) have put it, governments should ‘tunnel through the EKC’ (see figure 8). Via appropriate policy measures - such as the removal of energy subsidies, the introduction of more secure property rights over natural resources, and the internalization of externalities (Panayotou 1997, 469) - the EKC will become flatter and the turning point of the EKC will be located at a smaller pollution level. Hence, as set out in subsection 3.2, the pollution level at the turning point of the EKC is more important than the income level because the pollution level determines whether or not (irreversible) damage will occur (Agras and Chapman 1999, Borghesi 1999, and Perrings and Ansuategi 2000). Since we have established that

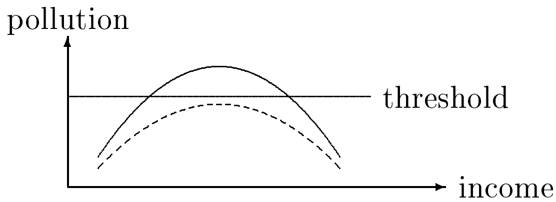

Figure 8: Tunneling through the EKC.

each country follows its own EKC (see paragraph 3.3.6), developing countries may be able to follow a flatter EKC than developed countries (although the migration of dirty industries could make this a difficult task).

Tunneling through the EKC may imply that economic growth will slow down (Munasinghe 1999). Nevertheless, this may still be the wiser development strategy because otherwise money will have to be spent at higher income levels 'on extremely costly, time-consuming, and often ineffectual assessment, cleanup, and restoration activities' (Schindler, 1996, 18). The problem, however, is that the thresholds are not known (Neumayer 1998, 170). Furthermore, the interrelation between different pollutants are frequently unknown, so that their joint effect on the environment remains unfathomable. This often leads to an 'underestimation of their true harmfulness' (Vogel 1999, 182).

Nevertheless, the fear of crossing a threshold - even if it is not precisely known - may increase the demand for environmental quality and thus cause the EKC. It might be thought that this fear can only explain why pollution stops increasing, but not why it turns down. However, to prevent concentrations from increasing, emissions may possibly have to fall. This implies an EKC for emissions (cf. figure 7). If the concentration causes damage, it may also be necessary to decrease the concentration in order to prevent further damage. Taking greenhouse gases as an example, the fear of large anthropogenic climate changes has led to the Kyoto protocol. Thus the world is about at the income level Y_2 in figure 7, where emissions start declining but the concentration continues to rise.

15.2 The location of the turning point

Three results on the location of the turning point of the EKC may be important to determine whether the turning point lies below or above a threshold level, i.e., whether or not we can succeed in tunneling through the EKC. López and Mitra (2000) develop a model to show that in a more corrupt country the turning point occurs at a higher pollution and income level. With corruption, pollution is always higher than in the social optimum because polluting firms give lobby payments to the government, and the government repays this with lax environmental policies. The more corrupt the government, the higher the pollution. Thus to tunnel through the EKC it may be crucial to combat corruption. However, it is unlikely that growth will reduce corruption rapidly because 'institutions and cultural norms typically show extraordinary resilience' (López and Mitra 2000, 149).

Hence, fast-growing developing countries with high corruption levels - such as China, India, and Indonesia - tend to reach higher pollution levels than the ones suggested by EKC estimates obtained from relatively corruption-free developed countries (López and Mitra 2000, 149-150).

A second result deals with transboundary pollutants. Based on an extension of Selden and Song's (1995) model, and assuming non-cooperative behaviour of several identical countries, Ansuategi and Perrings (2000) find that both the level of income and pollution at the turning point of the EKC are higher when the pollutant is more transboundary, i.e., when more emissions are transported to other countries. The reason is that the incentives to abate a transboundary pollutant are smaller because part of the benefits of abatement accrue to foreign countries. If a high percentage of emissions can be externalized to other countries, the PIR is actually monotonically rising. Ansuategi (2000, chapter 5) finds some evidence to back up this theory, but he does not analyse whether or not the relatively small (4700-6600 $, cf. table 1) differences in turning point estimates are significant.

A third result considers intergenerational externalities. Due to selfish, myopic behaviour, the turning point of the EKC will also lie at higher pollution and income levels when a greater part of the damage can be externalized to future generations (Ansuategi 2000, chapter 4). Although intuitive, this result - based on an extension of the overlapping generations model by John and Pecchenino (1994) - rests on many restrictive assumptions.

The last two theoretical results - namely that the turning point lies at higher pollution and income levels when the damage can be externalized to other countries or future generations - underpin and explain empirical findings. They show that international cooperation and far-sighted behaviour are crucial in tunneling through the EKC of transboundary and long-lived pollutants - or in ensuring that the PIR of these pollutants is not monotonically rising in the first place. However, the Helsinki Protocol of 1985 and the Sofia Protocol of 1988, which deal with the emissions of two transboundary pollutants - sulphur and NO_x - in Europe, do not seem to have been very effective in fostering cooperation. When the protocols were signed, many of the signatory countries had already reached their reduction targets or were just about to reach them (Murdoch et al. 1997). Hence, these protocols only made the reductions binding that the countries had already reached on their own given that in Europe 'the majority of nations receive over 50% of their own sulphur emissions as depositions' (Ansuategi 2000, 20).

By contrast, some progress has been made with the Kyoto Protocol on greenhouse gases. However, most studies find a monotonically rising PIR for CO_2 emissions (see table 2). This is probably because while the latest data used in empirical studies are those of 1996, most researchers use older data. Hence, the reductions to take place by 2010 are not yet visible in the EKC studies to date.

Therefore it could be argued - and we will come back to this argument below - that *an EKC only emerges for pollutants for which policy measures have been taken, whereas* *for other pollutants the PIR is monotonically rising when the regulator remains inactive.* Hence, regulation is 'a necessary condition for a downward sloping' PIR (Kelly 2000, 11). Another good example is chlorofluorocarbons (CFCs). The cross country PIR for CFCs was monotonically rising in 1986 before the signing of the Montreal Protocol in 1987, but in 1990 it is an EKC (Cole et al. 1997). After 2006, the cross country PIR for CFCs should be horizontal at zero emissions, as CFC emissions will be banned after 2006 in both developed and developing countries (Houghton 1997, 39). The Montreal Protocol allows developing countries to tunnel through their EKC for CFCs (Cole 2000b, 114). This leads Cole et al. (1997, 412) to conclude that 'without [multilateral action] global air pollutants will increase monotonically with income'.

For local pollutants this argument may explain why different countries follow different PIRs (as established in paragraph 3.3.6). Each country has its own environmental policy. The argument is also in line with the finding that local and flow pollutants follow an EKC, whereas global and stock pollutants exhibit a monotonically rising PIR. Flow and local pollutants are more easily internalized than stock and global pollutants (Cole 2000b, 24 and 66) because the benefits of abatement are immediately discernible and accrue fully to the local population.

The government will only tackle a certain pollutant if this pollutant has received considerable public attention. Otherwise, regulations would not be politically feasible (in a democracy). Hence, *without public concern, no measures are taken* either by the government or by private actors *to reduce pollution* and there are no incentives to invent cleaner technologies. So pollution will increase with income. Public concern, in turn, can only arise when natural scientists are able to track down the source of a given damage, i.e., when a substance is revealed to be a pollutant.

In this section we have shown that the falling branch of the EKC is not necessarily equivalent to a rise in environmental quality, especially if there is irreversible damage. Thus the fear of overstepping a threshold is another possible reason for a policy-induced downturn of the EKC. This has led to the view that policy makers should tunnel through the EKC.

16 Summary of possible causes of the EKC

In the second part of this article we have reviewed the many possible causes of the EKC from a theoretical point of view and we have assessed their validity by looking at some further empirical results. Before summarizing the causes of the EKC, note that we have also found five different explanations for the N-shaped PIR. The final upturn may occur because the PIR is upward sloping once internalization is complete, because abatement opportunities are exhausted, because there is a thermodynamic lower bound on material and energy use per unit of GDP, because at higher income levels the abatement technology exhibits no longer increasing, but decreasing returns to scale, or because the downturn is caused by a shock and the rising path is an equilibrium relationship.

Economic growth leads to more output and thus *ceteris paribus* to higher pollution. This scale effect can, however, be counteracted by several forces. There is empirical evidence that demand for environmental quality increases with income. One of the reasons why this demand may rise is fear of incurring irreversible damage. Provided that relatively advanced political institutions exist, higher demand for environmental quality causes increasingly stricter environmental regulations. This is actually the conclusion from several theoretical models that assume perfect internalization of external effects. In a less perfect world, internalization makes progress in the course of economic growth. Hence, the EKC is explained by zero and positive abatement expenditures. The evidence suggests that income distribution is not crucial to the strictness of policy measures. Inequalities in political power seem to be more important than income inequalities. A more equal distribution of political power may help to cause the downturn of the EKC. The internalization of external effects may be a continuous process or it may occur in sudden jumps (shocks).

Internalization can cause technological progress to move in an environmentally friendly direction. For example, the policy-induced introduction of end-of-pipe technologies has been important for the reductions in several air pollutants. This is corroborated by decomposition analyses, which show that changing technologies have been crucial for the downturn of the EKC. However, when appropriate policies are absent, technological progress may well be pollution-enhancing. Smulders and Bretschger (2000) propose that pollution increases after introduction of a new technology, that after pollution has raised public concern a tax is imposed, and that this tax induces the invention of a clean technology that allows the downturn of the EKC. However, it may later transpire that a substance emitted by the 'clean' technology is also polluting. This opens up the possibility of cycles. These cycles imply that one pollutant is substituted for by another. A regulated flow or local pollutant could be replaced by a stock or global pollutant which is not subject to regulation. In fact, end-of-pipe technologies have precisely this effect. Nuclear power has also replaced energy gained from fossil fuels.

It has been argued that structural change - the rise and fall of heavy industry - is 'the most common explanation' of the EKC (Millimet, 2000, 1). However, the evidence is weak. Structural change can explain the rising branch of the EKC in poor countries, but to cause the downturn the absolute production level of an industry must shrink. This is only plausible when dirty industries migrate from developed into developing countries. The evidence suggests that structural change alone cannot explain the EKC. Therefore the migration of dirty industries is usually not so rapid that the absolute level of production of these industries will decline considerably in developed countries. Nevertheless, dirty industries can grow fast in developing countries. Hence, while the migration of dirty industries may explain the cross country EKC, it cannot explain the EKC of a single, growing developed country over time. Migration causes serious problems as soon as the developing countries attempt to lower pollution because they cannot relocate pollution but must actually reduce it. It has also been shown that the cross country EKC shifts upward with economic growth when the EKC is based on migration. Therefore a country on the falling branch of the cross country EKC may well see its pollution rise in the course of economic growth due to this upward shift of the EKC.

Finally, increasing returns to scale in abatement can allow rich countries to abate at lower average costs than poor countries. This may bring about the EKC.

Hence, we have found four empirically validated explanations for the EKC of a growing country over time: increasing demand for environmental quality, technological progress, substitution between pollutants, and increasing returns to scale in abatement. All these causes could be part of the explanation. A certain cause may be important for one pollutant, but not for another. Several causes may also work together. For instance, growing demand for environmental quality may lead to tighter policies, which in turn induce producers to (invent and) use other technologies. These technologies may emit other unregulated pollutants.

Satisfying the increasing demand for environmental quality requires policy measures, technological progress is only environmentally friendly if appropriate incentives are provided by policy makers, and substitution is caused by regulations or by technological progress. Increasing returns to scale in abatement are the only explanation of the EKC that does not directly rely on policy. However, without internalization, the EKC lies at inefficiently high levels of pollution. Moreover, without policy measures, there may not be any abatement at all. So policy is also crucial here. Hence, we conclude that environmental policy is of the utmost importance for the downturn of the EKC: *for a given pollutant, an EKC will only exist when policy measures are taken, but the PIR will be monotonically rising if the government remains inactive.* Therefore fighting corruption is a potentially important factor, since corruption may postpone the implementation of environmental policies. Moreover, since every country has its own environmental policy, this explains why each country has its own PIR.

Nevertheless, 'there appears to be an increasing reliance on the EKC to address environmental degradation' (Li 1999, 147). 'Economic growth is still generally seen as the dominant policy objective' although the resilience of the natural system may be threatened (Common 1995, 101). However, as we have shown, the idea that economic growth is good for the environment is not tenable. Ayres (1995, 97) even goes so far as to say that this idea is 'false and pernicious nonsense'. In fact, the key role is played by environmental policy because 'the strongest link between income and pollution in fact is via the induced policy response' (Grossman 1995, 43) so that 'the existence of an EKC could be solely the effect of environmental policy' (de Bruyn 1997, 499). Hence, 'in the absence of carefully targetted policies [...] economic growth may be just as harmful as its strongest critics suggest' (Ansuategi et al. 1998, 158). Many other authors also conclude that policy is of prime importance for the downturn of the EKC (see Barbier 1997, Cole et al. 1997, Lim 1997, Panayotou, 1997, Hilton and Levinson 1998, Unruh and Moomaw, 1998, Selden et al. 1999, Barrett and Graddy 2000, Cole 2000b, de Bruyn 2000, Hettige et al. 2000, Kelly 2000, Smulders and Bretschger 2000, Minliang et al. 2001, and Skonhoft and Solem 2001). To solve transboundary or global pollution problems, multilateral or global agreements are therefore needed (Cole 2000b, 130). Moreover, it has been argued that policy makers should tunnel through the EKC before severe or even irreversible damage has occurred. This is important because due to irreversibilities even the falling branch of the EKC does not necessarily imply that environmental quality is improving with rising income.

17 Conclusion

Most conclusions have already been drawn in sections 6 and 16, in which we summarized the empirical and theoretical literature, respectively. We have shown that an EKC can only be expected when policy measures are taken. However, in most cases emission reductions are due to *local* (in space and time) environmental policy reforms (Arrow et al. 1995, 92 and Huesemann 2001, 283). 'But such reforms often ignore international and intergenerational consequences' because the incentives to take them into account 'are likely to be weak' (Arrow et al. 1995, 92). In fact, it is impossible to internalize all environmental damages, first, because of coordination problems and transaction costs (Smulders 2000, 641-642), which make it simply infeasible to closely monitor all (potential) pollutants,[21] and, second, because some damages are difficult to measure, notably soil erosion (van Kooten and Bulte 2000, 387), desertification, pollution and depletion of groundwater aquifers, biodiversity loss (Cole 1999, 95), acidification (Neumayer 1998, 168), extinction of animal and plant species, climate change, and the risks of nuclear power stations. Similarly, Huesemann (2001, 274) argues that 'considering the limited budgets for environmental research, it is obvious that only a few selected [environmental problems] can ever be studied'. Therefore Huesemann (2001, 278) concludes that 'in practice [...] only the obvious problems are addressed, i.e. those situations where sufficient scientific evidence is available to indicate that environmental pollutants [...] might pose a risk to humans or whatever human values. All other environmental problems [...] are ignored'.

Hence, on the one hand, policy measures - and, accordingly, an EKC - can only be expected for a few selected pollutants. These tend to be the (flow and local) pollutants that currently cause severe damage. For these pollutants policy measures find a majority in the electorate and we observe an EKC. However, policy 'adjustments tend to be made [...] as a belated response to evidence of environmental degradation' (Perrings and Ansuategi 2000, 34) or even of 'severe environmental degradation' (Schindler 1996, 17-18).

[21] We will never be able to determine all adverse effects that synthetic chemicals - pure and in mixture - have on the environment because the costs would be prohibitive and because it is impossible to analyse the effects on all species since we do not even know all the species that exist (Huesemann 2001, 274).

This may be the case because policy makers respond to the public concern that arises when the damage is (clearly) visible and when scientific knowledge about the sources of this damage becomes available and because the process of finding acceptable regulations is time-consuming.

On the other hand, there are always unregulated (stock and global) pollutants and unregulated potential pollutants, i.e. unregulated substances whose effects on the environment are not yet known. Firms have no incentives to abate these pollutants. Accordingly, the PIR is expected to be monotonically rising. It follows that *the EKC is not valid for all pollutants.* The empirical evidence presented in paragraph 3.2.1 also shows that *the EKC is not valid for aggregate pollution.* Huesemann (2001, 274) even states that 'the focus of current environmental science is too narrowly anthropocentric to truly ensure the long-term protection of human health and welfare.'

The main findings of this survey are as follows. We observe an EKC for flow and local pollutants, but a monotonically rising PIR for stock and global pollutants. The reason for this is that for a given pollutant an EKC will only exist when policy measures are taken with respect to this pollutant as for flow and local pollutants. By contrast, the PIR is monotonically rising when the government remains inactive with regard to this pollutant as for stock and global pollutants.

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