Economic Growth and the Environment

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Abstract

Will the world be able to sustain economic growth indefinitely without running into resource constraints or despoiling the environment beyond repair? What is the relationship between steadily increasing incomes and environmental quality? This paper builds on the author's earlier work (1993), in which he argued that the relationship between economic growth and environmental quality – whether inverse or direct -- is not fixed along a country's development path. Indeed, he hypothesized, it may change as a country reaches a level of income at which people can demand and afford a more efficient infrastructure and a cleaner environment. This implied inverted-U relationship between environmental degradation and economic growth came to be known as the "Environmental Kuznets Curve," by analogy with the income-inequality relationship postulated by Kuznets (1965, 1966).

The objective of this paper is to critically review, synthesize and interpret the literature on the relationship between economic growth and environment. This literature has followed two distinct but related strands of research: an empirical strand of ad hoc specifications and estimations of a reduced form equation, relating an environmental impact indicator to income per capita; and a theoretical strand of macroeconomic models of interaction between environmental degradation and economic growth, including optimal growth, endogenous growth and overlapping generations models. The author concludes that the macroeconomic models generally support the empirical findings of the Environmental Kuznets Curve literature. He suggests further empirical investigation related to the assumption of additive separability, as well as development of additional macroeconomic models that allow for a more realistic role for government.

Key Words: Economic Growth, Environment, Kuznets Curve

JEL Codes: O11, O13

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I. Introduction

Will the world be able to sustain economic growth indefinitely without running into resource constraints or despoiling the environment beyond repair? What is the relationship between a steady increase in incomes and environmental quality? For some social and physical scientists such as Georgescu-Roegen (1971), Meadows et al. (1972), Ehrlich and Holdren (1971), (1974), and Cleveland (1984), higher levels of economic activity (production and consumption) require larger inputs of energy and material, and generate larger quantities of waste byproducts. Increased extraction of natural resources, accumulation of waste, and concentration of pollutants would overwhelm the carrying capacity of the biosphere and result in the degradation of environmental quality and decline in human welfare, despite rising incomes (Daly 1977). Furthermore, it is argued that degradation of the resource base would eventually put economic activity itself at risk (Jansson et al. 1994). To save the environment and even economic activity from itself, economic growth must cease and the world must make a transition to a steady-state economy.

At the other extreme, are those who argue that the fastest road to environmental improvement is along the path of economic growth: with higher incomes comes an increased demand for goods and services that are less material-intensive, and for improved environmental quality that leads to the adoption of environmental protection measures. As Beckerman (1992) puts it, "The strong correlation between incomes, and the extent to which environmental protection measures are adopted, demonstrates that in the longer run, the surest way to improve your environment is to become rich," (quoted by Rothman 1998, pp. 178). Some went as far as claiming that environmental regulation, by reducing economic growth, may actually be reducing environmental quality (Barlett 1994).

Yet, others (e.g., Shafik and Bandyopadhyay (1992), Panayotou (1993), Grossman and Krueger (1993) and Selden and Song (1994)) have hypothesized that the relationship between economic growth and environmental quality, whether positive or negative, is not fixed along a country's development path; indeed it may change sign from positive to negative as a country reaches a level of income at which people demand and afford more efficient infrastructure and a cleaner environment. The implied inverted-U relationship between environmental degradation and economic growth came to be known as the "Environmental Kuznets Curve," by analogy with the income-inequality relationship postulated by Kuznets (1965, 1966). At low levels of development, both the quantity and the intensity of environmental degradation are limited to the impacts of subsistence economic activity on the resource base and to limited quantities of biodegradable wastes. As agriculture and resource extraction intensifies and industrialization takes off, both resource depletion and waste generation accelerate. At higher levels of development, structural change towards information-based industries and services, more efficient technologies, and increased demand for environmental quality result in leveling-off and a steady decline of environmental degradation (Panayotou 1993).

The issue of whether environmental degradation (a) increases monotonically, (b) decreases monotonically, or (c) first increases and then declines along a country's development path, has critical implications for policy. A monotonic increase of environmental degradation with economic growth calls for strict environmental regulations and even limits on economic growth to ensure a sustainable scale of economic activity within the ecological life-support system (Arrow et al. 1995). A monotonic decrease of environmental degradation along a country's development path suggests that policies that accelerate economic growth lead also to rapid environmental improvements and no explicit environmental policies are needed; indeed, they may be counterproductive if they slow down economic growth and thereby delay environmental improvement.

Finally, if the Environmental Kuznets Curve hypothesis is supported by evidence, development policies have the potential of being environmentally benign over the long run, (at high incomes), but they are also capable of significant environmental damage in the short-to-medium run (at low-to-medium-level incomes). In this case, several issues arise: (1) at what level of per capita income is the turning point? (2) how much damage would have taken place by then and can it be reduced? (3) Would any ecological thresholds be violated and irreversible damages take place before environmental degradation turns down, and how can they be avoided? (4) Is environmental improvement at higher income levels automatic, or does it require conscious institutional and policy reforms? and (5) how to accelerate the development process so that poor countries can experience the same improved economic and environmental conditions enjoyed by developed countries?

The objective of this paper is to critically review and attempt to synthesize and interpret the literature on the relationship between economic growth and the environment.

This literature has followed two distinct but related strands of research: an empirical strand of mostly ad hoc specifications and estimation of a reduced form equation relating an environmental impact indicator to income per capita; and, a theoretical strand of macroeconomic models of interaction between environmental degradation and economic growth, which includes optimal growth, endogenous growth and overlapping generations models. With a few exceptions, the empirical models are built on heuristic theory or resort to *ex post* theoretical justifications of their findings rather than en ante formal derivations from optimizing behavior or other theoretical constructs. Also, with a few exceptions, the results of theoretical models have not been subjected to rigorous empirical testing, but they are broadly consistent with the findings of the empirical literature. Indeed, EKC-type relationships between pollution by-products of production and income are imbedded in the early models of environment and growth (e.g. Ramsey 1928 as extended by Koopmans 1960 and Cass 1965), which predates the EKC literature. Indeed, the search for a theoretical justification to the empirical finding of a non-monotonic relationship between certain pollutants and income per capita led to these earlier models and their extension (e.g. Tahnoven and Kuuluvainen 1994, and Selden and Song 1995).

Departing from conventional approach, we will review first the empirical literature, environment, growth, and then the theoretical models of optimal and endogenous growth and other macro models. We will conclude with lessons learned and areas for future research.

II. Empirical Models of Environment and Growth

The environment-growth debate in the empirical literature has centered on the following five questions. First, does the often-hypothesized inverted-U shaped relationship between income and environmental degradation, known as the Environmental Kuznets Curve actually exist, and how robust and general is it? Second, what is the role other factors, such as population growth, income distribution, international trade and time-and space-dependent (rather than income-dependent) variables? Third, how relevant is a statistical relationship estimated from cross-country or panel data to an individual country's environmental trajectory and to the likely path of present day developing countries? Fourth, what are the implications of ecological thresholds and irreversible damages for the inverted-U shaped relationship between environmental degradation and economic growth? Can a static statistical relationship be interpreted in terms of carrying capacity, ecosystem resilience and sustainability? Finally, what is the role of environmental policy both in explaining the shape of the income-environment relationship, and in lowering the environmental price of economic growth and ensuring more sustainable outcomes?

Empirical models of environment and growth consist usually of reduced form single-equation specifications relating an environmental impact indicator to a measure of income per capita. Some models use emissions of a particular pollutant (e.g. SO_2, CO_2, or particulates" as dependent variables while others use ambient concentrations of various pollutants as recorded by monitoring stations; yet other studies employ composite indexes of environmental degradation. The common independent variable of most models is income per capita, but some studies use income data converted into purchasing power parity (PPP) while others use incomes at market exchange rates. Different studies control for different variables, such as population density, openness to trade income distribution, geographical and institutional variables. The functional specification is usually quadratic, log-quadratic or cubic income, as one of the objectives of these studies is to test the shape of the relationship between income and environmental degradation. They are estimated econometrically using cross-section or panel data and many test for country and time fixed effects. The ad hoc specifications and reduced form of these models turns them into a "black box" that shrouds the underlying determinants of environmental quality and circumscribes their usefulness in policy formulation. There have been some recent efforts to study the theoretical underpinnings of the environment-income relationship and some modest attempts to decompose the income-environment relationship into its constituent scale, composition and abatement effects. However, as Stern (1998) has concluded, there has been no explicit empirical testing of the theoretical models and still we do not have a rigorous and systematic decomposition analysis.

We begin with an overview of the theoretical Microfoundations of the empirical models, followed by a survey of studies whose primary purpose is to estimate the income-environment relationship. In section II.3 to II.5, we surveyed studies that focus on mediating or conditioning variables such as international trade, population density/growth, and income distribution. In sections II.6 to II.9 we survey household level EKC's, decomposition analysis, structural transition models, and non-linear dynamics. We conclude the empirical section with ecological and sustainability considerations (II.10), and issues of political economy and policy (II.11).

II.1 Theoretical Underpinnings of Empirical Models

The characteristics of production and abatement technology, and of preferences and their evolution with income growth, underlie the shape of the income -environmental relationship. Some authors focus on production technology shifts brought about by structural changes accompanying economic growth (Grossman and Krueger 1993, Panayotou 1993). Others have emphasized the characteristics of abatement technology (Selden and Song 1995, Andreoni and Levinson 1998). And yet others have focused on the properties of preferences and especially the income elasticity for environmental quality (McConnell 1997, Kriström and Rivera 1995, Antle and Heidebrink 1995). A few authors have formulated complete growth models with plausible assumptions about the properties of both technology and preferences from which they derive Environmental Kuznets Curves (Lopez 1994, Selden and Song 1995). In this section, we will briefly review the main theoretical strands of the EKC literature. A more complete review of theoretical models of growth and environment is found in Section III.

The model by Lopez (1994), reviewed in detail in Section III, consists of two production sectors, with weak separability between pollution and other sections of production (labor and capital), constant returns to scale and technical change and prices that are exogenously determined. When producers free ride on the environment or pay fixed pollution prices, growth results inescapably in higher pollution levels. When producers pay the full marginal social cost of pollution they generate, the pollution-income relationship depends on the properties of technology and of preferences. With homothetic preferences pollution levels still increase monotonically with income but with non-homothetic preferences, the faster the marginal utility declines with consumption levels and the higher the elasticity of substitution between pollution and other inputs, the less pollution will increase with output growth. Empirically plausible values for these two parameters result in an inverted-U-shaped relationship between pollution and income. This tends to explain why in the case of pollutants such as SO2 and particulates, where the damage is more evident to consumers and, hence, pollution prices are near their marginal social costs, turning points have been obtained at relatively low income levels. In contrast, turning points are found at much higher income levels, or not at all for pollutants such as CO2, from which damage is less immediate and less evident to consumers, and hence underpriced, if priced at all.

Selden and Song (1995), using Foster's (1973) growth and pollution model with utility function that is additively separable between consumption and pollution derive an inverted-U path for pollution and a J-curve for abatement that starts when a given capital stock is achieved; i.e. expenditure on pollution abatement is zero until "development has created enough consumption and enough environmental damage to merit expenditures on abatement" (Selden and Strong 1995 p. 164). Two sets of factors contribute to early and rapid increase in abatement: (a) on the technology side, large direct effects of growth on pollution and high marginal effectiveness of abatement, and (b) on the demand side, (preferences) rapidly declining marginal utility of consumption and rapidly rising marginal concern over mounting pollution levels. To the extent that development reduces the carrying capacity of the environment, the abatement effort must increase at an increasing rate to offset the effects of growth on pollution.

A number of empirical EKC models have emphasized the role of the income elasticity of demand for environmental quality as the theoretical underpinning of inverted-U shaped relationship between pollution and income (Beckerman 1992, Antle and Heidebrink 1995, Chadhuri and Pfaf 1996). Arrow et al. (1995) state that because the inverted-U shaped curve "is consistent with the notion that people spent proportionately more on environmental quality as their income rises, economists have conjectured that the curve applies to environmental quality generally" (p. 520). A number of earlier studies (Boercherding and Deaton 1972, Bergstrom and Goodman 1973, and Walters 1975) found income elasticities for environmental improvements greater than one. Kriström (1995) reviewed evidence from CVM studies (Lomber et al. 1991 and Carson et al. 1994) that found income elasticities for environmental quality much less than one. Does the finding of a low-income elasticity of demand for environmental quality present a problem for EKC models?

McConnell (1997) examines the role of the income elasticity of demand for environmental quality in EKC models by adapting a static model of an infinitely lived household in which pollution is generated by consumption and reduced by abatement. He finds that the higher the income elasticity of demand for environmental quality, the slower the growth of pollution when positive, and the faster the decline when negative, but there is no special role assigned to income elasticity equal or greater to one. In fact, pollution can decline even with zero or negative income elasticity of demand, as when preferences are non-additive or pollution reduces output (e.g. reduced labor productivity due to health damages, material damage due to acid rain deposition or loss of crop output due to agricultural externalities). He concludes that preferences consistent with a positive income elasticity of demand for environmental quality, while helpful, are neither necessary nor sufficient conditions for an inverted-U shaped relationship between pollution and income. McConnell found little microeconomic evidence in valuation studies that supports a major role for responsiveness of preferences to income changes in macroeconomic EKC models.

Kriström (1998, 2000) interpreting the EKC as an equilibrium relationship in which technology and preference parameters determine its exact shape, proposed a simple model consisting of: (a) a utility function of a representative consumer increasing in consumption and decreasing in pollution; and (b) a production function with pollution and technology parameters as inputs. Technological progress is assumed to be exogenous. He interprets the EKC as an expansion path resulting from maximizing welfare subject to a technology constraint at each point in time; along the optimal path the marginal willingness to pay (MWTP) for environmental quality equals its marginal supply costs (in terms of forgone output). Along the expansion path the marginal utility of consumption, which is initially high, declines and the marginal disutility of pollution (MWTP for environmental quality) is initially low and rises. Technological progress makes possible more production at each level of environmental quality, which creates both substitution and income effects. The substitution effect is positive for both consumption and pollution, while the income effect is positive for consumption and negative for pollution. The substitution effect dominates at low-income levels and the income effect dominates at high-income levels producing an inverted-U shaped relationship between pollution and income. Of course, the exact shape of the relationship and the turning point, if any, depend on the interplay of the technology and preference parameters, which differ among pollutants and circumstances.

In overlapping generation models by John and Pecchenino (1994, 1995), John et al. (1995) and Jones and Mannelli (1995), reviewed in Section III in more detail, pollution is generated by consumption activities and is only partially internalized as the current generation considers the impact of pollution on its own welfare but not on the welfare of future generations. In these models, the economy is characterized by declining environmental quality when consumption levels are low, but given sufficient returns to environmental maintenance, environmental quality recovers and may even improve absolutely with economic growth.

Andreoni and Levinson (1998) derived inverted-U shaped pollution-income curves from a simple model with two commodities, one good and one bad, which are bundled together. Income increases result in increase consumption of the good which generates more of the bad. This presents consumers with a trade-off: by sacrificing some consumption of the good they can spend some of their income on abatement to reduce the ill effects of the bad. When increasing returns characterize the abatement technology, high income individuals (or countries) can more easily achieve more consumption and less pollution than low income individuals (or countries), giving rise to an optimal pollution-income path that is inverted-U shaped. The abatement technology is characterized by increasing returns when it requires lumpy investment or when the lower marginal cost technology requires large fixed costs (e.g. scrubbers or treatment plants); poor economies are not large enough or polluted enough to obtain a worthwhile return on such investments and end up using low fixed cost, high marginal-cost technologies, while rich economies are large enough and polluted enough to make effective use of high fixed-cost, low marginal-cost technologies. Different pollutants have different abatement technologies and correspondingly the income environment relationship may or may not be inverted-U shaped. The authors argue that similar results are obtained from other "good-bad" combinations e.g. driving a vehicle associated with mortality risk which can be abated by investments in safety equipment: "both the poor who drive very little and the rich, who invest in safe cars face lower risk from driving than middle-income people". Indeed, empirically, Khan (1998) found such an inverted-U shaped relationship between hydrocarbon emissions and household income in California, and Chaudhuri and Pfaf (1998) between indoor pollution and household income in Pakistan.

II.2 The Basic Environmental Kuznets Curve

The 1990s have seen the advent of the Environmental Kuznets Curve (EKC) hypothesis and an explosion of studies that tested it for a variety of pollutants. In this subsection, we review the basic EKC studies that focused on the income-environment relationship,; in subsequent subsections we examine more closely those studies that focus on mediating or conditioning variables. Table 1 summarizes the empirical studies of the environmental Kuznets curve hypothesis; Table 2 summarizes the main types of models used in empirical estimation; and Figure 1 summarizes the main types of models used in empirical estimation; and , Figure 1 summarizes the results of these studies by environmental indicator (pollutant) in diagrammatic form. The Appendix Table provides a more detailed summary of data, models and results of all the major studies. The first set of empirical EKC studies appeared independently in three working papers by: Grossman and Krueger (1991), in an NBER working paper as part of a study of the likely environmental impacts of NAFTA; by Shafik and Bandyopadhyay (1992) for the World

Bank's 1992 World Development Report; and by Panayotou (1992) in a Development Discussion Paper as part of a study for the International Labor Office. It is reassuring that these three early studies found turning points for several pollutants (SO_2, NO_x, and SPM) in a similar income range of \$3,000 - \$5,000 per capita.

Grossman and Krueger (1991, 1994) estimated EKCs for SO_2, dark matter (smoke) and suspended particles using GEMS (Global Environmental Monitoring System) data for 52 cities in 32 countries during the period 1977-88, and in per capita GDP data in purchasing power parity (PPP) terms. For SO_2 and dark matter, they found turning points at \$4000-\$5000 per capita; suspended particles continually declined at even low-income levels. However, at income levels over \$10,000-\$15,000 all three pollutants began to increase again, a finding which may be an artifact of the cubic equation used in the estimation and the limited number of observations at high-income levels.

Shafik and Bandyopadhyay (1992) estimated EKCs for 10 different indicators for environmental degradation, including lack of clean water and sanitation, deforestation, municipal waste, and sulfur oxides and carbon emissions. Their sample includes observations for up to 149 countries during 1960-90 and their functional specification log-linear, log-quadratic and logarithmic cubic polynomial functional forms. They found that lack of clean water and sanitation declined uniformly with increasing incomes and over time; water pollution, municipal waste and carbon emissions increase; and deforestation is independent of income levels. In contrast, air pollutants conform to the EKC hypothesis with turning points at income levels between \$300 and \$4000. Panayotou (1992,1993, and 1995), using cross section data and a translog specification found similar results for these pollutants, with turning points at income levels ranging from \$3000 to \$5000. (The lower figures are due to the use of official exchange rates rather than PPP rates).

Panayotou also found that deforestation also conforms to the EKC hypothesis, with a turning point around \$800 per capita; controlling for income deforestation is significantly greater in tropical, and in densely populated countries. Cropper and Griffith (1994), on the other hand, using panel data for 64 countries over a 30-year period, obtained a turning point for deforestation in Africa and Latin America between \$4700 and \$5400 (in PPP terms). These turning points are a multiple of those found by Panayotou and by Shafik and Bandyopadhyay's studies, a possible consequence of Cropper and Griffith's use of panel data. A study by Antle and Heidebrink (1995), which used cross-section data, found turning points of \$1,200 (1985 prices) for national parks and \$2,000 for afforestation. On the other hand, Bhattarai and Hammig (2000), who used panel data on deforestation for 21 countries in Latin America found an EKC with a turning point of \$6,800. Furthermore, while earlier studies of deforestation were content to control for population density (see below), more recent studies have controlled for institutional factors such as the quality of government institutions and macroeconomic factors, such as the level of indebtedness, and found them to have the expected signs, negative and positive respectively (Bhatterai and Hammig 2000).

Returning to urban environmental quality, the mid-1990's have seen a large number on studies focusing on airborne pollutants, Selden and Song (1994) estimated EKC's for SO_2, NO_x, and SPM and CO using longitudinal data on emissions in mostly developed countries. They found turning points of \$8,700 for SO_2, \$11,200 for NO_x,

$10,300 for SPM, and $5,600 for CO. These are much higher levels than Grossman and Krueger's, a discrepancy that which the authors explain in terms of reduction of emissions lagging behind reductions in ambient concentrations. However, this reasoning does not explain the large difference of their results from those of Panayotou, who also uses emissions data; the use of longitudinal data versus cross-section may help explain part of the difference. Cole et al. (1997) estimated income-environment relationships for many environmental indicators, including total energy use, transport emissions of SO_2, SPM and NO_2, nitrates in water, traffic volumes, CFC emissions and methane. They found inverted-U shaped curves only for local air pollutants and CFC's and concluded that "meaningful EKC's exist only for local air pollutants, while indicators with a more global, more indirect, environmental impact either increase with income or else have high turning points with large standard errors" (p.411). This conclusion would lead one to expect that CO_2, the global pollutant *par excellance,* would increase monotonically with income, at least within any observable income range since the impacts of global warming are (totally) externalized to other countries and future generations. Indeed, earlier studies (e.g. Shafik and Bandyopadhyay 1992) obtained such a result. Holtz-Eakin and Selden (1995) estimated EKC's for CO_2 using panel data, and found that CO_2 emissions per capita do not begin to decline until income per capita reaches $35,000, a result that confirms earlier findings by Shafik (1994).

However, more recent studies, using better data and more sophisticated estimation techniques, have obtained turning points for CO_2 emissions, while higher than those of local pollutants, still within the range of observable income levels. Schmalensee et al. (1998), using a spline regression with ten piece-wise segments and the Holtz-Eakin and

Selden data, have obtained an inverted-U shaped relationship between CO_2 emissions and income per capita in PPP$ (1985). They found negative CO_2 emission elasticities with respect to income per capita at the lowest and highest income splines, and a turning point in the range of $10,000 to $17,000 per capita. Galeotri and Lanza (1999a,b) have tested alternative functional specifications for the CO_2-income relationship, including Gamma and Weibrill functions as well as quadratic and cubic functions. They found turning points between $15,000 and $22,000 depending on the specification and sample.

Another recent study by Panayotou, Sachs, and Peterson (1999), using a ten segment piece-wise spline function and panel data for 150 countries during 1960-92, have found results quite similar to those of Schmalensee et al. The income elasticity of emissions was low at the lowest income spline, and rose to a maximum at around $11,500 per capita (tuning point) and turned negative at incomes of about $17,500. Finding an inverted-U shaped relationship for an invisible pollutant with much delayed effects and ample scope for a free-riding behavior, is a bit puzzling but fully explainable by structural changes accompanying economic growth: from agriculture, to industry, to services, three sectors with different carbon emissions intensities.

II.3 International Trade

An alternative explanation for the downward sloping segment of the inverted-U shaped relationship between certain pollutants and income per capita, may be found in the hypothesized propensity of countries as they get richer to spin-off pollution-intensive products to developing countries with lower environmental standards, either through trade or direct investment in these countries. If this is true, the past is not a good predictor of the future: developing countries, as Grossman and Krueger (1995) noted, "will not always be able to find still poorer countries to serve as havens for the production of pollution-intensive goods" (p. 372). There is little evidence, however, that either the patterns of trade or the location of investment are significantly influenced by differential environmental standards among countries (see Tobey 1990, Grossman and Krueger 1993, Jaffe et al. 1995, and Panayotou and Vincent 1997). This is not to say that environmental dumping does not take place, but that it has not been significant enough to explain observed reductions of pollution in developed countries, despite continued economic growth. Hettige et al. (1992) observed that there is some evidence of "industrial displacement effect" on the dirtier industries, as a result of tightening of environmental regulations in the industrialized nations since 1970. Another contributing factor has been the "import protection" imposed by developing countries (pp. 480). For example, countries with high tariffs and quota on chemicals have experienced faster growth of toxic intensity in their industrial production mix than those that followed outward oriented policies (Grossman and Krueger 1993).

Copeland and Taylor (1994), in a simple, two-country static model of North-South trade, examine analytically the relationship between income, pollution, and international trade. The high-income country adopts more stringent environmental regulations, and specializes in the production of cleaner goods. Under these conditions (a) an income increase resulting from trade affects pollution differently than an income increase resulting from economic growth. (b) Economic growth effects pollution differently in the presence of trade than under Autarchy. Income growth under Autarchy can be made pollution-neutral through optimal environmental policy that induces a switch to cleaner technology which exactly offsets the scale effect. Income growth resulting from trade creates composition effects (in the form of a cleaner product mix in the rich country, and a dirtier product mix in the poor country), that so dominate the scope and technology effects, as to increase aggregate world pollution. Furthermore, Copeland and Taylor found that, asymmetric growth that favors the wealthy North, widens the gap in pre- and post-trade factor prices, resulting in composition effects that increase world pollution. In contrast, asymmetric growth that favors the poor South, narrows the labor price gap, resulting in reduced world pollution levels.

Whether these results hold in a more general model depends on the generality of the premises that: (a) in the absence of trade, the relative prices of pollution-intensive goods are higher in high-income countries; and (b) trade serves to reduce, but not totally eliminate, differences in factor prices among countries. Were these results to turn out to have general validity, they would be encouraging, given the faster growth of poor countries predicted by conditional convergence theory (e.g. Barro 1990). They would be discouraging if the income gap between rich and poor countries continued to widen as has been the case in recent years. They certainly imply that policies that help developing countries accelerate their development, (e.g. development assistance and capital transfers from North to South) may also help reduce world pollution levels.

Empirical tests of the role of trade openness in the environment-income growth relationships, date back to the origins of EKC literature. Grossman and Krueger (1993) included in their EKC formulation a trade intensity variable, represented by the ratio of exports + imports to GDP, in order to test the hypothesis that greater openness to trade, would lead to lower environmental standards in an effort to preserve competitiveness in the face of international competition. They did not find significant associations between pollution and trade, except in the case of urban concentrations of SO_2, for which they found evidence that trade actually helped lower rather than raise pollution levels. Stefik and Bandyopadhyay (1992) used the same measure of openness, as well as the Dollar's index of openness (which reflects the extent of price distortion in the economy), to test the hypothesis that the more open an economy is, the cleaner the production methods it employs are. Openness and competition are seen as inducements for investment in new and more efficient technology that is also cleaner, on account of the higher environmental standards of technology-exporting countries. They found weak evidence that economies that are more open tend to pollute less. In contrast, Lucas et al. (1992), and Low and Yeats (1992), found some evidence in support of the pollution haven hypothesis in the displacement of dirty industries from OECD to developing countries.

One problem with these earlier attempts to investigate the role of international trade in the income-environment relationship, has been the absence of explicit consideration of the impact of the movement of pollution-intensive goods between countries (pollution generated in the production of these goods in one country is related to the consumption of another country.) A related issue is what is known as "carbon leakage" in climate change agreements; for example, a high carbon tax in developed countries may induce carbon intensive industries to move to developing countries. Peezy (1992) estimated that a 20% unilateral cut in carbon energy consumption in the European Union would result in less then one percent reduction in world consumption. Furthermore, Wycckoff and Roop (1994) estimated that about 50% of the carbon embodied in the imports of developed countries are in the production of goods that were not thought to be energy-intensive themselves. They found that the ratio of carbon embodied in imports, to the total carbon emissions in developed countries, ranged from 10-40 percent.

Suri and Chapman (1998) use pooled cross-country and time-series data on commercial energy consumption to quantify the impact of the actual movement of goods between countries. They found that industrialized countries have increased their energy consumption by exporting manufactured goods (which contributed to the upward sloping portion of their EKC). Industrialized countries, on the other hand, have been able to reduce their energy requirements by importing manufactured goods. This may account for the downward slope of developed country EKC: a 10% increase in the ratio of imports of all manufactured goods to domestic production of all manufacturers has been associated with a 1.3 - 1.7% reduction in energy consumption in industrialized countries. The authors also found that incorporating trade variables explicitly into EKC models raises the turning point for energy consumption and energy related emissions from 55,000 to 224,000, both far outside their sample range.

International trade obscures the link between income and environment in a given country by delinking consumption from production within the country. This has led some authors to take a consumption, rather than production, approach to the income-environment relationship; income changes are seen to drive shifts in consumption patterns, and consumption patterns are seen to drive environmental degradation. Ekins (1997) argues that when consumption patterns do not shift to match shifts in production patterns, environmental effects are being displaced from one country to another, an opportunity that may not be available to today's least developed countries. In order to get a sense of how consumption and its composition changes with income levels, Rothman (1998) fitted second-order polynomials to data on per capita consumption for eight categories of consumer goods. He found that, while composition changed with income, only food, beverages, and tobacco exhibited an inverted-U shaped relationship to income, with a turning point ($12,890) that fell within the range of the data. This was mainly due to a decline in the consumption of grains and starches, both environmentally benign commodities. Ekins (1997) tested the EKC hypothesis using a consumption-based aggregate indicator of environmental impact; developed by the OECD to include: local and global pollutants, access to water and sanitation, imports of tropical timber, energy intensity, private road transport, water abstraction, nitrate fertilizer application, and threatened species, among others. Not surprisingly, he found no support for the EKC hypothesis; aggregation of so many dissimilar indicators into one may have eliminated any systematic co-variation with income.

An interesting variant of the consumption-based approaches using an aggregate environmental impact indicator, is provided by Wacknernagel et al. (1997); they estimated the "ecological footprints" for 52 nations in terms of food consumption, wood consumption, direct and embodied energy, and built area. Rothman (1998) has fitted alternative functional forms to these ecological footprints and found that linear and "log-log" specifications fit the data well; the addition of a quadratic term, that yielded an out-of-sample-range turning point of $22,000, did not improve the results significantly.

Clearly, more work needs to be done to fully understand the role of international trade in mediating the relationship between environment and economic growth. On the one hand, there appears to be little evidence in support of the pollution haven hypothesis;

to the contrary, there is increasing evidence that open economies tend to be cleaner than closed economies. On the other hand, a growing body of ecological economics literature marshals evidence showing that, while the production patterns of developed countries may have grown cleaner over time, their consumption patterns continue to be as environmentally burdensome as ever. To resolve these issues, we need more analytical and disaggregated structural models than the standard reduced-form specifications.

II.4 Income Distribution

The literature has typically expressed environmental quality as a function of average income and ignored the way income is distributed as a potential mediating factor. More recently, social equity and the distribution of income and power has been raised in at least three separate contexts. First, Selden and Song (1994) and Stern et al. (1996) pointed out that because global income distribution is skewed (the median income per capita is less than the mean), total emissions of a pollutant can continue growing beyond the turning point at which per capita emissions peak and begin to decline. In other words, the turning point for total emissions may be attained at a significantly higher income level than average per capita emissions. Second, Ravallion et al. (1992) examined the linkage between carbon emissions, economic growth and income distribution both between and within countries, and identified trade-offs between climate control and social equity. Third, Torras and Boyce (1998) hypothesized that more equitable distribution of income and power (represented by literacy, political rights and civil liberties), contributes to larger improvements of air and water quality by increasing the influence on policy of those who are benefiting from polluting activities.

One of the channels through which income inequality may affect the income-environment relationship is through differential marginal propensities to pollute between the rich and the poor. If the marginal propensity to pollute is higher in poor than rich countries, higher inequality among countries would increase aggregate pollution levels for any given average world income level; and any effort to improve income distribution may come at the expense of environmental quality (Ravallion et al. 1997). On the other hand, redistribution may interact with growth; the trade off between equity and environmental quality may improve with growth; and the trade-off between growth and environmental quality may improve with redistribution. Another channel through which inequality may affect environmental outcomes, but in an opposite direction, is by strengthening the power of the rich to impose environmental cost on the poor (Boyce 1994) and by reducing the ability of the society to reach cooperative solutions to environmental problems (Ostrom 1990).

Ravallion et al. (1997), using data on carbon emissions from fossil fuel combustion, per capita GDP in PPP-adjusted values, and Gini indices compiled by Deininger and Squire (1996) for 42 countries, estimated an economic model that explicitly incorporates inequality and its interaction with per capita income and population. They found an income-elasticity of emissions of about 1 and a significant negative effect of inequality on the level of emissions; the income-elasticity of emissions declines as average income increases, and "the elasticity of emissions to redistribution from the richest tenth of the countries to the poorest tenth is about 0.5%" (p.22). The income-elasticity of emissions was found to be an increasing function of the Gini index, indicating that the greater the inequality, the greater the effect a given income growth had on emissions. Furthermore, the authors found that while emissions were lower with higher inequality within a country, the impact of inequality was lower with the higher level of average income. Thus while lower inequality may be initially associated with higher emissions rates, it may result in lower emission levels over the long run because it lowers the income-elasticity of emissions. They conclude that, while poverty reduction leads to increased emissions, the trade-off between reducing inequality and reducing emissions improves with growth and disappears when countries reach the income levels of today's middle-income countries; hence, with sufficiently high growth and/or low inequality, emission rates will eventually start to decline" (p.24).

Torras and Boyce (1998), building on Boyces' earlier work on the "power-weighted social decisions rule" (Boyce 1994, 1996), include in their income-emission relationship, income inequality represented by the Gini index, and non-income determinants of power inequality such as the literacy rate, political rights, and civil liberties. Their aim is to test the hypothesis that the less equitable the distribution of power the more unfavorable the environmental outcomes for any given level of income per capita, since those who suffer the costs of pollution are too weak relative to those that benefit from polluting activities influence policy. They use GEMs data on sulfur dioxide, smoke, heavy particles, dissolved oxygen and Chloroform, PPP adjusted real income data from Penn Tables, Gini ratios from World Bank (1996), literacy dates from UNDP (1994), and political rights and liberties from Finn (1996). The inclusion of a power inequality variable in all seven pollution indicators, lowers the statistical significance of per capita income as a determinant of environmental quality; literacy, political rights, and civil liberties appear to be better proxies for power inequality; and inequality effects tends to be stronger in poor countries.

The authors conclude that (1) greater inequality in the distribution of power (more than of income) results in more pollution, (2) "literacy and rights are particularly strong predictors of pollution levels in low income countries" (p. 158); and (3) measures to promote more equitable distribution of power, such as wider literacy, greater political liberties and civil rights, and improved income distribution are effective policies for improving environmental quality in poor countries.

The studies that explicitly incorporate income and/or power distribution as a mediating factor of the income-environment relationship seem to agree on at least two conclusions: that (a) distributional issues are important determinants of environmental quality in poor countries and (b) reduced inequality is good for the environment in the long run, (even if in the short run may appear detrimental with regard to certain pollutants such as carbon emissions), and hence, Kuznets' original hypothesis of an inverted-U relationship between inequality and income, could be an additional channel through which economic growth might help improve environmental quality.

II.5 The Role of Population Growth

Much of the income-environment literature assumes the relationship is homogeneous of degree one, i.e. population does not matter to emissions per capita independently of income per capita. This need not be the case. For example, Ravallion et al. (1997) argue that the demand for public goods, such as infrastructure and defense, may entail independent effects of population growth on emissions. The existence of public goods may result in both income per capita and total income having an effect on the demand of polluting goods; in other words, a higher population would result in higher emissions for given income per capita, and population growth would result in growth of emissions independently of the growth in per capita incomes.

Population density is another channel through which population growth might affect or intermediate the income-environment relationship. If population density does have and impact on per capita emissions independently of per capita income, population growth would impact emissions by increasing population density (rather than aggregate income). At least for the case of SO_2, Panayotou (1997) argued that there can be no *a priori* expectation as to the sign of the population density variable because, on the one hand, more people per square kilometer would result in higher SO_2 emissions due to the use of coal and non-commercial fuels in cooking and heating, not fully captured by the scale of formal economic activity; on the other hand, densely populated countries are likely to be more concerned than less populated countries about abating SO_2 at every level of income. In general, sparsely populated countries (e.g. Canada, Australia) tend to have higher emissions per capita than densely populated countries at the same per capita income (e.g. Netherlands, Germany) because of greater transportation distances and related emissions. On the other hand, they enjoy more natural assimilative capacity per capita and hence, *ceteris peribus*, less concentration/exposure/damage per unit of emission. Densely populated countries, on the other hand, may enjoy economies of scale, and compensation, in pollution abatement not available to more sparsely populated countries.

Panayotou (1993) found that higher population density delays the turning point at which further income growth slows down deforestation, while Panayotou (1997) found that population density raises the height of the EKC for SO_2 at every level of income. In the latter study, the relationship between population density and SO_2 emissions was found to be highly non-linear, with higher impacts at low and high densities. Controlling for all other factors, "low population densities of under 50 persons per square kilometer are associated with high ambient SO_2 levels (70 kg/km^3). . . [because of] less pressure to control emissions; as population density rises to around 170 persons per square kilometer, SO_2 levels drop to their lowest level (45 kg/km^3) and begin to rise again as the household use of coal and informal fuels by a denser population overwhelms the population pressure for more pollution abatement" (Panayotou 1997, pp. 479).

Nguyen (1999) hypotheses that fast growth of population damages natural resources and reduces the assimilative capacity of the environment, especially in countries that are highly dependent on natural resource exploitation. His hypothesis has two parts: (a) population is not neutral for the environment; and (b) it does affect the environment differently in different stages of economic development. He hypothesized that the higher the population density, the lower the turning point of the EKC and thus, the higher the environmental quality at any given level of income per capita. He tested these hypotheses for CO_2 emissions with data from three OECD countries (France, Japan, and the US) and three rapidly developing Asian countries (Korea, Thailand, and Vietnam). The results yield an EKC curve for CO_2 emissions reaching a turning point at \$18,000 (1987 prices) per capita. At low-income levels (under \$2,000 per capita), high population density affects the environment negatively: at \$1,000 per capita, a 70%

increase in population density results in 12% higher CO_2 emissions for the same level of income. At higher incomes, a more dense population has positive environmental impacts: at $10,000 per capita a 70% increase in population density results in 22% reduction of emissions, presumably reflecting increased pressures to control emissions as more people (at higher incomes) are being exposed to pollution.

Cropper and Griffiths (1994) included rural population density and percentage change in population in a reduced from quadratic equation relating topical deforestation to income per capita in Africa, Latin America, and Asia. They found that deforestation peaked at an income level of $4,760 for Africa and at $15,420 for Latin America (the results for Asia were not statistically significant). Higher rural population density was found to increase deforestation: 100 more persons per 1,000 ha raises the rate of deforestation by 0.33 in Africa. Rural population density shifts the relationship between income and deforestation upward and to the right, implying a trade-off between rural population density and income per capita: while a country with a population density of 0.1 persons per hectare reaches a peak deforestation rate of 1.26% per year at $4,760; it would take an income per capita of $11,650 per year to achieve the same rate in a country like Malawi, with a population density of 0.7 persons per hectare. However, in recognition of the role of market and policy failures as the root causes of tropical deforestation, the authors do not advocate population control policies for controlling deforestation.

Vincent (1997a), in a study that tested and rejected the EKC for total suspended particulates (TSP) in a single country (Malaysia), found that the net impact of population density on TSP concentration was positive, which he attributed to the fact that "household activities like cooking and heating, rubbish disposal, and transportation are important sources of particulate concentrations" (p.425). Vincent also found a negative interaction term between population density and time, indicating a downward pressure on population-driven TSP concentrations by the mere passage of time, which he attributes to increasingly effective anti-pollution regulations. The same study found analogous results for water quality: holding income constant, higher population densities were associated with worse water quality as measured by biological oxygen demand (BOD), and ammoniacal nitrogen (which reflect the growth of sewage discharge) and better quality as measured by suspended solids (which probably reflects the movement of people out of rural areas). The interaction between population density and time was again negative for the first two pollutants, reflecting more effective regulations over time pertaining to BOD discharges by palm-oil mills and reduction of the percentage of population without access to sanitary facilities.

Selden and Song (1994) have also tested the relationship between population density and airborne emissions while holding income constant. They found a negative relationship, which they attribute to the likelihood that in countries with low population densities, there will be less pressure to adopt stringent environmental standards; moreover, emissions due to transportation are likely to be higher. Their econometric results suggest that an additional resident per hectare would lower per capita SO_2 by 12-15 kgs, SPM by 3-5 kgs and CO by 10.3-16.2 kgs (per person). This density effect tends to particularly affect the scale effect of population growth. Indeed, with the exception of SPM, their models with population density forecast global emissions to peak and turn down earlier and at significantly lower levels than models without population density.

For example, SO_2 emissions (in the fixed-effects baseline) are projected to peak by the year 2046 at 144% above 1986 levels, when growing population density is considered, rather than in the year 2085 at 354% above 1986 levels, when population density is not considered. Population density, however, changes along the course of socioeconomic development. As Stern et al. (1996) pointed out, societies tend to go through a process of increasing, and then falling urban population densities as they develop." (pp.**). This trend may result in redistribution of pollution with ambient concentrations falling, even while emissions may continue to rise.

Kaufman et al. (1998) reject the inclusion of population density as an additive variable alongside per capita GDP, and opt for a multiplicative relationship that yields the spatial intensity of economic activity (i.e. (population / km^2) x (GDP/population) = (GDP/km^2)). The rationale is that increasing population density is likely to have a small effect on SO_2 concentrations when per capita GDP is low ,and therefore, emissions per person are low. It has a much larger effect when per capita GDP is high and emissions per person are high. Kaufman et al. (1998) specified a reduced form equation for SO_2 concentrations, quadratic in both GDP per capita and economic activity per unit of area, which they tested with a panel of international data for 23 developed, developing, and transitional economies for the years 1974 - 1989. Income figures are GDP in 1985 US dollars (PPP terms).

They found a U-shaped relationship between atmospheric concentrations of SO_2 and GDP per capita: concentrations of SO_2 tend to decrease as GDP per capita rises from \$3,000 to \$12,500 and increases thereafter. They attribute this to changes in energy use that accompanies economic development, with the shift to cleaner fuels dominating below $12,500 and the increase in energy consumption dominating at higher incomes. In contrast, the shape of the empirical relationship between concentrations of SO_2 and the spatial intensity of economic activity was that of an inverted-U; with a turning point of $6.7 million per square mile (similar to that of the UK or Israel) for a national measure of spatial intensity and $153 million per square mile for a city measure of spatial intensity. Kaufman et al. (1998) attribute the findings of earlier studies of an inverted-U relationship between income and emissions (or concentrations), to the omission of variables representing the mix, and spatial intensity of economic activity in developing countries that are experiencing population growth. The intensity of economic activity grows faster than incomes per capita, producing a scale effect that overwhelms the pure income effect. This results in an inverted-U shaped income-environment relationship, when spatial intensity (or scale) are not controlled for. In this context, showing population growth may reverse the effect of economic growth on the environment from net negative to net positive.

II.6 Microfoundations: Household-Level EKC's

At the aggregate level, the changes in the income-environment relationship in the course of economic development have been attributed to both structural and behavioral factors. Structural factors have to do with structural change that shifts the center of gravity of the economy from low-polluting agriculture to high-polluting industry and back to low-polluting services. Behavioral factors have to do with changing income elasticity for environmental services reflecting increasingly stronger demand, and hence, higher willingness to pay for environmental quality as incomes rise. The combination of these two effects eventually overwhelms the scale effect of economic growth on pollution, resulting in the downward slopping part of the EKC. Measuring the relative effect of behavioral factors compared to the structural factors requires an explicitly structural model; alternatively, one can obtain a measure of the strength of behavioral factors by analyzing micro- or household -level data of income and environmental quality.

A household-level income-environment relationship can be derived from the purchase of private goods with environmental characteristics (e.g. water filters against water pollution, air conditioning against air pollution, relocation to less polluting areas, etc.). As household incomes rise, the household is expected to increase disproportionately, its expenditure on the purchase of environmental quality enhancing goods. While Engel's curves for such goods can be estimated, it is not *a priori* evident why the level of environmental quality enjoyed by the household would be anything other than a monotonically increasing function of household income.

Chaudhuri and Pfaf (1998), however, found that the relationship between indoor air quality (an important health issue in many developing countries) and household income is anything but monotonic. Using household data from Pakistan, they estimated fuel-use, using Engle's curves; they found that as incomes rise, households climb an "energy ladder" from traditional fuels such as fuelwood and dung, to commercial fuels such as kerosene, LPG, and natural gas. While this transition implies improvement in indoor air quality with income growth, simulations by the authors (using the Engel's curve estimates and the plausible ratios of emissions from traditional and modern fuels), yield an inverted-U relationship between income and emissions: "increases in income appear to be associated initially with a deterioration in indoor air quality; only after household income crosses a threshold, do subsequent increases in income lead to reductions in emissions and improvements in indoor air quality (Chaudhuri and Pfaf 1998, pp.2). They attribute this result to the fact that fuels offer different bundles of cooking services and reductions in indoor air quality. Increases in income result in two opposing effects: (a) increased demand for cooking services (a normal good), which tends to increase emissions, and (b) increased demand for air quality (also a usual good) which tends to decrease emissions. As incomes grow, the household tends to use larger quantities of increasingly cleaner fuels, first resulting in a rise of total indoor emissions, and then fall, as the demand for cooking services is satisfied, while the demand for improved air quality continues to rise with income growth; hence, the inverted-U relationship between income and air quality.

This study provides insight into the behavioral linkages between household preferences, income levels, and environmental pollution under conditions where air quality is sufficiently private to be internalized into the household fuel choices without the need of prior policy or regulatory response. By presenting empirical evidence of this "household-level phenomenon and household-level microtheoretic explanations; distinct from exogenous government intervention or sectoral adjustment" (Chaudhuri and Pfaf 1998, pp.23) provide the "micro-foundations of one of the channels through which the aggregate Environmental Kuznets Curve might arise" (pp.2). Of course, since ambient environmental quality, unlike indoor air quality, is a public good, subject to all the market failures of undefined property rights, externalities, and free riding, analyzing household behavior alone cannot provide all the micro-foundations of the income-environment relationship.

In another study using microdata, Khan (1998) found a non-monotonic relationship between income and vehicle emissions at the household level. Using 1993 California vehicle microdata and 1990 median household income, Khan found a negative relationship between vehicle hydrocarbon emissions (measured in parts per million) and household income: vehicles owned by households in the income range of $60,000 - $69,000 (1993) generated hydrocarbon emissions of 46 parts per million compared to 95 PPM by vehicles owned by households with incomes in the range of $10,000 - $19,000. However, households in the higher-income bracket owned 2.31 cars compared to only 1.21 cars owned by households in the lower-income bracket. By multiplying numbers of vehicles per household by the amount of emissions per vehicle, Khan obtained an inverted-U shaped emissions-income relationship, with a turning point between $25,000 and $35,000 per household. Poor households tend to have very low total annual emissions despite owning older and “dirtier” cars because they own fewer of them and drive them less. Wealthy households also tend to have low total annual emissions despite owning more vehicles and driving them, because these vehicles are usually newer and cleaner. It is in the intermediate income range that annual vehicle emissions per household tend to be highest because vehicle ownership (and driving) rises faster than vehicle quality. While both are normal goods, the demand for vehicle quality rises faster at higher incomes and produces the downward sloping part of the EKC.

Unlike indoor air quality, vehicle emissions are an externality. They are internalized to the vehicle owner, however, by the fact that the vehicle quality (a private good) is bundled with the emission control technology (aimed to protect the environment, also a public good) in such a way that newer vehicles have more “drivability,” lower emissions per unit of driving and cost more (Khan 1998). Thus, bundling of lower-pollution intensity or environmental control technology with private goods facing income-elastic demand may be another channel through which the aggregate Environmental Kuznets Curve may arise.

The policy significance of household-level studies such as Khan’s, is that they help predict the effects on emission of changes in income distribution, as well as the regressivity of environmental policies targeting emission reductions.

II.7 Decomposition of the Income-Environment Relationship

The income-environment relationship specified and tested in much of the literature is a reduced form function that aims to capture the “net effect” of income on the environment. Income is used as an omnibus variable representing a variety of underlying influences, whose separate effects are obscured. For this reason, some authors termed the reduced form specification as a “black box” that hides more than it reveals; “without explicit consideration of the underlying determinants of environmental quality, the scope of policy intervention is unduly circumscribed.” (Panayotou 1997, pp. 469). In order to understand why the observed relationship exists, and how we might influence it, more analytical and structural models of the income-environment relationships are needed. As a first step, it must be recognized that the observed environmental quality is the outcome of the interplay of emissions and abatement within a location specific context, and try to identify the different effects of economic development on environmental quality transmitted through the income variables.

Panayotou (1997) and Islam, Vincent, and Panayotou (1999) identify three distinct structural forces that affect the environment: (a) the scale of economic activity, (b) the composition or structure of economic activity and (c) the effect of income on the demand and supply of pollution abatement efforts. They name the respective effects on the environment: the scale or level effect, the structure or composition effect, and the pure income or abatement effect.

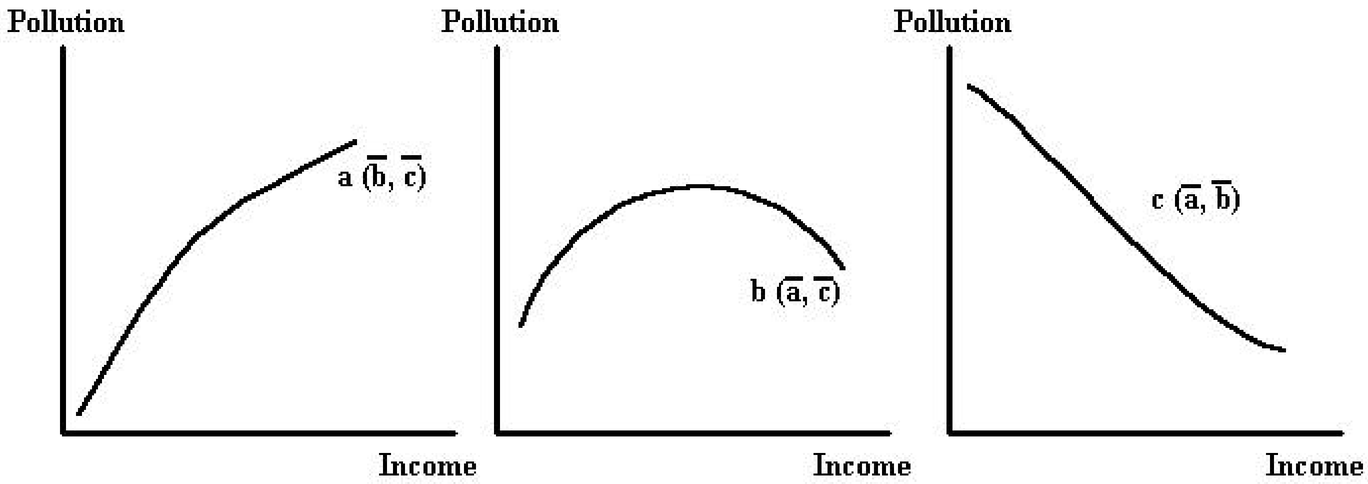
Algebraically:

$$\begin{bmatrix}\text{Ambient}\\\text{Pollution}\\\text{Level}\end{bmatrix} = \begin{bmatrix}\text{GDP per}\\\text{Unit Of}\\\text{Area}\end{bmatrix} \text{ X } \begin{bmatrix}\text{Composition}\\\text{of}\\\text{GDP}\end{bmatrix} \text{ X } \begin{bmatrix}\text{Abatement}\\\text{Efforts}\end{bmatrix}$$

Kaufman et al. (1998) and Nguyen (1999) have identified analogous effects.

The scale effect on pollution, controlling for the other two effects, is expected to be a monotonically increasing function of income since the larger the scale of economic activity per unit of area the higher the level of pollution, all else equal. The structural change that accompanies economic growth affects environmental quality by changing the composition of economic activity toward sectors of higher or lower pollution intensity. At lower levels of income, the dominant shift is from agriculture to industry with a consequent increase of pollution intensity. At higher incomes, the dominant shift is for industry to services with a consequent decrease in pollution intensity. Hence, the changing share of industry in GDP may represent structural change. The composition effect is then likely to be a non-monotonic (inverted-U) function of GDP, i.e. as the share of industry first rises and then falls, environmental pollution will first rise and then fall with income growth, controlling for all other influences transmitted through income.

Stripped of its scale and composition effects, the income variable represents "pure" income effects on the demand and supply of environmental quality. On the demand side, at low incomes, income increases are directed towards food and shelter, and have little effect on the demand for environmental quality; while at higher income levels, income increases lead to higher demand for environmental quality since the latter is a normal (if not a superior) good. The Engel's curve for environmental quality translates into an inverted-J curve between income and environmental degradation (Selden and Song 1995); that is once the scale and composition effects of income growth are controlled for, pollution is a non-increasing function of income reflecting the non-negative elasticity for environmental quality. On the supply side, higher incomes make available the resources needed for increased private and public expenditures on pollution abatement, and induce stricter environmental regulations that internalize pollution externalities. The income variable (stripped of its scale and composition effects) captures the locus of the equilibrium abatement levels, where demand and supply, both income-dependent, are equal. Hence, the abatement effect is expected to be a monotonically decreasing function of income. Figure 2 below depicts these three effects based on Islam, Vincent, and Panayotou (1999):



a. Scale Effect b. Composition Effect c. Abatement Effect

Figure 2. Decomposition of Income Effects on the Environment

Panayotou (1997) specified a cubic functional form for all decomposition effects, and included variables representing population density, economic growth rate, and a policy variable (quality of institutions). He tested the model with a panel data set for thirty countries; he used SO_2 data from GEMS and PPP-adjusted GDP figures from Summers and Heston (1991). The decomposition of the income variable into its constituent channels improved the overall fit dramatically, compared with the reduced form equation. The scale of the economy increases SO_2 concentrations monotonically, but at a diminishing rate, and it is particularly strong up to income levels of $3 million per square kilometer.

The composition effect leads to monotonically increasing SO_2 emissions with increasing industry share (from 20% to 43%) up to per capita income of $8,000; beyond this level and up to $17,000, industry share levels off and declines slightly (to 37%) with analogous effects on emissions. (A tail effect of rising industry share and SO_2 emissions at even higher income levels might be due to the very few observations of countries at this level of income). Income per capita now stripped of its scale and composition effects captures only the abatement effect on ambient emissions, which is expected to be negative, at least up to income levels of about $13,000 per capita (again a tail upturn is difficult to explain because of too few observations at the high end of income levels).

Aside from being able to explain a larger percentage of the variations of ambient emissions, what is the policy significance of such decomposition? Panayotou (1997) demonstrates how a policy variable interacts with the abatement effect of income growth to reduce ambient emissions: a 50% improvement in the efficacy of environmental policies / institutions at income levels between $10,000 and $20,000 reduces ambient SO_2 by half; at much lower income levels, the same policy change does not bring about the same improvement because the demand (and supply) for environmental quality are relatively dormant. Panayotou concludes that "higher incomes tend to be associated with improved monitoring possibilities and hence, accelerate the speed of social adjustments, which, in turn, lowers the gap between the speed of environmental change and social change" (pp.482).

Islam, Vincent and Panayotou (1999) attempted a more explicit decomposition exercise with recovery of the scale, composition, and abatement effects from a reduced form equation with structural underpinnings. Using GEMS data on suspended particulate matter (SPM) from 23 countries, they estimated a multiplicative relationship among the scale, composition, and abatement effects, and use the estimated parameters to recover these effects. With regard to the scale effect, they found that SPM levels increase monotonically with GDP per square mile, but at a declining rate. At low incomes, an increase in GDP per square mile by $1000 increases the SPM level in air by 7 micrograms per cubic meter; the scale effect does not taper off until a GDP level of about $100,000 per square mile. The relationship between SPM and industry share was found to be quadratic with an inverted U-shape, with a peak at an industry share of 39%. The abatement effects reflect more of a backward-J rather than the expected inverted-J shape; with incomes under $10,000, particulates decline steeply and level off thereafter, suggesting that income growth begins to induce abatement of particulates starting at very low income levels.

The model used by Kaufman et al. (1998) to study the effects of the spatial intensity of economic activity is basically a decomposition model where GDP per square mile represents the scale variable, GDP per capita the abatement effect, the share of iron and steel exports in nominal GDP the composition effect, and time an exogenous technological change effect.

Their finding of an inverted-U shaped relationship between SO_2 concentrations and GDP per square mile and a U-shaped relationship between SO_2 and GDP per capita are in agreement with the two studies reviewed above, especially for income levels under $153 million per square mile and $12,500 per capita. The upturn and downturn, respectively, at higher incomes correspond to what these other studies dismissed as “tail effects.” With regard to composition effects, they found that exports of iron and steel increase SO_2 concentrations, an effect which is consistent with the positive effect of industrial share on pollution found by other decomposition studies (Panayotou 1997, and Islam et al. 1999) and the trade and product mix found by trade and environment studies (e.g. Suri and Chapman 1998). Time has a negative effect on SO_2 concentrations, reflecting improvements in coal treatment and combustion technologies over time.

Grossman (1995) suggested a more dynamic form of decomposition. He described emissions (E) in a country by the following identity:

$$E_t = \sum_{j=1}^{n} Y_t \left(\frac{E_{jt}}{Y_{jt}}\right)\left(\frac{Y_{jt}}{Y_t}\right) \qquad \text{for } j = 1, \ldots n \text{ sectors}$$

Where Y_t = GDP, E_{jt} = emissions from sector j at time t; Y_{jt} = sector GDP or value added;

E_{jt} / Y_{jt} = is the emission intensity of sector j, I_{jt} ;

Y_{jt} / Y_t = is the share of sector j in GDP, S_{jt}

The equation above may be rewritten as:

$$E_t = \sum_{j=1}^{n} Y_t \cdot I_{jt} \cdot S_{jt}$$

Differentiating the above equation with respect to time and dividing the derivatives by E_t one obtains the Grossman decomposition equation

$$\frac{\dot{E}}{E} = \frac{\dot{Y}}{Y} + \sum_{j} e_j \frac{\dot{S}_j}{S_j} + \sum e \frac{\dot{I}_j}{I_j}$$

Where e_j = the share of emissions of sector j in total emissions (i.e. e = E_j / E), and x=dx/dt. The first term on the right-hand side of the equation reflects the ‘scale’ effect, the second term the “structural change’ effect and the third term the ‘technological change’ effect.

A discrete approximation of the Grossman decomposition equation was tested by de Bruyn (1997) for commercial SO_2 emissions during 1980-90 for West Germany and the Netherlands. They found that technological change explains most of the reduction in SO_2 emissions, while structural change had little effect. This should not be surprising since both these countries are developed economies having undergone most of these structural changes prior to 1980. In contrast, there has been considerable technical change during the period especially in the form of policy-induced installation of end-of-the pipe abatement technology and more modest progress in terms of fuel substitution and use of more energy efficient technologies. This finding underlines the importance of environmental policies in bringing about environmental improvement at least in developed countries (see section on policy below).

II.8 Individual Country Analysis

Most empirical studies of the environment-income relationship analyze cross-sectional or panel data for samples of developed and/or developing countries, to obtain a single (average) curve. This is often interpreted as the trajectory of environmental degradation and recovery that present day developing countries are likely to experience. This approach may be misleading. An EKC obtained from cross-country regressions "may simply reflect the juxtaposition of a positive relationship between pollution and income in developing countries with a fundamentally different negative one in developed countries, not a single relationship that applies to both categories of countries" (Vincent 1997b pp. 417). This criticism may be valid even for results obtained from panel data because of the lack of overlap between developed and developing country data series: the short-time series available on pollution do not extend to a time when present-day developed countries were developing, and therefore almost all low-income observations come from developing countries and all high-income observations from developed countries (Vincent 1997b).

Furthermore, it does not seem appropriate to infer the time trajectory of emissions in a single country from a static relationship between emissions and income among countries at a single (or even different) point(s) in time. As Unruh and Moomaw (1998) put it: "It does not seem appropriate to infer a GDP-dependent dynamic equation of motion for a national pollution trajectory from a static analysis" (p.228). A more fruitful approach, as Stern et al. (1996) pointed out, is to analyze the historical experience of individual countries.

Vincent (1997a) did exactly that for air and water pollution in Malaysia, a developing country that has experienced a rapid economic growth since the 1970's and today is an upper-middle-income country. Moreover, Malaysia, unlike most developing countries, has long time series data on environmental quality. Vincent compared the results of econometric analysis of Malaysian monitoring data with the predictions of cross-country studies for a country at Malaysia's income level. While cross-country results would predict that SO_x emissions should have been rising during 1987-91 and particulates should have been falling during the late 1980's, Malaysian monitoring data indicate exactly the reverse: declining SO_x and rising levels of particulates. The predictions of cross-country studies were not consistent with the observed trends in BOD, COD, and ammoniacal nitrogen. When cross-country results predicted correctly the sign, as in the case of nitrogen oxides and carbon monoxide, they "overpredicted" the magnitude.

Vincent found no evidence of an inverted-U shaped EKC for any of the six air and water pollutants he analyzed. Income was either positively associated with pollutants (particulates, pH, and ammoniacal nitrogen) or not associated at all (BOD, COD, and suspended solids). The author explains the results as reflections of the country's resource endowment (e.g. natural gas discovery) changing population patterns and policies both environmental and otherwise. He is however, careful to point out that the lack of EKC evidence in Malaysia does not disprove the EKC existence elsewhere, but it simply underlines the often-repeated caution that policy makers should not assume that economic growth would automatically improve the environment. Both economic and environmental policies can and do play a role, and this role can be positive or negative and within the realm of their choices.

One reason for the absence of EKC evidence in Malaysia, in addition to the reasons just given, may be the fact that being a middle income country, Malaysia has not yet undergone the transition from positive to negative emissions elasticities. Carson et al. (1997) analyze air emissions data for the US, a country that clearly must have undergone such a transition, if any country has. They address per capita emissions for seven air pollutants in the 50 US states based on per capita income. They found that emissions per capita for all seven pollutants decrease with increasing per capita income, a finding which is consistent with the EKC hypothesis' prediction, that at high-income levels, the income elasticities of emissions are negative. It is also worth noting that the income-pollution relationship was weaker for long-distance transport pollutants, such as SO_2 and greenhouse gases, presumably reflecting the greater scope of externalization of environmental impacts and free-riding on the regional or global environment.

The results suggest that it takes time for change in income to affect pollution levels. A state's initial income level does affects pollution levels, suggesting that there is a slow dynamic process (perhaps), whereby rising incomes result in a more effective regulatory structure by changing public preferences and making resources available to regulatory agencies. States with low-income levels have a far greater variability in emissions per capita than high-income states suggesting more divergent development paths. This has the implication that it may be more difficult to predict emission levels for low-income countries approaching the turning point.

Both predictive power and policy usefulness calls for a dynamic relationship relating changes in per capita emissions to changes in per capita income. Carson et al. used such an approach in analyzing air toxins in the 50 states over the period 1988 - 94 but found no relationship between the two, which may be a reflection of a slow dynamic process, as suggested by the statistical significance of the state's initial income level. They also suggest an interesting permanent income hypothesis: when rich states, like California and Massachusetts, suffer per capita income losses continue to regulate toxic emissions according to their higher expected income trajectory while poor states like North and South Dakota, even when they enjoy large increases in per capita income regard them as transitory and pursue small percentage reduction in toxic emissions.

II.9 Structural Transition Models and Non-linear Dynamics

The reduced form models used in much of the Environmental Kuznets Curve literature, with their lack of insight as to the underlying determinants of change, have led some authors to challenge the environment-income relationship altogether and propose alternative formulations. Of particular note, are structural transition models and non-linear dynamic systems. Moomaw and Unruh (1997) formulated structural transition models for 16 OECD countries and showed that the transition of these countries from positive to negative emission elasticities correlate better with historical events such as oil price shocks, and related structural transitions than with income growth.

They first run time-series regressions for each of these countries using a piece-wise linear spline function for the periods 1950 -1973 and 1994 -1993. They found a very strong positive correlation with GDP in the first period (with all coefficients positive and highly significant) and a weaker negative correlation only for six of the countries, while two were positive and the rest were statistically insignificant. They then compared these results with those obtained from a conventional EKC, third-order polynomial model estimated as a panel, for the sixteen countries over the period 1950 -92. The fixed-effects estimates produced one turning point at $12,813 and another at $18,333 thus indicating an N-shaped curve (the upturn, however, was dismissed as an articraft of the polynomical curve fitting). The authors contrast the wide income range over which individual country transitions take place in response to historical exogenous events (shocks) in structural transition models to the smooth and continuous transitions from positive to negative emission elasticities as incomes rise in conventional EKC. Thus, the structural transition models identify multiple inverted V-shaped relationships (different for each country depending on its economic structure) compared to the unique turning-point income of the conventional inverted-U shaped EKC models. Thus, according to Moomaw and Unruh, the "historical nature" of the EKC appears in the case of CO_2 at least "to be misinterpreting a historical discontinuous change in the model parameters for a hypothetical income effect." (p.460).

While neither of these models can be used to forecast future emissions (since structural discontinuities cannot be predicted), the structural transition models leave much more room for activist government policy to either advance or retard the environmental transition to lower emissions. The findings of these models suggest that countries at different stages of economic development can transition from positive to negative emission elasticities, provided the avenues of response are open. For example, energy prices must be free to rise in response to scarcity or exogenous shocks and induce conservation, substitution, and technological change. Government policies can retard the transition of even high-income countries through energy price freezes and subsidies or speed up the transition of low-income countries through emission taxes or public investments in renewable energy. It is not clear however, why the authors believe that the impact of these exogenous historical events, such as the 1973 oil price shocks, cannot be captured through dummy variables, time fixed effects or by controlling for variables that are affected by these historical shocks such as world oil prices.

The "income determinism" of the EKC literature is further challenged through the formulation of non-linear dynamic systems that provide a more complete description of individual country pollution trajectories, and show abrupt transitions in response to exogenous events or internal policies (Unruh and Moomaw 1998). Dynamic systems are characterized by non-linear feedbacks that produce complex behavior (multiple solutions) from simple functions that, at an intuitive level, can be sorted out through phase space diagrams. A phase diagram describes the behavior of an individual variable (in our case, a single country's emissions per capita) through time. Unruh and Moomaw (1998) relate emissions in the previous year to emissions in the current year, in order to identify potential regularities or systematic changes (Figure 3). They find that CO_2 emission trajectories exhibit a behavior that may be described as a "punctuated equilibrium": emissions follow "a regular incremental path until subjected to a shock that leads to the establishment of a new trajectory" (p. 227). These shocks include both exogenous factors such as the oil price shocks of the 1970's and policy initiatives such as the British decision to phase out coal. While shocks may provide incentives for policy initiatives or remove inertia for action, high incomes provide access to financing and technology for responding effectively to shocks; yet the authors reject income level as a determining factor of change, either structurally or behaviorally. Wealth is seen as an enabling factor for faster action, and the lack of it is not considered a barrier to environmental improvement. A transition to lower emissions is seen to be driven by resource prices and policy choices, not incomes. However, to the extent that economic policy reforms and environmental regulations are not exogenous but income-dependent (e.g. Carson et al.. 1997, Ringquist 1993), income growth may still drive the transition from positive to negative emission elasticities.

Nevertheless, a major contribution of the structural transition models and non-linear dynamic systems has been their emphasis on (a) individual country time series analysis (as opposed to cross-section or panel data analysis for large groups of heterogeneous countries), and (b) the key role of policy in bringing about environmental change at both low and high levels of income.

II.10 Ecological Thresholds, Irreversibility and the Quest for Sustainability

The finding of an Environmental Kuznets Curve or inverted-U shaped relationship between income per capita and environmental degradation exhibited by a subset of pollutants seems to suggest that countries can out-grow their environmental problems by simply emphasizing economic growth without the need for special attention to the environment itself. While the environment is certain to get worse before it gets better, it seems that channeling a country's limited resources to achieve rapid economic growth and move quickly through and out of the environmentally unfavorable stage of development makes good environmental sense, as well as good economic sense.

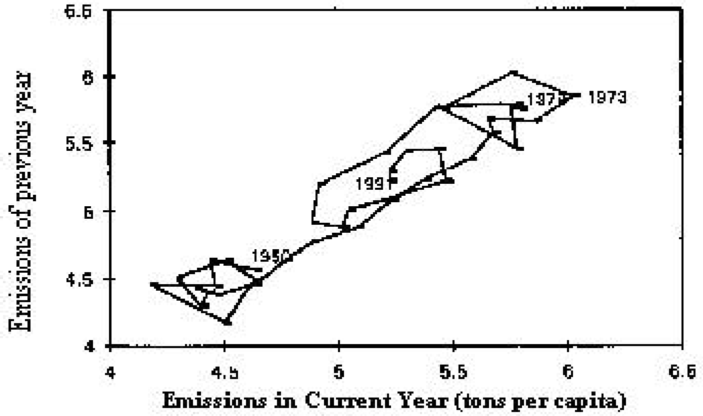


Figure 3. Phase diagram, CO_2 emissions USA 1950 - 1992
(Source: Unruh and Moomaw 1998, p.227)

However, the EKC, despite its theoretic microfoundations, is ultimately an empirical relationship which as been found to exist for some pollutants but not for others. There is nothing inevitable or optimal about the shape and height of the curve. First, the downturn of EKC with higher incomes may be delayed or advanced, weakened or strengthened by policy intervention. It is not the higher income *per se* which brings about the environmental improvement but the supply response and policy responsiveness to the growing demand for environmental quality, through enactment of environmental legislation and development of new institutions to protect the environment.

Second, since it may take decades for a low-income country to cross from the upward to the downward sloping part of the curve, the accumulated damages in the meanwhile may far exceed the present value of higher future growth, and a cleaner environment, especially given the higher discount rates of capital-constraint on low-income countries. Therefore, active environmental policy to mitigate emissions and resource depletion in the earlier stages of development may be justified on purely economic grounds. In the same vein, current prevention may be more cost effective than a future cure, even in present value terms; for example, safe disposal of hazardous waste as it is generated may be far less costly than future clean ups of scattered hazardous waste sites.

Third, the height of the EKC reflects the environmental price of economic growth: the steeper its upward section, the more environmental damage the country suffers for each increment in its income per capita. While this depends in part on income level (stages of development), the efficiency of markets and policies largely determines the height of the EKC curve. Where markets are riddled with failures (externalities, ill-defined property rights, etc.), or distorted with subsidies of environmentally destructive inputs, outputs, and processes, the environmental price of economic growth is likely to be significantly higher than otherwise. Economic inefficiency and unnecessary environmental degradation are two consequences of market and policy failures that are embodied to different degrees in empirically estimated EKCs. Perhaps more importantly, the higher the EKC, the more likely that critical ecological thresholds are crossed and irreversible changes taken place (Panayotou 1993). For example, tropical deforestation, the loss of biological diversity, extinction of species and destruction of fragile ecosystems and unique natural sites are either physically irreversible or prohibitively costly to reverse. Similarly, the economic and social consequences of damage to mental development and learning capacity from high lead levels in the blood of school-age children (due to lead emissions) are not easy to reverse, and certainly they are not reversed by switching to unleaded gasoline at later stages of development.

Panayotou (1993, 1995) argued that, while an inverted-U shaped relationship between environmental degradation and income per capita is an empirical reality for many pollutants and an inevitable result of structural and behavioral changes accompanying economic growth, it is not necessarily optimal: “In the presence of ecological thresholds that might be crossed irreversibly, and of complimentarities between environmental protection and economic growth, a deep EK-Curve (implying high rates of resource depletion and pollution per unit of incremental GDP per capita) is neither economically nor environmentally optimal, because more of both could be obtainable with the same resources, if better managed.” (Panayotou 1995, pp.30).
In order to reduce the environmental price of economic growth and lower the EKC below ecological thresholds, as seen in Figure 4, the author recommends removal of environmentally harmful subsidies (e.g. on energy and pesticides), better-defined and enforced property rights, full cost pricing of resources to reflect growing scarcities, and internalization of environmental costs (e.g. through pollution taxes and tradable permits).

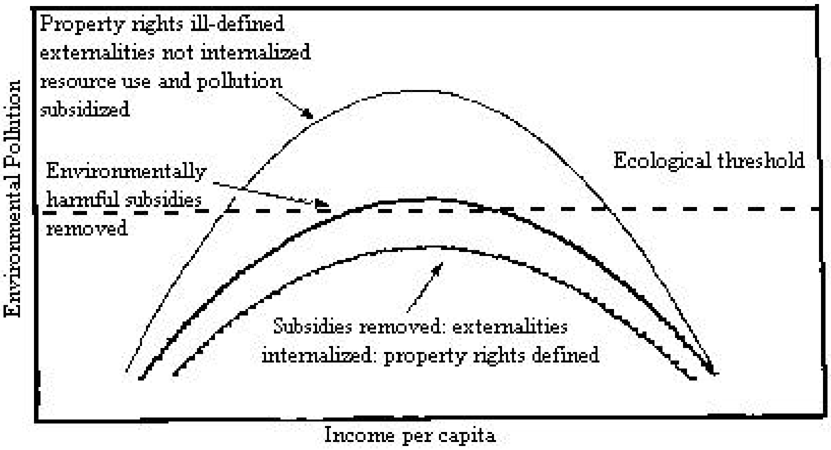


Figure 4. The income-environment relationship under different policy and institutional scenarios; the environmental Kuznets curve is flattened out by removing environmentally harmful subsidies, internalizing externalities and ensuring a clear definition of and enforcement of property rights over natural resources. (Source: Panayotou, 1993, 1995, 1997)

Munasighe (1995) is concerned that structural adjustment policies and other economy-wide reforms aimed to accelerate economic growth in poor countries might produce environmental impacts that violate safe ecological limits. He recommends adjustment of the timing and sequencing of policy reforms and complementary measures to address specific distortions and "tunnel through" the EKC while cautioning against the temptation of making major changes in economy-wide policies merely to achieve minor environmental (and social) gains" (p.124).

Arrow et al. (1995) called attention to the ever-expanding scale of economic activity, as a result of economic growth, against the finite limits of the carrying capacity of the planet, while recognizing that these limits are neither fixed nor static. In the absence of endogenously (within the economic system) generated signals of increasing scarcity (e.g. rising environmental resource prices), economic activity may expand at a pace and scale that overwhelms the much-more-slowly expanding carrying capacity of the planet resulting in irreversible damage to the productivity of the resource base, and unsustainability of economic growth itself. Sustainability of economic activity may also be undermined by the loss of ecosystem resilience that results from growth-driven reduction in diversity of organisms and heterogeneity of ecosystems. Discontinuous changes in ecosystem functions, irreversible loss of future options, new uncertainties, and increased vulnerability to natural disasters are a few avenues through which reduced ecosystem resilience may impair economic sustainability.

Arrow et al. (1995) argue for a better understanding of ecosystem dynamics, and recommend reforms to improve the signals received by economic agents, including better-defined property rights and institutions that "provide the right incentives for protecting the resilience of ecological systems" (p.521). However, given the inherent uncertainties and discontinuities, they also counsel use of precaution to maintain diversity and resilience of ecosystems.

The EKC relationship being unidirectional and without feedbacks from the environment to the economy does not address sustainability concerns, which would involve long lags and require a dynamic model with reciprocal causality. Moreover, as de Bruyn et al. (1998) pointed out "the outcomes of statistical analysis cannot be interpreted in terms of ecosystems resilience or carrying capacity" (p. 173). They make a modest attempt to introduce dynamics by formulating a growth model based on "intensity-of-use" analysis, which they estimate for CO_2, NO_x, and SO_2 in the Netherlands, the UK, USA, and West Germany. They find that the time patterns of emissions correlate with economic growth and attribute any reductions in emissions to structural and technological change. They then define "sustainable growth" as the rate of economic growth that leads to zero growth in emissions, i.e. any increase in emissions due to scale expansion is offset completely by structural change and technical progress.

$$\ln \left(\mathbf{Y}_{\mathbf{j,t}} / \mathbf{Y}_{\mathbf{j,t-1}}\right) = - \left(\mathbf{B}_{\mathbf{2}} \ln \mathbf{Y}_{\mathbf{j,t-1}} + \mathbf{B}_{\mathbf{1}}\right) / \mathbf{B}_{\mathbf{0}}$$

Where B's are the estimated parameters from a reduced form income-environment relationship expressed in growth rates: B_0 represents the marginal effect of growth on emissions and B_1 and B_2 the influence of structural change and technological progress. Sustainable growth rates were calculated for each pollutant for the 4 countries (see Table 3). With few exceptions, these rates are significantly lower than the 3% annual growth rate for developed countries and 5% for developing countries that the Brundland Report (WCED 1987) considered sustainable.

Table 3

Sustainable growth rates using income levels of 1990

Country	CO_2 (%)	NO_x (%)	SO_2
Netherlands	1.8	2.1	11.2
UK	1.8	1.2	2.4
USA	0.3	2.6	3.8
West Germany	2.9	4.5	5.2

source: de Bruyn et al.. 1998

II.11 Political Economy and Policy

Despite a general recognition that the empirical relationship between environmental degradation and income is neither net of policy effects nor immune to policy intervention, very few researchers attempted to include policy variables into either reduced-form or structural models. This is probably due to the lack of data on policy variables in general and environmental policy in particular. For example, Panayotou (1997), in one of the very few studies that attempted to incorporate policy variables, used as proxies the quality of institutions to represent environmental policies. He experimented with a set of five indicators of the quality of institutions in general: respect/enforcement of contracts, efficiency of bureaucracy, the rule of law, the extent of government corruption and the risk of appropriation obtained from Knack and Keefer (1995). Enforcement of contracts and a composite index of all five variables worked best. It was found that improvements in the quality of institutions (policies) by 10% resulted in reduction of SO_2 emissions by 15%. Having found a much smaller emissions elasticity with respect to the role of economic growth and the density of population, the author argues that the efforts of pro-environment reforms should focus on improving the quality of institutions and policies rather than attempting to slow down economic or population growth. Indeed, Panayotou found that improvements in policy institutions are likely to have higher payoffs at higher incomes which also tend to be associated with improved monitoring possibilities.

Nguyen (1999) found similar results for improvements in institutional capacity for controlling CO_2 emissions in France, Japan, Korea, Thailand, the United States, and Vietnam. Bhattarai and Hamigg (2000), using indicators of socio-political institutions from the Freedom House and from Knack and Keefer (1995), found that the quality of government institutions has statistically significant negative effects on deforestation, especially in developing countries with publicly managed forests. Strengthening of property rights institutions, such as tenure security and enforcement of contracts was also found to reduce deforestation pressures, all else equal.

While the study of the role of policy in mediating the environment-growth relationship is still in its infancy, the question arises as to what determines environmental policy itself. If it is not simply income-dependent but, at least in part exogenous, what explains the difference in environmental policies of countries at similar levels of economic development? Torras and Boyce (1996) examine how various indicators of democracy affects the formation of preferences and mediates between individual preferences and public policy. They show, for example, that when democracy variables are included, income loses some of its significance in explaining variations in emissions. Deacon (1999) showed that the income-environment relationship varies across political systems and environmental quality tends to be lower in non-democratic regimes. Since only the elite-specific costs and benefits are usually considered in setting policies in such regimes, one would expect underinvestment in environmental quality and other public goods characterized by non-excludability of benefits. Deacon finds strong empirical evidence for his hypothesis in public investments in roads, public education, access to safe water and sanitation, and unleaded gasoline in a cross-section of 118 countries. Controlling for differences in income (undemocratic countries tend to be poorer) Deacon found statistically significant differences in the provision of public goods and environmental protection between the most democratic regime and each of the other regimes in 56 out of 65 cases, consistent with his hypothesis. Military and police expenditures is the major exception among public goods, as they tend to be higher in dictatorial regimes, apparently because they are viewed as conferring protection to the privileges of the elite. While Deacon's results are preliminary, they do suggest that political systems and political economy have autonomous influence on environmental quality, or at any rate mediate the income-environment relationship. The recent trends towards democratization should have beneficial effects on environmental quality (through a more complete accounting of benefits from public goods), as well as on economic growth, through introduction of the rule of law and more secure property rights, factors that may also benefit the environment.

III. Theoretical Macro-Models of Environment and Growth

In this section, I consider macroeconomic models of the interaction of environmental degradation on growth. These are divided into four major categories: optimal growth models, models in which the environment (rather than pollution) is a factor of production, endogenous growth models, and other macroeconomic models of growth and the environment. This section concludes with a brief analysis of the results of this line of research, and suggests avenues that may be pursued in the future.

A. *Optimal growth models* build on a Ramsey (1928) framework, as extended by Koopmans (1960) and Cass (1965). These are dynamic optimization models, in which the utility-maximization problem of the infinitely lived consumer is solved using the techniques of optimal control theory. Either the stock, or the flow of pollution is an argument of both the production function and the utility function of the representative consumer. Most of these models support the Environmental Kuznets Curve that has been found empirically, and which has been discussed in detail in the previous section.

B. *Models of the environment as a factor of production* include, not only pollution as an argument of the production and utility function, but the environment itself. This may be interpreted as the stock of natural capital that the economy is endowed with, or as the aggregate level of environmental quality. In these models, property rights are decisive in determining whether environmental degradation eventually declines with growth.

C. *Endogenous growth models* relax the neo-classical specification of the production function assumed in the optimal growth models. Building on the work of Romer (1986, 1990) in particular, production functions in these models are characterized by increasing returns to scale, and spillover effects. Tightening pollution standards with economic growth is optimal in these models.

D. *Other macroeconomic models* include an overlapping generation model (Diamond 1965), and a two-country general equilibrium model of growth and the environment in the presence of trade. These models add support to the results of the optimal growth models and suggest that their results may be arrived at in other contexts as well.

III.1 Optimal Growth Models Including the Environment

As discussed previously, the initial impetus for the environmental Kuzents curve (EKC) literature was observed empirical regularities. A search for a theoretical justification followed econometric evidence of a non-linear relationship between certain pollutants, and income per capita. In fact, EKC-type relationships between a composite pollution by-product of production and income were embedded in many of the early models of environment and economic growth that used a Ramsey (1928) framework, as extended by Cass (1965) and Koopmans (1960). A flurry of optimal growth models that included pollution or nonrenewable resource depletion appeared in the 1970s, prompted in part by the popular fear that the dependence of industrialized economies on petroleum constituted a “limit to growth.” More recent extensions of these Ramsey models, including Selden and Song (1995) and Tahvonen and Kuuluvainen (1994) are more broadly interpreted to be models of development generally, where there is a trade-off between the disutility of a pollution byproduct and the utility of consumption.

These models may be separated into optimal growth models that consider the effects of pollution and those that consider the effects of natural resource depletion on the growth path of an economy. In general, the solution procedure is straightforward; in both cases the social planner’s problem of maximizing an infinite stream of consumption is considered, and may be contrasted to the decentralized result. In general, models of pollution and optimal growth suggest that some abatement or curtailment of growth will be optimal. Models of natural resource depletion on the other hand find that full extraction or extinction may be optimal, depending on the discount rate and society’s technology. The discussion below considers only growth models with pollution. Models of natural resource extraction and growth, such as Dasgupta and Heal (1979), Stiglitz (1974), Solow (1974), and Smith (1977) are addressed elsewhere in this volume.

III.2 Pollution and Optimal Growth

Keeler et al. (1971), D’Arge and Kogiku (1973), Mäler (1974), Forster (1977), Gruver (1976), Brock (1977), Becker (1982), Heal (1982), Tahvonen and Kuuluvainen (1994), Selden and Song (1995), and Stokey (1998) all present models that extend the basic dynamic optimization of Ramsey, Cass and Koopmans to include the disutility of pollution that arises as a result of economic activity. As Selden and Song (1995) point out, even the 1970s pollution models that did not explicitly solve the dynamic path of pollution, may be interpreted to yield a non-linear path like the empirically observed Environmental Kuznets Curve. A review of these models affirms this finding, but also suggests that both the models of the 1970s, and more recent models, are unsatisfyingly sensitive to assumptions about the form of the utility function.

Keeler, Spence and Zeckhauser (1971) identify three important considerations that must be addressed when designing an optimal control model augmented for pollution. The first is whether pollution impacts consumption, production, or both. This has implications for the form of the utility function and the production function. A second consideration is whether a pollutant has its effect on utility and production as a stock or a flow. If pollution is to be analyzed primarily for its stock effects, then it must be considered a state-variable in the formulation of the optimal control problem, much as physical capital is in the traditional Ramsey model. This conclusion constitutes the third consideration identified by Keeler, Spence and Zeckhauser (1971).

The first distinction of Keeler, Spence, and Zeckhauser (1971) has been decided nearly unanimously. In general, in this class of models pollution enters directly into the social utility function with a negative marginal utility. On the production side however, most models assume that pollutants have positive marginal products. This means that pollution may be interpreted as an input to production, or a non-productive byproduct as a result of production. An exception to this convention is Heal (1982), reinterpreting Ryder and Heal (1973) as a model of economic growth with a stock pollutant. This model assumes that pollution is a byproduct of consumption. Another exception is Mäler

(1974) that assumes that pollution occurs as consumption goods depreciate, not as they are produced.

Within this basic framework, authors have made differing assumptions about the function of pollution in the production function. As noted by Tahvonen and Kuuluvainen (1993), assuming that emissions are strictly a byproduct of production neglects the potential for substitution between physical capital, and pollution, as the marginal product of capital changes. Keeler, Spence and Zeckhauser (1971), Forster (1977), Gruver (1976) and Heal (1982), assume that pollution is a constant byproduct of production with no independent productive value. Brock (1977), Becker (1982), and Tahvonen and Kuuluvainen (1993), allow productive substitution possibilities to exist.

Different choices have also been made with respect to the effects of pollution on utility. Keeler, Spence, and Zeckhauser (1971) argued strongly that it is the stock of pollution that affects utility, not the instantaneous emissions. Following Brock (1982), this has been accepted by Becker (1982), D'Arge and Kogiku, (1973) and Tahvonen and Kuuluvainen (1993). Forster (1977) and Gruver (1976) both argue that a specification in which the flow of pollution affects utility is a reasonable approximation for many pollutants, such as sulfur dioxide, and water pollution.

Perhaps surprisingly, the stock-flow distinction has had little impact on the results of these models with respect to the optimal consumption path. A more important assumption that must be made with regards to the utility function, is whether the cross derivative of consumption and pollution is positive or negative. The usual assumption is that if utility is defined to be U(c, z), where z is either the stock or the flow of pollution, then $U_{cz} \leq 0$. Additive separability, implying $U_{cz} = 0$, is often imposed to ease calculation. $U_{cz} \leq 0$ corresponds to the case in which increasing pollution lowers the marginal utility of consumption. However, it may be that an increase in consumption lowers the marginal disutility of pollution; Keeler, Spence and Zeckhauser (1971) give the example of air conditioners that mask the effects of pollution.

An example of the form of these models is Tahvonen and Kuuluvainen (1993), which is based on Brock (1982). Unlike some other versions of this optimal control model, this specification neglects the possibility of investment in abatement technology. The problem of the social planner is to

$$\begin{aligned}
&\max_{c,e} W = \int_0^{\infty} U(c,z)e^{-rt}\,dt \\
&s.t.\,\dot{k} = y(k,e) - c \\
&\dot{z} = e - \alpha z \\
&k(0) = k_o, z(0) = z_o \\
&\lim_{t\to\infty} k(t) \geq 0, \lim_{t\to\infty} z(t) \geq 0
\end{aligned}$$

where α is the rate of pollution decay, z is the stock of pollution, and e is emissions.

Using a Hamiltonian to solve this model, Tahvonen and Kuuluvainen (1993) find that there is a steady state level of consumption and capital accumulation that is lower than the steady state consumption and capital accumulation of a model without pollution. This steady state is unique only if $U_{cz} \leq 0$. This is consistent with the result of Brock (1976).

A similar result is found in the third model presented in Stokey (1998). She assumes a different specification of the means by which pollution enters the production function; the central planner specifies an optimally chosen emissions standard that must be achieved. Cost-effectively meeting this target lowers the growth rate of consumption below its level if there were no pollution. This result is the same whether the pollutant is a stock or a flow. While Heal (1982) finds that steady state consumption need not be lower in the presence of pollution, he also notes that his solution is not robust to the assumption of an additively separable utility. In general, if the restriction $U_{cz} \leq 0$ is not imposed, there may be multiple steady states with widely varying levels of pollution and consumption.

The weakness of these models is not confined to those that do not include the possibility of abatement investment, though it is these models which most clearly include an inverted-U shaped pollution path. Gruver (1976) specifies a model in which capital may be allocated to production of consumer goods, or abatement of a flow pollutant. In this case, it is never optimal to build up abatement and productive capital simultaneously. Rather, utility is maximized when capital is devoted entirely to producing consumer goods when income is low, and pollution initially increases with income. Only later, when income has increased, and the effects of decreasing marginal utility of consumption are stronger, should investment in abatement begin. Thereafter, pollution declines with income along the balanced growth path. Similarly, Selden and Song (1995) show that the model specified by Forster (1977) implies an Environmental Kuznets Curve path for pollution and a “J-curve” for abatement.

The optimal growth models provide one general class of theoretical foundation for the empirically observed Environmental Kuznets Curve. They also represent an independent literature, conceived of separately from the EKC investigation. That both research endeavors have yielded similar results is encouraging, but the optimal growth models are in general very sensitive to the specification of the utility function. Caution must be used in generalizing from the results that these models have given thus far.

III.3 Models of the Environment as a Factor of Production

The class of optimal growth models examined above includes pollution as a factor of production. Either this same pollution, or an aggregate measure of environmental quality, also appears as an argument of the utility function. This measure of environmental quality can be conceptualized as a stock that is degraded by production or pollution. There are other models that include this stock of environmental resources as a function of production. The environment itself is required to generate output. Important versions of this sort of model are Lopez (1994), and Chichilinsky (1994). Neither of these models deviate from the neo-classical production functions considered in the previous section; endogenous growth models that include the environment as a factor of production, such as Bovenberg and Smulders (1995) and Bovenberg and Smulders (1996), are considered below. In general, the predictions of these models with regard to the effect of growth on environmental degradation, depend on whether economic factors internalize the specified stock feedback effects. The presence of the environmental stock in the production function means that optimal pollution taxes or pollution regulations are not sufficient to achieve the optimal level of environmental quality in the steady state.

Lopez (1994) begins by specifying a production function that includes pollution as a factor of production, but not the stock of environmental capital. As in the optimal growth models discussed above, he finds that if pollution is unpriced, firms will use it until its marginal product is reduced to zero. If the government imposes the optimal pollution tax, he finds the familiar requirement, that the cross derivative of the utility function with respect to consumption and pollution, must be negative ($U_{cz} \leq 0$), to achieve long-run growth and declining pollution. If the cross derivative is positive, pollution will grow without bound until the physical limits of the environment are reached. At this point, growth depends on "pollution-augmenting" technological change. Only with technical advances, in the lower the amount of pollution necessary to achieve a level of output with a fixed amount of capital, can growth continue.

Lopez extends his model to include the stock of environmental quality as a factor of production by using an agricultural motivation. Particularly in the tropics, agricultural output depends not only on the amount of land under cultivation ("pollution" if deforestation is necessary to use land for farming), but also on the stock of biomass. The remaining amount of forest partially determines the quality and fertility of the soil used for farming. The forest level also affects the vulnerability of cultivated land to soil erosion and flooding. Practically, Lopez posits an agricultural production function that is increasing and concave in capital, labor, biomass and cultivated land. The law of motion for the stock of biomass is proportional to the level of the cultivated area. A production function for the non-agricultural sector is also specified, so that the total revenue of the economy depends on joint output.

The predictions of this model depend crucially on the existence of property rights or contractual arrangements that ensure that producers consider the negative effect of increased cultivation on the stock of biomass. If the level of conventional inputs is exogenously increased, increasing the area of land under cultivation is privately optimal if the feedback effect is not considered. Conversely, if agricultural producers fully internalize the effect of biomass on production, an increase in capital or labor increases the value of biomass. Producers will benefit from an increase in the stock of biomass and act accordingly. This model predicts that deforestation, or environmental degradation more generally, will decline with growth, only if institutions exist that ensure that investments in the environmental stock will be privately expropriable.

Property rights and institutional development are also the key drivers of the model developed by Chichilinsky (1994). She presents a general equilibrium model with two regions: “North” and “South,” both of which use the environment as a factor of production, and two goods, one of which is relatively resource intensive. To illustrate the important role of property rights for environmental factors of production, Chichilinsky assumes that the North and South have equal endowments of all factors of production, and are equally productive. World markets and domestic input markets then clear. In a traditional Ricardian framework there would be no gains from trade.

The two regions do differ in the property rights regimes that prevail over environmental resources. In the South, the environment is managed as a common property resource; in the North, it is privately owned. Since in the North, the supply of environmental resources will be determined by the marginal productivity of the resource, and in the South, it will be determined by the average productivity of the resource, at any price the South will supply more resources than the North. This gives the South an apparent comparative advantage in the supply of the environment-intensive good, though, by definition, equal factor endowments mean that no actual advantage exists. In this model, trade is harmful to the South, and to the world as a whole, because too much environmental degradation occurs.

A tax on the use of environmental resources is not sufficient to correct for the welfare losses that arise as a result of the common property regime in the South. Chichilinsky assumes that subsistence workers, who have an opportunity cost of labor that is close to zero, extract environmental resources. A tax on producers of the environment-intensive good increases the demand for the non-resource intensive good in this simple model because this is that on which tax revenue is spent. Therefore, the relative price of the resource-intensive good and the environmental resource falls. Subsistence laborers respond to this relative price change by increasing their extraction effort; extraction may actually increase, in spite of the tax.

Introducing the stock of environmental quality as a factor of production, adds an additional level of complexity to the optimal growth models that began this discussion. Optimal pollution taxes or pollution regulations are not sufficient to obtain the optimal level of environmental quality as growth occurs. The next section shows that this result is robust to relaxing the neo-classical assumption of constant returns to scale; additional government intervention beyond pollution taxes is necessary in endogenous growth models of environment and growth, as well when the stock of environmental resources or quality is a factor of production.

III.4 Endogenous Growth Models of Environmental Degradation and Growth

Models that generate long-term growth, without recourse, to an exogenous rate of technological progress include Romer (1986, 1990), Barro (1990), Robelo (1991) and Lucas (1988). Endogenous growth arises as a result of constant or increasing returns; to scale to some factor, or a class of factors. In Romer (1986) and Romer (1990), the private returns to investment may differ from the social returns to investment, often because of externality effects. In Barro (1990), and Robelo (1991), the neo-classical assumption of decreasing returns to capital is relaxed, on the grounds that a broad definition of capital, including human capital, is more accurately characterized by a constant marginal product. Several models exist that extend the ideas of this "new growth theory" to include the environment, or pollution, as a factor of production and environmental quality as an argument of the utility function. Bovenberg and Smulders (1995, 1996) modify the Romer (1986) model to include the environment as a factor of production. Ligthhard and van der Ploeg (1994), Gradus and Smulders (1993), and Stokey (1998) extend the simple "AK" model used by Barro to include environmental considerations, and Hung, Chang, and Blackburn (1994) use the Romer (1990) framework. Several of these classes of environment-augmented endogenous growth models are reviewed in turn below.

Bovenberg and Smulders (1995, 1996) use a framework similar to the optimal growth models discussed above for the consumption side of the economy. Utility is a function of consumption and the stock of environmental quality. They extend these models by arguing that the stock of environmental quality is a public production factor. If pollution causes productivity losses, as well as acts as a factor of production, then the neo-classical production functions must be extended to reflect this trade-off. This is analogous to the argument used by Lopez (1994) to justify including both the amount of cultivated land, and the amount of biomass in an agricultural production function.

Bovenberg and Smulders (1995, 1996) go further than Lopez in this specification, however, by arguing that, not only does the stock of environmental capital enhance productivity, but also investments in abatement technology that lessen the effects of pollution on the environment have a public-goods character. This allows them to use the Romer (1986) framework in which the generic R&D sector is specifically defined to be an abatement technology research sector. The production side of the economy is described by the following equations:

$$\begin{aligned} &Y = A(N)F(K_Y, Z_Y) = C + \dot{k} \\ &H = A(N)G(K_H, Z_H) = \dot{h} \\ &K_Y + K_H \leq K \\ &Z_Y + Z_H \leq Z = hP \end{aligned}$$

Here, N is the stock of environmental capital, Y is the output of consumption goods, and H is the output of the research sector. Technological advancements produced in R&D lower the amount of actual pollution, P, associated with any level of output; environmental technology capital, h, augments pollution to create effective pollution, Z. Private capital K is used in both sectors, as is effective pollution. In both sectors, there are constant returns to the rival inputs.

The stock of natural resources is defined by the following equation:

$$\dot{N} = E(N) - P$$

Since total factor productivity is defined to depend positively on N, the production function specification captures the hypothesized non-rival relationship between environmental quality and productivity. This is analogous to the Romer (1986) specification of A as A(K) where K is physical capital.

This specification is such, that without government intervention, pollution would increase without bound, and no investment would be made in abatement technology. Producers do not internalize the relationship between environmental quality and economic productivity. In this context, Bovenberg and Smulders (1995, 1996) make the, perhaps not fully justified assumption that, while the government efficiently subsidizes abatement R&D, and cost-effectively meets a pollution target, it chooses a pollution ceiling that is sub-optimally low. This allows them to characterize the balanced growth path, and then to analyze the effects of a lower pollution ceiling on consumption and output.

Assuming that utility depends positively on both consumption and the stock of environmental capital, Bovenberg and Smulders (1995, 1996) find that this model does have a balanced growth path, given sub-optimal pollution taxation and subsidized abatement R&D. Just as suggested by Lopez (1994), the existence of "pollution-augmenting" technical progress allows positive long-run growth of consumption, and environmental and conventional capital. In this steady state, both N and P are constant because the shadow prices of pollution, and thus its tax, are increasing over time.

Tightening the pollution standard unambiguously increases welfare, proportional to how inefficiently low the pollution tax initially was. However, the effects of a lower pollution ceiling on consumption and output depend on whether the environment is more strongly a pure consumption good, or a pure production good. In effect, this is precisely the result found by the neo-classical optimal growth models; the predictions of the model are very sensitive to the precise specification of the utility function. In this case, to the extent that environmental capital is more important as a consumption good than as a production good, tighter regulation results in slower consumption growth. To smooth utility, households can increase their current consumption in anticipation of higher future environmental quality. If environmental quality is a pure production good, higher levels of environmental quality increase the rate of return on private capital, and thus increase the growth rate of consumption. On balance, the additional complications added by Bovenberg and Smulders (1995, 1996), do not clarify the ambiguous predictions of the neo-classical growth models because the results again depend on the form of the utility function.

Ligthhard and Van der Ploeg (1994), and Stokey (1998) have developed less complicated endogenous growth models including the environment. Both of these models use an "AK" specification in which the marginal product of capital is not declining. Ligthhard and Van der Ploeg (1994) extend the model presented by Barro (1990) that examines the role of government spending in an endogenous growth context. Stokey (1998) shows that if there is a government mandated emissions standard, the effective marginal product of capital may no longer be constant with a simple AK specification. As such, growth eventually slows to zero, much as in the neo-classical framework when a constant return to scale production function is imposed.

Ligthhard and Van der Ploeg (1994) place their endogenous growth model in the realistic context, in which the government taxes output, to raise revenue to purchase consumption goods. Utility is a function of private consumption, government consumption, and pollution. In order to maximize social welfare, the government can increase taxes on output as a means of lowering pollution. To derive the optimal choice of taxes in this second best setting (Sandmo, 1975), the government takes into account the concern that environmental degradation lowers the marginal cost of public funds and the optimal tax rate, relative to their levels without environmental considerations. A lower rate of economic growth, and a larger public sector is desirable as concern for environmental quality increases. This is consistent with the stylized fact that the size of the public sector increases with growth.

Stokey (1998) specifies a simple model in which output is a function of conventional inputs and pollution. Abatement technology exists, that can lower effective pollution per unit of output, but using this technology lowers the productivity of the economy. Thus, actual output $c = yz$, where z $[0,1]$ is a technology index and y is potential output per capita. Actual output equals potential output only when the dirtiest production method is used. The link between abatement technology and emissions, x, is given by $x = y\phi(z)$, where ϕ is increasing and convex, but bounded above.

When the production function $y = AK$ is specified, it takes a simple algebraic calculation to show that the marginal product of capital is not constant, but is decreasing in K, endogenous growth does not take place. Intuitively, stricter emissions standards are optimal as the capital stock and income increase; this lowers the rate of return on capital. When the rate of return is sufficiently low, there is no incentive for further investment.

Imposing the functional form $\phi(z) = z^{\beta}$, and specifying additive and separable utility in consumption and pollution, Stokey (1998) finds that there is a level of $y = y$, below which the dirtiest production technology is used. There is such a premium on consumption that a high level of pollution is acceptable, but as incomes increase and the marginal utility of consumption declines, abatement is optimal.[1] This result is robust to whether the model used is static or dynamic, and also holds when a neo-classical production function is specified, as was mentioned in the earlier discussion of optimal growth models. Again, however, this result is not robust to the specification of the utility function as additive and separable.

The endogenous growth models of augmented to include environmental changes buttress the results of neo-classical growth theory with respect to environmental degradation. In general, optimal pollution control requires a lower level of growth than would be achieved in the absence of pollution. Moreover, the results are sensitive to the specification of the utility function; as will be discussed further at the end of this section an important empirical task appears to be determining whether additive separability is a reasonable approximation of individuals utility functions. The model presented in Ligthhard and Van der Ploeg (1994) also suggests a new avenue of research; it is easy to be wary of results from models that assume dynamically optimal pollution taxation, particularly if what practitioners are interested in are policy implications relevant to developing countries. Further work on environment and growth in a second-best world would be valuable.

III.5 Other Macroeconomic Models of Environmental Degradation and Growth

There are several other macroeconomic models of environmental degradation and growth beyond those already discussed. In particular, Copeland, Taylor (1994), John,

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[1] Note that the shape of the curve implied by this result is not a smooth inverted U, instead it has a single sharp peak. Stokey (1998) points out that this is better approximated by a cubic specification than a quadratic equation for econometric purposes.

and Pecchenino (1994, 1995) add additional insight to the results of the optimal growth and endogenous growth models.

John and Pecchenino (1994) develop an overlapping generation's model, like that in Diamond (1965). This allows an explicit consideration of intergenerational equity. In models of infinitely lived or infinitely altruistic agents like those in the Ramsey model, there is no difference between inter- and intra-generational considerations. In this model by contrast, consumption (c_t) by the old degrades the environment available to future generations, while maintenance investment by the young (m_t) improves it. As such, environmental quality, E evolves according to the following equation:

$$E_{t+1} = (1 - b)E_t - bc_t + gm_t$$

In the absence of human intervention, the quality of the environment would take the value zero; the parameter b measures the speed at which it reverts to that level. Agents with little capital or high environmental quality may initially choose not to do any maintenance. The country will move out of the "zero-maintenance" region and make investments to reverse the effects of economic growth on the environment only if the returns to maintenance are sufficiently high. This means that if the steady state level of maintenance is positive, then the steady state may have either degraded or improved environment depending on the parameter values that characterize the sensitivity of the environment to human activity.

It is unclear in this context exactly how to interpret a value of E>0, as this would imply that development and growth have improved environmental quality above the level that would exist without human activity. This ambiguity represents a potential weakness of the model. However, it is important that John and Pecchenino (1994, 1995) have determined that the central results of the optimal growth models can also be arrived at in an overlapping generation's framework. The economy may initially be characterized by declining environmental quality when consumption levels are low; but given sufficient returns to environmental maintenance, in this case a sufficiently high value of γ, maintenance will eventually be undertaken and environmental quality will recover. This model can even give the unrealistic result that economic development improves the quality of the environment absolutely.

Copeland and Taylor (1994) present a many-goods general equilibrium model with two regions, North and South. This is a similar specification to that chosen by Chichilinsky (1994), as previously discussed, but in that case, the factor endowments of the two regions are identical. In this model the regions differ because of different human capital endowments, specifically, the South has a lower level of human capital than the North. This means that welfare gains from trade unambiguously exist, even when pollution is added to the firms' production functions, and even if pollution increases as a result of trade.

To provide a link between income and pollution levels, Copeland and Taylor (1994) make the strong assumption that there are optimal pollution taxes in both regions. These taxes are endogenous because as income increases they are raised to satisfy the increased preference for environmental protection that accompanies higher income. In this sense, the Environmental Kuznets Curve derived in other macro models is assumed here.

When trade begins, wages are lower in the South and as a result, pollution taxes are lower there. In deciding where to relocate, firms trade-off the levels of human capital in each region against the prevailing levels of pollution taxes. In response to the differential rates of taxation, relatively “dirty” industries locate in the S where they can optimally pollute more per unit of output than they would choose if located in the North. To take advantage of the higher levels of human capital, relatively “clean” firms migrate to the North. This means that compared to autarky, Southern workers reallocate from clean industries to dirty ones. Even though trade increases income and thus the optimal pollution tax, this does not offset the increased regional pollution by dirty firms once located in the North and now located in the South. Trade increases both Southern pollution and world pollution.

The results of the model are more nuanced when an increase in human capital in either region is exogenously imposed. In autarky an increase in human capital increases pollution in either region via a “scale” effect. Increased human capital makes firms more productive and output of all firms is increased. However, because optimal taxation is endogenous to income this is exactly offset by increases in taxes. In net, the level of pollution is unaffected by economic growth. This is also the result under free trade between the regions if equal growth occurs in the North and the South.

If human capital increases in only the South, marginal industries migrate there to take advantage of the increased worker productivity. These marginal industries are cleaner than the average industry in the South. This “composition” effect, combined with increased pollution taxes as a result of growth, implies that Southern pollution falls. Likewise, Northern pollution also falls because that region lost its dirtiest industries to the South as a result of the human capital increase there. Under the strong assumption of worldwide endogenous optimal pollution taxation, trade alone increases pollution; trade and growth on the other hand, defined in this case as an increase in the stock of human capital, can lower pollution. This section has reviewed major theoretical models of the macro interaction between environmental degradation and growth. I close this section by summarizing the implications of these models and suggesting avenues for future research that these models present.

IV. Lessons From Macroeconomic Models Of Environment And Growth and Areas for Future Research

The macroeconomic models presented here have similar solution methods and motivations, despite their different specifications. In general, the model is specified to be concerned with either a stock or a flow of pollution; functional forms for utility and output production are chosen. Most often, whatever the model structure, the social planner's problem is solved. When a decentralized result is presented, it is often burdened by the strong assumption that the government is able and willing to achieve the optimal regulation standard, and do so in a cost effective way (Stokey, 1998, Copeland and Taylor, 1994). As Stokey (1998) points out, these optimal regulation problems may reasonably approximate relatively wealthy democratic countries. However, it is more likely to be a heroic leap to impose this specification on the entire world as Copeland and Taylor (1994) do.

When the social planner's problem is solved, these models generally support the empirical findings of the Environmental Kuznets Curve literature (Panayotou 1993, Grossman and Krueger 1995) that was reviewed in the previous section of this chapter. As Selden and Song (1995) point out, the inverted-U shaped relationship between environment and growth is implicit in many of the models of the 1970s such as Forster (1977). Later authors, such as Lopez (1994) and Stokey (1998) explicitly compare their theoretical results to the findings of Grossman and Kreuger (1995), among others.

The results of both the optimal growth models and the endogenous growth models are sensitive to the specification of the utility function. As discussed above, the assumption of additive separability with respect to consumption and pollution is not a harmless simplification. Much the macroeconomic theoretical support for the Environmental Kuznets Curve depends on this specification.

The discussion above suggests several promising areas for research. First, to the extent possible, empirical investigations should be undertaken to determine that additive separability or a negative cross derivative is a reasonable assumption. As presciently recognized by Keeler, Spence, and Zeckhauser (1971), this is a critical assumption that is not fully justified simply by introspection.

Second, there is a need for models that find a middle ground between a decentralized world in which firms pollute without bound and an optimal but highly stylized world in which pollution taxes are optimally set and collected at all points in time. The work of Ligthhard and Van der Ploeg (1994) is starting point for a more realistic role of government in these macroeconomic models. The same is true for the work of Bovenberg and Smulders (1995, 1996) in which the tax set by the government is sub-optimally low. These models suggest that extensions motivated by the results of the "double-dividend" hypothesis (Sandmo 1975, Goulder 1995) regarding the interaction of traditional and environmental taxes, and extensions that draw on the results of the literature regarding the cost of sub-optimal regulation (Grey 1987, Jaffe, et al. 1995) may be both interesting and useful.

Table 1. A Summary of Empirical Studies of the Environmental Kuznets Curve (EKC) Hypothesis.

Author and explanatory indicator	***Dependent Variable***	***Relation Shape***	***Turning Point (GDP/per)***	***Remarks***
I	***II***	***III***	***IV***	***V***
Shafik & Bandyopadhyay (1992) GDP/per US$ 1985 ppp	Lack of clean water	Linear downward	Decline monotonically	Sample includes 149 countries for the period 1960-1990
	Lack of urban sanitation	Linear downward	Decline monotonically	
	Level of particulate matters,	Quadratic	na	
	Sulfur oxides(SO2)	Quadratic U-inverted	3000	
	Changes in forest area	Quadratic	na	
	Annual rate of deforestation	Quadratic U-inverted	2000	
	Dissolved oxygen in rivers	Quadratic	na	
	Municipal waste per capita	Quadratic	na	
	Carbon emissions per capita	Quadratic U-inverted	4000	
Hettige, Lucas &Wheeler (1992) GDP/per US$ 1985	Toxic Intensity by GDP	Quadratic U-inverted	12790	Global; Toxic intensity of 80 countries; Logarithm
	Toxic Intensity by par industrial output	Quadratic	na	
Holtz-Eakin & Selden (1992) GDP/per US$ 1985	CO2	Quadratic U-inverted	35400	Global; Emissions per Capita
		Cubic N-normal	28010	
Panayotou (1993) GDP/per US$ 1985	SO2	Quadratic U-inverted	3000	Global; Emissions per Capita Deforestation
	NOx	Quadratic U-inverted	5500	
	PES	Quadratic U-inverted	4500	
	Deforestation rate	Quadratic U-inverted	1200	
Grossman and Krueger. (1993) GDP/per US$ 1985 ppp	SO2	Cubic N-normal	a) 4107 b)14000	Global; Data of GEMS Urban concentration of pollutants
	SPM	Cubic N-normal	Decreasing	
	Smoke	Cubic N-normal	a) 5000 b) 10000	
Shafik (1994) GDP/per US$ 1985 ppp Time series	Lack of safe water	Linear downward	na	Global; Data of the World Bank (WDR 1992, environmental data appendix) Linear, quadratic et cubic logarithm are tested
	Lack of urban sanitation	Linear downward	na	
	Annual deforestation	Quadratic U-inverted		
	Total deforestation	Quadratic U-inverted		
	Dissolved oxygen in rivers	Linear downward	na	
	Fecal coliform in rivers	Cubic N-normal	a) 1375 b)11500	
	Ambient SPM	Quadratic U-inverted	3280	
	Ambient SO2	Quadratic U-inverted	3670	
	Municipal waste per capita	Linear upward	na	
	Carbon emission per capita	Linear upward	na	
Selden and Song (1994) GDP/per US$ 1985 Population density	Estimation by random effect:			Global Data from WRI 1991 30 countries in the sample
	- SO2	Cubic N-normal	10700	
	- SPM	Cubic N-normal	9600	

	- Nox	Cubic N-normal	21800	
	- CO	Cubic N-normal	19100	
	Estimation by fixed effect:			
	- SO2	Cubic N-normal	8900	
	- SPM	Cubic N-normal	9800	
	- Nox	Cubic N-normal	12000	
	- CO	Cubic N-normal	6200	
Cropper and Griffiths (1994) GDP/per US$ 1985 Wood price Density of rural population	Deforestation rate	Quadratic,		Regional: 64 countries in the sample Deforestation observed during 1961-1991 Data from FAO
		Africa, U-inverted	4760	
		L. America, U-inverted	5420	
		Asia, na	na	
Kazuki (1995) GDP/per. Yen 70	Deforestation	Quadratic U-inverted	446 $70	Japan; Annual concentration in ppm; Yen is converted to Dollar
	SO2	Quadratic U-inverted	1295 $70	
	NOx	Quadratic U-inverted	1587 $70	
Antle and Heidebrink (1995) GDP/per US$ 1985	Total area of parks and protected areas (PARKS)	Quadratic U-inverted	U-shape pattern	Data from World Development Report 1987, Environmental Data report and from the World Resource 1990-91
	Deforestation (DEFOR)			
	Afforestation (AFFOR),	Quadratic U-inverted	U-shape pattern	
	Total forest area (FOR)	Quadratic U-inverted	U-shape pattern	
Grossman and Krueger (1995) GDP/per US$ 1985 et Mean GDP/ per	Sulfur dioxide (SO2)	Cubic N-normal	a)4053 b)14000	Global; Data are from GEMS Pollutant concentration in cities and rivers
	Smoke	Cubic N-normal	6151	
	Heavy particles	Cubic N-normal	Decreasing	
	Dissolved oxygen	Cubic N-normal	2703(*)	
	Biological oxygen demand (BOD)	Cubic N-normal	7623	
	Chemical oxygen demand (COD)	Cubic N-normal	7853	
	Concentration of nitrates	Cubic N-normal	10524	
	Fecal coliform	Cubic N-normal	7955	
	Total coliform	Cubic N-normal	3043	
	Concentration of lead	Cubic N-normal	1887	
	Cadmium	Cubic N-normal	11632	
	Arsenic	Cubic N-normal	4900	
	Mercury	Cubic N-normal	5047	
	Nickel	Cubic N-normal	4113	
Rock (1996) GDP US$ 1985	Heavy metals	Quadratic U-inverted	10800	Emissions of heavy metals
Panayotou (1997) GDP/per US$ 1985 ppp Population density; Industrial share; GDP growth; Policy	SO2	Cubic N-normal	a) 5000 b) 15000	The sample includes 30 developed and developing country for the period 1982-94
Roberts and Grimes (1997) GDP/per US$ 1987	CO2	Quadratic U-inverted	na	Data come from World Bank and from the Carbon Dioxide Information and Analysis Center (CDIAC)
Schmalensee, Stoker and Judson. (1997) GDP/per US$ 1985 ppp	CO2	Log –linear	10000	National level panel data set for 47 countries from 1950 to 1990
Cole, Rayner and Bates	Nitrogen oxides (NOx)	Quadratic U-inverted	15100 (14700) **	Cross-country/region data

(1997)	Sulfur dioxide (SO2 SPM CO NOx of transport sector SO2 of transport sector SPM of transport sector Nitrates Carbon dioxide (CO2) Energy consumption CFCs and halons Methane (NH4) Municipal waste Transport energy use Traffic volume	Quadratic U-inverted Quadratic U-inverted Quadratic U-inverted Quadratic U-inverted Quadratic U-inverted Quadratic U-inverted Quadratic U-inverted Quadratic U-inverted Quadratic U-inverted Quadratic U-inverted Quadratic U-inverted Quadratic U-inverted Quadratic U-inverted Quadratic U-inverted	5700 (6900) 8100 (7300) 10100 (9900) 15100 (17600) 9400 (9800) 15000 (18000) 15600 (25000) 25100 (62700) 22500 (34700) 15400 (12600) na na 400000 (4 mill.) 108200 (65300)	from OECD countries.
Vincent J. (1997) GDP/per RM78 Population density	SPM Biochemical oxygen demand (BOD) Chemical oxygen demand (COD) Ammoniac nitrogen pH Solid particles in rivers	Cubic N-inverted Cubic N-inverted Cubic N-inverted Cubic, na Cubic, na Cubic, na	na (increasing) na (decreasing) na (increasing) na (no form) na (no form) na (no form)	Malaysia Use the data set with observations from the late 1970's into the early 1990's.
Hettige, Mani and Wheeler (1997)	Industrial Water Pollution	Linear upward	na	Factor level-data on industrial water pollution from twelve countries
Carson , Jeon and McCubbin (1997) GDP/per US$ 1982	Greenhouse gases, Air toxics,90 Carbon monoxide Nitrogen oxides Sulfur dioxide Volatile organic carbon Particulate matter Air toxics,88-94	Linear downward Linear downward Linear downward Linear downward Linear downward Linear downward Linear downward Linear downward	Decreasing Decreasing Decreasing Decreasing Decreasing Decreasing Decreasing Decreasing	Data come from the 50 US states
Moomaw and Unruh (1997) GDP/per US$ 1985	CO2 (panel) CO2 (for each country)	Cubic N-normal Linear downward	12813 18333 na	Data are from the Oak Ridge National Laboratory and from the Penn World Tables
Komen, Gerking & Folmer (1997) GDP/per US$ 1991	PRD	Linear upward	na	19 countries of OECD
Ravallion, Heil and Jalan (1997) GDP/per US$ 1985 ppp	Carbon Emissions	Cubic N-normal	U-shape pattern	Data are from the Oak Ridge National Laboratory and from UN statistical division
Torras and Boyce (1998) GDP/per US$ 1985 ppp	SO2 Smoke Heavy particles Dissolved Oxygen Fecal coliform Access to safe water Access to sanitation	Cubic N-normal Cubic N-normal Cubic N-normal Cubic N-normal Cubic N-normal Cubic N-normal Cubic N-normal	3890 4350 Decreasing Increasing Increasing 11255 10957	Data cover the period 1977-1991 and are taken from GEMS
Unruh and Moomaw (1998) GDP/per US$ 1985 ppp	Carbon dioxide (CO2) emissions	Cubic N-normal	na	Data is obtained from Summers and Heston (1994), for 16 countries
Suri and Chapman (1998) GDP/per US$ 1985 ppp	Consumption of primary commercial energy per capita, expressed in terms of oil equivalents	Quadratic U-inverted	55000	Data consist of observations on 33 countries over the period 1971-1990. Data are from IEA

Bruyn, Bergh and Opschoor (1998) Economic growth rate	CO2 NOx SO2	Linear logarithm Linear logarithm Linear logarithm	na na na	Data from the Netherlands, Western Germany, the UK and the USA, For various time intervals between 1960 and 1993
Rothman (1998) GDP/per US$ 1985 ppp	Food, beverages and tobacco Garment and footwear Gross rent, fuel and power Medical care and services Other commodities	Quadratic U-inverted Quadratic U-inverted Quadratic U-inverted Quadratic U-inverted Quadratic U-inverted	12889 35263 23278 47171	Data from United Nation International Comparison Programme
Kaufman, Davidsdottir, Garnham and Pauly (1998) GDP/per US$ 1985	SO2 (cross-section) SO2 (fixed effects) SO2 (random effects)	Quadratic U-inverted Quadratic U-inverted Quadratic U-inverted	11577 12500 12175	Data are from UN Statistical Yearbook 1993. Panel of international data for 23 countries
Chaudhuri and Pfaff (1998)	Indoor air pollution	Quadratic U-inverted	na	The micro data come from the Pakistan Integrated Household Survey (PIHS) 1991
Kahn (1998)	Vehicle hydrocarbon emissions	Quadratic U-inverted	35000	Data from the Random Roadside Test, created by the California Department of Consumer Affairs Bureau of Automotive Repairs
Islam, Vincent and Panayotou (1999)	Suspended particulate matter (SPM)	Quadratic U-inverted	na	GEMS data on suspended particulate matter. The data contain 901 observations from 23 countries for the period 1977-88
Panayotou, Sachs & Peterson (1999) GDP/per US$ 1985 ppp	Carbon dioxide (CO)	Quadratic U-inverted	12000	The study combined time series and cross-section national level data to construct a panel with 3,869 observations for the period 1960-92
Galeotti and Lanza (1999)	Carbon dioxide (CO2)	Quadratic U-inverted	13260	New data set developed by IEA that covers the period between 1960-1995
Bhattarai & Hammig (2000) GDP/per US$ 1998 ppp	Deforestation	Quadratic U-inverted	6800	Data from FAO, WRI and the UNEP for 1980, 1990 and 1995. National Income, exchange rates and trade data are taken from the Penn World Tables, from Summers and Heston (1991).

Table 2. DIFFERENT MODELS OF THE ENVIRONMENTAL KUZNETS CURVE (EKC) HYPOTHESIS.

1) Income per capita (y)

The most simple model specification shows a relationship between an environmental indicator (E) and the income per capita (y).This form also includes, in some cases, a time trend. The following forms are normally present in the studies on the EKC hypothesis:

Linear	$E_{it}=\beta_0 + \beta_1 y_{it} + \varepsilon_{it}$
Quadratic	$E_{it}=\beta_0 + \beta_1 y_{it} + \beta_2 y^2_{it} + \varepsilon_{it}$
Log-linear	$E_{it}=\beta_0 + \beta_1 \ln(y_{it}) + \varepsilon_{it}$
Log-Quadratic	$E_{it}=\beta_0 + \beta_1 \ln(\mathbf{y}_{it}) + \beta_2 (\ln \mathbf{y}_{it})^2 + \varepsilon_{it}$

where: E = environmental indicator
y = income per capita
ε = error term
β = parameter to be estimated
t = time trend

Among the studies that followed this specification, we found: Shafik and Bandyopadhyay (1992), Hettige, Lucas and Wheeler (1992), Shafik (1994) and Rothman (1998), Kahn (1998)

2) Income per capita (**y**) and Population (**P**)

Several models on the EKC hypothesis include population as an important variable, the most common specification includes population density (**P**) in a log-quadratic form.

Log-Quadratic $$E_{it}=\beta_0 + \beta_1 \ln(\mathbf{y}_{it}) + \beta_2 \ln(\mathbf{P}_{it}) + \beta_3 (\ln \mathbf{y}_{it})^2 + \beta_4 (\ln \mathbf{P}_{it})^2 + \varepsilon_{it}$$

Among the studies that followed this specification, we found: Panayotou (1993), Selden and Song (1994), Cropper and Griffiths (1994), Roberts and Grimes (1997), Vincent (1997), Carson, Jeon and MacCubbin (1997)

3) Income per capita (**y**), Population (**P**) and Geography (**G**)

Some models include income per capita, population density and geographic characteristics in order to reflect the dispersal properties of the local atmosphere. The most common specification is shown in a quadratic form.

Quadratic $$E_{it}=\beta_0 + \beta_1 (\mathbf{y}_{it}) + \beta_2 (\mathbf{P}_{it}) + \beta_3 (\mathbf{G}_{it}) + \beta_4 (\mathbf{y}_{it})^2 + \beta_5 (\mathbf{P}_{it})^2 + \beta_6 (\mathbf{G}_{it})^2 + \varepsilon_{it}$$

Among the studies that followed this form, we found: Grossman and Krueger (1993), Grossman and Krueger (1995)

4) Income per capita (**y**), Population (**P**), Growth (**g**), and Policy (**p**)

More comprehensive models include income per capita, population density and growth and policy variables. The most common specification is shown in a cubic form

Cubic $$E_{it}=\beta_0 + \beta_1 (\mathbf{y}_{it}) + \beta_2 (\mathbf{y}_{it})^2 + \beta_3 (\mathbf{y}_{it})^3 + \beta_4 (\mathbf{P}_{it}) + \beta_5 (\mathbf{P}_{it})^2 + \beta_6 (\mathbf{P}_{it})^3 + \beta_7 (\mathbf{g}_{it}) + \beta_8 (\mathbf{g}_{it})(\mathbf{y}_{it}) + \beta_9 (\mathbf{p}_{it}) + \beta_{10} (\mathbf{p}_{it})(\mathbf{y}_{it}) + \varepsilon_{it}$$

Among the studies that followed this form, we found: Panayotou (1997)

Table 2. (cont.) DIFFERENT MODELS OF THE ENVIRONMENTAL KUZNETS CURVE (EKC) HYPOTHESIS

5) Income per capita (**y**), and Trade variables (**T**)

Other models include income per capita and variables related to trade, for example, intensity of commerce, import-manufacturing ratio; Export-manufacturing ratio or prices for important goods such as, steel or wood. The most common specification is shown in a quadratic form

Quadratic $E_{it}=\beta_0 + \beta_1 \mathbf{y}_{it} + \beta_2 \mathbf{y}^2_{it} + \mathbf{T}_{it} + \varepsilon_{it}$

Among the studies that followed this form, we found: Cropper and Griffiths (1994); Cole , Rayner, and Bates (1997); Suri and Chapman (1998); Kaufmann, Davidsdottir, Garnham, and Pauly (1998)

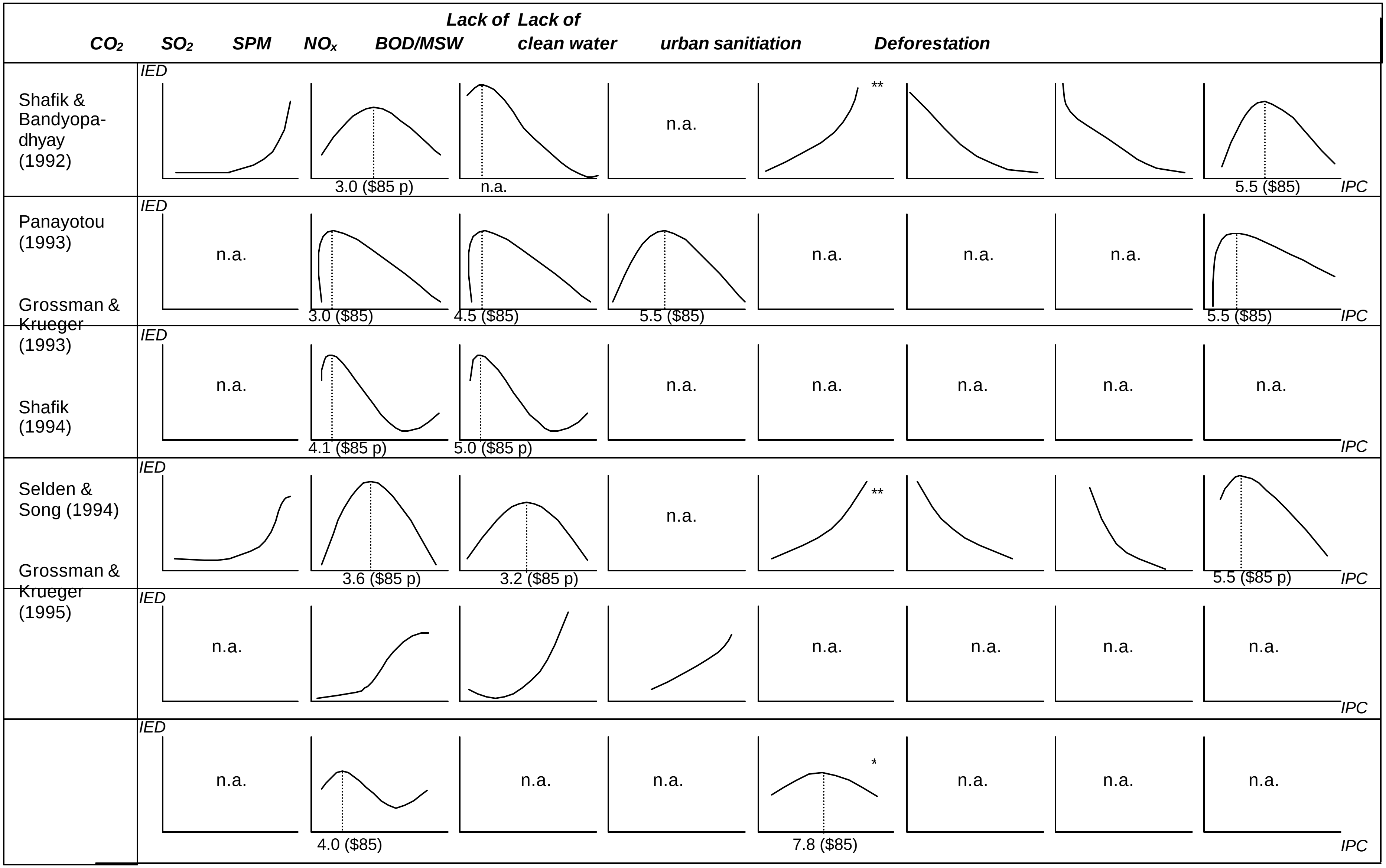
6) Income per capita (**y**), institution related variables (**I**), and Macro-policy related variables (**M**)

Different models include income per capita and variables related to Institutions such as political rights and civil liberties, and macro-policy related variables such as black market premium on the exchange rate or debt as a proportion of GDP. The most common model specification is shown in a linear form

Linear $E_{it}=\beta_0 + \beta_1 y_{it} + \beta_2 I_{it} + \beta_2 M_{it}$

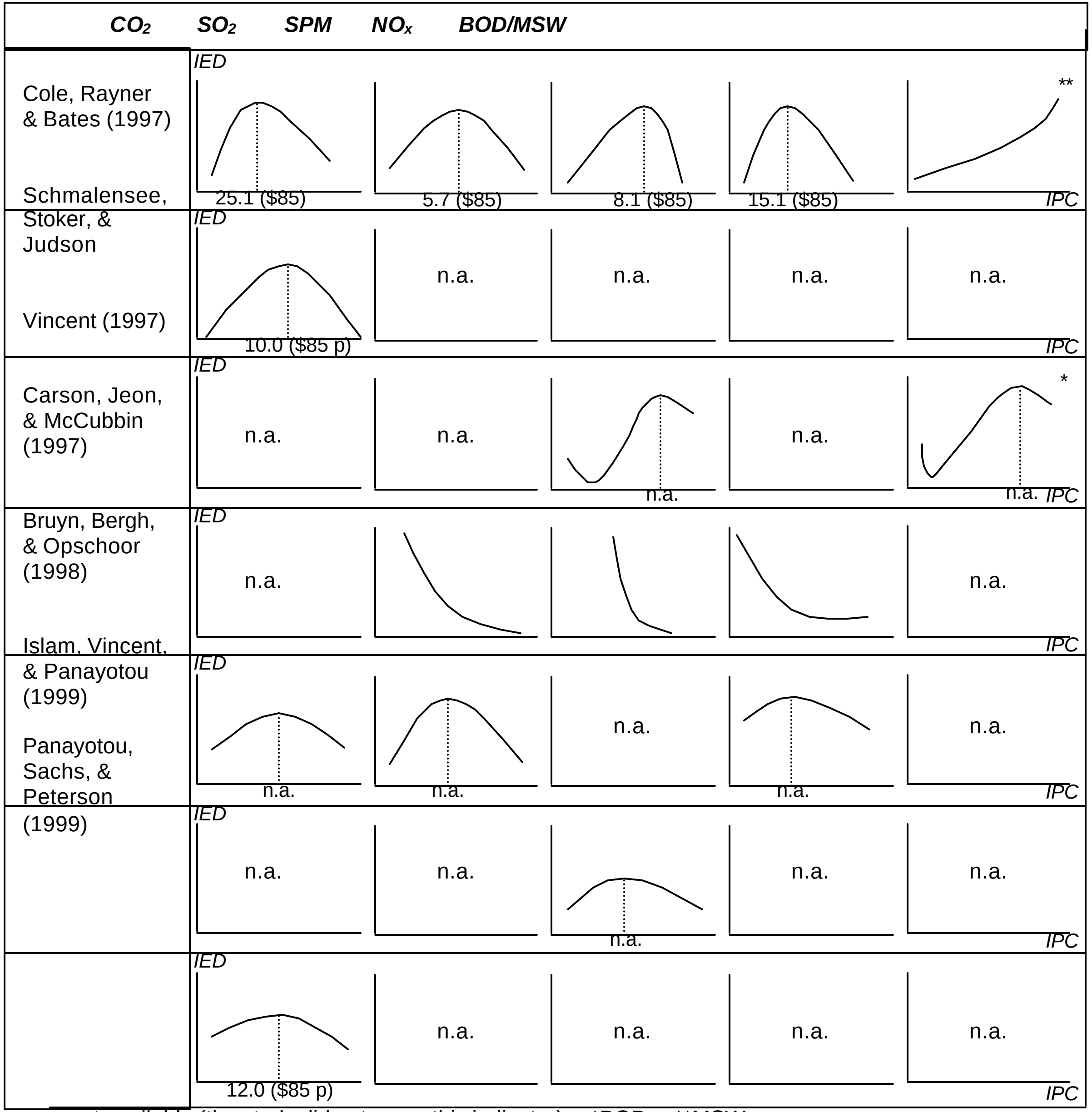
Among the studies that followed this form, we found: Torras and Boyce (1998) and Bhattarai and Hammig (2000)

Figure 1. *Empirical Relationship Between Income per Capita (IPC) and Selected Indicators of Environmental Degradation (IED), Estimated by Selected Studies*



n.a. = not available (the study did not cover this indicator)   *BOD   **MSW

Figure 1. (cont.) ***Empirical Relationship Between Income per Capita (IPC) and Selected Indicators of Environmental Degradation (IED), Estimated by Selected Studies (1)***



n.a. = not available (the study did not cover this indicator) *BOD **MSW

Notes:

CO_2 = Carbon Dioxide
SO_2 = Sulfure Dioxide
SPM = Suspended Particulate Matter
NO_x = Nitrogen Oxides
BOD = Biochemical Oxygen Demand
MSW = Municipal Solid Waste

Turning Points:

First two digits mean thousands, ei 7.6
($85) = GDP/per capita in US $ of 1995
($85 p) = GDP/per capita given in PPP based on US $ of 1985

(1)

The studies in this page did not cover “Lack of clean water,” “Lack of urban sanitation,” and “Deforestation.”

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Appendix. A Summary of Empirical Studies of the Environmental Kuznets Curve (EKC) Hypothesis.

Author (Source)	Dependent Variables	**Data**	**Model**	• Results/ **Turning point**
Shafik and Bandyopadhyay (1992)	Lack of clean water, lack of urban sanitation, level of particulate matters, sulfur oxides, changes in forest area, annual rate of deforestation, dissolved oxygen in rivers, municipal waste per capita and carbon emissions per capita.	The sample includes up to 149 countries for 1960-1990, though the coverage is very patchy. Some of the dependent variable are for cities within countries other for countries as a whole.	The study uses three different functional forms: log-linear, log-quadratic and in the general case logarithmic cubic polynomial in GDP per capita and time trend. GDP per capita was measure in $PPP terms and site-related variables are added where relevant.	Turning point for deforestation is around **$2000** per capita. Lack of clean water and lack urban sanitation decline monotonically with increasing income. River quality tends to worsen with increasing income. The two air pollutants conform to EKC, the turning points for both pollutants are for incomes between **$3000** and **$4000**. The time trend is significantly positive for fecal coliform and significantly negative for air quality. Municipal waste and carbon emissions per capita unambiguously increase with rising income.
Hettige, Lucas and Wheeler (1992)	Toxic intensity of manufacturing	Measures of toxic intensity in 80 countries from 1960-1988. For each country and year the authors have used UN industrial data to calculate shares of total manufactured output for 37 sector defined in the international standard industrial classification (ISIC).	The authors distinguish between the pattern of change in pollutant intensity measured per unit of GDP and intensity measured per unit of industrial output. In all equation the left-hand variable is log of pollutant intensity. The authors allow for a direct quadratic effect of per capita income and include an interaction between per capita income and time to test for the impact of per capita income on the change of intensity.	The authors found an inverse U-shape pattern for intensity per unit of GDP. However, they found no such pattern for intensity per unit of industrial output. The results suggest that the pollution intensity of manufacturing output rises steadily with income. The authors conclude that the GDP-based intensity result is due solely to a broad shift from industry toward lower-polluting services as development proceeds. The authors also made the analysis for toxic intensity change and trade policy, they found that intensity has grown more rapidly in economies that are relatively closed to international trade.

Appendix. A Summary of Empirical Studies of the Environmental Kuznets Curve (EKC) Hypothesis.

Author (Source)	Dependent Variables	**Data**	**Model**	- Results/ **Turning point**
Panayotou (1993)	Sulfur dioxide (SO2), nitrogen oxides (NOx), suspended particle matter (SPM) and deforestation.	Cross-sectional data; GDP is in, 1985, nominal US dollars. The three pollutants are measured in terms of emissions per capita on a national basis. There are 68 countries in the deforestation sample and 54 in the pollution sample.	The fitted equation for the three pollutants are logarithmic quadratic in income per capita. For reforestation the author fits a translog function in population density and income per capita, with the addition of a dummy variable for tropical countries. The author uses official exchange rates rather than $PPP rates.	All the estimated curves are inverted U's. For the sample mean population density, the turning point for deforestation is **$823** per capita. For SO2 emissions the turning point is around **$3000** per capita, for NOx around **$5,500** per capita, and for SPM around **$4,500**. (all in 1985 dollars)
Grossman and Krueger. (1993)	Sulfur dioxide (SO2), dark matter (fine smoke), and suspended particle matter (SPM); part of a study assessing the impact of NAFTA in Mexico	The data were taken from GEMS by the World Health Organization. These data refer to measurements of ambient air quality in two or three locations in each group of cities in a number of countries during 1977-88.	Each regression involves a cubic function of real 1985 per capita GDP measured in $PPP taken from the Summers and Heston (1991) data. Each includes site-related variables, a time trend, and a trade intensity variable. The site-related variables were included to differentiate between variations in ambient levels of pollution due to the influence of city and site characteristics and that due to the EKC relationship.	The turning points for SO2 and dark matter are at around **$4000-5000**. The joint significance levels for the three income variables in each of these regressions are less than 0.0001. The concentration of suspended particles appeared to decline even at low-income levels. Both the time trend and trade intensity variables had a significant negative coefficient in the SO2 regression. Neither the time trend nor the trade variables were significant in the equation explaining the concentration of dark matter. The time trend was significant in the suspended particles regression but again the trade variable was insignificant. At an income level of **$10000-15000** Grossman and Krueger's estimates show increasing levels for all three pollutants. Though economic growth at middle-income levels would improve environmental quality, growth at high-income levels would be detrimental to the environment.
Shafik (1994)	Lack of safe water, lack of urban sanitation, annual deforestation, total deforestation,	Data from up to 149 countries for the period 1960-90. The data for change in forest area is	The focus is on the relationship between environmental quality and per capita income. The indication are use as dependent variables in panel regression based on ordinary	The results indicate that access to clean water and urban sanitation clearly improves with higher per capita income. The results for deforestation are more complex. The annual variation in deforestation rates is deceptive since countries that depleted their forest in the distant past and have slowed

Appendix. A Summary of Empirical Studies of the Environmental Kuznets Curve (EKC) Hypothesis.

Author (Source)	Dependent Variables	**Data**	**Model**	• Results/ **Turning point**
	dissolved oxygen in rivers, fecal coliform in rivers, ambient SPM, ambient SO2, municipal waste per capita, carbon emission per capita.	between 1961-86, the annual rate of deforestation is between 1962-82. Real per capita gross domestic product in PPP were used for the period 1960-88 for 95 countries from Penn World Tables. For safe water, data were available only for two years 1975 and 1985 for 44 countries. For urban sanitation, data were available for years 1980 and 1985 for 55 countries. Fecal coliform's data are for 52 rivers in 25 countries. Sulfur dioxide data were available for 31 countries for the years 1972-82.	least squares estimates. Three models were tested, log linear, quadratic and cubic.	down more recently would appear to be doing better than countries with substantial forest resources that have only recently begun to draw down timber stock. In deforestation none of the income terms are significant in any specification. The measures of rivers quality worsen with rising per capita income. Local air pollution tends to behave as a "bell shape" curve. The turning point for SPM is at per capita income around **$3280**. The turning point for sulfur dioxide is at per capita income around **$3670**. For local air pollution a bell shape curve was found, turning point was **$3670**. Municipal waste is an indicator that worsen with rising incomes. Carbon emissions per capita also worsen with rising incomes; the turning point in a quadratic specification for carbon emissions occurs at income levels well outside the sample range.
Selden and Song (1994)	Four airborne emissions: sulfur dioxide (SO2), nitrogen oxides (NOx), suspended particle matters	The data are pooled time-series and cross-sectional data drawn from WRI 1991. The data are averages for	The focus of the analysis is on the relationship between per capita emissions, *m*, real per capita GDP, *y*, and population density, *d*, $m_{it} = b_0 + b_1 y_{it} + b_2 y^2_{it} + b_d d_{it} + e_{it}$ where *i* is the country index, and *t*	With the exception of the CO model, the coefficient estimates for the income terms were significantly different from zero. The estimated turning points are: SO2 **$8709**, NOx **$11217**, SPM **$10289** and CO **$5963.** The authors explain that these are higher than Grossman and Krueger's (1993).

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Author (Source)	Dependent Variables	**Data**	**Model**	• Results/ **Turning point**
	(SPM), and carbon monoxide (CO). The emissions are measured in terms of kilograms per capita on a national basis; derived for fuel consumption figures.	1973-75, 1979-81 and 1982-84. Of the 30 countries in the sample, 22 were categorized as high income, six as middle income and two as low income.	*is the time index, and* ε is a disturbance term with mean zero and finite variance. Dummy variables are included to capture the year effects. To control for the country effects, the authors estimate both fixed-effects and random-effects version of the model.	
Cropper and Griffiths (1994)	Deforestation	The regions are Africa, Latin America, and Asia. Deforestation observed during 1961-1991 for 64 countries	For each region pooled time series cross-section data are used. The dependent variable is the percentage change in forest area between two years. The independent variables in each regression are: rural population density, percentage change in population , timber price, per capita GDP and percentage change in per capita GDP ($PPP), square of per capita GDP, a dummy variable for each country, and a time trend.	The results for Africa show adjusted R-squares of 0.63 and 0.47 respectively, which given the use of dummy variables are low. Neither the population growth rate nor the time trend were significant in either region, and the price of tropical logs was insignificant in Africa. None of the coefficients in Asia regression were significant and the R-square is only 0.13. For Africa the turning point is **$4760** and for Latin America **$5420**.
Antle and Heidebrink (1995)	Total area of parks and protected areas (PARKS), deforestation (DEFOR), afforestation (AFFOR), total forest area (FOR)	Values for AREA and for 1985 GNP per capita are from the World Development Report 1987. PARKS data are from the 1989/1990 Environmental Data Report by the UNEP. FOR and DEFOR data are from World Resources 1990-91	Equations were estimated using ordinary least squares. To capture the nonlinearity hypothesized to exist between the dependent variables and income, the equation were specified as quadratic in income	The authors suggest a U-shape pattern. They found that the income elasticity of demand for environmental quality is near zero for countries with per capita income less than about $1200. The income elasticity for higher income countries is found to be positive and generally greater that one.

Appendix. A Summary of Empirical Studies of the Environmental Kuznets Curve (EKC) Hypothesis.

Author (Source)	Dependent Variables	**Data**	**Model**	• Results/ **Turning point**
Grossman and Krueger (1995)	Sulfur dioxide (SO2), smoke, heavy particles, dissolved oxygen, biological oxygen demand (BOD), chemical oxygen demand (COD), concentration of nitrates, fecal coliform, total coliform, concentration of lead, cadmium, arsenic, mercury and nickel	Data are from GEMS. The sample for air quality includes the years 1977, 1982 and 1988 and comprised a total of 42 countries for SO2; a total of 29 countries for heavy particles; a total of 19 countries for smoke. The data for dissolved oxygen, BOD, COD and nitrates cover the period from 1979 to 1990 and include 58 different countries. For fecal coliform the data set includes 42 countries and for total coliform it includes 22 countries. For heavy metals the data set includes 10 countries.	The authors estimate several reduced-form equations that relate the level of pollution to a flexible function of the current and lagged income per capital in the country. The authors measured the dependent variable as concentration level, with the exception of fecal coliform and total coliform, which were measured as log(1+Y), where Y is the concentration level. The authors included a cubic of the average GDP per capita in the preceding years to proxy the effect of "permanent income". The authors adjusted for the year by including a linear time trend as a separate regressor. The author also included additional covariates to describe characteristics of the site where the monitoring stations where located.	For the three urban air pollutants, the authors found that increases in income are associated with lower concentration at both **$10000** and **$12000**. For water quality indicators the turning points are at least **$7500** except for dissolved oxygen at **$10000** and **$12000**. For nitrates the turning point is at **$12000**. For fecal colifrom the turning point is at **$8000**. For total colifom the authors found a N-shape pattern, by **$10000** the relationship is upward sloping. In the case of the heavy metals, the results are the following: for lead, the relationship is downward sloping, for cadmium it is flat, and for arsenic it resembles an inverted U. The turning point for arsenic is at **$4900**.
Panayotou (1997)	Sulfur dioxide (SO2)	The sample includes 30 developed and developing countries for the period 1982-94.The GDP variable is taken from the World Tables (1995) and is measured in terms of 1985 constant US dollars. PPP – adjusted GDP figures were not used because they were not available beyond	A basic model is employed, which includes only income per capita and population density and two variables of special interest: the rate of economic growth and a policy variable. In order not to unduly constrain the relationship, a cubic functional form is postulated. A linear time trend is also included to capture exogenous advances in technology and/or increases in	Two models were estimated. All variables in Model I are statistically significant at least at the 10% level and have the expected signs indicating the presence of an inverted U-shaped relationship between ambient SO2 and income per capita within the range of income data. A similar relationship exists between SO2 and population density. The overall fit of Model I is not high (R^2 = 0.148), implying that variables other than income and population density also matter. Model II introduced two variables of interest: GDP growth rate and a policy variable, represented by enforcement of contracts. The overall fit increased by over

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Author (Source)	Dependent Variables	**Data**	**Model**	• Results/ **Turning point**
		1992.	environmental awareness. A third model decomposed economic growth into scale, composition and pure-income effects. Scale of economic activity is represented by GDP per unit of area, the composition of economic activity by industry share and income effects by GDP per capita, which determines both the demand and supply for environmental quality.	60% from 0.148 to 0.238. The square of population density became statistically insignificant; the constant became negative and less significant as did all income terms through still significant at least at the 10% level. Both the growth rate and the policy variables as additive terms were highly significant and had the expected signs.. The EKC for SO2 attains a turning point at a per capita just under **US$5000.** The decomposition of income growth into its constituents improves the fit dramatically and income stripped of its scale and structure effects captures only the abatement effect.
Roberts and Grimes (1997)	Carbon dioxide (CO2)	The authors examine for the 30 years during 1961-91 how many kgs of carbon dioxide countries emitted per unit of their GDP (National Carbon Intensity, NCI). Test for an inverted U-curve relationship for CO2 and track the changes in NCI of low, middle and high income countries. Data come from World Bank and from the Carbon Dioxide Information and Analysis Center (CDIAC). World Bank GDP values were adjusted for inflation using WB 's GDP deflator and exchange rate for 1987.	ln (CO2/ GDP). For the time-series they compare NCI with GDP per capita. They use GDP per capita at market exchange rate rather than $PPP partly because of more extensive availability for countries and years.	The relationship between NCI and level of economic development has changed from essentially linear in 1965 to curvilinear in 1990. The quadratic is statistically significant in the early 1970's and then again since 1982. The only group of countries showing a net improvement in CO2 intensity over the period were the high-income countries. As a group the low-income countries have become steadily less efficient in carbon terms over the period. The middle-income countries have worsened in carbon intensity over the period, but less severely than the poor nations. The findings suggest that the EKC for carbon emissions is the result not of individual countries passing through stages of development, but of a relatively small number of wealthy ones becoming more efficient since 1970 while the average for the rest of the world worsens.

Appendix. A Summary of Empirical Studies of the Environmental Kuznets Curve (EKC) Hypothesis.

Author (Source)	Dependent Variables	**Data**	**Model**	• Results/ **Turning point**
Schmalensee , Stoker and Judson. (1997)	Carbon dioxide (CO2)	Large national-level panel data set for 47 countries from 1950 to 1990. The data set contains 4018 observations. In 1991 it covers 141 countries or 98.6% of the world's population. The geographic coverage of these data increases in 1970 with 60% of the observations coming from the period 1970-1990. The data for GDP are in PPP millions of 1985 US dollars taken from Penn World Tables.	Projections derived from a reduced-form econometric model. Using i to refer to country and t to refer to years, they specify: Ln (cit)=a + B +F[ln(yit)]+Eit Where c=C/N and y= Y/N and a and b are country and year fixed effects, respectively, F is some reasonably flexible function . The authors employed per capita quantities. Log-linear specifications are more attractive because multiplicative country and year fixed effects seem more plausible than additive effects, given the vast differences among nations in the data.	They initially approximated the function F by polynomials. Sixth order functions had all significant coefficients and fit the data well. However, lower order polynomials fit the data nearly as well, and polynomials with essentially identical fits and in-sample shapes imply wildly different predictions for income level above the sample. Their forecast involve the assumption that the income elasticity estimated for the sample observations with the highest levels of per-capita GDP will also apply at all higher income levels. Developing countries, with lower GDP per capita, experience continued rapid carbon emissions growth. The developed countries showed a clear change in carbon emission from growth to either stability or decline. The turning point for the US is **$10000 GDP** per capital.
Cole, Rayner and Bates (1997)	Carbon dioxide (CO2), CFCs and halons, methane, nitrogen oxides (NOx), suspended matter, sulfur dioxide (SO2), municipal waste, energy consumption and traffic volume	Use cross-country/region data. For nitrogen dioxide, sulfur dioxide, and suspended particulate matter (SPM) the data are for the period 1970-90, for OECD countries. For carbon dioxide the data are for 1960-91, for 7 regions. For CFCs the data are for the period 1986-90, for 38 countries. Municipal waste data are for the period 1975-90, for 13 countries. Total energy use data are for	Using generalized least square (GSL), standard errors at the estimated turning points were calculated. Exogenous shift variables are included: in particular, country region-specific intercept dummy variables to allow for the differential impact of natural endowments on environmental quality; a linear time trend to allow technological change; and, trade intensity to represent trade openness. Two alternative functional forms were used for estimating the equation,	The estimated turning points in 1985 US$ for emissions per capita are the following: Variable — Quadratic log — Quadratic levels Sulfur dioxide — $6900 — $5700 Sulfur dioxide(Trans) — $9800 — $9400 Particulate matter — $7300 — $8100 Part. matter(Trans) — $18000 — $15000 Carbon monoxide — $9900 — $10100 Nitrogen dioxide — $14700 — $15100 Nitrogen dioxide(Trans) — $17600 — $15100 Nitrates — $25000 — $15600 Carbon dioxide — $62700 — $25100 CFCs / Halons — $12600 — $15400 Traffic volumes — $65300 — $108200 Energy use — $34700 — $22500

Appendix. A Summary of Empirical Studies of the Environmental Kuznets Curve (EKC) Hypothesis.

Author (Source)	Dependent Variables	**Data**	**Model**	• Results/ **Turning point**
		1980-92, for 22 countries and methane data are late 1980's, for 88 countries.	quadratic in levels and quadratic in logarithms. A cubic function was also considered. The study concentrates on quadratic relationships. For CFC's and halons log-linear relationships were also considered	Transp. energy use $4 mill $0.4 mill For municipal waste and methane there were no turning points estimated.
Vincent J. (1997)	Suspended particulates (TSP), and five water-quality parameter; biochemical oxygen demand, chemical oxygen demand, pH and suspended solids	Analysis of pollution-income relationship for Malaysia. Use data set with observations from the late 1970's into the early 1990's. The data are ambient levels from monitoring stations. The sample included at least one station in all Malaysian states except Kelantan and Perlis.	Population density is measured at a monitor station locations. Per capita population impact is specified as a function of a constant (per capita GDP in the state where the station was located) The constant aims to capture per capita impacts invariant to income and time. Both fixed effect and random effect model specifications are estimated.	For any of the variables, the pollution-income relationship was not an EKC. The relation was positive for all the variables. Higher income was associated with higher concentration of ammoniacal nitrogen and higher pH values; there was lack of significant relationship between biochemical oxygen demand or chemical oxygen demand and per capita GDP. There was also a lack of relationship between suspended solid and per capita GDP.
Hettige, Mani and Wheeler (1997)	Industrial water pollution	The authors have collected factory-level data on industrial water pollution from twelve countries: Brazil, China, Finland, India, Indonesia, Korea, Mexico, Netherlands, Philippines , Sri Lanka, Taiwan, Thailand and USA. They use organic water pollution because it provides the most reliable information for cross-country comparison	Using panel data, the authors investigate the effects of income per capita, regulatory strictness and relative input prices on factory-level pollution intensity (pollution/output). They also add a measure of regulatory strictness to a cross-country labor intensity equation to test the impact of regulation on the demand for labor. To test EKC the authors measure the effect of income growth on three determinants of pollution: the share of	They found that manufacturing share follows an EKC trajectory, but the other two determinants do not. Sectoral composition improves through middle-income status and then stabilizes. At the end-of-pipe, pollution intensity declines strongly with income. The authors attribute this result to stricter regulation as incomes increase, and partly to pollution-labor complementarity in production. The authors find that income elasticities of both pollution and labor intensity are approximately minus one and conclude that a sector's pollution/labor ratio is constant across countries at all income levels. The results do not support the Kuznets hypothesis for industrial water pollution.

Appendix. A Summary of Empirical Studies of the Environmental Kuznets Curve (EKC) Hypothesis.

Author (Source)	Dependent Variables	**Data**	**Model**	- Results/ **Turning point**
			manufacturing in total output, the sectoral composition of manufacturing and the intensity of industrial pollution at the end-of-pipe.	
Carson , Jeon and McCubbin (1997)	Greenhouse gases, air toxins, carbon monoxide, nitrogen oxides, sulfur dioxide, volatile organic carbon and particulate matter	The data come from the 50 US States. The income is expressed in thousands of 1982 US dollars. The authors analyze 1990 state-level per capita emissions for greenhouse gases converted to pounds of equivalent carbon dioxide, air toxins and point-source emission of CO, NOx, SO2, VOC and PM. Of the air pollutants, only air toxins emissions for the period 1988-94 were analyzed	Using OLS the authors regress the per capita emissions for each emission class on per capita income. Since the results are likely to be influenced by outliners, the author provide regression estimates based on Turkey's bi-weight loss function and correction for multiplicative heteroscedasticity. The author also estimated log-log models.	The coefficients of GNP per capita are all negative showing that air emissions per capita decrease as GNP per capita increases. The results are consistent with the relation predicted by EKC. The environmental Kuznets curve is stronger when relatively low-income states as West Virginia and Wyoming are given equal weight with other states. The high-income states have low per capita emissions while emissions in the lower- income states are highly variable.
Moomaw and Unruh (1997)	Carbon dioxide (CO2)	CO2 emissions data are from the Oak Ridge National Laboratory (1995) and the income series in real per capita GDP (1985 US$) from Penn World Tables. Panel of 16 countries, data for the periods 1950-1973 and 1974-1992	Authors set data up as a panel of pooled cross-country and time series data in order to test the standard EKC models. Two models were estimated fixed-effects and cross sections. The authors also used structural transition models as an alternative to EKC models	EKC emission reversal at higher incomes is present in the data. All t-statistics indicate the results to be significant. The fixed-effects estimates indicate an income turning point of **$12813**. In the second model, the cubic term is also statistically significant indicating an N-shape curve with a income turning point is **$18333**. This indicates that emission will begin to rise again once this second turning point is passed. The authors conclude that EKC models may not be appropriate for forecasting future emission behavior. They consider structural transition models a better description by accounting for historical shocks but these are equally inappropriate for predicting future change.

Appendix. A Summary of Empirical Studies of the Environmental Kuznets Curve (EKC) Hypothesis.

Author (Source)	Dependent Variables	**Data**	**Model**	• Results/ **Turning point**
Ravallion, Heil and Jalan (1997)	Carbon Emissions	Data are from Oak Ridge National Laboratory. Data on fuel use are from UN statistical division. The method of Marland and Rotty (1994) is applied to these data in order to convert fuel consumption and cement manufacturing into carbon emissions. Per capita GDP is given in PPP adjusted values based on 1985 US dollars. The data include a total of 42 countries.	The authors give fitted values from a cubic function of income, estimated as a simple pooled model by OLS. The regression also includes a time trend and population. The time trend is negative and the population effect is positive. The bi-variate relationship between carbon emissions and average income suggests a decreasing Marginal Propensity to Emit (MPE). The authors also tried regressing the log of the emission rate against both a quadratic and cubic function of the log of average income.	The authors found that trade offs do exit between reducing carbon emissions and promoting both lower inequality (between and within countries) and higher average incomes. In the short term, poverty reduction will tend to increase carbon emissions. The authors however, found signs of a flattening out of the relationship between emissions and average incomes at middle to high income levels, and signs of a reversal in the curvature at high incomes. The authors also found interaction effects between average incomes and inequality in their effects on carbon emissions. They found a sizable positive impact of higher income inequality on the aggregate income elasticity of carbon emissions.
Torras and Boyce (1998)	Sulfur dioxide, smoke, heavy particles, dissolved oxygen, fecal coliform, safe water (%), sanitation (%)	The data cover the period 1977-1991 and are taken from GEMS. The air pollution data contain observations from 19-42 countries. The water data contain 58 countries. All these data are location-specific. The variable percentage of population with access to safe water and access to sanitation are taken from UNDP 1994. Per capita income is measured in PPP.	A structural model was used, in the form POL= f(Y, π, Z), where POL is the level of pollution and Z is a vector of non-economic determinants of pollution levels, (such as income inequality, literacy and political rights) and π is power inequality . Per capita income is included to allowed for possible effects on pollution aside from those mediated by power inequality. The authors predict that greater power inequality will be associated with higher levels of pollution, as those who benefit from pollution-generating activities are better able to prevail against those who bear the cost.	Sulfur dioxide showed a EKC form; however, significant positive coefficients imply that the pollutants eventually resume a rising trend. Airborne heavy particles diminish with income. Dissolve oxygen in water improves with income. Fecal coliform shows a inverted-U shape pattern. The percentage of population with safe water and sanitation increases with income. The peak points are the following: Power Inequality Included Excluded Sulfur dioxide $3360 $3890 Smoke NSS $4350 Heavy particles NSS MD Dissolved Oxygen $19865 MI Fecal colifom NSS MI Access to safe water $6900 $11255 Access to sanitation MI $10957

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Author (Source)	Dependent Variables	**Data**	**Model**	• Results/ **Turning point**
				NSS= not statistically significant MD= monotonic decrease MI= monotonic increase
Unruh and Moomaw (1998)	Carbon dioxide (CO2) emissions	The data is obtained from Summers and Heston (1994), for 16 countries: Austria, Belgium, Canada, Denmark, Finland, France, West Germany, Iceland, Italy, Japan, Luxembourg, Netherlands, Sweden, Switzerland, UK and USA	In order to evaluate whether income is the determining variable of reduction of pollution, the authors applied a nonlinear dynamic model to CO2 emission data used in earlier studies. The analysis is applied to 16 OECD countries that in previous studies showed an EKC pattern.	The authors conclude that income is not the determining variable, the interpretation of applying a nonlinear dynamic model is that CO2 emission exhibit a behavior that could be called punctuated equilibrium. Emissions are expected to follow a regular, incremental path until subjected to a shock that leads to the establishment of a new trajectory. There are many sources of shock in complex socio-economic systems. The oil price shock provides an impetus that changes the trajectory of CO2 emissions.
Suri and Chapman (1998)	Consumption of primary commercial energy per capita, expressed in terms of oil equivalents	The data consists of observations on 33 countries over the period 1971-1990 or 1991 in some cases. The data on energy was obtained from IEA. GDP data were obtained from Penn World table and it is in 1985 PPP.	The authors use commercial energy, the main source of a number of pollutants, to study the EKC hypothesis. Total emission of pollutant j (pij) from energy source Ei is defined as pij = aijEij, where aij is emission per unit of energy. The focus of the model is on the impact of growth, international trade and structural change on the turning points of pollutants through their influence on E .	Two types of models are presented. In the first model, the impact of structural change and international trade are implicitly captured in a catch-all term, GDPSQ. The turning point for energy consumption **is $55000**, well outside the sample range. In the second model, the authors analyze the effect of international trade on commercial energy consumption with trade the turning point increases to around **$224000**. Ceteris paribus, this would imply that incorporating trade effects would also tend to raise the turning point of pollutant emissions related to energy use.
Bruyn, Bergh, and Opschoor (1998)	Carbon dioxide (CO2), nitrogen oxide (NOx), and sulfur dioxide (SO2)	Data from the Netherlands, Western Germany, the UK and the USA. For various time intervals between 1960 and 1993. CO2 emissions (1961-1990) were taken from the Oak Ridge National Laboratory. SO2 and NOx are taken from the	They use a reduced form model, relating per capita emissions to per capita income. The overall fit of the model is satisfactory. The R^2 range in most cases between 0.35 and 0.7, i.e., on average, half of the variations in emissions is explained by the factors in the model. The only exception is SO2	The parameter representing the effect of economic growth on emissions, is positive and significant in all cases, except for SO2 emissions for the Netherlands. These results clearly suggest that economic growth does have a positive influence on the growth of emissions. Emissions may decline over time probably due to technological and structural change. The analysis suggests that only in haft of the investigated cases, income accumulation may have explained the reduction in the level of emissions. The

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Author (Source)	Dependent Variables	**Data**	**Model**	- Results/ **Turning point**
		EPA emissions trend report (1994) and OECD (1993)	in the Netherlands where the model does not fit the data.	authors derived the conclusion that the presumption that economic growth results in improvements in environmental quality is unsupported by the evidence in the countries in the analysis.
Kaufmann, Davidsdottir, Garnham and Pauly (1998)	Sulfur dioxide (SO2)	Data on SO2 are from UN Statistical Yearbook 1993, GDP is in 1985 US dollars. The authors use a panel of international data for 23 countries. These include 13 developed nations, 7 developing nations and 3 centrally planned economies.	The authors estimate a new model that attempts to identify how economic activity affects the concentration of SO2. $SO2=\alpha+\beta 1(GDP/Population)+ \beta 2(GDP/Population)^2+ \beta 3(\text{Economic activity}/Area)+ \beta 4(\text{Economic Activity}/Area)^2+ \beta 5(\text{Iron and Steel export}/\text{Nominal GDP})+\beta 6\ Year$ the authors use fixed and random effects estimators to estimate the above equation.	The results indicate a U-shape relationship between GDP per capita and the concentration of SO2 regardless of the variable used to proxy the spatial intensity of economic activity. The concentration of SO2 tends to decrease as per capita GDP rises from **$3000** to **$12500**. Beyond $12500, further increases in per capita GDP are related to an increase in SO2. Time as a negative effect on concentrations. The inverted U-shape found by previous authors may only be a proxy for changes in the mix of economic activity that are associated with changes in per capita GDP. Previous studies may be biased by omission of variables that represent changes in the mix and spatial intensity of economic activity.
Chaudhuri and Pfaff (1998)	Indoor air pollution	The micro data come from the Pakistan Integrated Household Survey (PIHS) 1991. The PIHS includes individual and household-level data covering among other, energy consumption for 4800 households. The sample was drawn using a multi-state stratified sampling procedure from the Federal Bureau of Statistics based on the 1981 census.	The model includes the quantity of fuel consumed per month per capita by households. The key independent variable is the monthly per-capita income of the households. Dummy variable are intended to represent month and area. The authors used a maximum-likelihood Tobit procedure to estimate the equation	The major finding is statistically significant evidence in the fuel-choice behavior of a transition between traditional and modern fuel as per capita income rises. All of the modern fuel quantities, in the regression, rise with income, forming a concave shape. The author found a inverted-U relationship between household income and emissions.

Appendix. A Summary of Empirical Studies of the Environmental Kuznets Curve (EKC) Hypothesis.

Author (Source)	Dependent Variables	**Data**	**Model**	• Results/ **Turning point**
Kahn (1998)	Vehicle hydrocarbon emissions	The author used the Random Roadside Test, created by the California Department of Consumer Affairs Bureau of Automotive Repairs. The author also used the 1990 Census of Population and Housing.	The author merges household income to each record in the Random Roadside Test. The model $E(I) = e(I)*gpm(I)*miles(I)$ *represents a household's total annual contribution to local pollution as a function of its income (I). Where e represents emissions flow and gpm represents the inverse of vehicle miles per gallon..*	The author presents evidence of an inverted U shaped emissions/income relation. The turning point occurs at **$35000**. Households with incomes above that level create relatively less pollution. Average emissions for vehicles owned by households with income below $35000 are twice as high as average emission for households with income above $45000.
Islam, Vincent and Panayotou (1999)	Suspended particulate matter (SPM)	The authors use the GEMS data on suspended particulate matter. The data contain 901 observations from 23 countries for the period 1977-88. Canada, China and the USA are the most important sources of data. The number of cities in the data is 56.The author also used the World Tables.	The authors use panel data in fixed effects and random effects models. They started by identifying some of the forces that influence environmental quality: I) the level effect, ii) the composition effect and iii) the abatement effect. The author derive a multiplicative relationship among these variables. This resulted in a reduced form specification with structural mooring. The structural relationships were then recovered from the results of the reduced form regression.	The level effect is found to be monotonically increasing over the relevant range of values of GDP per unit of area. The composition effect displays an inverted-U shape. The abatement effect curve proves to be generally declining. From the results on the level effects the authors found that the ambient level of SPM has a positive relationship with the level of GDP per unit of area. The composition effect showed a hump-shaped relationship of the SPM level with the share of industry in GDP (Q). The peak is not reached until a long range of values of Q is passed, during which the SPM level increase almost linearly.
Panayotou, Sachs & Peterson (1999)	Carbon dioxide (CO)	The study combined time series and cross-section national level data to construct a panel with 3,869 observations for the period 1960-92. The sample includes 127 countries	A relationship is estimated between per capita CO2 emissions , expressed as thousands of metric tons of carbon, and per capita income (y), expressed in 1985 PPP in dollars. Both variables are in logarithms:	The equation is estimated with three alternative spline functions, 5 segments, 10 segments and 12 segments. The authors chose the 10-segment specification because, at the 0.05 significant level, the 10 and 12-segment models were indistinguishable, while the 5-segment model was significantly different. The 10-segment specification explained 61% of within country variation and 81% of

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		accounting for approximately 95% of the world population and 90% of the global CO2 emissions from fossil fuels. These countries are those with population over 1 million for which emissions and income data are available. GDP (in 1985 $) PPP terms is taken from the Penn World Tables, updated for 1992, and the CO2 emissions data are from Marland et al. (1999).	$\ln (c_{it} = a_I + \beta_t + F[\ln(y_{it})] + \varepsilon_{it}$ Where i refers to countries and t refers to time in years. The set of parameters a_I reflects country-fixed effects, that is, persistent differences across countries in climatic conditions, fossil fuels and renewable energy endowments, in preferences, in economic structure, in regulations, and the like. The set of parameters β_t reflect changes over time such as changes in world oil prices, in technologies and environ. policies as well as in preferences unrelated to income levels.	between country variation. Overall 74% of the variation was explained. For all segments except the first, the estimated income elasticity was statistically significant at the 95% level. The income elasticities of emissions were positive for income levels below **$12000**. The elasticities become negative as incomes rise above that level. The largest elasticity is 1.05, and occurs for per capita incomes in the range of **$1500-$4000**. The findings suggest an inverted U-shaped relationship between income per capita and CO2 emissions per capita. As income increases from very low levels, emissions increase at an increasing rate; emissions reach a plateau at an intermediate level of income beyond which additional increases in incomes result in smaller and eventually negative additions to CO2 emissions.
Galeotti and Lanza (1999)	Carbon dioxide (CO2)	New data set developed by IEA that covers the period between 1960-1995. They use data that cover the 1971 to 1995 period for 108 countries. In 1995 these accounted for 88% of the CO2 emissions generated by fuel combustion. The sample consists of 2700 annual observations. They also consider a sub-sample of 28 OECD countries with 700 observations and 80 non-OECD countries for 2000 observations.	They use a linear in variables model and a log-linear specification. For each sample, two different specification were tried, respectively including an excluding a cubic income term. The fit of both equation is satisfactory when judged according to the adjusted R^2, with the log-linear specification performing marginally better especially in the case of the samples of "all countries" and "non-OECD countries". The reported F test show the statistical relevance of the country effects as well as that of the time effects, although	The fit is satisfactory in all cases and the parameter strongly significant. On this basis the authors are led to conclude that the estimated relationship display a bell shaped curve and that a well-behaved EKC is supported by the data. The turning points are the following : Gamma Weibull All Countries **$13260** **$13648** Non-OECD Countries **$17868** **$17079** OECD Countries **$15582** **$15709** The author concluded that when alternative functional forms are employed for describing the reduced –form relationship between CO2 emissions and GDP relative to

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			differences among countries are far more important that changes within countries over time. They have also tested two alternative functional forms Gamma and Weilbull and found them to give a superior fit compared to the conventional linear and log linear forms	the standard ones, the emergence of a bell-shaped ECK with reasonable turning point is a possibility that cannot be discarded.
Bhattarai & Hammig (2000)	Deforestation	The authors examine the relationship between income and deforestation in 21 countries in Latin America from 1972 to 1995. They also used data from FAO, WRI and the UNEP for 1980, 1990 and 1995. National Income, exchange rates and trade data are taken from the Penn World Tables, from Summers and Heston (1991). Index measures of sociopolitical institutions are taken from the Freedom House tables. Other variables are taken from the World Bank Development Report (1998). The authors used GDP per capita (PPP adjusted US dollars 1998)	Simple pooled regression, as well as fixed affects and random effects models were tested. The study uses the following equation: $DF_{it} = \boldsymbol{a}_i + \boldsymbol{b}_1 Y_{it} + \boldsymbol{b}_2 Y^2_{it} + \boldsymbol{b}_3 Y^3_{it} + \boldsymbol{b}_4 I_{it} + \boldsymbol{b}_5 Z_{it}$ Where DF is “deforestation measure in country *i*, year t”; Y is “GDP per capita (PPP adjusted US dollars)” ; T is “time trend”, I is “intuition related variables” and Z is “other macro-policy related variables. The fixed effect models performed better than the constant intercept and random effect models. The constant intercept model was rejected in favor of the fixed effect model by the Chow test, and the random effect model was rejected in favor of the fixed effect model by significant Hauseman test statistics.	The results of the study confirm the existence of an EKC for Latin America. The turning point is around **$6800** which is within the sample range –close to the income of Venezuela and Argentina, and less than the income of Trinidad and Tobago. Macroeconomic factors such as indebtedness, inflation and exchange rate policies would shift the intercept of the EKC. The results from the different forms the institution related variables in the analysis suggest that strengthening of socio-political institutions would reduce the present level of tropical deforestation in the region

Other authors that have made literature reviews and theoretical analysis of the Environmental Kuznets Curve (EKC) include: -Grossman (1995), Selden and Song (1995), Kaufman, Davidsdotter and Garnhan (1995), Arrow et al (1995), Rothman (1996), Stern, Common and Barbier (1996), Barbier (1997), Elkins (1997), Komen, Gerking and Folmer (1997), Andreoni and Levinson (1998), Stern (1998), Hilton and Levinson (1998)