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Desperately Seeking (Environmental) Kuznets: a New Look at the Evidence

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DESPERATELY SEEKING (ENVIRONMENTAL) KUZNETS: A NEW LOOK AT THE EVIDENCE

by

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Abstract. The number of studies seeking to empirically characterize the reduced-form relationship between a country economic growth and the quantity of pollutants produced in the process has recently increased significantly. In several cases researchers have found evidence pointing to an inverted-U "environmental Kuznets" curve. In the case of a major greenhouse gas, CO_2, however, the evidence is at best mixed. This paper attempts to shed further light on this issue by using a newly developed dataset on emissions and by employing a new highly flexible functional form.

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Keywords: Environment, Growth, CO_2 Emissions, Panel Data
JEL Classification: O13, Q30, Q32, C12, C23

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DESPERATELY SEEKING (ENVIRONMENTAL) KUZNETS: A NEW LOOK AT THE EVIDENCE

<u>Non-Technical Summary</u>

The relation between economic development and environmental quality is a very complex issue. For this reason, in the last few years several studies have tried to characterize this problem as an empirical reduced-form relationship. In particular, a few studies have identified a bell shaped curve for the pollution intensity of GDP. This behavior implies that, starting from low (per capita) income levels, (per capita) emissions or concentrations tend to increase but at a slower pace. After a certain level of income, emissions or concentrations start to decline as income further increases. In the case of a major greenhouse gas, CO_2, however, the evidence of an inverted-U "Kuznets curve" is at best mixed.

While all the studies have focused upon the empirical emergence of the environmental Kuznets curve and have typically discussed its implications with special reference to the value of the income turning point, the analysis concerning the robustness of the basic findings has not been, somewhat surprisingly, a major concern. The issue of the functional form for the reduced-form relationship between CO_2 emissions and GDP appears to be critical for the emergence of a bell shaped curve and for the crucial policy implications that could be drawn from such an empirical finding.

In this paper we reexamine the empirical relationship between a country GDP and the emissions of CO_2 using an alternative, possibly better, dataset. In addition, we propose and implement a new, highly flexible functional form relative to the norm in the literature.

Keywords: Environment, Growth, CO_2 Emissions, Panel Data

JEL Classification: O13, Q30, Q32, C12, C23

DESPERATELY SEEKING (ENVIRONMENTAL) KUZNETS: A NEW LOOK AT THE EVIDENCE

1. Introduction

The threat of climate change due to global warming is an issue whose relevance is by now recognized by all experts, governments, and public opinions throughout the world. The 1992 Rio Earth Summit and the 1997 Kyoto Agreement have called the international attention upon the negative consequences as well as upon the potential instruments to tackle this problem.

One of the most important issues in the policy arena is related to the role that should be played by developing countries. In fact, while the industrialized countries have agreed in Kyoto upon an overall 5% reduction in greenhouse gas emissions relative to 1990 levels, no such commitment has been taken by developing countries. The usual argument in favor of this position is that the industrialization and economic growth process should require no constraint particularly for energy production and consumption.

Whatever the fate of the Kyoto Protocol, underlying this position there is a long-standing debate on the relationship between economic development and environmental quality. This is quite complicated an issue to analyze and depends upon a host of different factors. This fact may explain why most of the work on the topic, at least until recently, has taken the form of empirical reduced-form investigations (out of many, see the very recent survey by Panayotou, 2000).

After the seminal work of Shafik and Bandyopadyay (1992), Selden and Song (1994) and Grossman and Krueger (1995) several empirical studies have looked for or identified a bell shaped curve for the pollution intensity of GDP. This behavior implies that, starting from low (per capita) income levels, (per capita) emissions or concentrations tend to increase but at a slower pace. Beyond a certain level of income - the "turning point" - emissions or concentrations start to decline as income further increases. This bell shaped relationship between per capita income and pollution has been termed "Environmental Kuznets Curve" (EKC hereafter), after Simon Kuznets' work on growth and income distribution.

Although many authors warn about the non-structural nature of the relationship, if supported by the data, the inverted-U shape of the curve contains a powerful message: GDP is both the cause and the cure of the environmental problem. Among other things, the argument would provide strong support for developing countries to resist binding emission reduction targets such as those envisaged by the Kyoto Protocol.

Particularly in the case of CO_2 emissions this fact has such far-reaching implications that extreme caution and careful scrutiny are necessary when analyzing the issue. Indeed, the global nature of this pollutant and its crucial role as a major determinant of the greenhouse effect attribute to the analysis of the CO_2 emissions-income relationship special interest.[1]

The typical EKC study has the following features: (i) in general, in the relationship between per capita CO_2 emissions and per capita income no other explanatory variables are included, except possibly for a time trend; (ii) the analysis is usually conducted on a panel dataset of individual countries around the world. Due to the almost complete coverage of world countries, the estimation technique employed is the least square dummy variable method, allowing for both fixed country and time effects;[2] (iii) the data for CO_2 emissions almost invariably have come from a single source, the Oak Ridge National Laboratory;[3] (iv) the functional relationship considered is either linear or log-linear, with a few studies considering both.

Looking at the literature, an initial set of studies sharing the above characteristics have focused upon the empirical emergence of a bell shaped EKC and have typically discussed its implications with special reference to the level of the income turning point. A more recent crop of contributions has instead criticized the previous empirical practice and findings, the most recurrent criticism being the omission of relevant explanatory variables in the basic relationship. However, the analysis

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[1] Studies which have considered CO_2 emissions are Shafik and Bandyopadyay (1992), Holtz-Eakin and Selden, (1995), Tucker (1995), Cole, Rayner, and Bates (1997), Moomaw and Unruh (1997), Roberts and Grimes (1997) and Schmalensee, Stoker, and Judson (1998).

[2] Holtz-Eakin and Selden (1995) is the only study considering also a random effects specification, although fixed effects appear to be a more appropriate choice given that sample and population almost coincide in this case.

[3] The data for real per capita GDP are typically drawn from the Penn World Table and are on a PPP basis.

concerning the robustness of the basic findings has not been, somewhat surprisingly, a major concern.

One important aspect that has not undergone close scrutiny in essentially all the papers mentioned so far is the issue of functional forms relating CO_2 emissions to GDP. The only noticeable effort in that direction has been the explicit consideration of a third-order, rather than just a second-order polynomial for the linear or log-linear models. Also, only a couple of studies have estimated both linear and log-linear specifications. The issue of the functional form for the reduced-form relationship between CO_2 emissions and GDP appears to be critical for the emergence of a "well-behaved" EKC and for the crucial policy implications that could be drawn from such an empirical finding. Indeed, while many researchers warn that a reduced-form relationship is ill-suited for drawing policy prescriptions, it cannot be denied that an inverted-U relationship for CO_2 emissions intensity suggests that pollution reduction might be expected to occur as a natural by-product of economic development.

In this paper we reexamine the empirical relationship between a country GDP and the emissions of CO_2 using an alternative, possibly better, dataset. In addition, we propose and implement a new, highly flexible functional form relative to the norm in the literature.

The structure of this note is the following. Section 2 discusses the new data on emissions vis-à-vis the standard dataset used by others. In section 3 we present and estimate an alternative functional form for the EKC as well as show the econometric results. Concluding remarks close the paper.

2. The Data

Our analysis exploits a dataset developed by IEA (International Energy Agency, 2000). It covers the period between 1960 to 1998 for the Annex II countries of the United Nations Framework Convention on Climate Change (Rio de Janeiro, 1992) and between 1971 to 1998 for all the other countries. In 1997 all countries accounted for nearly 90% of the CO_2 emissions generated by fuel combustion.

As mentioned in the Introduction, the data generally used in EKC studies concerned with CO_2 emissions have been those made available by the Carbon Dioxide

Information Analysis Center (CDIAC) of the Oak Ridge National Laboratory (Marland, Anders, Boden, Johnston, and Brenkert, 1998). CDIAC distributes and updates a specific dataset concerning global, regional, and national CO_2 emission estimates from fossil fuel burning, cement production, and gas flaring. The data are calculated using energy statistics published annually by the United Nations and using the methods described in Marland and Rotty (1983). Cement production estimates come from the U.S. Department of Interior's Bureau of Mines, while gas-flaring estimates are derived principally from United Nations energy statistics but supplemented with estimates from the U.S. Department of Energy. The available data are annual and cover the period 1950-1997.

There are several differences between the CDIAC dataset and the one used in this paper. The IEA dataset is based on energy balances and does not include either cement production or gas flaring. The impact of these emissions is however rather small and they collectively contributed less than 5% to total emissions in 1997. The IEA dataset appears to be more precise mainly because it has been able to use specific emission coefficients for different energy products, while in the CDIAC case a single coefficient is used for gas, oil, and solid fossil fuels without any distinction among individual energy products.[4]

As for the other variables, the series of Gross Domestic Product (GDP) and population of the OECD countries (with the exception of Czech Republic, Hungary, Poland and the Republic of Korea) come from the OECD Main Economic Indicators. The corresponding series for the other countries have been obtained from the World Bank.[5]

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[4] CO_2 emissions associated with a certain fuel are given by the product of the amount of fuel consumed (so called "apparent consumption", AC) times the average carbon content of the fuel (CC) times the fraction of the fuel which is oxidized in combustion (OF). This fraction in turn depends upon two factors: inefficiency of combustion plants (OF1) and non-energy use of the fuel (OF2). There are several differences in the computation of the above components between IEA and CDIAC methodologies. As for AC, the disaggregation of fuel types is higher for CDIAC than for IEA, but it is not exploited because, on the contrary, the former source uses fewer CC coefficients: in fact, while IEA uses 27 fuel specific CC coefficients, CDIAC uses only 3 (liquid, solid, and gas). Note that these coefficients vary neither over time nor across countries, with the exception of solid fuels in the IEA approach. Procedures in the computation of OF1 and OF2 are roughly similar. An appendix available from the authors provides a more detailed description of the two methodologies than is possible here.

[5] GDP data for the Czech Republic from 1990 onwards come from the OECD and from 1971 to 1989 are IEA estimates. As said in a previous footnote, the bulk of the literature uses GDP series drawn from the

In order to exploit all available information and, at the same time, account for the different stage of economic development, position relative to the technological frontier, and other structural differences, we carry out our empirical investigation separately for the samples of high income (OECD) and low income (non-OECD) countries.[6] The former includes 29 nations for 1131 observations, while the latter includes 105 countries for a total of 2940 observations.[7]

While it is not the purpose of this paper to conduct a detailed analysis of differences between the two datasets, we present a quick comparison of the two datasets by estimating a standard cubic log-linear EKC relationship for a comparable number of countries and period.[8] The evidence is presented in Table 1. The results are generally similar, except for a few aspects. Adjusted R^2s are a touch higher in the IEA case; the cubic term is not significant in the non-OECD/CDIAC sample. The most notable difference pertains to the estimated turning points which are distinctively higher when the IEA data are employed. This appears to be a reason good enough for not considering the two datasets as perfect substitutes.

3. A New Functional Form and Empirical Results

Basically all papers in the literature assume that the empirical relationship between per capita CO_2 emissions and GDP can be adequately described by a parametric model, and specifically by a polynomial function of income. The estimated regression models have often differed in two respects: (i) the equation is either linear or log-linear in the variables; (ii) the equation is either quadratic or cubic. Thus, for instance, Moomaw and Unruh (1997) consider a linear-in-variables specification with either

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Penn World Tables. However, the data publicly available are limited to 1992. For this reason and in order to focus more on the differences in emissions data, we use throughout the same GDP and population data.

6 Quantitatively speaking, the differences are not significant. The IEA numbers, however, are slightly bigger than the CDIAC in both sub-samples. Mean and median values of CO_2 (tons per capita) for CDIAC (IEA) are 8.577 (9.300) and 7.258 (7.662) in the OECD case and 3.538 (4.009) and 1.342 (1.368) in the non-OECD case respectively. The importance of distinguishing between high income and low income countries for EKC analysis is stressed in the recent paper by Stern and Common (2001).

7 There is a number of missing data in our samples either at the beginning or at the end of the series. In particular, 38 data points are missing in the OECD sample and 452 in the non-OECD dataset. Effective sample sizes are therefore 1093 and 2488 respectively.

8 The samples are limited to 1997 because CDIAC data are not available after that year. Moreover, we use 28 OECD countries excluding Norway, because CDIAC itself recognises that their data are not totally

quadratic or cubic income terms; Holtz-Eakin and Selden (1995) and Cole, Rayner, and Bates (1997) consider the two functional forms for both quadratic and cubic cases.

The choice between linear and log-linear models has been the subject of several contributions to the econometric literature and a central topic in the theory of non-nested hypothesis testing. While on conceptual grounds the selection of either specification is not without implications, for the purpose of studying the possible emergence of an inverted-U environmental Kuznets relationship a few remarks are important. Firstly, the log-linear model imposes non-negativity restrictions upon the variables, which the linear model does not. Secondly, the linear model imposes a symmetric behavior on the estimated relationships, a fact which appears unwarranted on a priori grounds. Thirdly, when a cubic linear-in-variables relationship is fitted to the data, the attractiveness of easily interpretable coefficients is lost. However, if significant, a cubic income term ought to be always included, no matter the magnitude of the corresponding coefficient. The possibility of obtaining an N-shaped curve which this fact implies, with two turning points and emissions increasing as income goes further up, can not be ruled out.[9] Finally, in the case of the log-linear specification, because of the non-linear transformation of the model variables, there is no closed form analytical expression for the income turning point and it is not possible to predict a priori the behavior of the function on the basis of the parameter signs, thus limiting their interpretability.

An alternative approach may consist of a non-parametric approach which in principle imposes no parametric restrictions on the form of the empirical EKC relationship. This is, for example, the strategy followed by Schmalensee, Stoker, and Judson (1998) who postulate a log-linear model with a spline (piecewise linear) function of income. While this is a sensible strategy, non-parametric approaches have their own limitations, which include the need of many data points and the so called curse of dimensionality which comes into play when more than one explanatory variable is

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reliable. The non-OECD sample has got 103 countries, as two nations are missing altogether from the dataset, unlike IEA.

[9] Some authors feel uncomfortable with this result. For instance, Holtz-Eakin and Selden (1995) refer to it as an "unattractive property", neglect the significant cubic term focusing the attention on the quadratic model.

considered. In this respect, we do not regard parametric and non-parametric approaches as perfect substitutes.[10]

The difficulties with the standard functional forms noted above, both from an analytical standpoint and in terms of empirical performance, have prompted us to search for alternative functional forms which were more desirable from the vantage point of (some or all) the following criteria: (i) easily interpretable parameters; (ii) range of possible shapes which can characterize the relationship under study not restrained a priori; (iii) possibility to obtain analytical closed-form expressions for the income turning point, so as not to be data dependent. In view of these aspects, consider the following non-linear functional form:

$$y = \frac{\alpha}{\beta}\left(\frac{x-\gamma}{\beta}\right)^{\alpha-1} \exp\left[-\left(\frac{x-\gamma}{\beta}\right)^{\alpha}\right] \tag{1}$$

In the statistical literature this expression is known as three-parameter Weibull function. It has also been used in applied environmental and ecological economics (Bai, Jakeman, and McAleer, 1992) and is widely employed in duration models. One of its advantages is the interpretability of the parameters: in fact, α, β, and γ are associated with "shape", "scale", and "shift" of the function: depending upon the values it takes on, the relationship can assume a variety of different behaviors. In particular, the scale parameter β can be directly related with the height of the function, and therefore with the amount of emissions at which the turning point, if it exists, occurs. The shift or location parameter γ controls the position of the function along the horizontal axis, and can thus be traced to the value of the income turning point.[11] Finally, the most crucial parameter is the shape parameter α, which governs the shape of the function.

A further valuable aspect of the Weibull functional form is that it admits an analytical closed form expression for the turning point. In fact, taking the derivative of y

[10] Bredford, Schlieckert, and Shore (2000) is a very recent example of empirical EKC study using an alternative functional parametric specification.

[11] The two-parameter version of the function, which is also a popular functional specification, obtains when γ=0. In the above expression both scale and shape parameters are expected to be positive and γ is less than the minimum observed sample value.

in (1) with respect to *x*, setting it equal to zero and solving for *x* yields the "turning point" x^{TP} as follows:

$$x^{TP} = \gamma + \beta\left(\frac{\alpha-1}{\alpha}\right)^{1/\alpha} \tag{2}$$

From these expression the role played by the function parameters clearly emerges.

The Weibull functional form is quite flexible but does not allow for the "N" shape, a behavior which can be quite relevant in the EKC context, as it indicates that emissions further increase as a country gets better and better off. A simple extension of the Weibull function which overcomes this important limitation consists of adding a parameter to (1), obtaining the following analytic formula:

$$y = \frac{\alpha}{\beta}\left(\frac{x-\gamma}{\beta}\right)^{\alpha-1} \exp\left[-\left(\frac{x-\gamma}{\beta}\right)^{\alpha} + \delta\left(\frac{x-\gamma}{\beta}\right)^{-\alpha}\right] \tag{3}$$

It easy to see that when $\delta = 0$ we go back to the Weibull family (1), whereas when $\delta > 0$ for suitable values of α we obtain an "N"-shaped function. In this respect, in Figures 1 we have plotted a few theoretical curves for arbitrary different values of the corresponding parameters. The graphs range from the inverted-U to exponentially decreasing, from increasing to N-shaped, all these patterns depending on the values of the two critical parameters, δ and α.[12] We further note that also a "reverse N" shape can be in principle obtained, and that the "standard" Weibull distribution ($\delta = 0$) becomes similar to the exponential distribution when $\alpha = 1$, reverse "J" shaped when $\alpha < 1$, and bell shaped when $\alpha > 1$. From the inspection of the graphs it also emerges that the requirement that emissions can not get negative is implicitly imposed.

[12] Also the Extended Weibull function produces an analytical expression for the income turning point. Space constraints however prevent us from a complete treatment of this issue, as the precise formula differs depending upon the values taken on by parameters δ and α. A short note on this issue is available from the authors upon request.

Turning to the empirical investigation, for our samples we have estimated (3) after introducing multiplicative fixed effects and taking logs, so that the regression model becomes:[13]

$$\log CO_{2it} = \psi_i + \psi_t + (\alpha - 1)\log\left(\frac{GDP_{it} - \gamma}{\beta}\right) - \left[\left(\frac{GDP_{it} - \gamma}{\beta}\right)^{\alpha} + \delta\left(\frac{GDP_{it} - \gamma}{\beta}\right)^{-\alpha}\right] + \omega_{it} \quad (4)$$

where CO_2 and GDP are emissions and income per capita.

The results of the estimation of (4) are presented in Table 2. The fit is satisfactory in all cases with a slight superiority of the non-OECD estimates when judged on the basis of the adjusted R-squared. In terms of statistical significance of the estimated parameters there are a few notable differences. While α and β are always significant, γ is not in a couple of cases, while most importantly δ is significant in the OECD sample and insignificant in the non-OECD case. This implies, on the one hand, that a Weibull functional form is an appropriate specification for the non-OECD countries, whereas that representation is not adequate for the other sample. It is of interest to visualize the shape that the two functions assume on the basis of our data and estimation results. From Figure 2 we see that all the estimated relationships display a bell shaped curve, with a marked asymmetry for the OECD sample and with a much less pronounced bell for the non-OECD data. Nevertheless on the basis of this evidence we are led to conclude that a "well-behaved" EKC is supported by our data. The turning points occur at reasonable values, with figures that are significantly higher in the case of non-OECD than of OECD countries, a fact that is consistent with the usual rationales put forth to justify hump-shaped EKCs.

Finally, in order to assess the robustness of our findings we have carried out the estimation using also the more popular CDIAC data. The results are presented in Table 3. There are a few notable differences. Firstly, the adjusted R^2s are slightly smaller, thus pointing to a somewhat inferior empirical performance relative to the IEA data. Secondly, the parameter δ is always insignificant, suggesting that a Weibull representation is adequate for this dataset. Finally, the estimated turning points occur at

[13] Note that the constant term corresponding to (1) is absorbed into the coefficients of the fixed effects.

about two thirds of the previous values. It can nonetheless be shown that also the CDIAC data lead to estimated EKCs with a bell-shape.[14]

4. Conclusions

The empirical research on the link that appears to exist between emissions of a major greenhouse gas and the degree of economic development of a country has been recently spurred by the renewed attention of scientists, policy-makers, and public opinion to the issue of climate change. The reduced-form relationship between per capita CO_2 emissions and per capita GDP is known as the Environmental Kuznets Curve and in a few studies it has conveniently displayed a bell shape. If supported by the data, this finding implies that emissions ought to "naturally" diminish as a country becomes richer and richer. Moreover, identifying the "turning point" would allow the observer of a country to precisely know where his/her country is located along the curve. There is econometric evidence, however, which does not find an inverted-U EKC, but rather, a more problematic N-shaped curve.

In this paper we have started from the observations that nearly all papers in the EKC literature use the same source of data for CO_2 emissions and almost invariably fit to the data either linear-in-variables or log-linear functional relationships. Departing from this practice, we have described and used a newly developed dataset for emissions. After having noted a few theoretical and empirical drawbacks of the standard functional specifications employed in the literature, we have proposed two alternative functional forms, the Weibull and a more flexible extension of it, which have been subsequently implemented. The estimated results are satisfactory and the features of the EKC relationship reasonable.

In summary, the evidence here presented demonstrates that, when alternative new functional forms are employed for describing the reduced-form relationship between CO_2 emissions and GDP relative to the standard ones, the emergence of a bell-shaped Environmetal Kuznets Curve with reasonable turning points is a possibility that cannot be discarded.

[14] For space reasons we do not display the corresponding figures, which are avalilable upon request.

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Table 1: Carbon Dioxide Emissions - GDP Relationship
Comparison between IEA and CDIAC Datasets

	OECD		Non-OECD	
	CDIAC	IEA	CDIAC	IEA
GDP	-19.51 (-5.341)	-40.981 (-9.600)	1.834 (0.881)	6.084 (3.181)
GDP square	2.604 (6.273)	4.972 (10.381)	-0.064 (-0.250)	-0.611 (-2.613)
GDP cube	-0.112 (-7.010)	-0.198 (-11.23)	-0.0022 (-0.224)	0.021 (2.23)
Number of Observations	1032	1026	2256	2317
SSR	34.899	30.216	227.712	192.761
Log Likelihood	283.542	352.798	-615.456	-407.028
Adjusted R square	0.931	0.936	0.954	0.966
Turning Point	*9860*	*11974*	*14638*	*34203*

Footnotes:

(1) Dependent variable: log of carbon dioxide emissions per capita; independent variable: log of GDP per capita. Estimated coefficients of country and time effects not reported.
(2) T-statistics in parenthesis. SSR stands for sum of square residuals.
(3) The turning point is expressed in PPP 1990 U.S. dollars.
(4) Sample period: 1960-1997 for OECD countries and 1971-1997 for non-OECD countries.

Table 2: Carbon Dioxide Emissions - GDP Relationship
Estimated Alternative Functional Forms – IEA Data

	OECD		Non-OECD	
	Extended Weibull	Weibull	Extended Weibull	Weibull
α	1.532 (35.63)	1.506 (24.69)	1.428 (22.31)	1.473 (43.32)
β	24027 (39.26)	24402 (37.20)	69335 (2.723)	56379 (4.878)
γ	963.4 (8.008)	180.5 (0.409)	-127.03 (-0.802)	148.65 (4.302)
δ	0.0019 (4.268)	-	-5.11E-04 (-1.085)	-
Number of Observations	1093		2488	
SSR	35.201	36.109	220.171	220.362
Log Likelihood	326.6	313.1	-513.831	-514.911
Adjusted R squared	0.926	0.925	0.965	0.965
Turning Point	*12886*	*12015*	*29829*	*26220*

Footnotes: see table 1.
(1) The sample period here includes the year 1998 in both sub-samples.

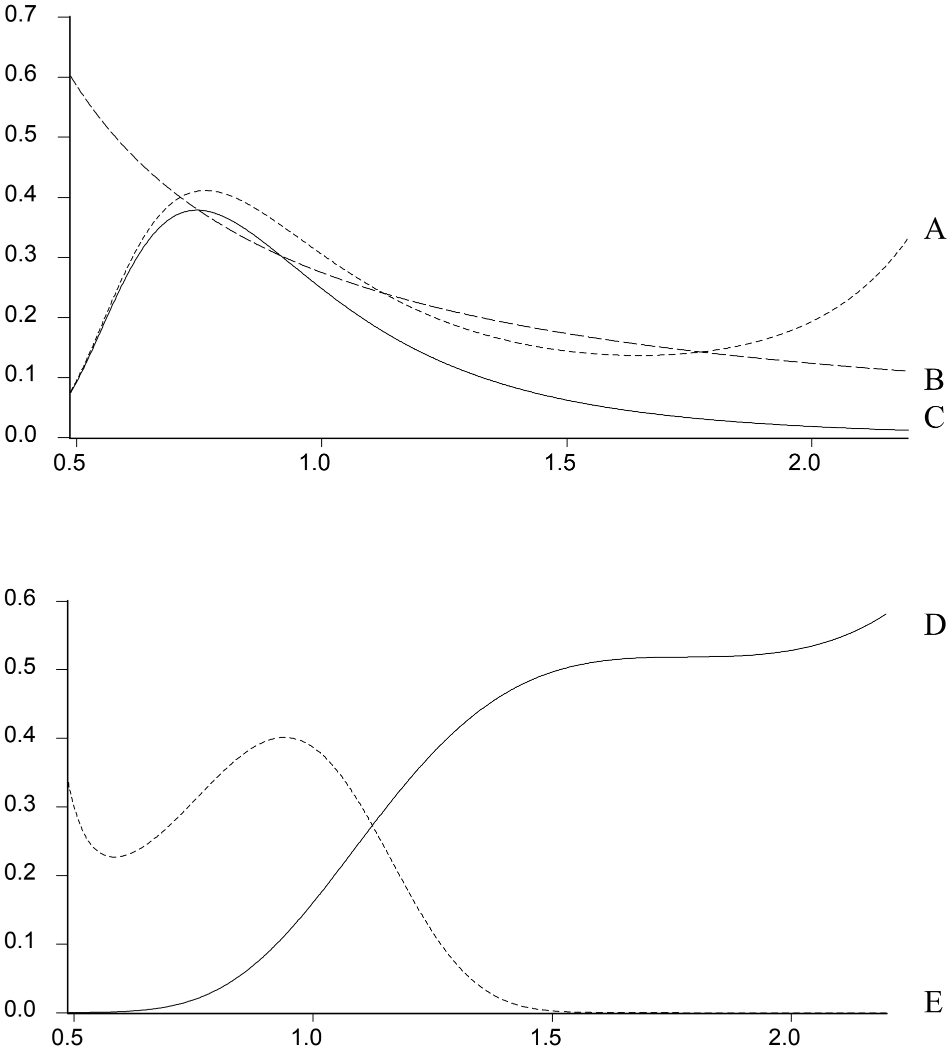
Table 3: Carbon Dioxide Emissions - GDP Relationship
Estimated Alternative Functional Forms – CDIAC Data

	OECD		Non-OECD	
	Extended Weibull	Weibull	Extended Weibull	Weibull
α	1.387 (20.42)	1.385 (48.70)	1.288 (11.20)	1.388 (24.79)
β	21898 (30.72)	21884 (33.43)	50570 (2.147)	38517 (4.448)
γ	1022.1 (0.967)	1052.0 (14.53)	57.709 (0.573)	213.07 (10.27)
δ	-9.42E-05 (-0.028)	-	-0.0011 (-0.831)	-
Number of Observations	1032		2256	
SSR	36.580	36.501	728.284	730.051
Log Likelihood	259.025	258.951	-1926.50	-1928.47
Adjusted R squared	0.928	0.928	0.868	0.867
Turning Point	*9754*	*9745*	*16129*	*15599*

Footnotes: see table 1.

Figure 1: Theoretical Extended Weibull Functions

$$\log CO_2 = \theta + (\alpha - 1)\log[(GDP - \gamma)/\beta] - [(GDP - \gamma)/\beta]^{\alpha} + \delta[(GDP - \gamma)/\beta]^{\alpha}$$



Possible Shapes:

(A) N-shaped: $0<\delta<1/4$; $\alpha \notin \left]\alpha_1, \alpha_2\right[$; $\alpha<0$ or $\delta>1/4$; $\alpha \in \left]\alpha_1, \alpha_2\right[$; $\alpha<0$

(B) exponentially decreasing $\delta>1/4$; $\alpha \in \left]\alpha_1, \alpha_2\right[$; $\alpha>0$ or $\delta>1/4$; $\alpha>\alpha_2>0$ or $0<\delta<1/4$; $\alpha \in \left]\alpha_1, \alpha_2\right[$

(C) bell-shaped: $\delta<0$ or $\delta=0$ (Weibull)

(D) increasing: $\delta>1/4$; $\alpha<\alpha_1<0$

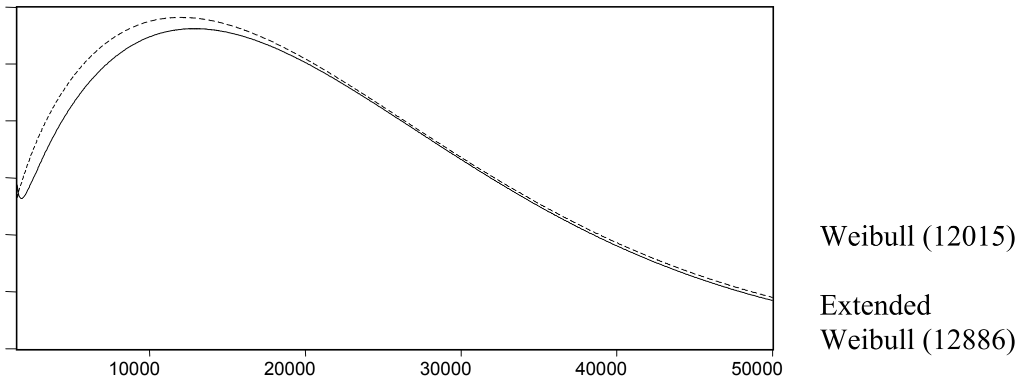
(E) reverse "N" $0<\delta<1/4$; $\alpha \notin \left]\alpha_1, \alpha_2\right[$; $\alpha>0$

where:

$$\alpha_1 = \frac{1+2\sqrt{\delta}}{1-4\delta}; \quad \alpha_2 = \frac{1-2\sqrt{\delta}}{1-4\delta}$$

Figure 2: Estimated Weibull Functional Forms – IEA Data
(Turning points in Brackets)

OECD Countries



Non-OECD Countries