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A CONSUMPTION-BASED APPROACH TO ENVIRONMENTAL KUZNETS CURVES USING THE ECOLOGICAL FOOTPRINT INDICATOR

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A consumption-based approach to environmental Kuznets curves using the ecological footprint indicator

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Abstract

Recent research suggests that consumption-based measures offer an insightful perspective on the debate on the relationship between economic growth and the environment. In this article, we deepen the consumption-based line of inquiry by investigating the empirical evidence in support of the environmental Kuznets hypothesis using 1961-2001 ecological footprint data. We test not only inverted-U and linear functions, but also power functions as potentially suitable models to represent the relationship between per capita income and environmental impact. Our results do not show evidence of delinking: the rate of growth of the ecological footprint slowly decreases when per capita income increases, but the growth itself never stops. The best model approximating this relationship is therefore not a quadratic but a power function, which does not support the case for indefinite economic growth as a prospective solution to environmental problems.

Keywords: Environmental Kuznets curves; ecological footprint; consumption; environmental cost-shifting; economic development, trade, power function.
JEL Classification: Q00, Q20, Q32, O13

1. Introduction

The relationship between economic growth and environmental impact has been object of a major debate in environmental economics for over a decade. Several authors argue that whereas in most countries, at low income levels, an increase in national income corresponds to increased environmental pressure, in later stages of development a stronger demand for greener goods and environmental regulation, improved technology and more abundant resources available for investment generally lead to a de-linking between economic growth and environmental degradation. The inversion in trend would give rise to an inverted-U relationship between indicators of environmental degradation and income per capita, similar to that found by Simon Kuznets (1955) in his work on inequality at different stages of development and hence conventionally known as the environmental Kuznets curve (EKC).

The EKC hypothesis and its policy implications are contested by theoretical analyses that stress the physical impossibility of an unbounded growth in a limited world. This view criticizes the assumption, implicit in the idea of a virtuous circle between economic growth and environmental quality, that there is no threshold level of environmental damage that can produce irreversible ecological consequences or start having a negative impact on the level of income (e.g. Arrow et at. 1995, Lucas et al. 1992, Hettige et al. 1992, Selden and Song 1994). Furthermore, according to several methodological studies most of the EKC literature contains econometric weaknesses that crucially influence their results (Holtz-Eakin and Selden 1995, Cole et al. 1997, Perman and Stern, 2003).

As the body of research concerning the EKC pursues successive refinements, the empirical evidence remains mixed, with local air pollutant concentrations often conforming to the EKC hypothesis and most other indicators of environmental quality showing monotonic relations with income or no relation at all (e.g. Grossman 1995, Cole et al 1997, de Bruyn et al. 1998). Recent research suggests that, whereas the indicators generally adopted focus, for each country, on the emissions generated by local production processes, more consumption-based measures, such as CO_2 emissions or municipal waste, could offer interesting new insights (Rothman 1998, Roca 2003).

The objective of this paper is to deepen the consumption-based line of inquiry through an investigation based on the ecological footprint – a concise environmental impact indicator which estimates the total quantity of natural services that a population uses, by calculating the total area of land and water ecosystems necessary to sustainably provide all the resources needed for consumption and to reabsorb the residuals. We investigate the empirical evidence using 1961-2001 ecological footprint data at the global level and 2001 national data for 148 countries. We test not only inverted-U and linear functions, but also power functions as potentially suitable models to represent the relationship between per capita income and environmental impact.

Our results do not support the hypothesis of an inversion in trend in environmental impact, neither in the world time series nor in cross country data: models with a monotonically increasing relationship between ecological footprint and per capita GDP perform at least as well as – and in general, better than – the quadratic function needed to generate an inverted-U curve. This result becomes all the more clear cut if the population variable is used to weight the data, so as to consider also the total pressure that each country imposes on global ecosystems.

The first part of the paper offers a brief overview of the literature on the environmental Kuznets curves most relevant for our work (section 2), and explains our choice of the indicator used as dependent variable in the empirical investigation (section 3). After presenting the conceptual foundations of the models being tested (section 4), we analyze the data and discuss the results (section 5). Section 6 concludes.

2. Theoretical background

Early analyses of the EKC have been reviewed in detail for example in Forrest (1995), Ekins (1997), Ansuategi et al. (1998), Borghesi (1999). Stern (2003) includes also more recent contributions and, besides describing the empirical evidence, discusses the theoretical and methodological critiques to the EKC literature.

Beginning with Grossman and Krueger (1992), in order to understand the underlying determinants of the EKC relationship, the literature has decomposed such relationship into the different effects economic growth may have on environmental quality. Following that line, also Panayotou (1993, 1997, 2000), Grossman (1995), Kaufmann et al. (1998), Torras and Boyce (1998), Islam et al. (1999), and Galeotti (2003) converge in identifying three distinct structural forces: (i) a scale effect, by which a larger scale of economic activity implies the extraction of more natural resources and the creation of more residuals; (ii) a composition effect, referring to the structural changes in the economy that lead, as income rises, to an increase in the share of cleaner activities; (iii) a technology effect, describing the change in resource and emission intensity of production due to technological modernization. The environmental pressure E generated in each country then results from the following identity:

$$E = \sum_{j=1}^{n} Y \left(\frac{Y_j}{Y} \right) \left(\frac{E_j}{Y_j} \right) = \sum_{j=1}^{n} Y \cdot C_j \cdot T_j$$

where Y is GDP, Y_j is sectoral GDP, E_j is environmental pressure due to sector j, C_j is the share of the GDP in sector j over total GDP, and T_j is the jth sector's environmental pressure intensity. Although most authors use emissions as the dependent variable, we prefer a more general expression such as environmental pressure, so as to include not only end-of-pipe effects but also impacts such as deforestation and other forms of resource depletion.

This decomposition is production-based in that it takes into account, in each country, the environmental damage generated by domestic production activities. It is also possible to conceive of an alternative accounting procedure, one that counts, for each country, the environmental pressure incorporated in the goods and services consumed by its population, wherever they have been produced. A consumption-based approach also captures the impacts directly due to consumption activities, such as emissions from private cars, household heating and household waste, which are generally missed by analyses based on production. The main difference between a production and a consumption-based approach is a different choice on where to ascribe the responsibility for the generation of environmental impact.

Since consumption activities are the ultimate cause of environmental degradation, several authors stress the interest of looking at the EKC hypothesis from a consumption-based viewpoint. They advocate empirical analyses using as dependent variable indicators of the environmental impact caused either directly by domestic consumption activities or by the productions needed to satisfy them.

Ekins (1997) notes that when income increases, a change towards a greener structural composition of the economy does not necessarily imply a corresponding change in consumption patterns. A reduction in environmental impact ascribed to the composition effect could therefore be due to a mere displacement from one country to another. Ekins' hypothesis is supported by Suri and Chapman (1998)'s empirical analysis of the effects of cross-country movement of goods embodying pollution: the turning point of their EKC for energy-related pollutants moves from an already high $55,000 to about $224,000, far beyond an attainable level of income per capita, when trade variables (such as import-manufacturing ratio) are introduced. Also Roca (2003) insists that focussing on the evolution of the consumption structure of a country allows us to go beyond analyses that neglect the international displacement of environmental costs.

Making progress in the study of the growth-environment relationship is, ultimately, a matter of improving the choice of the dependent variable, i.e. of finding appropriate measures of environmental impact and natural resource requirement. Rothman (1998) argues in favour of aggregate consumption-based indicators such as the OECD composite indicator used by Ekins (1997)[1], measures of total material requirement (Adriaanse et al. 1997), ecotoxicity indicators (Ayres and Marinas 1995), the environmental space (Opschoor 1995), and the ecological footprint. In his 1998 paper, Rothman first proposed a concise but insightful analysis relating ecological footprint to real GDP per capita. He used early data on ecological footprint, estimated by Wackernagel et al. (1997) for 52 countries. He tested four model specifications – linear, quadratic, log-linear, log-quadratic – finding no evidence in support of an inverted-U behaviour.

In the meantime, the methodology for the calculation of the ecological footprint has substantially improved. The sources of primary data have been standardized in a common accounting framework, which greatly increased the reliability and coverage of data. Spatial resolution is now an order of magnitude greater than former accounts. More reliable ecological footprint analyses from the perspectives of trade are now feasible, since some of the new sources distinguish changes in stocks, production, waste and secondary uses (Wackernagel et al. 2002; Monfreda et al. 2004). Furthermore, improved sources made it possible to extend a systematic calculation of ecological footprint to almost all countries (WWF and UNEP-WCMC 2004).

The above mentioned improvements give reason for further analyses of the relationship between income and the environment based on the ecological footprint. In this paper we replicate Rothman (1998)'s cross country analysis with 141 nations, using both total ecological footprint and its disaggregated components, and replicating the analyses with population weights. We also investigate the relationship between a country's biocapacity and the tendency to show EKC patterns. Finally, we have included a time series analysis at the global level, for the period 1961-2001. This is the desirable way ahead, as national time series on ecological footprint are becoming available.

3. The case for ecological footprint

Introduced by Rees (1992) and developed by Rees and Wackernagel (1994) and Wackernagel and Rees (1996), the ecological footprint is a concise indicator of environmental sustainability which "represents the critical natural capital requirements of a defined economy or population in terms of the corresponding biologically productive areas" (Wackernagel et al. 1999: 377). A country's footprint is the total area required to produce the resources it consumes and to absorb the waste it generates, using prevailing technology.[2] It is a consumption-based indicator because it includes all the natural capital directly or indirectly used for the supply of the goods and services consumed by the local population, independently of where the supplying area is located: it counts the natural capital embodied in locally consumed goods and services, whether domestically produced or imported, and subtracts the natural capital embodied in exports.

After the pioneering analyses by Rees and Wackernagel, the concept of ecological footprint has been adopted in a progressively larger number of studies applied to geographical regions, nations as well as specific productive activities. The early works are extensively reviewed in the *Ecological Economics* special issue (vol. 32(2), 2000). Both theoretical and applied studies, however, since then have developed into a wide and still growing literature which has reached

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[1] Which includes, besides emissions of key pollutants such as NOx, CO_2, SO_2 and fertilizers, also consumption-based measures such as water abstraction, generation of municipal solid waste, and private road transport.

[2] This area is measured in global hectares (gha) – one hectare of ecologically productive land with world average productivity.

influential scientific outlets such as *Nature* (Rees, 2003) and *PNAS* (Wackernagel et al., 2002), whose comprehensive survey is however beyond the scope of this paper. The most representative collections of data are the biannual WWF *Living Planet Reports,* that contain EF data for almost all countries up to 2001 (WWF and UNEP-WCMC 2000; 2002; 2004), and, for the 25 European countries, the WWF 2005 Report to the European Parliament.

An important element in this accounting approach is represented by the calculation of the biocapacity. Complementarily to the domestic demand for natural capital provided by the ecological footprint, the biocapacity estimates the domestic supply of natural capital by calculating the total area of ecologically productive land. This joint information enables the calculation of an environmental budget by subtracting ecological footprint from biocapacity for a definite period of time. An ecological deficit (surplus) corresponds to a negative (positive) balance-sheet, meaning that the local consumption of natural resources is greater (lower) than the level of regeneration of local ecosystems.

Both indicators take into account six different types of bio-productive areas: cropland, grazing land, forest area, fishing grounds, built-up land, and energy land.[3] Different aggregations of these components can be of use depending on the purpose of the analysis. The major distinction is between energy (which comprises both direct consumption and embodied energy) and non-energy footprint (the latter including all the other five types), which allows us to discern the uses of natural capital that affect only the global environment by increasing the greenhouse effect, from those uses whose impact is felt on local ecosystems (e.g. generation of household waste, overgrazing, overfishing). Furthermore, the non-energy footprint can be decomposed into 'built-up land' and 'food, fiber and timber footprint'. The latter, which groups cropland, grazing land, forest and fishing grounds, focuses on the extraction of renewable resources.

A few important components of the environmental impact of economic activities are not accounted for in the EF. Emissions of heavy metals, radioactive materials, persistent synthetic compounds and of any other pollutant for which nature has no significant assimilative capacity cannot be translated into areas required for their absorption, and are therefore excluded by definition from he EF account. As to emissions for which ecosystems have some assimilation capacity, current data already include CO_2 and other greenhouse gases, whereas ongoing theoretical work is trying to increase coverage, including for example sulphur emissions (Vieira 2004). Whereas resource extraction in terms of biomass (e.g. timber and agricultural harvesting, hunting and fishing) is accounted for in detail within the EF, capturing freshwater withdrawals still presents difficulties since their impact on biocapacity crucially depends on local conditions.

Most critiques to the EF concept are indeed grounded on these limitations, which make it of little use as an instrument for investigating the full scope of local impacts from production activities, whose polluting emissions other than greenhouse gases often represent a crucial point. For our purposes, however, the EF represents nonetheless a good instrument because, first, it is a concise indicator capturing both environmental impacts on the input side (extraction of almost all renewable resources and of several nonrenewable resources) and on the output side (generation of household and industrial waste, greenhouse gases emissions). This is particularly important in studying the EKC which aims at describing a general relationship between economy and the environment. Secondly, among consumption-based indicators it is the only one for which data are available, within a standardized database, for all countries with more than a million inhabitants.

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[3] Energy land refers to the forest areas needed for the sequestration of the CO_2 generated in energy production by fossil fuels. For detailed definitions of the various components see e.g. UNEP-WCMC (2004: 35).

4. Conceptual foundations of the tested models

Although the relationship between per capita income and environmental impact could, in principle, be analyzed with a number of different functional forms, we restrict our attention to four basic qualitative behaviors: (i) linear, (ii) monotonically increasing, at an increasing rate, (iii) monotonically increasing, at a decreasing rate, and (iv) inverted-U shaped. The first three can be represented by functional forms belonging to the $EF = b_0 + b_1 GDP^k$ family. When $k=1$ this is a linear equation, whereas cases (ii) and (iii) require, respectively, $k>1$ (resulting in a convex power function) and $0<k<1$ (resulting in a concave power function). Case (iv) is described by a straightforward quadratic function, as for example in Rothman (1998).

(i) If the relationship between GDP and environmental impact, in per capita terms, were linear, any increase in income would result in a proportional increase in consumption and any increase in consumption would impose a proportional environmental toll, in terms of resource extraction and/or generation of residuals. In the context of a decomposition analysis this implies that the scale effect is likely to be the only driving factor. The corresponding scenario is one of an ecological-economic system where neither changes in GDP composition by sector nor technological improvements intervene to influence environmental degradation, the environment reacts to environmental pressure in a linear way, and there are not economies of scale in nature-intensity per unit of GPD of the kind observed by Panayotou (1997).

(ii) A relationship that increases monotonically at an increasing rate would imply a positive feedback between income and environmental impact.[4] This can be the result of several interconnected and partially overlapping factors, among which:

- higher incomes may induce changes in individual consumption bundles towards goods and services with higher impact on the environment, both in terms of environmental unfriendly ways of satisfying given needs (for instance, from water coming from the main supply to mineral bottled water, or from wood to fossil fuel heating systems), and in terms of the creation of new needs (e.g. leisure air travel).
- Economic growth could bring about environmental unfriendly technological change – both in the sense of increased extractive capacity (e.g. mechanized logging or refrigerated fishing vessels) and of resource-intensive products (e.g. more powerful and accessorized cars, larger and more powerful household appliances).
- Even technological change implying resource or energy saving per unit of product may induce a rebound effect due to behavioural responses by which increases in efficiency are overcompensated by a rise in demand for the same or other commodities (e.g. Binswanger 2001).

These factors, although not falling neatly into the EKC decomposition (the first can be seen as the consumption side of the composition effect, the second can result from the technology effect, whilst the third from an interaction between the technology and the scale effect) lead to an increasing rate of environmental degradation per unit of income as countries become richer.

(iii) If the environmental impact continued to raise indefinitely, but at a decelerating rate, i.e. with a reduction in the increase in environmental pressure per unit of income, the resulting relationship could be represented by a power function where the value of the exponent falls in the interval (0, 1). Despite the negative second derivative, such a function continues to raise indefinitely as the independent variable tends to infinity:

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[4] A similar qualitative behaviour but with a much steeper growth can be described by means of an exponential function, which we discarded after preliminary analyses because of its poor fitting.

This scenario implies that, besides the above mentioned factors that make degradation increase as countries get richer, there are also mechanisms at work that tend to reduce environmental impact per unit of income:

- the capacity for consumption by individuals may be subject to physical constraints that do not allow it grow indefinitely at a rate proportional to the increase in income (a decreasing scale effect).
- Many services that make up the individual demand, once basic needs have been satisfied, tend to have a lower natural resource intensity and could bring about a change in the demand structure, with an increase in the size of the service sector relative to the industrial one (the demand side of the composition effect).
- The tendency to give priority to environmental protection is stronger in wealthier countries (Diekmann and Franzen, 1999). The higher willingness to pay may act both via market mechanisms (through an increased demand for green products) and through a demand for environmental regulation aimed at correcting the under-provision resulting from the public good nature of environmental quality (technology effect).
- On the supply side, higher incomes are necessary to lead to the development and diffusion of cleaner, resource saving technologies (technology effect).

In reality further variables, namely international trade and the relocation abroad of polluting activities, may play an important role on countries' environmental quality, which do not appear in Grossman and Krueger's decomposition precisely because the latter is grounded on a production point of view.

(iv) An inverted-U or environmental Kuznets curve would imply, as is well known, that environmental impact increases at initial stages of growth but at a decelerating rate, up to a point when the first derivative changes sign and a true de-linking of economic growth and environmental degradation takes place. A suitable functional form is a quadratic function with the vertex falling within the GDP data range.[5] In this scenario, the braking forces operating under (iii) are strong enough to overwhelm the scale effect and the other factors that determine an augment of environmental degradation as income increases.

The tested models are summarized in Table 1.

Table 1. Regression models

i) Linear

$$EF = b_0 + b_1 GDP + \varepsilon$$

where $b_1 > 0$

ii) Convex power

$$EF = b_0 + b_1 GDP^k + \varepsilon$$

where $b_1 > 0$ and $k > 1$

iii) Concave power

$$EF = b_0 + b_1 GDP^k + \varepsilon$$

where $b_1 > 0$ and $0 < k < 1$

iv) Quadratic

$$EF = b_0 + b_1 GDP + b_2 GDP^2 + \varepsilon$$

where $b_1 > 0$ and $b_2 < 0$

Note: ε is a random error term.

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[5] A quadratic function with a turning point corresponding to levels of GDP above the data range depicts a scenario logically equivalent to that in point (iii).

5. Data and analysis

Our models are estimated from ecological footprint (EF) and biocapacity (BC) data for the world, and for the 141 countries where reliable data exists for both ecological footprint and Gross Domestic Product (GDP). The source for total ecological footprint and its components as well as for biocapacity is the *Living Planet Report 2004* (WWF and UNEP-WCMC 2004), which provides the most recent and consistent figures presently available. GDP and population data for most countries come from the World Development Indicators 2001 database (The World Bank 2002). Monetary figures are expressed in 1995 US dollars. We perform both Ordinary Least Squared (OLS) and robust[6] regressions on the four models summarized in Table 1.[7] The same regressions are run also weighting the data by each country's population. Since the outcomes of the ordinary and robust procedures are substantially equivalent we limit our discussion to OLS and WLS results.

5.1 Time series analysis at the world level

The global model is estimated using world 1961-2001 figures for total ecological footprint (WWF and UNEP-WCMC, 2004: 32). The OLS results in Table 2 report, besides the R^2 of the tested models, the Akaike Information Criterion (AIC) and the Schwarz Criterion (SC), criteria for model selection that, unlike the R^2 statistics, acknowledge parsimony in the parameterization of the model (e.g. Amemiya 1985, Judge et al. 1988).

The relationship between total ecological footprint and world GDP in the past four decades does not show signs of inversion in trend (Figure 1). All tested models fit well, with R^2 above 0.9, although the concave power and quadratic models perform slightly better than the linear model. The absence of a turning point in the quadratic function for levels of income in the data range means that both the concave power and the quadratic curves depict a monotonically increasing trend.

5.2 Cross-country analysis

The proper way to test the EKC hypothesis is to observe the variations in the dependent variable through time, in relation to changes in the independent one, as we do at the world level. Doing so for individual countries would ideally require long EF time series, which were not available while this paper was being written[8]. On the other hand, the expedient adopted in large part of the empirical literature on the EKC is to conduct a cross-sectional analysis on national data (for example Hettige et al. 2000; Rothman 1998; Selden and Song 1994; Cole et al. 1997). Well aware that this is by no means ideal, as it requires us to assume that all countries follow a similar path of environmental impact over time (Vincent 1997; Stern 2003), with this analysis we aim at drawing insights from a comparison with previous empirical works based on the same approach.

As a first step, we analyze 2001 per capita GDP and ecological footprint for 141 countries (Figure 2). Regression coefficients were estimated with OLS. The fit of the concave power ($R^2 = 0.76$) and quadratic ($R^2 = 0.75$) functions are sensibly better than those of the linear ($R^2 = 0.67$) and convex power models ($R^2 = 0.66$) (Table 3). The AIC and SC criteria slightly reinforce the performance of the concave power with respect to the quadratic function.

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[6] As robust regression procedure we use iteratively reweighted least square with Huber (1981) weight function.

[7] Notice that the concave and convex power functions, besides the two coefficients (b_0 and b_1), contain a parameter k. Being impossible to minimise the residuals sum of squares simultaneously for b_0, b_1 and k, we performed OLS with a fixed value of k. The latter was chosen by testing values within the allowed range at an interval of 0.05 so as to maximise R^2, an operation legitimated by the fact that R^2 was, for all the regressions, a smooth function of k.

[8] Time series data for national footprints have become available early in 2006 in the *2005 National Ecological Footprint and Biocapacity Accounts*, by the European Environment Agency in coordination with the Global Footprint Network.

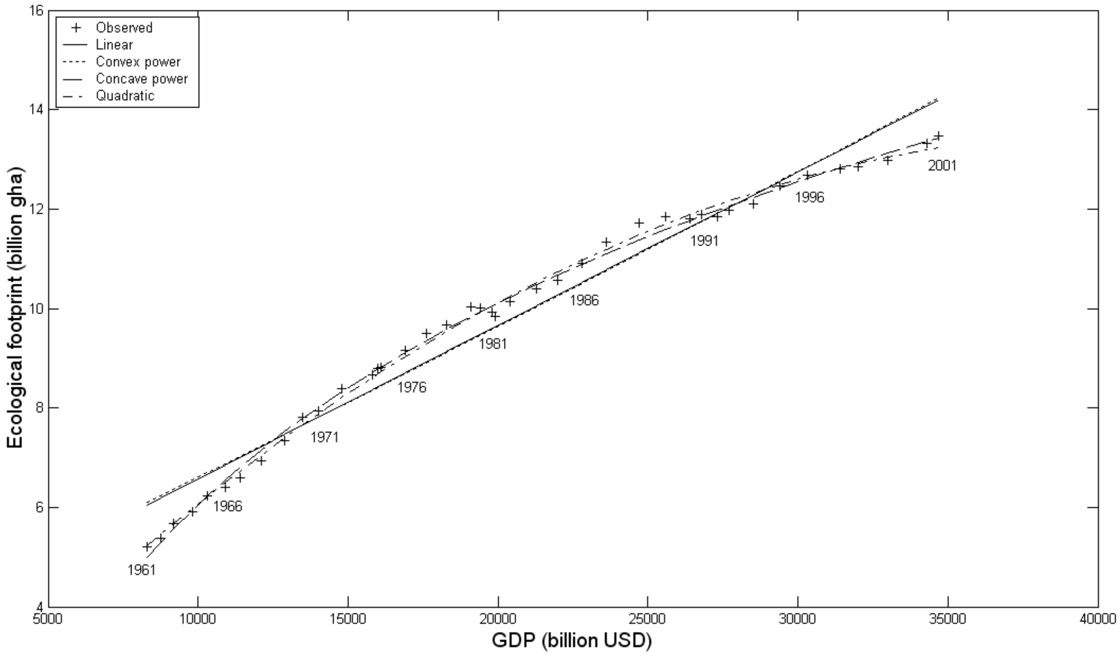

Figure 1. Ecological footprint vs. GDP, 1962-2001 world data. The chart shows linear, convex power, concave power and quadratic OLS regression curves.

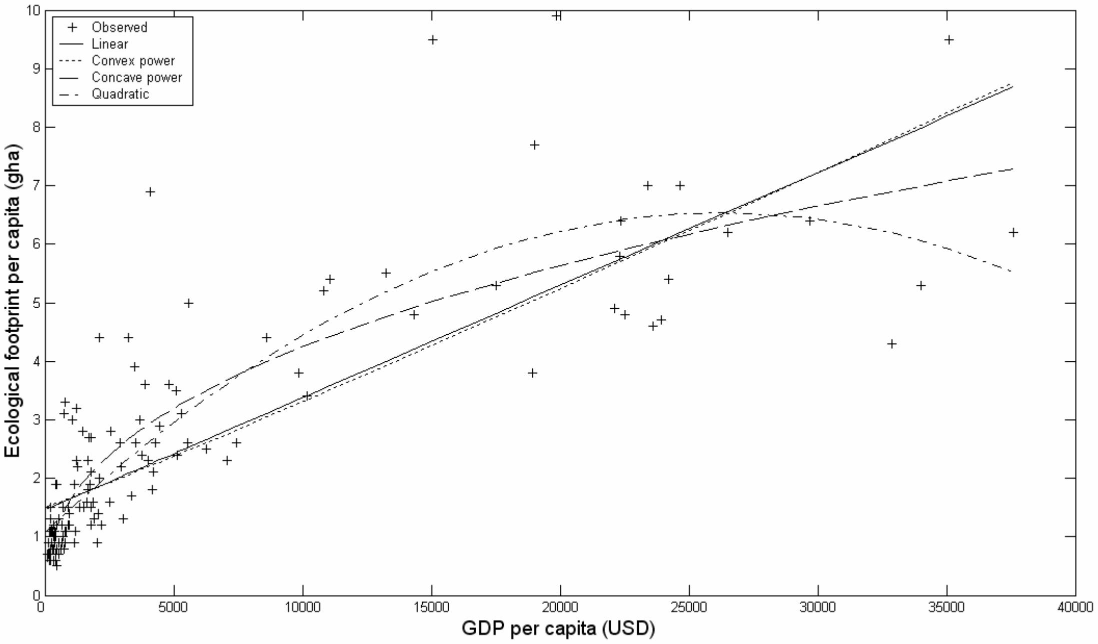

Figure 2. Ecological footprint per capita vs. GDP per capita, 2001 cross country data. The chart shows linear, convex power, concave power and quadratic OLS regression curves.

On the one hand, the quadratic specification is consistent with the EKC hypothesis because the quadratic parameter is negative and confirms an inverted-U shape for the parabola, with an estimated turning point of 26,280 US dollars per capita which falls inside the range of empirical data.[9] Notice that the inversion in trend would correspond, however, to an ecological footprint of an unsustainable 6.54 gha per capita, since global biocapacity per capita was estimated at 1.8 gha in 2001 (WWF and UNEP-WCMC, 2004: 10). On the other hand, the concave power model suggests that the rate at which environmental degradation raises would slow down when GDP increases, but its absolute level would continue to increase indefinitely.

5.3 Cross-country analysis of ecological footprint by components

Disaggregating the ecological footprint into its non-energy and energy components is of interest since the latter is the main responsible for the total world footprint. In 40% of world countries it accounts for more than half of the national footprint, and for countries with a GDP over 10,000 US dollars per capita its share goes up to 75%.

The non-energy component replicates a behavior similar to that of the total footprint, where the concave power specification performs best both according to the R^2, AIC and SC criteria, followed closely by the quadratic (Table 3). Further subdividing the non-energy footprint in food, fiber and timber, and built-up land does not significantly alter the results.

In the regression relative to the energy component the quadratic specification fits slightly better than the concave power according to two of the three criteria, with a turning point corresponding to a GDP of 24,906 US dollars per capita, well inside the data range. Energy appears therefore to be the factor of environmental impact marginally more susceptible to the composition and technology effects generally advocated as sources of EKC behavior, but possibly also to the export of environmental impact through embodied energy in traded commodities.

5.4 The weight of population

Using ecological footprint and GDP data in per capita terms permits a comparison between countries with different population sizes, but hides a crucial aspect of the problem, namely the total impact that each country imposes on global ecosystems (the product of per capita footprint times population). For instance, the per capita ecological footprint of both USA and Kuwait are equal to 9.5 gha while their total footprints are, respectively, 2,736 millions and 23 millions of gha. This can be accounted for by means of a weighted instead of an ordinary least square regression, where the population variable is used to weight the data. Weighted and unweighted analyses represent two different perspectives: the theoretical model of the development path and its relationship with environmental impact in the unweighted regressions, the actual impact that countries have on global ecosystems in the weighted ones.

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9 It should be noted that propagating the coefficient standard errors in the formula used for the turning point calculations resulted in a relative error of 17-31%, depending on the performed regression.

Table 2. 1961-2001 world data: OLS regression results

	R2	AIC	SC	b_0	b_1	b_2	Turning point[10]
Linear	0.9649	-1.4860	-1.4024	3.4841***	0.0003***		
Convex power (k=1.05)	0.9616	-1.3962	-1.3127	3.7692***	0.0001***		
Concave power (k=0.05)	0.9970	-3.9387	-3.8551	-108.9418***	72.5557***		
Quadratic	0.9969	-3.8559	-3.7305	0.4700**	0.0006***	-7.8 E-9***	40 917

$* p<0.05$ $** p<0.01$ $*** p<0.001$

Dependent variable: EF per capita 2001 (gha per capita)

Independent variable: GDP per capita 2001 (billions USD per capita)

Table 3. 2001 cross country data: OLS regressions

EF							
	R2	**AIC**	**SC**	**b_0**	**b_1**	**b_2**	**Turning point**
Linear	0.6655	0.3443	0.3861	1.4588***	0.0002***		
Convex power (k=1.05)	0.6550	0.4052	0.4470	1.5048***	0.0001***		
Concave power (k=0.40)	0.7568	0.0255	0.0673	-0.1020	0.1092***		
Quadratic	0.7521	0.0588	0.1215	1.0677***	0.0004***	-7.9E-9***	26 280
Energy EF							
	R2	**AIC**	**SC**	**b_0**	**b_1**	**b_2**	**Turning point**
Linear	0.5486	-0.0841	-0.0422	0.6055***	0.0001***		
Convex power (k=1.05)	0.5393	-0.0434	-0.0016	0.6349***	7.18E-5***		
Concave power (k=0.40)	0.6297	-0.2821	-0.2403	-0.3869**	0.0692***		
Quadratic	0.6394	-0.2945	-0.2317	0.3272**	0.0003***	-5.64E-9***	24 906
Non-Energy EF							
	R2	**AIC**	**SC**	**b_0**	**b_1**	**b_2**	**Turning point**
Linear	0.5071	-1.0135	-0.9717	0.8528***	7.01E-5***		
Convex power (k=1.05)	0.5002	-0.9859	-0.9441	0.8692***	4.16E-5***		
Concave power (k=0.40)	0.5660	-1.1407	-1.0989	0.2923**	0.0395***		
Quadratic	0.5486	-1.0872	-1.0245	0.7397***	0.0001***	-2.29E-9**	29 449

$* p<0.05$ $** p<0.01$ $*** p<0.001$

Dependent variable: EF per capita 2001 (gha per capita)

Independent variable: GDP per capita 2001 (USD per capita)

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[10] The calculation of the turning points are based on available decimals, rather than on the figures rounded to the fourth decimal place appearing in the Tables.

Table 4. 2001 cross country data: WLS regressions

EF							
	R2	**AIC**	**SC**	**b0**	**b1**	**b2**	**Turning point**
Linear	0.8102	3.6286	3.6704	1.2237***	0.0002***		
Convex power (k=1.05)	0.8072	3.6443	3.6861	1.2594***	0.0001***		
Concave power (k=0.50)	0.8289	3.5249	3.5667	0.2304*	0.0390***		
Quadratic	0.8122	3.6324	3.6951	1.1674***	0.0002***	-1.34E-9	89 605
Energy EF							
	R2	**AIC**	**SC**	**b0**	**b1**	**b2**	**Turning point**
Linear	0.8013	2.8901	2.9319	0.4952***	0.0001***		
Convex power (k=1.05)	0.7993	2.8998	2.9416	0.5188***	7.83E-5***		
Concave power (k=0.65)	0.8092	2.8491	2.8909	0.1708*	0.0052***		
Quadratic	0.8014	2.9036	2.9663	0.4849***	0.0001***	-2.46E-10	284 614
Non-Energy EF							
	R2	**AIC**	**SC**	**b0**	**b1**	**b2**	**Turning point**
Linear	0.7083	1.9918	2.0546	0.7292***	6.49E-5***		
Convex power (k=1.05)	0.7041	1.9918	2.0337	0.7414***	3.85E-5***		
Concave power (k=0.35)	0.7495	1.8255	1.8673	0.0454	0.0695***		
Quadratic	0.7167	1.9627	2.0254	0.6882***	9.61E-5***	-9.74E-10*	49 344

*$p<0.05$ **$p<0.01$ ***$p<0.001$

Dependent variable: EF per capita 2001 (gha per capita)

Independent variable: GDP per capita 2001 (USD per capita)

Table 5. 2001 cross country data: multiple regressions, dependent Ecological footprint p.c.

OLS								
	R2	**AIC**	**SIC**	**bioc**	**b_0**	**b_1**	**b_2**	**Turning point**
Linear	0.6830	0.3049	0.3677	0.0778**	1.2789***	0.0002***		
Convex power (k=1.05)	0.6735	0.3342	0.3969	0.0801**	1.3174***	0,0001***		
Concave power (k=0.40)	0.7639	0.0101	0.0728	0.0502*	-0.1719	0.1062***		
Quadratic	0.7606	0.0383	0.1220	0.0546*	0.9585***	0.0004***	-7.57E-9***	26 485
WLS								
	R2	**AIC**	**SIC**	**bioc**	**b0**	**b1**		**Turning point**
Linear	0.8568	3.3470	3.3888	0.1845***	0.9626***	0.0002***		
Convex power (k=1.05)	0.8557	3.3547	3.3965	0.1879***	0.9895***	0.0001***		
Concave power (k=0.75)	0.8599	3.3249	3.3667	0.1645***	0.7308***	0.0025***		
Quadratic	0.8568	3.3612	3.4239	0.1847***	0.9634***	0.0002***	2.51E-11	-

*$p<0.05$ **$p<0.01$ ***$p<0.001$

Dependent variable: EF per capita 2001 (gha per capita)

Independent variables: GDP per capita 2001 (USD per capita), Biocapacity 2001 (gha per capita)

Table 4 shows the output of the three WLS regressions using as dependent variables the ecological footprint and its energy and non-energy components. The GDP^2 coefficient of the quadratic models is no longer significant in the total ecological footprint regression and in the energy component. For the non-energy component, whose quadratic coefficient is significant at the 0.5 level, the turning point falls far beyond the income data range (49,344 US dollars per capita), thus causing also the quadratic curve to follow, within the relevant interval, a monotonically increasing behaviour. The R^2 of all functional forms is around 0.8, but all three statistics (R^2, AIC and SC) weakly prefer the concave power model over the others. These data would not allow anyone to establish a strong hierarchy among the different models. What emerges with statistical and economic significance, however, is a scenario where environmental impact undoubtedly increases monotonically with GDP (Figure 3).

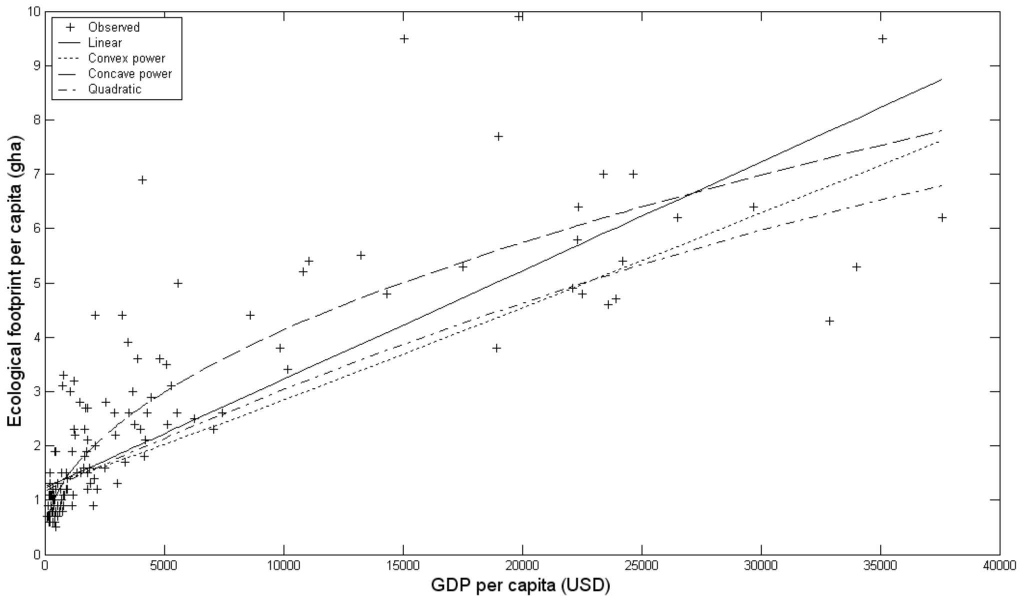

Figure 3. Ecological footprint per capita vs. GDP per capita, 2001 cross country data. The chart shows linear, convex power, concave power and quadratic WLS regression curves.

5.5 Biocapacity as independent variable

The theoretical arguments generally used to explain an inverted-U relationship between income and environmental degradation concern wealth-induced changes in consumer demand both in terms of a shift towards sectors with less environmental impact and in terms of increased demand of environmental quality (Roca 2003). The latter could in turn be potentially affected by the locally available biocapacity. One could expect to observe a heightened concern for environmental degradation, given the level of income, in contexts where pollution, congestion and resource scarcity are getting more serious; and conversely less sensitiveness towards environmental issues in areas still perceived as 'lands of plenty', where the biocapacity per capita is high. Should this hypothesis hold, we would then observe a stronger tendency towards U-shaped income-environment relationships in countries with low biocapacity per capita. In order to explore this idea we run OLS and WLS multivariate regression to test our original models where we introduced linearly the biocapacity as a further independent variable. The results are summarized in Table 5.

The introduction of biocapacity does not significantly alter the analysis: the concave power fits weakly better according to all our model selection criteria in both the OLS and WLS regressions, and the quadratic coefficient is not significant again in the WLS regressions. The interest of this exercise is that the biocapacity coefficient is significant in both the OLS and WLS regressions. In particular, the role of biocapacity in determining a country's behavior towards the environment acquires a nontrivial weight when population is taken into account: an increase of 1 gha per capita in biocapacity results in an increase of the country's ecological footprint between 0.16 and 0.19 gha per capita depending on the model specification.

6. Discussion and conclusions

The analysis proposed in this paper highlights that, when an aggregate consumption-based indicator like the ecological footprint is used to investigate the relationship between economic growth and the environment, one no longer finds any compelling evidence in favour of an inverted-U behaviour. The best performance of the quadratic specification of the model is in our OLS cross-country analyses of 141 countries in the year 2001, where its fit is almost as good as the one of a monotonically increasing concave power function. However, both in the 1961-2001 time series analysis and in the WLS regressions (where the environmental indicator is weighted by population, thus revealing the actual impact of a country on global ecosystems) the absence of a turning point in the quadratic function for levels of income in the data range means that a monotonically increasing trend is the only one supported by the empirical evidence. Even in the OLS regressions, where the turning point falls within the data range, the magnitude of the relative error (ranging from 17% to 31%) is such that prudence would suggest not to derive strong policy implications.

As a whole, rather than the decoupling of impact from GDP at high levels of income implied by the EKC hypothesis, the most likely scenario is one of an unbounded growth of environmental impact. Among the tested models, a concave power functional form prevails, even if by a small margin, on the other monotonically increasing specifications. Stronger evidence would require more sophisticated analyses based on sufficiently long panel data, which is an important next step for further research.

The difference between our results and previous EKC analyses may derive from the fact that consumption-based indicators like the ecological footprint account for the displacement of environmental damage away from high income countries. The fact that we do not find an inverted-U relationship is a hint that the change in the composition of production often advocated as a drive behind the EKC can takes place also through a change in the localization of supply – not only through a change in the composition of demand. The localization of supply is changed by importing a large share of the goods whose production requires polluting technologies as well as part of the biomass required as nutrition by human population and livestock, and by de-localizing dirty national production processes in low income countries by foreign direct investments (e.g. Andersson and Lindroth 2001; Bagliani and Bravo 2005; Suri and Chapman 1998). For instance, Mayer et al. (2005) argued that the forest protection policies adopted in Finland and other European countries in recent decades, without a simultaneous decrease in the domestic consumption of wood, resulted in a dramatically increased logging pressure on Russian forests. Similar trends are evidenced by Berlik et al. (2002) for USA's demand for wood and Schütz et al. (2004) on the spatial distribution of global consumption and extraction of natural resources. National environmental policies often results in a simple export of environmental pressures with no net gain in the overall conservation of nature.

Our argument is not one about the superiority of a consumption-based approach. Appropriately chosen production-based indicators can, in principle, account for all (or almost all) environmental damage somewhere – where it is produced. Production-based and consumption-based approaches simply imply a different choice on where to ascribe the responsibility for the generation of environmental impact. The conceptual mistake arises when the EKC hypothesis is used to argue that rapid development is the fastest road to a clean environment. Studies of the type conducted in this paper circumstantiate the argument that developing countries will not be able to replicate the development pattern of today's industrialised countries by delocalizing their environmental impact elsewhere. A consumption-based approach makes it explicit that economic growth within a clean environment cannot be achieved simultaneously by the whole planet, since it can only work locally until there are countries whose environment is allowed to deteriorate.

Our finding of a monotonically increasing ecological footprint means that the economic behaviour of today's rich countries (their consumption pattern) is actually more environmentally damaging than their economic behaviour when they were poorer. In order to legitimately derive the well known EKC policy implications, one would need empirical evidence on the existence of an inverted U-shaped relationship between income and consumption-based environmental indicators - the required condition that would guarantee an actual reduction in environmental impact.

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