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Decomposing the Impact of Population Growth on Environmental Deterioration

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Decomposing the impact of population growth on environmental deterioration: some critical comments on a widespread method in ecological economics*

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Abstract

The IPAT-model developed by Ehrlich and Holdren is widespread in ecological economics in order to quantify the impact of population growth on environmental deterioration. We comment on this model and extensions proposed by several authors from a theoretical and empirical point of view.

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1. Introduction

Population growth is commonly regarded as one of the most important sources of environmental degradation. This opinion is often justified by the following arguments: nations with a high population growth – such as many African states - are often not able to produce enough goods to meet the basic needs of their inhabitants. An expansion of the production of various goods seems to be necessary in order to help people to survive. But, an increase in the amount of goods produced may aggravate environmental problems, in particular if the less developed countries follow the pattern of development of western industrialised countries.

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However, even if there is a consensus that population growth is one important source of environmental problems, there is a debate about the exact relationship between population growth, economic development and the surrounding environmental systems. It is a priori not evident that population growth leads to higher environmental degradation. Normally, the use of the environment as a sink of waste is indirectly determined by population. The amount and type of emissions are furthermore determined by production technologies and consumption patterns. Hence, even a growing population does not necessarily lead to an increasing deterioration of environmental quality. If people substitute goods of less polluting character for consumption causing high pollution, environmental quality could improve even if population increases. In addition, technical progress might reduce the amount of emissions produced per unit of output.

The fact that environmental deterioration is not only the result of the number of people living in an area is often expressed by a fundamental identity formulated by Ehrlich and Holdren (1972) for the first time. They argued that the environmental impact is the result of the number of people living in an area, as well as of their affluence and the implemented technology. On the basis of this idea numerous empirical studies, the so-called decomposition studies, tried to quantify the contribution of population, affluence and technology to a change in environmental deterioration. However, the theoretical foundations of this approach and hence the interpretation of its empirical applications are controversial. Since this method is frequently used in ecological economic analyses, as e.g. the studies by Wexler (1996), Raskin (1995), Bongaarts (1992), Harrison (1992) and Holdren (1991) show, it seems to be useful, to investigate the problems of such decomposition studies more closely. This is the aim of the following paper. In section two we present the general approach and discuss its limitations. In section three we critically asses an extension of these approaches by Preston, who tries to solve some of the theoretical problems of the decomposition analysis. Section for suggests an extension of these approaches, which tries to avoid the mentioned shortcomings. Section 5 summarises the results.

2. The decomposition method and its critique

The starting point of all decomposition studies is an identity which goes back to Ehrlich and Holdren (1972). They describe the environmental impact of an economic system by the following equation:[2]

$$I \equiv P \cdot A \cdot T \, .$$

In this expression *I* denotes the environmental impact; *P* represents the population size, *A* stands for affluence, and *T* for the state of technology applied. For empirical investigations, it must be indicated by which observable variables the environmental impact, the affluence and the state of technology should be measured. Normally emissions (*E*) are used as an indicator for the environmental impact, the affluence is measured by per capita gross domestic product (*Y/P*), and the state of technology by the emissions per unit of gross national product (*E/Y*).

Taking into account that all these variables are time dependent one gets the following equation:

$$E(t) = \frac{E(t)}{Y(t)} \cdot \frac{Y(t)}{P(t)} \cdot P(t) \, . \qquad (1)$$

If we take the logarithm of equation (1) and the derivatives with respect to time we get the following relationship for the relative current growth rates:

$$\frac{\dot{E}(t)}{E(t)} = \frac{\left(\dot{\frac{E}{Y}}\right)(t)}{\frac{E}{Y}(t)} + \frac{\left(\dot{\frac{Y}{P}}\right)(t)}{\frac{Y}{P}(t)} + \frac{\dot{P}(t)}{P(t)} \, . \qquad (2)$$

Integration of equation (2) over the considered range $\left[0, \tilde{T}\right]$ and the division by the length of the time horizon $\tilde{T}$ gives us the average relative annual growth rates of the emissions for the interval $\left[0, \tilde{T}\right]$:

$$E^* = \left(\frac{E}{Y}\right)^* + \left(\frac{Y}{P}\right)^* + P^* \qquad (3)$$

with

$$E^{*}=\frac{1}{\tilde{T}}\int_{0}^{\tilde{T}}\frac{\dot{E}(t)}{E(t)}dt;\left(\frac{E}{Y}\right)^{*}=\frac{1}{\tilde{T}}\int_{O}^{\tilde{T}}\frac{\left(\dot{\frac{E}{Y}}\right)(t)}{\frac{E}{Y}(t)}dt;\left(\frac{Y}{P}\right)_{j}^{*}=\frac{1}{\tilde{T}}\int_{0}^{\tilde{T}}\frac{\left(\dot{\frac{Y}{P}}\right)(t)}{\frac{Y}{P}(t)}dt;P^{*}=\frac{1}{\tilde{T}}\int_{0}^{\tilde{T}}\frac{\dot{P}(t)}{P(t)}dt\,.$$

In equation (3), the average annual relative change of the emissions is assigned to the sum of the average annual change of emissions per unit of gross domestic product, of per capita gross domestic product, and population size respectively.

This identity has been applied quite frequently in order to describe the importance of different factors determining environmental damage. The analysis is normally carried out on different levels of aggregation, i.e. for nations, regions or for the whole world. However, empirical application of these approaches depends crucially on several assumptions[3]:

(1) In most empirical applications the components of the IPAT equation are specified such that it is an identity. In these applications – as e.g. in the above model – the term T (technology is the residual of an accounting identity.

(2) We have to assume that the development of the variables on the right hand side is independent of each other.

(3) We have to assume that no other factor than affluence, technology[4] and population determine the environmental impact.

(4) We have to assume that the change of the variables during the time horizon captured by a study could be described by an exponential function

As the first assumption is the most important one for the application of the decomposition method and for the interpretation of the results, we will discuss the related problems more extensively.

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[2] A summary of the history of the IPAT identity is given by Chertow (2001:15pp).
[3] In addition problems may occur, if the results obtained on an national level should be aggregated and if the relative importance of the different variables on the right hand side of equation (3) should be calculated by the division through the value of the left hand side. However, such problems are solvable as the work of Wexler (1996), Lutz, Prince and Langgassner (1993a), Raskin (1995), Ang (1993) and Boyd et al. (1987) show.

The assumption of independence between the variables on the right hand side is necessary for the applicability of the decomposition method. However, from a theoretical point of view, we cannot expect that this assumption is always fulfilled. In particular, one could not expect that the change of per-capita income is independent of population growth and that there is no relationship between per capita income and the emission per unit of gross domestic product.

The previous criticism of the use of decomposition analysis is in a striking contrast to the use of this approach, in particular in ecological economic investigations. There are numerous studies which try to identify driving forces of the environmental impact of economic systems on the basis of identities of the IPAT type (for an overview c.f. Certow 2001 or the literature mentioned in Diez, Rosa 1994.) This might not be surprising. A typical valuation of the IPAT identity for the analysis of environmental problems and the design of environmental policy is found in York, Rosa, Diez (2002:19), who argue that the IPAT "(...) model permits clear conceptual explications about the relationship between anthropogenic driving forces and impacts". However, the use of the IPAT identity is often criticised because of many conceptual problems, in particular when used for empirical investigations.

There are two different applications for the use of the identity and the related decomposition: (i) one can consider the decomposition analysis as an ex-post description or (ii) alternatively as an analytical concept of positive economics. If we use the decomposition analysis as an ex-post description, the assumption of an independent development of the variables on the right hand side of equation (1) is a "technical" one. It allows us to assign precisely one growth rate to every output variable. The advantage of such an ex-post description is, that it is not burdened with non-established hypotheses. This might be particularly interesting for concidering the importance of population growth for the environment, since in the theoretically oriented literature one can find opposite positions as to the question whether population pressure does harm the environment or will automatically contribute to a solution of environmental problems (Jöst 2003).

Even if the ex-post approach reflects reality, it does not exclude any conceivable development of the variables. Thus ex-post descriptions cannot contribute to an

[4] Since the influence of technology is measured by the term E/Y it contains not only the effect of technological change in a narrow sense. A change in this variable is e.g. also influenced by structural change. Thus E/Y is the residual of the decomposition of an identity representing different effects.

explanation of relationships within an ecological-economic system. If we want to use decomposition approaches in order to explain and forecast real systems, the independence assumption has to be introduced as a scientific hypothesis based on theoretical models and empirical studies. Hence, the reliability of empirical results of the decomposition analysis depends crucially on the assumption of an independent development of the components explaining the change of environmental impact.

3. Interdependencies between the variables: a variance analysis

In order to meet with the above formulated critique, Preston (1996) suggested to use a somewhat different approach. He proposes not to carry out the analysis for each country separately, but to do the analysis on inter-country differences as to the growth rate of emissions, the change of technology, the growth of per capita gross national product and population growth. Specifically, variations of E* between countries are attributed to corresponding variations of growth rates just mentioned above. Therefore he computes the variance of the average growth rates of the emissions for a specific observation period on the basis of equations (1) and (3). This leads to the following relationship:

$$s_E^2 = s_{\frac{E}{Y}}^2 + s_{\frac{Y}{P}}^2 + s_P^2 + 2 \cdot \mathrm{cov}\left(P, \frac{Y}{P}\right) + 2 \cdot \mathrm{cov}\left(P, \frac{E}{Y}\right) + 2 \cdot \mathrm{cov}\left(\frac{E}{Y}, \frac{Y}{P}\right). \quad (4)$$

In equation (4) the variance of the average growth rate of emissions results from the sum of the variances of the growth rate of the “technology effect”, the per capita gross national product and the population growth rate respectively, twice the sum of the covariances concerning population and per capita gross national product, population and technology effect, and between technology and per capita gross national product. In this relationship, the interdependencies between the variables are measured by the covariances. If these are close to zero, the interdependencies between the variables are considered to be unimportant.

The following table shows the results obtained by Preston for different environmental problems and regions. In many cases the covariance term differs from zero, indicating interdependencies between the developments of the respective variables.

Table 1: Decomposition of variances. Source: Preston (1996)								
		Impact (I)	Population (P)	Affluence (A)	Technology (T)	2 * Covariances		
Hazard	Units	S^{2}_{E}	S^{2}_{P}	$S^{2}_{\frac{Y}{P}}$	$S^{2}_{\frac{E}{Y}}$	$(P,\frac{Y}{P})$	$(P,\frac{E}{P})$	$(\frac{E}{Y},\frac{Y}{P})$
Carbon dioxide emissions (1)	9 regions 1980-1990	5,20	0,62[a]	5,56	3,71	-1,91	2,62	-5,40
Carbon monoxide emissions (2)	15 OECD countries 1970-1987	8,83	0,13[b]	1,04	11,7	-0,04	-0,52	-3,48
Nitrogen oxide emissions (2)	16 OECD countries 1970-1987	4,89	0,11[b]	1,60	7,65	0,06	-0,12	-4,40
Pesticide use in agriculture (2)	10 OECD countries 1975-1986	10,98	0,07[c]	1,13	8,96	-0,28	-0,60	1,72
Nitrogen fertilizer usage in agriculture (2)	18 OECD countries 1975-1986	4,26	0,13[c]	0,92	3,91	-0,40	0,50	-0,80
Sorces: (1) World Bank (1992), and Commoner (1994)				[a] Indicator: GNP per capita [b] Indicator: vehicle kilometers per capita [c] Indicator: agricultural produktion per capita				

In order to judge Preston's approach, it is decisive to realize that it is based on equation (3). Nevertheless we know from regression analysis that we can compute the coefficient of determination as the sum of variances and covariancies of the explanatory variables divided by the variation of the dependent variable. This computation method is regarded in econometrics as a method, which allows calculating the contribution of the variation of the independent variables to the variation of the dependent variables (Gollnick 1968: 59). Obviously, Preston's decomposition approach is based exactly on these arithmetic operations. Hence, from an econometric perspective with equation (3) Preston applies implicitly a linear deterministic model, for which the intercept is equal to zero, regression coefficients are unity and the coefficient of determination R^2 is equal to one.

For being able to calculate the importance of population, technology and affluence on the change of emissions, Preston has to assume that all components on the right hand side of equation (3) explain the change of the emissions. In this case, the relationship in equation (1) is obviously not regarded as an identity, but as an ecological-economic model with a strong hypothesis: the independence of the change of the variables explaining the change of emissions. However, this hypothesis has not been founded by Preston neither on the basis of a theoretical model nor by empirical investigations.

In addition, it can be shown (see e.g. Gollnick 1968, 59f) that the interpreting the contribution of an explanatory variable to the change of a dependent variable on the basis of the equation determining the coefficient of determination, is highly problematic if dependence between the explanatory variables exists. Indeed, as table 1 shows, many covariances between the explanatory variables used in the decomposition analysis differ substantially from zero.

4. Extending the IPAT approach

The previous considerations show that the IPAT identity needs a theoretical foundation if one an analysis of the impact of population growth on the use of the environment is wanted. The simple IPAT identity is a suitable starting point. However, two problems should be taken into account if we extend the IPAT approach: (i) we should be able to test empirically if the variables on the right hand side of the IPAT equation are significant for the explanation of the change in the use of the environment; (ii) we should take into account, that there exist interdependencies between the variables on the left hand side of the IPAT equation.

An extension of the identity which takes the first problem into account is given by Dietz, Rosa (1997). They propose a stochastic representation of the IPAT model for an empirical analysis of the impact of population growth on the environment. They use the IPAT model in the following stochastic formulation for an observation unit i:

$$I_i = b_1 P_i^{b_2} A_i^{b_3} T_i^{b_4} u_i \,. \qquad (5)$$

The stochastic model[5] could be empirically investigated with econometric methods. If appropriate measures for the technology impact are available, we can calculate the coefficients b_1, b_2, b_3 *and* b_4 and test the significance of the explaining variables Because of the difficulties to obtain appropriate empirical indicators for the technology variable, Diez, Rosa (1997:175) use a simplified model. They neglect the technology variable and argue that this impact is summarized in the error term, i.e. it is the residual of the empirical model. Hence, they test the following specification of the IPAT model:

$$I_i = b_1 P_i^{b_{21}} A_i^{b_3} u_i \,. \qquad (6)$$

[5] The original IPAT approach is not new, but a deterministic version of model (5) with $b_1=b_2=b_3=b_4=1$.

In order to allow for non-linearities Diez and Rosa use methods of non-parametric regression analysis, which require no a priori assumption concerning the functional forms linking population and affluence to the environmental impact. Their analysis shows that the best fit of the model fits best when using a log-polynomial model with significant linear and quadratic terms in the population variable and significant linear, quadratic and cubic terms in the affluence variable. In addition, they show that the coefficient of determination of a log-linear model is only slightly lower than the one in the log-polynomial model. Hence, it seems to be reasonable to use a log-linear specification. According to their empirical study, which is based on 111 countries and CO2-emission data and the gross domestic product capita for the year 1989 the population coefficient is 1,149 and the affluence coefficient is 1,084. Thus, both coefficients are slightly above unity, suggesting that the original identity might be a reasonable approximation.

However, even if we use the stochastic model of Diez, Rosa (1997), which rests on a scientific hypothesis concerning the relationship between the variables, we neglect possible interdependencies between the variables on the right hand side of equation (8), in particular, between population growth and a change in the affluence. This is also an important assumption in new empirical studies on these issue published by Shi (2003) and York, Rosa, Diez (2003). The former study is based on panel data and the author uses a more elaborate measure for the technology effect than emissions per unit of cross domestic product. The latter study extents the model given in equation (7) by taking into account additional factors determining the environmental, e.g. different types of fuels used for producing energy.

Results of the economic theory of fertility and the theory of demographic transition as well as empirical studies suggest, that the development of population crucially depend - besides other factors - on economic welfare (c.f. Bergstrom 1997, Lee 1997 for theoretical insights and Barro, Sala-I-Martin 1995:chapter 12 for empirical results). These strong evidences of interdependencies between variables on the right hand side of the IPAT equation could be taken into account, if we extend the approach of Diez, Rosa (1997) by using a simultaneous equation model. At a first step, we suggest to take into consideration that population growth depends on the development of per-capita income, and - in line with many studies - that the social status of women also determines population growth. This leads to the following system of two structural equations:

$$I_i = b_1 P_i^{b_2} A_i^{b_3} e^{u_i} \ , \tag{7}$$

$$P_i = d_1 A_i^{d_2} SW_i^{d_3} e^{v_i} \ . \tag{8}$$

The notion of the variables I_i, P_i, A_i is the same as above; SW_i indicates the status of women in a society; u_i, v_i are the error terms. Assuming that the appropriate model is log-linear and neglecting the index *i* for notational convenience, we get the following two equations:

$$I = b_1 + b_2 P + b_3 A + u \ , \tag{9}$$

$$P = d_1 + d_2 A + d_3 SW + v \ . \tag{10}$$

These two equations describe an empirical model based on theoretical and empirical insight into the interdependencies between variables on the left hand side of the IPAT identity and further exogenous driving forces of population change. The model given by equation (9) and (10) is a more appropriate starting point for empirical work quantifying the impact of population growth on the environment than the IPAT identity and Preston's model. It is also a useful extension of the empirical approaches discussed in section 4, because interdependencies between variables explaining the environmental impact are taken into account.

5. Conclusions

Decomposition approaches are a widespread methodology in ecological-economics, in particular in order to identify the importance of population growth for the change in environmental deterioration. Our note shows that decomposition approaches can be used either for the ex-post description or for explanation and forecast purposes. The use of this approach as a theoretical model presupposes that the independent development of the variables on the right hand side of Ehrlich and Holdren's identity can be justified on the basis of theoretical or empirical investigations. This problem cannot be solved if the perspective of the analysis is changed by formulating the decomposition equation in terms of variances as Preston (1996) suggested. Obviously there is no simplistic way to circumvent sound economic modelling for estimating the impact of population growth on environmental purposes.

6. Literature

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