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Drivers of environmental impact: A proposal for nonlinear scenario designing

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A B S T R A C T

Drivers of environmental impact are commonly studied in the related literature through the IPAT and STIPAT models. The first is an accounting model and the second is a stochastic approach that enables both statistical tests of significance of the drivers and the consideration of a larger set of drivers. These methodologies, however, are unable to take account of the level of all drivers in a nonlinear structure, i.e., different impacts according to the level of the variable. This paper presents a global Ordered Logistic Model that estimates the probability of four ordinal categories of environmental impact (four defined categories of Ecological Footprint). The results further the analysis of environmental impact offering an additional understanding of what to expect in terms of environmental pressure when the current level of the drivers are changing. The study demonstrates the proposed methodology by offering some examples of scenario analysis based on the estimated model.

1. Introduction and background

The complex relationship between economic growth and the environment has been dealt with in specialized literature based on the Environmental Kuznets Curve (EKC) since the 1990s (Grossman and Krueger, 1995; Dinda, 2004). Nevertheless, significant efforts to understand the impacts of human activities on the environment date back to the 1970's (Ehrlich and Holdren, 1971; Commoner, 1972). A classic model of analysis, credited to Paul Ehrlich and John Holdren, is known in the literature as "IPAT". This model proposes that environmental impact results from the multiplicative relation between population, affluence and technology $(\text{Impact}(I) = \text{Population}(P) \cdot \text{Afluence}(A) \cdot \text{Technology}(T))$.[1]

Although the model is seminal and widely replicated,[2] the IPAT presents some significant limitations. One of them – which had already been pointed out by Ehrlich and Holdren during debates with Commoner – is discussed in the well-known paper by Thomas Dietz and Eugene Rosa "Rethinking the environmental impacts of population, affluence and technology" (Dietz and Rosa, 1994). According to the authors, typical applications of the IPAT models are grounded on data for population and affluence. Technology, however, is indirectly obtained from the other variables: $T = I/(P \cdot A)$. So, since one has the three variables available (impact, population and affluence), the fourth one is automatically determined.

From an empirical point of view, this characteristic of the model can eventually underestimate the impacts of population and affluence – because technology is defined endogenously and might be incorporating factors other than just the technological aspect. Dietz and Rosa (1994) call attention to the observations of Ehrlich and Holdren on this matter indicating that "… calculations underestimate the effect of population on the environment by attributing to the T term changes that could more properly be allocated to P or A" (p. 10). So, on one hand, IPAT is useful as a model with an accounting characteristic, which can generate conclusions on the intensity of the environmental impact from population size and from the environmental efficiency of production. On the other hand, the model does not prove to be suitable for relative analysis where the motivation is to test the hypothesis of the significance of the human drivers of environmental impact, for instance.

It is exactly this limitation that forms the basis of the work of Dietz and Rosa (1994). The authors suggest that the IPAT should be reconsidered to establish a wider debate about the role played by population, economic growth and technology in terms of the environment. Two points are especially important. The first is that

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[1] Chertow (2001) presents a historical perspective of IPAT.

[2] It is also replicated with some adjustments, for instance: Waggoner and Ausubel (2002), Schulze (2002).

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the model should be stochastic instead of an accounting exercise, to make it possible to test the hypothesis on the significance of the drivers. The second point is the explicit need to incorporate a larger number of variables to be tested and studied.

In this context, an important step forward in the formulation of models of environmental impact is the proposition of a model named STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) (Dietz and Rosa, 1994, 1997). The model is formulated as follows:

$$I_i = aP_i^b A_i^c T_i^d e_i \quad (1)$$

It can firstly be observed that in this formula, the index "i" appears by the variables. These indexes indicate that the quantities vary across the observations.[3] The coefficients (a, b, c, e, d) are the terms that have to be estimated from the set of observations considered (countries, for example). For the sake of recognizing that this model theoretically derives from IPAT it has to be clear that the IPAT classic is obtained from this very formulation when we have the special case where $a = b = c = d = 1$.

The STIRPAT's theoretical equation should be estimated in natural logarithms. In this case the model is presented as follows:

$$\ln(I) = a + b[\ln(P)] + c[\ln(A)] + \sum_{i=1}^{n} \beta_i[\ln(X_i)] + e \quad (2)$$

where a and e are logarithms of those same terms as in the multiplicative formulation of the model. The technology component (T) is incorporated into the error term in the same way it is executed when dealing with the traditional IPAT model. Considering the logarithm formulation the results are basically presented and discussed as elasticity.

As previously mentioned, an important characteristic of this model is the possibility of expansion of the drivers in the formulation. The technology term is not frequently considered because of the absence of an adequate variable that can work properly as proxy.[4] However, variables that represent other dimensions such as institutions, culture, and geography, for instance, can be added to the model since they are conceptually consistent with the original multiplicative formulation. This is done through the X_i in the formula above. They represent all variables that the researcher would like to evaluate as a significant driver of environmental impact.

Studies carried out by researchers such as Szutukowski (2010), Shi (2003), York et al. (2003), Knight and Rosa (2012), Wei et al. (2011), York and Rosa (2012), Liddle (2012) and others, have applied the STIRPAT model in different contexts and with different propositions. Szutukowski (2010), for example, analyzes the impact of population, income per capita and climate oscillation on the emissions of CO_2 in several sectors for municipalities in USA. Knight and Rosa (2012), for their part, applied the STIRPAT model to investigate the impact of household dynamics on the consumption of fuelwood.

These applications, however, are especially dedicated to the identification of main drivers of environmental impact and relative importance when compared with each other. There are few references in these studies about projections or scenarios though.[5] What would happen if the population grew by 10%? What would happen if the population grew by 10% when the population is small? What about a very large population? The answers to this sort of questions are not statistically explored in these studies because they are not usually meant to design scenarios.

Returning to the STIRPAT formulation, it is worth noting that the estimated coefficients b, c and d are obviously constants, i.e., they represent fixed effects. This means that regardless of the level or frontiers of the driver, the proportional impact caused by them is constant through the entire range of the variable. However, there is plenty of evidence in the literature emphasizing that the effects of the drivers of environmental impact are level-dependent – for example, the recent "Planetary boundaries: exploring the safe operating space for humanity" by Rockström et al. (2009) empirically demonstrates some irreversible turning points of sustainability.

On one hand, Dietz and Rosa (1997) argue that the stochastic model would handle the nonproportional effects if the coefficients were replaced by more complex functions – we have not identified any application of this methodology in the current literature. Some studies, on the other hand, make use of quadratic terms of the drivers for that same purpose: Shi (2003), York (2007), York et al. (2003), York and Rosa (2012), and Jorgenson and Clark (2013). However, those studies have explored just a couple of drivers in quadratic terms (generally GDP and urbanization); *and not all of them*. The reasons for that are probably the lack of justification for all the drivers and also the difficulties in estimating well-adjusted models containing a number of (significant) quadratic variables.

Regarding this matter, it is worth quoting the recent work of Liddle (2013) which also points out some critical aspects concerning the traditional STIRPAT modeling. According to the author it is important to check if the environmental impact does vary across the different levels of development. The methodology applied consists in estimating panels counting on poor, middle, and rich countries. The results – based on time-series techniques – indicate significant distinctions in the estimated coefficients (elasticity) according to the level of development.

Therefore, there is clearly a caveat in the current STIRPAT models for the purpose of scenario designing. It is mandatory to take into consideration that the impact caused by every driver might strongly depend on its level (Stern, 2004; Dinda, 2004; Cavlovic et al., 2000; Cole et al., 1997). It is important to mention, however, that the STIRPAT models have not been proposed to explore scenarios in the way just described – although some projections that are not dependent on the driver's levels can be identified in outstanding works in the literature: York (2007), Liddle (2011a,b).

To be able to perform a scenario investigation it is necessary to draw on a model that is able to take into account levels of all drivers in a nonlinear fashion. A potential alternative for this is a nonlinear probability model. This sort of model can measure the impact of independent variables on the probability of a specific outcome, whether it is binary, categorical or ordered. Although these models do not estimate the environmental impact itself as IPAT and STIRPAT do, they are able to present interesting scenario analyses in terms of probabilities.

In this context, the main contribution of this paper is to propose a nonlinear probability model that can design scenarios based on the theoretical scope of IPAT and STIRPAT models. Secondly, it aims to present some specific scenarios based on the model proposed in order to demonstrate the feasibility and characteristics of the methodology. To accomplish these objectives the paper is composed of two sections besides the introduction and conclusion. Section 2 presents the methodology, and Section 3 demonstrates the results and some illustrative scenarios.

2. A nonlinear model for scenario designing: methodology, variables and the sample

For scenario designing of environmental impact we are assuming that three characteristics must be present: i) adequate

[3] For the classic IPAT there is no need for the index because the accounting is supposed just for one observation or point in the time series.

[4] The paper of Wei (2011) presents a discussion on this matter.

[5] A study which presents some projections is York (2007).