Department of Economics- FEA/USP

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GUILHERME DE OLIVEIRA

GIANA DE VARGAS MORES

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Guilherme de Oliveira (guilherme.decon@usp.br)

Giana de Vargas Mores (gimores@gmail.com)

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Keywords: Carbon dioxide emissions; conditional convergence; economic growth; environmental dynamics; panel data.

JEL Codes: Q5; Q52; C33.

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Convergence in *per capita* carbon dioxide emissions: a panel data approach

Guilherme de Oliveira
Department of Economics, Univesity of São Paulo, Brazil.
E-mail: guilherme.decon@usp.br

Giana de Vargas Mores
Cepan, Federal University of Rio Grande do Sul.
E-mail: gimores@gmail.com

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1. Introduction

Over the last decade, the number of papers testing the convergence hypothesis in carbon dioxide (CO_2) emissions among countries has increased considerably. At the same time, however, the controversy over whether those countries are converging or diverging increased as well. These set of contributions on environmental literature has been largely influenced by the empirical contributions of the theory of economic growth.

Strazicich and List (2003) it is recognize by the environmental literature as the first formal model testing the convergence hypothesis for *per capita* CO_2 emissions. The authors evaluated the patterns of emissions from 1960 to 1997, testing stochastic and conditional convergence. Overall, they found significant evidence that CO_2 emissions has converged.

From that work, a similar debate seen previously in the theory of economic growth has been realized over the last few years in the environmental literature. Papers such as Strazicich and List (2003), Westerlund and Basher (2007) and Romero-Ávila (2008), among others, have found evidence of convergence on *per capita* CO_2 emissions. In contrast, Aldy (2006) and Criado and Grether (2011) did not; that is, there is no evidence of convergence or countries are possibly diverging in emissions.

One source of this controversy is the sample size. As the sample of countries increase and, therefore, get global, convergence evidence decreases. For example, Aldy (2006) used two data samples, one with 88 countries and other with the members of the Organization for Economic Cooperation and Development (OECD). The author found that convergence occurred only in the smaller group; that is, in the sample with 88 countries there is no convergence evidence.

Another important point is related to the recursive specifications (lagged dependent variables) estimated through ordinary least squares (OLS). It is widely know that, in this context, the identification strategy based on OLS may be inconsistent, since relevant variables to explain the CO_2 emissions, especially all country-specific effects, are usually omitted, which violates the strict exogeneity assumption on econometric models.

In the present research, the empirical approach advances in this sense, proposing an econometric model of panel data to estimate conditional convergence for a set of countries from 1970 to 2005, which addresses two issues: First, in the model, country-specific characteristics are explicitly modelled through a fixed effect estimator. By this procedure, it is possible to explore how country-specific effects are related to CO_2 emissions. The article also contributes to the environmental literature by estimating the convergence hypothesis for distinct samples sizes and groups of countries, as Asian, Latin American, OECD and a global sample as well, which shows significant heterogeneous behavior among countries.

The remainder of this paper is organized as follows: In Section 2, literature related to the convergence hypothesis in carbon dioxide emissions is briefly reviewed, the theoretical model is presented in Section 3, and in Section 4, the identification strategy is described, followed by the interpretation of the results in Section 5. The conclusions and future studies are then discussed.

2. Related literature

Empirical literature on environmental economics concerned with the convergence hypothesis in *per capita* carbon dioxide emissions is recent, from the beginning of the 2000s. The literature is less autonomous and it is influenced by past empirical developments of the theory of economic growth, which is not by chance, since *per capita* emissions and income are correlated over time. This section presents a briefly literature review, inspired in Pettersson *et al.* (2013).

Strazicich and List's (2003) work was pioneering. The authors used a database from 1960 to 1997 for 21 OECD countries to test absolute and conditional convergence hypothesis with data in cross-section (1997) and unit root tests in panel data. The authors observed significant evidence of absolute convergence in emissions, and conditional when gas prices and average temperature during winter are explicitly modelled.

Using an empirical strategy that combines cross-sections and a panel data estimated via OLS and Arellano and Bond's (1991) methodology, Nguyen (2005) used 26 countries that had high CO_2 emissions and a global sample with 100 other countries. The author found convergence evidence in 26 countries using OLS, but the result was not supported by the dynamic panel strategy. Furthermore, when the sample size was expanded there was no convergence evidence.

Aldy (2006) increased the Strazicich and List's (2003) sample to test the hypothesis for a group of 88 countries, including the OECD members, using a stochastic technique. Unlike the pioneers, Aldy observed that *divergence* between countries is more likely when an extended sample is considered. It was possible to find convergence evidence only for the OECD's countries. In turn, Westerlund and Basher (2007) enlarged the period from 1870 to 2002, using similar statistical techniques and the same 21 country sample as Strazicich and List's (2003). They supported convergence hypothesis in conditional and absolute terms. Their contribution was computing the convergence rate, which, according to them, increased considerably since the 1970s.

Along the same lines, Romero-Ávila (2008) used a sample of 23 countries from 1960 to 2002, and conducted the same cross-section estimates with OLS and stationary tests in panel. The original evaluation considered possible structural breaks into unit root tests. When they were considered, evidence of convergence on CO_2 emissions increased among countries. However, Barassi, Cole and Elliot (2008) applied a stochastic analysis that estimated distinct unit root tests for 21 OECD countries from 1950 to 2002, and did not empirically support the convergence hypothesis. A similar result was verified by Lee and Chang (2008), who used the technique of seemingly unrelated regressions (SUR) and several unit root tests for the same set of 21 countries. The authors found statistically relevant evidence of divergence in 14 of 21 OECD economies.

Brock and Taylor's (2010) study was one of the few that attempted to develop a formal theoretical model before the researchers conducted empirical estimates of emission convergence. The authors developed an elegant mathematical association among empirical evidence on the environmental Kuznets curve and Solow's (1956) canonical model. From this theoretical derivation, they proposed an empirical model by testing absolute and conditional convergence for a group of 22 OECD countries. Evidence points out to the convergence hypothesis.

Jobert, Karanfil and Tykhonenko (2010) evaluated previous econometric data and proposed a Bayesian estimate for the period between 1971 and 2006, in order to make the set of hypotheses less restrictive. Using the Bayesian estimate improves previous results considerably, as well as supporting convergence for 22 OECD member countries. In contrast, Criado and Grether (2011) criticized the data basis of most previous studies, and emphasized the need to increase the country sample. The authors thus used data for 166 countries from 1960 to 2002, and estimated the convergence hypothesis with Markov chains. However, the authors did not find support for the hypothesis, and inferred that in the long term divergence is more likely to occur among countries.

Herrerias (2012) applied a distributional dynamic analysis to data from 25 countries from 1920 to 2007, and determined convergence occurred, although slowly. As a new result, the author estimated regressions by controlling the result through characteristics observed in the countries, such as population size and economic activity. In the face of control, the conditional convergence increased and became faster. However, the result was still unstable, since it is difficult to consider all characteristics on regression, even when well observed.

Camarero, Picazo-Tadeo and Tamarit (2013) attempted to control what supports convergence by controlling the energy intensity of the countries. In addition to this support, the authors concluded that energy intensity, measured as the ratio of the energy consumption to the gross domestic product (GDP), may not have much weight in the convergence process, which is explained by the differences in the countries' carbonization index.

We note a pattern in this literature review: usually, simple models of cross-section and other unit root tests in panel data find convergence evidence, while dynamic statistic techniques, such as Markov chains, achieve distinct results. Hence, the result may depends on the statistical technique adopted. Another element that contributes to the determination of convergence is the sample size: large country samples do not report convergence, which is determined only in small samples.

In this paper, we emphasize these two aspects: the sample size and the inconsistency of estimate for least squares in cross-sections. We control the convergence parameters with countries' observable and non-observable characteristics in a panel data, a partial environmental reconsideration of Islam's (1995) classical work on growth empirics.

3. The convergence hypothesis in *per capita* CO_2 emissions modeled as a dynamic panel data

The panel data approach for studying convergence in carbon dioxide emissions may be modeled using Solow's (1956) model, which is explored in Mankiw, Romer and Weil's (1992) and Islam's (1995) work. However, to link carbon dioxide emissions and economic growth, an additional hypothesis must be made: a joint production mechanism is supposed, in which the use of labor and capital in a production function generates two outputs: one good (economic growth) and one bad (CO_2 emissions). Hence,

$$Y = K^{\alpha}(AL)^{1-\alpha} \rightarrow E, \tag{1}$$

in which Y is the output, K is the capital stock, A is the technological level, L is the number of workers and E is the bad output. In fact, the logic is similar to the green Solow model set forth in Brock and Taylor (2010). Due to the strong empirical correlation between income and emissions, the building process of CO2 emissions can be assumed to be the same as the one that generates income for the economy. Then $E = K^{\alpha}(AL)^{1-\alpha}$.

As in the canonical neoclassical model, it is supposed that the population and technology growth rates are exogenously given by $L_t = L(0)e^{nt}$ and $A_t = A(0)e^{gt}$, respectively. Since a fraction s of income is saved and automatically reverted into investment, and defining emissions and capital *per* effective worker as $e = {E}/{AL}$ e $k = {K}/{AL}$, respectively. The capital-labor ratio changes over time according to:

$$\frac{dk}{dt} = sk^{\alpha} - (n + g + \delta)k. \tag{2}$$

Solving (2) for the capital stock *per* effective worker, it is obtained the value of capital stock *per* worker in steady-state:

$$k^* = \left[\frac{s}{(n+g+\delta)}\right]^{1/(1-\alpha)}. \tag{3}$$

In steady-state, capital stock growth is determined by the population growth rate, saving rate, technical progress and an exogenous parameter of depreciation δ. Substituting the balanced capital stock on the emissions by effective worker, *per capita* emission in steady state is obtained (which is determined by the same parameters of Eq. (3)). Applying the logarithm to the expression of *per capita emissions*, Eq. (4) is reached, a linear expression for the emissions in balance. Hence,

$$ln\left[\frac{E}{L}\right] = lnA_0 + gt + \frac{\alpha}{1-\alpha}\ln(s) - \frac{\alpha}{1-\alpha}\ln(n+g+\delta). \quad (4)$$

Now the emissions are normalized by the number of workers, and not by the number of effective workers; thus, the technological level, *A*, is on the right hand of equation. If the intention were to estimate Eq. (4) for analyzing the sensibility of *per capita* emissions for a group of countries, at some moment in time, with OLS, it is possible to assume that $lnA_0 = a + \mu$, a constant plus stochastic perturbation. The following model would be estimated:

$$ln\left[\frac{E}{L}\right] = a + \frac{\alpha}{1-\alpha}\ln(s) - \frac{\alpha}{1-\alpha}\ln(n+g+\delta) + \mu. \quad (5)$$

Using OLS, the linear adjustment in Eq. (5) is inconsistent, since the terms contained in the error that explain emissions and are correlated with the savings and population growth rates affect the signal of the parameters $\frac{\alpha}{1-\alpha}$. The basic conjecture in this article is about modeling emissions *per capita,* considering that "a" can be estimated for each country, the fixed effect, and that *gt* by a set of time dummies, in panel data.

Thus, the equation of *per capita* convergence, adapted from Mankiw, Romer and Weil (1992), is derived assuming that ϵ* is the *per capita* emissions in steady-state and ϵ the current emissions in *t.* Approaching the steady-state, the equation for convergence in time is given by:

$$\frac{dln\epsilon_t}{dt} = \varphi[ln\epsilon^* - ln\epsilon], \quad (6)$$

in which $\varphi = (n+g+\delta)(1-\alpha)$. Integrating Eq. (6), it follows that:

$$ln\epsilon_{t2} = (1 - e^{-\varphi\tau})ln\epsilon^* + e^{-\varphi\tau}ln\epsilon_{t1}, \quad (7)$$

in which ϵ_{t1} is the emissions at the initial time and $\tau = (t2 - t1)$. Deducting the initial *per capita* emissions from the both sides of Eq. (7) and rearranging, follows that:

$$ln\epsilon_{t2} - ln\epsilon_{t1} = (1 - e^{-\varphi\tau})(ln\epsilon^{*} - ln\epsilon_{t1}). \quad (8)$$

Deducting ϵ*, inserting the technological parameter to the right-hand side, and collecting ϵ_{t1}, result in:

$$ln\epsilon_{t2} = (1 - e^{-\varphi\tau})\frac{\alpha}{1-\alpha}\ln(s) - (1 - e^{-\varphi\tau})\frac{\alpha}{1-\alpha}\ln(n + g + \delta) + e^{-\varphi\tau}ln\epsilon_{t1} + (1 - e^{-\varphi\tau})lnA_0 + g(t2 - e^{-\varphi\tau}t1). \quad (9)$$

Eq. (9) is the main equation in this paper, because it covers the equation of conditional convergence that will be modeled by a dynamic panel. When modeling in Eq. (9) $(1 - e^{-\varphi\tau})lnA_0$, technology, as an fixed effect in time, and $g(t2 - e^{-\varphi\tau}t1)$ - technical progress, as a set of dummy variables of time, a dynamic panel is defined according to:

$$y_{it} = \gamma y_{i,t-1} + \sum_{l=1}^{2}\beta_j x_{it}^{j} + \pi_t + \theta_i + \vartheta_{it}, \quad (10)$$

in which:

$y_{it} = ln\epsilon_{it2}$: logarithm of CO_2 emissions *per* worker in $t_{2;}$

$y_{i,t-1} = ln\epsilon_{t1}$: logarithm of CO_2 emissions *per* worker in the initial time;

$\gamma = e^{-\varphi\tau}$: parameter used for estimating the convergence rate; it measures the impact that the initial emission has on the current level;

$\beta_1 = (1 - e^{-\varphi\tau})\frac{\alpha}{1-\alpha}$: elasticity of the savings rate on the emissions;

$\beta_2 = (1 - e^{-\varphi\tau})\frac{\alpha}{1-\alpha}$: elasticity of population growth, technology and depreciation rate;

$x_{it}^{1} = \ln(s)$: logarithm of the savings rate;

$x_{it}^{2} = \ln(n + g + \delta)$: logarithm of the population growth rate, technology and depreciation;

$\pi_t = g(t2 - e^{-\varphi\tau}t1)$: effect of the technical progress at time, modeled with a set of temporal dummies;

$\theta_i = (1 - e^{-\varphi\tau})lnA_0$: country fixed effect;

ϑ_{ijt}: idiosyncratic perturbation term that varies among countries.

The identification hypothesis from the fixed effects model are: the absence of serial correlation between the idiosyncratic error and the explanatory variables plus the fixed effect, that is, strict exogeneity, $FE1: E\left[\vartheta_{it}\middle|x_{ij},\theta_i\right] = 0$; Full rank, that is, the variables vector *x* must have an inverse $FE2: rankE[x_{ij}{}'x_{ij}] = k$; Finally, homoscedasticity between individuals in cross-sections is assumed; however, this hypothesis is related among the error in time, $FE1: E\left[\vartheta_{it}\vartheta_{it}{}'\middle|x_{ij},\theta_i\right] = \sigma^2\vartheta I_t$.

The dynamic panel estimate helps control the results of conditional convergence on CO_2 emissions by specific observable and non-observable country effects in the present sample, which is composed of data for 118 countries from 1970 to 2005.

4. Methods and data

Several techniques estimate panel data consistently (Wooldridge, 2002). The central point is how to model country-specific effects. In this work, two techniques were applied, one that considers the effects as random and one that considers the effects as fixed. In the first one, by construction, it is assumed that the consequent random effect is not correlated with the explanatory variables of the model in Eq. (10). In the second approach, the fixed effects technique modelled *via* dummies, as well as in Islam (1995), country-specific effects are explicitly modeled.

It is expect that the estimated convergence rate, using the model of effects at random, is underestimated, once the intrinsic country effects are correlated with the explanatory variables. Considering the model of fixed effects, the rate must change considerably, because the characteristics are explicitly modeled. In general, details from both estimates are very well known and may be verified in Greene (2000) and Wooldridge (2002).

In this context, the estimates are not based on Hausman’s test, because the strategy of this research does not pass by the identification *ad hoc* from the right model, but from an empiric history about a convergence hypothesis on *per capita* carbon dioxide emissions. In addition, in this paper, Hausman’s test is not essential, since it estimates two models for comparative purposes.

As in Islam (1995), we assume that the time is sufficiently large to bring inconstancy problems, given the recursive character of the models in Eq. (10). Thus, when time is very large, the model converges dispensing possible endogeneity of the panel at time. Then, Arellano and Bond’s (1991) estimates through GMM are not presented.

4.1. Sample

The data used in this article were collected in the Extended Penn World Table (EPWT), a cross-country database produced by Marquetti and Foley (2011), from which we used 118 countries for which information from 1970 to 2008 was available. The selected data were carbon dioxide emissions in kilograms *per* worker, savings rate and population growth rate. Following the empirical literature on economic growth, a depreciation growth rate plus technical change of 0.05 was applied (Islam, 1995).

The lag structure of the model was defined as five years, to access a long-term convergence perspective, in the following cohorts: 1975, 1980, 1985, 1990, 1995, 2000 and 2005. Data after 2005 are not available to all countries in the sample. In addition, even with additional information available for some countries, data after 2008 were not included in the analysis. The pattern of CO_2 emissions may have changed abruptly during the global economic crisis (post 2008), which can influence the results for the convergence rate. It is prudent, therefore, to analyze the convergence hypothesis during the pre-crisis period. Finally, the time for convergence on random and fixed effects were measured using the *half-life*, in intervals of five-year.

The sample countries from the EPWT were grouped into subsets determined by specific features: NOIL, all countries in the sample, except the major oil producers, in order to isolate the strong effect that they have on the pattern of global emissions; INTER, all countries in the sample, excluding those with less than one million inhabitants and data of dubious quality, according to EPWT rank; OECD, all member countries of the Organization for Economic Cooperation and Development with available information; ASIA, all Asian countries with available information; LAC, all Latin America countries and the Caribbean, for which information was available.

This classification was used to evaluate the performance of convergence in small and large samples, as well as developed and developing countries separately, which can also be understood as a contribution to the previews empirical literature on environmental economics.

5. Results

The results are presented by countries' samples. Table 1 highlights the results for NOIL and INTER samples. The signs of variables from the canonical neoclassical model – savings rate and population growth rate, technology and depreciation rate - were as expected according to theory[1]. Both were significant in all models for the INTER and NOIL samples, as demonstrated by the *p*-values in brackets. When the estimates of fixed and random effects are compared, the random effect bias decreases in 2.5%, in many cases.

Regarding the response of CO_2 emissions, the coefficient was positive in all models in Table 1, as required in this empirical approach. The gain of the use of fixed effects is robust. For example, the coefficient of the INTER sample is 0.9558 in the random effects model, and when corrected for country-specific characteristics, the parameter becomes 0.5971. The same occurs in the non-oil producing countries sample, NOIL, in which the parameter changes from 0.9574 to 0.6758. Statistically, both are significant at the 1% significance level.

Table 1 – Econometrics results of random and fixed effects estimations for the samples: *INTER* (535 Observations) and *NOIL* (680 Observations).

	INTER			**NOIL**		
lne_{t2}	***Random effects***		***Fixed effects***	***Random effects***		***Fixed effects***
Independet variables	Absolute	Conditional	Absolute	Conditional	Absolute	Conditional
lne_{t1}	0.9698	0.9558	0.5971	0.9753	0.9574	0.6758
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Ln(s)	-	0.1594	0.1636	-	0.1881	0.2076
	-	[0.000]	[0.000]	-	[0.000]	[0.000]
Ln(pop)	-	-0.0851	-0.1039	-	-0.0799	-0.0960
	-	[0.017]	[0.032]	-	[0.007]	[0.004]
Average R^2	0.9755	0.9770	0.9753	0.9735	0.9759	0.9477
Convergence φ	0.0061	0.0090	0.1031	0.0050	0.0087	0.0784
Time (years)	*113*	*77*	*7*	*138*	*80*	*9*

Note: p-value between brackets.

The parameter associated with lne_{t1} has a negative relationship with the convergence rate φ, given by $\gamma = e^{-\varphi\tau}$. Therefore, the higher the γ parameter associated with lne_{t1}, the lower the convergence rate; consequently, the longer the time for each country to reach steady state emissions. Note that results presented in Table 1 is robust for a large set of countries, a result that is very unstable in the previews literature.

In the random effects model, the conditional convergence rate is low. Using fixed effects, it increases from 0.0090 to 0.1031, and from 0.0087 to 0.0784 in the INTER and NOIL samples, respectively. The estimated time for convergence is high with random effects: 77 (INTER) and 80 (NOIL) years. However, it decreases significantly when controlled by the specific-country effects, 7 (INTER) and 9 (NOIL) years.

This result have relevant policy implications. The time for countries entering growth trajectories of constant carbon dioxide emission is less than 10 years. When considering that the sample is until 2005, this would mean that in the absence the 2008 great recession, emissions of CO_2 would grow at constant rates in the present decade. This is also a strong result related to the previews literature, which in most cases ignore country-specific effets.

Further, we explore the results for smaller sets of countries: Asia, Latin America and the Caribbean and OECD. Table 2 shows information for the set of Asian countries, for which the sample was available.

Table 2 - Econometrics results of random and fixed effects estimations for *ASIA* (140 observations).

lne_{t2}	***Random effects***		***Fixed effects***
Independent variables	Absolute	Conditional	Conditional
lne_{t1}	0.9582	0.9466	0.4976
	[0.000]	[0.000]	[0.001]
Ln(s)	-	0.0848	0.3276
	-	[0.271]	[0.018]
Ln(pop)	-	-0.0983	-0.1731
	-	[0.216]	[0.111]
Average R^2	0.9799	0.9802	0.9447
Convergence φ	0.0084	0.0109	0.1395
Time (years)	*81*	*63*	*5*

Note: p-value between brackets.

The signs were as expected in relation to the canonical model. However, the savings rate was not significant in the random effects model, while population growth was not significant in both models. It is likely that the China effect causes a lot of heterogeneity in the cross-sections from 1995, mainly due to the high savings and population growth rates. Nevertheless, the convergence rate remains statistically significant.

The convergence results for Asian countries improve considerably using the country-specific effects, from 0.0109 in random to 0.1395 in fixed effects, which reduces the convergence time from 63 to 5 years. That means, probably, all other factors held constant, the emissions of Asian countries would increase at a constant rate over time in a few years, as well.

Of the 15 largest economies in the world in 2013 (GDP purchasing power parity), five are located in our Asia sample: China, India, Japan, Russia and South Korea. Population growth and economic importance have been increasing energy consumption. In particular, China and Japan have concentrated on expanding major industrial centers and a tertiary sector, which involves recurrent non-renewable energy use (for example, coal and oil). In the five countries emphasized, there is a high correlation between electricity consumption derived from fossil fuels: China (69.1%), India (65.8%), Japan (63.8%) and Russia (67.7%). The only country that contradicts this level is South Korea; 74.4% of its electricity is generated from fossil fuels.

The energy matrix effect is captured by the specific effect of the model. Therefore, this homogeneity in energy consumption may condition the high convergence rates of the sample set.

A major economic challenge for Asian governments is containing the environmental and social problems that result from the rapid economic transformations observed in recent decades.

Table 3 illustrates the result for Latin America countries and the Caribbean. The parameters of the neoclassical model are as expected in theory and are statistically significant, with a noticeable improvement when the intrinsic effects of these countries are considered.

Table 3 – Econometrics results of random and fixed effects estimations *LAC* (140 observations).

lne_{t2}	***Random effects***		***Fixed effects***
Independent variables	Absolute	Conditional	Conditional
lne_{t1}	0.9543	0.9268	0.5919
	[0.000]	[0.000]	[0.000]
Ln(s)	-	0.2265	0.2906
	-	[0.000]	[0.000]
Ln(pop)	-	-0.1518	-0.1392
	-	[0.008]	[0.005]
Average R^2	0.9668	0.9722	0.9667
Convergence φ	0.0093	0.0152	0.1049
Time (years)	*74*	*46*	*7*

Note: p-value between brackets.

The same occurs with the parameter associated with CO_2 emissions in the initial period, which ranges from 0.9268, with random effects, to 0.5919 in the model with fixed effects. This implies higher convergence rates, from 0.0152 to 0.1049, respectively. In years, this represents a decrease from 46 to 7 years for Latin American countries to achieve steady-state. Furthermore, the model parameters were adjusted as predicted by the neoclassical model.

Of the 15 major nations in terms of 2013 GDP, Brazil (7^{th} position) and Mexico (15^{th}) are the only two Latin American representatives. It is also important to emphasize the large population of these countries. Linking the economic dynamics and the use of productive resources, in relation to the installed capacity of electricity, in Brazil, 19.6% comes from fossil fuels and 71.0% from hydroelectric plants; in Mexico, these values are 76.2% and 18.3%, respectively. In this scenario, Brazil is popularly known as the “green lung” of the world, due to the wealth of natural resources, such as the Amazon region. In addition, environmental aspects and legislation include the new Brazilian Forest Code, a regulatory process for sustainable practices and the use of natural resources in Brazil.

Table 4 presents the same results for the OECD member countries, namely, an approximation of the more developed countries, in addition to a direct comparison with the precursor studies of convergence analysis of *per capita* CO_2 emissions, as Strazicich and List’s (2003).

Table 4 – Econometrics results of random and fixed effects estimations for *OECD* (190 observations).

lne_{t2}	***Random effects***		***Fixed effects***
Independent variables	Absolute	Conditional	Conditional
lne_{t1}	0.8454	0.8385	0.7013
	[0.000]	[0.000]	[0.000]
Ln(s)	-	0.1170	0.2024
	-	[0.041]	[0.012]
Ln(pop)	-	-0.1049	-0.1372
	-	[0.000]	[0.016]
Average R^2	0.9480	0.9500	0.9420
Convergence φ	0.0336	0.0352	0.0709
Time (years)	*21*	*20*	*10*

Note: p-value between brackets.

Initially, the model signals are as expected according to theory, and both are statistically significant. In particular, the effect prediction of the saving rate in emissions has improved considerably with the fixed effects estimate.

Regarding the associated parameter with emissions in the initial period, this has improved, but it was minor compared to the perceived gain in other sets of countries considered in this work: from 0.8385 in random effects to 0.7013 in fixed effects. The initial parameters result in a convergence of 0.0352 for random effects and 0.0709 with fixed effects. Chronologically, this represents a difference of 10 years, decreasing from 20 to 10 years, respectively.

The similar result for the fixed and random effects models is explained by the similarity in specific effects between OECD countries, which have similar technology levels and institutions. That is, in homogeneous sample sets, the estimate considering fixed effects may bring a slightly smaller gain than in heterogeneous sets.

In short, the results show that countries that are converging rapidly to steady-state are in Asia, followed by Latin America, both with above-average speed (INTER and NOIL samples). The convergence speed between the richest countries (the OECD sample), however, is lower than the average of all estimated sample sets, and they are slower to achieve the steady-state of *per capita* carbon dioxide emission in the entire sample set. In most samples, the utilization of fixed effects result in a high reduction in the random effect bias, suggesting that country-specific effect are important to determine the pattern of CO2 emissions.

5.1. A possible interpretation of the country effect

The analysis is complemented by a correlation estimative between country-specific effects and *per capita* carbon dioxide emissions. To compute the fixed effect in the panel, it is necessary to isolate θ_i in Eq. (10), estimated from the average of the covariates and the predicted *per capita* emission. To recover A_0 the equation used is $\theta_{i=}(1 - e^{\varphi t}) lnA_0$, estimated in Eqs. (9) and (10), isolating lnA_0.

The specific effect result is a variable (or a set of variables) that explains the variations in per capita carbon dioxide emissions but does not vary over the period considered in the analysis, 1975–2005. To intuit about their behavior, we constructed an index relativizing the specific effect of each country by the minimum value, $A_{0(\min)}$. of the entire sample, which in this case was Malawi (Africa). To illustrate the technique, the specific effects were recovered for the NOIL sample that excludes the major global oil producers.

In Table 5, the sample countries are divided into five groups, measured with the score index: very low (0–25), low (25–50), medium (50–100), high (100–150) and very high (over 150). The major oil producers are not in the sample, and the North American countries were not listed. Then the sets were named: Europe, Asia and Oceania, Latin America and Caribbean, Africa and Middle East.

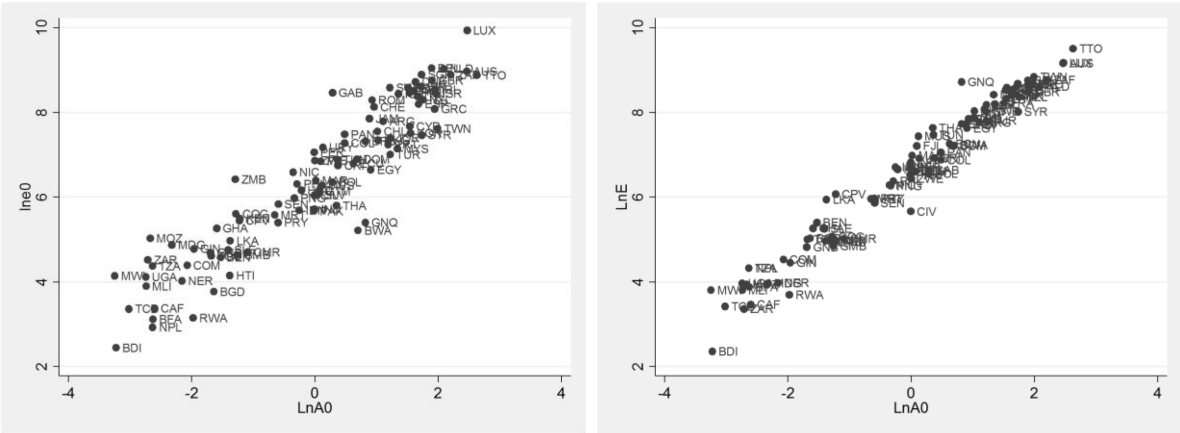
Table 5 - Distribution of regions and emissions by specific effect index (sample: *NOIL*)

	Very high	***High***	***Medium***	***Low***	***Very low***
Europe	6	8	4	0	0
Asia and Oceania	2	5	3	3	7
Latin America and the Caribbean	1	0	4	9	4
Africa and Middle East	1	0	4	8	26
Average CO_2 emissions in 1975	7356.96	4320.38	1944.70	997.98	176.61
Average CO_2 emissions in 2005	7257.47	4610.22	2929.25	1054.85	207.63
Emissions growth rate CO_2	0.03	0.04	0.24	0.09	0.07
Average index	225.98	130.59	72.90	32.81	6.88

A pattern in the distribution of specific effects occurred: Countries classified as high and very high are located in Europe; low or very low classified countries are located in Latin America, Caribbean, Africa and Middle East. The exception to the pattern are Asia and Oceania countries, whose distribution is more uniform. Moreover, the higher the country-specific effect, the greater the *per capita* carbon dioxide emissions, as shown by the averages of each group, in 1975 and 2005 in Table 1. For example, in the group of high specific effects, the average emissions is 7356.9 tons of CO_2, and in very low classification, this value is 207.6 *per* worker.

Fig. 1 shows the correlation between the parameter logarithm of A_0 (*x* axis) and carbon dioxide emissions (*y* axis) in 1975 (left) and 2005 (right). This country-specific characteristic is strongly correlated with the CO_2 emissions in 1975 and 2005, a correlation that is probably stronger than the savings rate, population growth or income.

Figure 1 – Scatter plot of the logarithm of the fixed effect parameter and per capita CO_2 emissions 1975 (left) and 2005 (right).



Note: The *x-axis* is the logarithm of the fixed effects index, and y-axis are the level of CO2 emission in 1975 and 2005, respectively.

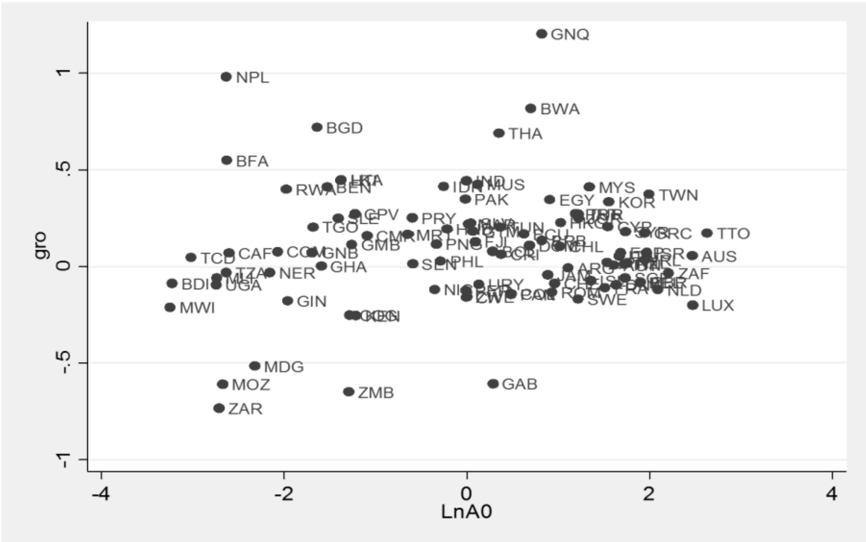
Among countries with high *per capita* emissions and fixed effect index are Trinidad and Tobago, Australia, the Netherlands, South Africa, Taiwan, Israel, Greece, Ireland, the United Kingdom and Belgium. One factor that may affect the ranking of the specific effect is the emission of CO_2 by energy use, since some of these countries have high consumption of electricity generated almost exclusively from fossil fuels, such as coal, for example: Trinidad and Tobago (99.7%), Israel (98.1%), South Africa (90.8%) and the Netherlands (85.1%). With an average of 75.0% of electricity from fossil fuels are Taiwan, Greece, Ireland and the United Kingdom. The only exception to this pattern is Belgium; 32.3% of the consumed electricity is generated from nuclear fuel. In this sense, even in countries with high consumption of fossil fuels, the energy matrix does not explain the entire emissions scenario.

However, some countries have low levels of specific effect and *per capita* emissions: Burundi, Nepal, Sierra Leone, Indonesia and Paraguay. Notably, this set of countries also has a low economic performance, and the majority of the emissions is from high capital concentration and consumption. It is natural that they are between the lowest countries by index of specific effect, while the energy use is low.

By analyzing the dynamic evolution over time, we observe that the relationship between the classification of specific effects of each country and the average growth rate in emissions per year (from 1975 to 2005) is the inverted U-shape: only in countries classified as medium specific effect did the average emissions rate increase, around 25.0% per year. Between the countries that are in the middle group of specific effect index, we emphasize Malaysia, Turkey, Sweden, Portugal, Argentina, Hong Kong, Chile, Switzerland; a very heterogeneous group of countries.

However, average growth has serious problems of extreme values, especially in countries that discovered natural resources or had low-quality data in the EPWT. Thus, when correlated with the average annual growth rate of emissions by country (Fig. 2), it is not possible to make statistical inferences about some nonlinear association, and a more sophistical estimation approach is not the intention of the present paper.

Figure 2 – Scatter plot of the logarithm of the country-specific and the average growth rate of *per capita* CO_2 between 1975 and 2005.



Note: x-axis is the logarithm of the country-specific, and y-axis is the average growth rate of *per capita* CO_2 between 1975 and 2005

In this context, the data suggest that the ranking of specific effects may be influenced by the level and quality of economic activity developed in the country. This performance matched the energy matrix, climate, geography and institutions to determine the size of the fixed effect. In the last point, if the reported configuration is stable to other econometric specifications, there may be an institutional conflict between promoting economic growth and emissions control: the same institutions that favor growth may not be able to develop initiatives to control and abate this type of externality, especially in rich and emerging countries. In the poorest countries, however, this conflict cannot exist, since the institutions are unable to promote development.

6. Conclusions

There is much disagreement over whether per capita CO_2 emissions are converging or not worldwide. This paper contributes to this controversial economic literature by analyzing this convergence hypothesis, controlling the estimates of panel data for observable and unobservable intrinsic characteristics between countries. Understanding CO2 dynamics is relevant to decisions over the global warming, especially as regarding the implementation of world emissions targets.

In this sense, the contributions of this paper can be summarized as follows. First, strong convergence evidence was found in large global and regional samples of countries. This result is new regarding previous literature, since in such studies convergence tends to be unstable in the sample size, and in general, only to OECD countries. In the present instance, there is also convergence evidence in such countries, but it tends to be faster in developing countries.

The use of the fixed effects estimator (via dummy-variables) has improved the prediction of convergence significantly for the five sets of countries. In particular, Asian and Latin American countries are converging to steady state at higher rates than the overall average (the INTER and NOIL samples). On the other hands, the OECD are converging below the average, about 10 years. In addition to corroborating the literature in terms of conditional convergence of CO_2, these results also improve them considerably. Especially, the data show that if there had not been strong changes in the regional distribution of carbon dioxide emissions, due to the global economic crisis, the emission pattern would be starting a stable growth trajectory.

The fixed-effects estimate also help recover the technological parameter of the production function. In this case, it was demonstrated that higher levels of this parameter are associated with increased *per capita* emissions, and its results is probably stronger than savings and population growth rates. From such perspective, variables related to development economics may be relevant to explain the level of CO_2 emissions as well.

Therefore, as in the past empirical growth literature, the environmental research have to advance in the study of other specific factors of countries that affect the emissions level, for example: What is the relationship between technology and CO_2 emissions? What is the role of institutional quality in such process? Do the most democratic countries have more responsibility for the environment? Answers to these questions may help understanding more about the complex relation between development and the environment.

Notes

[1] The entire sample set was estimated restricting the parameters of the savings and population growth rates to be statistically identical, as the Solow model predicts. However, the results in terms of convergence were similar, and are not presented.

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