NICOLAUS COPERNICUS UNIVERSITY IN TORUŃ

Bulletin of Geography. Socio-economic Series, No. 59 (2023): 83-93
http://doi.org/10.12775/bgss-2023-0006

BULLETIN OF GEOGRAPHY. SOCIO–ECONOMIC SERIES

journal homepages:
https://apcz.umk.pl/BGSS/index
https://www.bulletinofgeography.umk.pl/

Convergence of CO_2 emissions in the selected world countries

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How to cite:
Grodzicki, T. & Jankiewicz, M. (2022). Convergence of CO_2 emissions in the selected world countries. *Bulletin of Geography. Socio-economic Series*, 59(59): 83-93. DOI: http://doi.org/10.12775/bgss-2023-0006

Abstract. Nowadays, the topic of CO_2 emissions has been a subject of intensive debate. There is a significant policy push toward reducing emissions that cause air pollution and other environmental concerns. The aim of this paper is to analyze the CO_2 emissions as well as economic growth along with renewable energy use and the level of urbanization in the selected World countries in the period of 1995-2018. In general, almost all of the Northern part of the World was characterized by a high level of CO_2 emissions, while the majority of African territory was the least polluted. The empirical result shows that the growth rate of air pollution is much higher in countries that initially had a low level of CO_2 emissions, so the convergence process occurred. Conditioning convergence with the renewable energy use and the urbanization level indicates that its speed is higher. Club convergence analysis has proved that well-developed regions in terms of GDP per capita are able to improve the ecological situation despite further economic growth.

Article details:
Received: 20 September 2022
Revised: 11 November 2022
Accepted: 20 December 2022

Key words:
CO_2 emissions,
convergence,
renewable energy,
World countries,
urbanization and urban studies

Contents:

1. Introduction

Increasing CO_2 emissions on a global scale causes an incline in gas insulation worldwide, contributing to global warming. It results in a chain of catastrophic events such as a change in sea level, more frequent and intense fires, floods, droughts, heat waves, and hurricanes. Should a higher concentration of CO_2 is inhaled, humans and animals may also experience shortness of breath. Therefore, it is alarming that the concentration of carbon dioxide in the Earth's atmosphere is constantly increasing (Florides & Christodoulides, 2009; Keenan et al., 2013; Anwar et al., 2019; Pierrehumbert, 2019; Chovancová & Tej, 2020).

Several factors are responsible for the creation of pollution, such as the human population explosion, unplanned urbanization, deforestation, and uncontrolled technological change (Pritchard & Zimring, 2020; Živković, 2020; Ahmad et al., 2022). In developed countries, people, on average, consume more food and use more chemical substances (pesticides, insecticides, fertilizers), fuels, minerals, cars, and many other products. Uncontrolled production in recent decades has caused a significant increase in environmental pollution, and dealing with it is extremely difficult, costly, and at the same time, necessary. Currently, the industry is trying to limit the emission of harmful compounds into the atmosphere, including CO_2 (Carlsson-Kanyama, 1998; Fujii & Managi, 2016; Peter, 2018; Yoro & Daramola, 2020). Therefore, the industry is searching for new and alternative ways to reduce the carbon footprint, like the use of energy from renewable sources; replacing the lighting system from traditional to LED; introducing electric or hybrid vehicles and other low-carbon technologies; reducing the energy consumption in processes (Geels et al., 2017; Hoang et al., 2021; Mneimneh et al., 2022; Studzieniecki & Palmowski, 2022).

There is a strong policy push towards less air pollution, hence the urgent call for sustainable development. One of the United Nations' flagship projects is the so-called Sustainable Development Goals (SDGs). They were agreed by all United Nations Member States in 2015 and adopted in the form of the 2030 Agenda for Sustainable Development. There are 17 SDGs that call for immediate actions toward peace and prosperity for people and the planet (Chasek et al., 2016; Bexell & Jönsson, 2017;; Kanuri, n.d.; Semenenko et al., 2019; Skvarciany et al., 2021; Yuan, 2021). At the heart of the SDGs is the idea that economic growth is only sustainable when it goes hand in hand with social development and takes care of environmental issues. This paper especially concerns SDG 13, which calls for climate actions by improving energy efficiency, increasing environmental investments, reducing greenhouse gas emissions, especially carbon footprint, and tackling risks caused by climate change. The challenge set by the United Nations Framework Convention on Climate Change is to limit the global temperature increase to below 2°C above pre-industrial levels (Joshi et al., 2011; Gao et al., 2017; ; Warren et al., 2018). Therefore, countries worldwide must change the way they operate in agriculture, energy, industry, and transport systems (Sachs, 2006; Sovacool & Brown, 2010; Brown, 2013; Owusu & Asumadu-Sarkodie, 2016; Iglinski et al., 2021).

There have been a couple of applied papers analyzing CO_2 convergence. However, none of them focused on the current perspective and rarely included other factors (variables) in the analysis (in most cases, they only analyzed GDP per capita). Ordás Criado and Grether (2011) investigated the convergence process of per capita CO_2 emissions in 166 countries from 1960 to 2002. The results suggest that more divergence processes occurred in the World and larger per capita emissions in the long run. Another interesting study by Li and Lin (2013) analyzed the global convergence in per capita CO_2 emissions in 110 countries from 1971 to 2008. This study proved that a convergence process occurred within subsamples grouped by income level; however, there was just a little evidence on the whole sample. In conditional convergence, the study analyzed relationships between GDP and CO_2 emission growth at per capita levels. The results demonstrated that in high-income countries, per capita CO_2 emissions converge when the GDP level increases, which is contrary to the concept of the Environmental Kuznets Curve (where the CO_2 emissions will drop when GDP increases beyond a certain level). Moreover, Tiwari and Mishra (2017) analyzed CO_2 convergence in 18 Asian countries from 1972 to 2010, while Solarin (2014) focused on 39 African countries from 1960 to 2010. Both papers concluded that the CO_2 convergence process occurred.

2. Methodology and Data

2.1. Methodology

In the first step of an investigation, long-term tendencies in the formation of analyzed processes are considered. Therefore, polynomial time-trend models for panel data are estimated. The general form of the polynomial trend model is as follows:

$$Y_{i,t} = \alpha_{0i} + \sum_{k=1}^{n} \alpha_k t^k + \varepsilon_{i,t}, \quad (1)$$

where $Y_{i,t}$ is a considered process in i^{th} region in time t, t denotes the time variable, α_{0i} is the differentiated intercept for i^{th} country (defining individual characteristics of units), α_k – structural parameters, $\varepsilon_{i,t}$ – a random process and k – a degree of a polynomial trend.

The fixed effects included in the models characterize the heterogeneity of considered countries. When the non-stationarity in the average of processes is removed, the stationarity in the variance is tested. Wherefore, the test of the presence of the unit root in panel data proposed by Levin, Lin, and Chu (LLC) is applied (Levin et al., 2002). The zero hypothesis of the test claims that the panels contain unit roots.

The convergence panel data models are estimated and verified for stationary processes (filtered out from the non-stationarity in the average and variance). The convergence concept formulated by Solow based on the neoclassical economic growth model is considered (Solow, 1956). Initially, the absolute β-convergence panel data model is discussed. The general form of the model is as follows:

$$\ln\left(\frac{CO2_{i,t}}{CO2_{i,t-1}}\right) = \beta_0 + \beta_1 \ln(CO2_{i,t-1}) + \varepsilon_{i,t}, \quad (2)$$

where $CO2_{i,t}$ and $CO2_{i,t-1}$ are the levels of CO_2 emissions per capita in i^{th} country in time t and t-1, respectively, β_0,β_1 denotes the structural parameters and $\varepsilon_{i,t}$ – as above.

The model (2) can be written in the form of the dynamic panel data model, given as:

$$\ln(CO2_{i,t}) = \beta_0 + (1+\beta_1)\ln(CO2_{i,t-1}) + \varepsilon_{i,t}. \quad (3)$$

Less than unity and statistically significant parameter $1+\beta_1$ points out that the convergence process occurs. Based on model (3), the convergence characteristics such as convergence speed and *half-life* time can be calculated. These statistics are designated with the use of the formulas (4) and (5), respectively:

$$b = -\ln(1+\beta_1), \quad (4)$$

$$t_{hl} = \frac{\ln 2}{b}. \quad (5)$$

Next, the conditional convergence models are estimated and verified. The literature review allowed choosing processes that significantly influence CO_2 emissions. Thus, the model in the form (6) is formulated as follows:

$$\ln(CO2_{i,t}) = \beta_0 + (1+\beta_1)\ln(CO2_{i,t-1}) + \gamma_1 \ln(GDP_{i,t}) + $$
$$+ \gamma_2 \ln(RE_{i,t}) + + \gamma_3 \ln(URB_{i,t}) + \varepsilon_{i,t}, \quad (6)$$

where $CO_{2i,t}$ and $CO2_{i,t-1}$ are defined above, $GDP_{i,t}$, $RE_{i,t}$, $URB_{i,t}$ denotes the level of Gross Domestic Product per capita, the share of renewable energy use, and the urbanization level in i^{th} country in time t, respectively. Moreover, $\beta_0,\beta_1,\gamma_1,\gamma_2,\gamma_3$ are the structural parameters of the model and $\varepsilon_{i,t}$ is defined as above.

In turn, the club convergence of the CO_2 emissions is considered using switching regression models. The partitioning of data into subsamples allows for checking whether the convergence process differs depending on the level of CO_2 emissions. Countries are divided into two clubs using Ward method clustering (Ward, 1963): units with a low and high level of considered process, respectively. Ward algorithm is the agglomerative clustering method based on within-group dispersion minimizing (Murtagh & Legendre, 2014).

$$\ln(CO2_t) = \sum_{m=1}^{M} [\beta_{0,m} + (1+\beta_{1,m})\ln(CO2_{i,t-1})] + \varepsilon_{i,t}, \quad (7)$$

$$n(CO2_t) = \sum_{m=1}^{M} \begin{bmatrix} \beta_{0,m} + (1+\beta_{1,m})\,ln(CO2_{i,t-1}) + \gamma_{1,m}\,ln(GDP_{i,t}) + \\ +\gamma_{2,m}\,ln(REi_{,t}) + \gamma_{3,m}\,ln(URB_{i,t}) \end{bmatrix} + \varepsilon_{i,t}, \quad (8)$$

where $CO2_{i,t}$, $CO2_{i,t-1}$, $GDP_{i,t}$, $RE_{i,t}$, $URB_{i,t}$ and $\varepsilon_{i,t}$ are defined as above, M denotes the number of clusters (in this research M=2), $\beta_{0,m},\beta_{1,m},\gamma_{1,m},\gamma_{2,m},\gamma_{3,m}$ are the structural parameters of models estimated for m^{th} club.

2.2. Data

The research refers to the CO_2 emissions convergence between selected 158 World countries in the period of 1995-2018. Data used in this study come from the World Bank database (https://data.worldbank.org/indicator, access: 30.03.2022). They concern the levels of: (1) CO_2 emissions per capita, (2) the GDP per capita, (3) the share of renewable energy use, and (4) the share of the population living in cities.

Figure 1 presents the spatial differentiation of the CO_2 emissions per capita in the World in the years 1995 and 2018 – in parts (a) and (b), respectively.

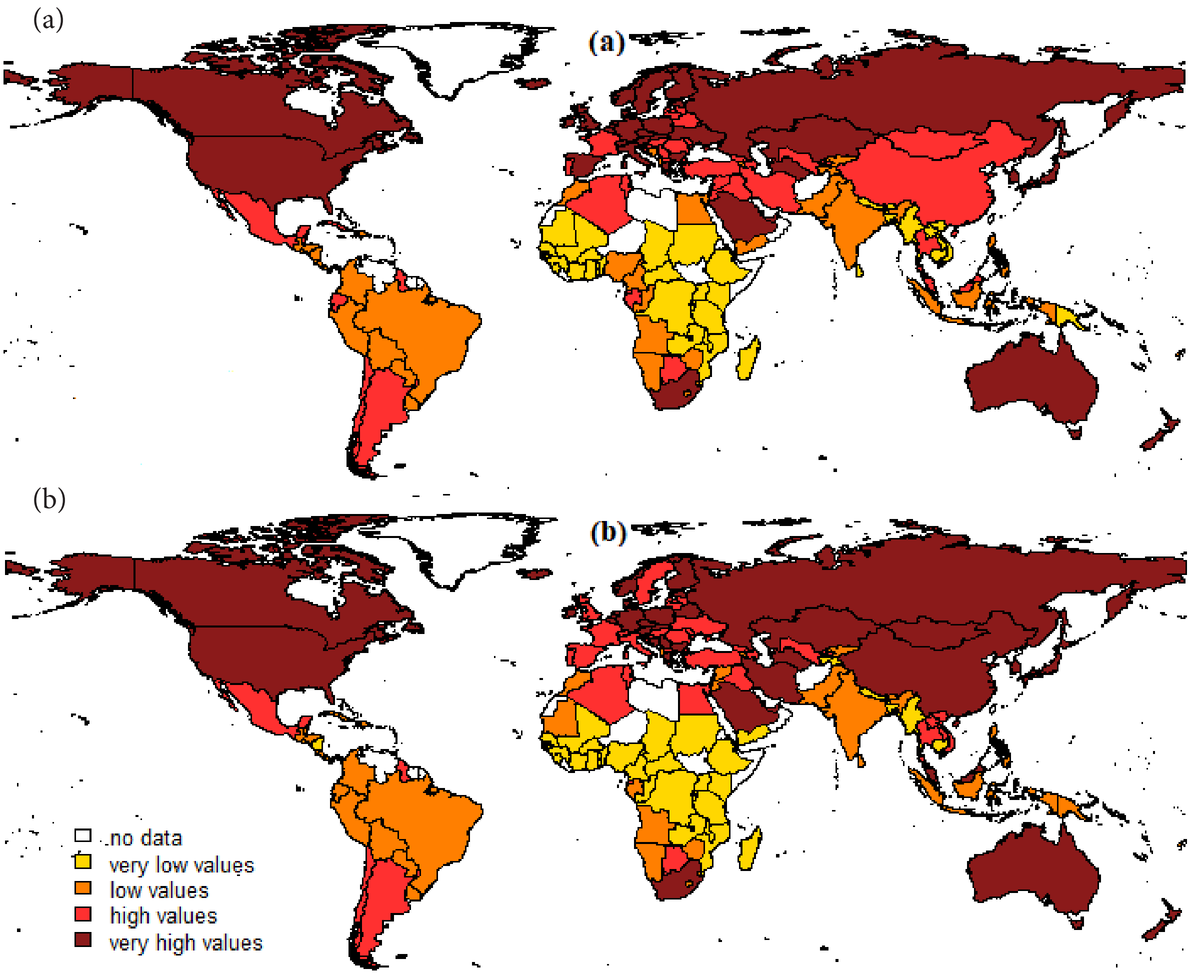

Fig. 1. The spatial differentiation of CO2 emissions per capita in the World in the years 1995 (a) and 2018 (b)
Source: own elaboration based on data from World Bank database.

In both years, the spatial distributions of the considered process are very similar. A high level of air pollution was noted in most countries in the northern part of the World. Almost all African states were included in the group of units with a very low level of CO_2 emissions. Instead, South American regions are classified into two groups with intermediate levels of the considered process. Consequently, from 1995 to 2018, the air pollution level between countries did not change significantly.

A very similar situation is noted in analyzing the GDP per capita level in the study's extreme years, presented in Figure 2. In both years, the highest level of the GDP per capita was observed in the Northern American and European countries. Moreover, in 1995 Argentina, Brazil, and Chile, which became weaker in 2018, were classified as well-developed regions. Comparing spatial distributions of processes in Figures 1 and 2, one may note that there are no significant differences related to African countries. Instead, Asian regions were classified into collections with countries of the intermediate level of GDP per capita.

In turn, Figure 3 shows the spatial differentiation of the renewable energy use share in the final energy use. Such as in the case of previous processes, in the years 1995 and 2018 – in part (a) and (b), respectively. In both years of the study, distributions of the process values were almost the same. The highest use of renewable energy was observed in African countries and a few other countries in the middle part of the World. Moreover, in 2018 the Scandinavian states, as the only European states, were classified into groups with the highest level of the analyzed process. Most Northern World countries were characterized by low and very low renewable energy use in both years of the investigation. South America was the most differentiable part of the World, considering renewable energy use.

The spatial differentiation of the last analyzed process in the years 1995 and 2018 – the urbanization level – is presented in Figure 4. Similarly to other variables, the differences between

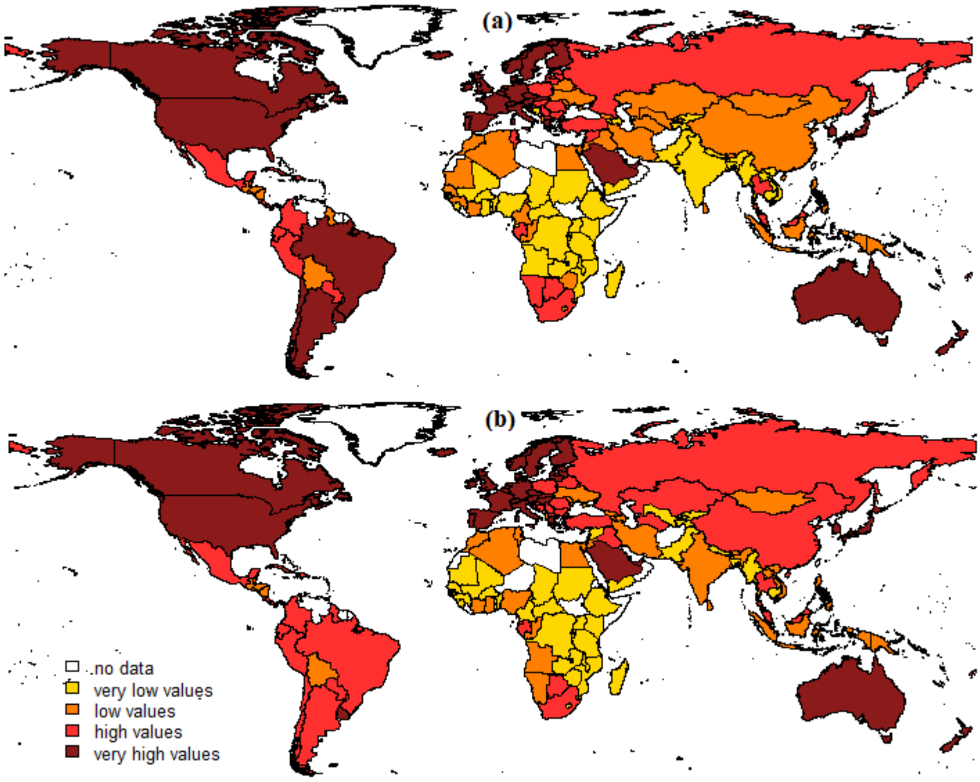

Fig. 2. The spatial differentiation of the GDP per capita in the World in the years 1995 (a) and 2018 (b)
Source: own elaboration based on data from World Bank database.

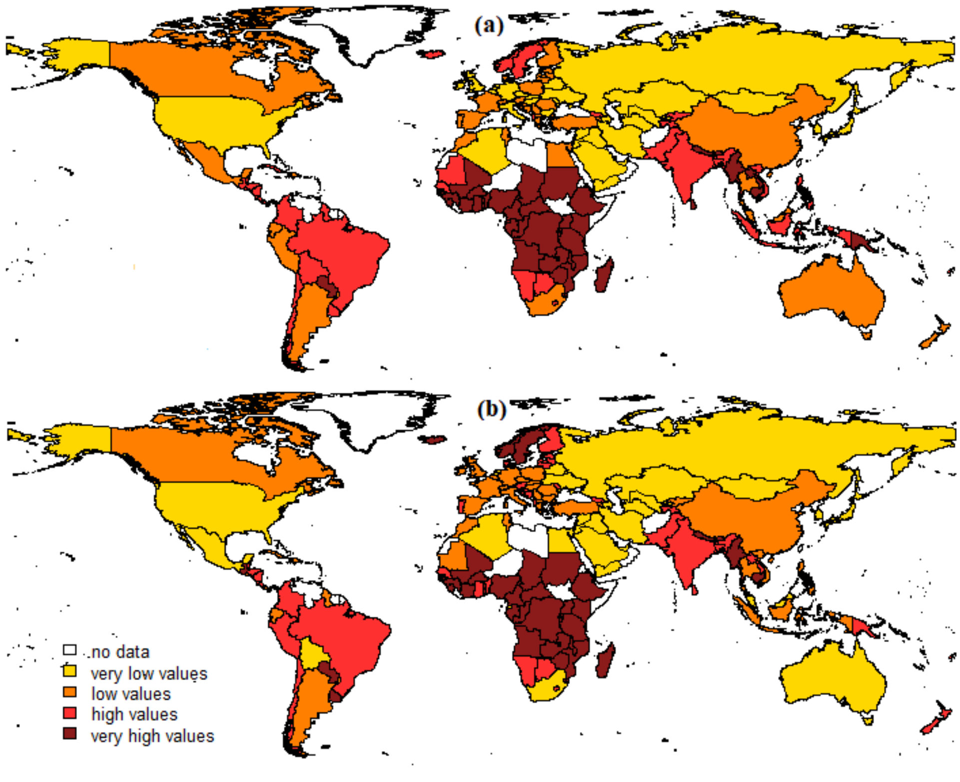

Fig. 3. The spatial differentiation of the share of renewable energy use in the World in the years 1995 (a) and 2018 (b)
Source: own elaboration based on data from World Bank database.

the spatial distribution of the urbanization level in the study's extreme years were insignificant. The countries with the highest level of a considered process dominated the western part of the World. The high share of urban population was noted in Australia, Europe, and Northern Asia too. In turn, the lowest percentage of people living in cities was observable in most African countries and Sothern Asia regions.

When comparing the levels of analyzed processes in the selected World countries, it can be presumed that the economic development and migration of the population to cities caused an increase in air pollution. On the other hand, ecological degradation can be stopped by increasing the usage of renewable energy sources.

Figure 5 presents the CO2 emissions per capita growth rate from 1995 to 2018. In most countries in the analyzed period, an increase in air pollution was observed. A particular dependency can be noticed when comparing the maps in Figure 5 with Figure 1 (a). Its growth rate is negative in countries with the highest level of CO2 emissions, unlike in regions with the lowest level of the analyzed process. It can be the basis for presuming about the convergence of the CO2 emissions in the World.

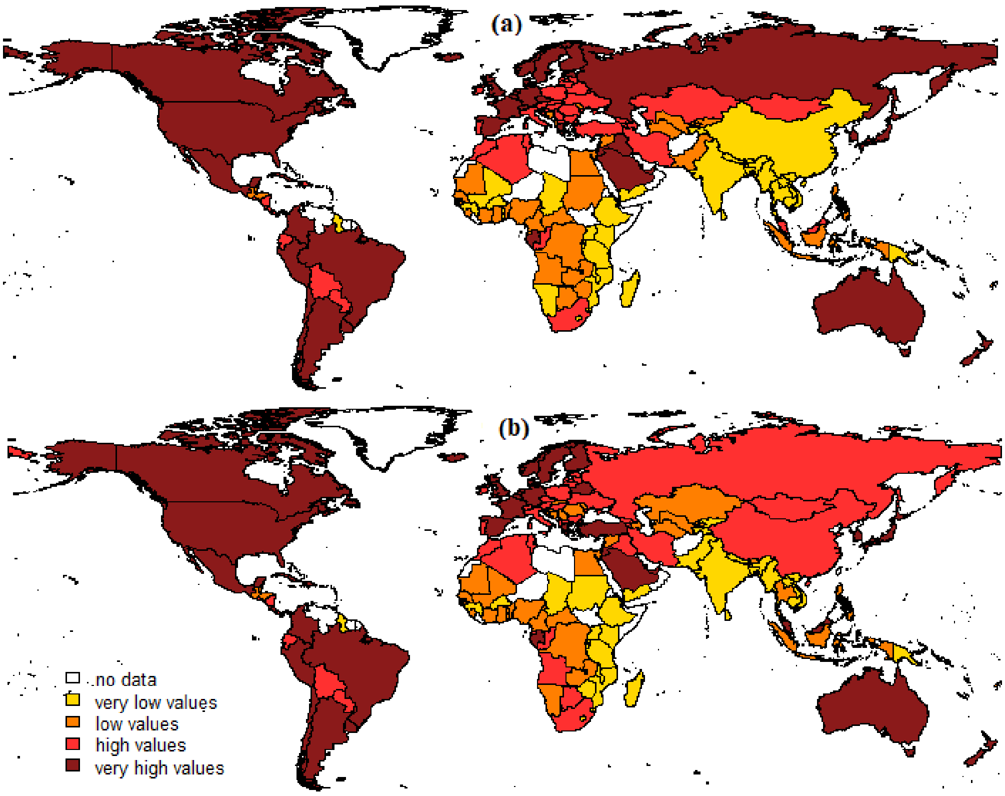

Fig. 4. The spatial differentiation of the urbanization level in the World in the years 1995 (a) and 2018 (b)
Source: own elaboration based on data from World Bank database.

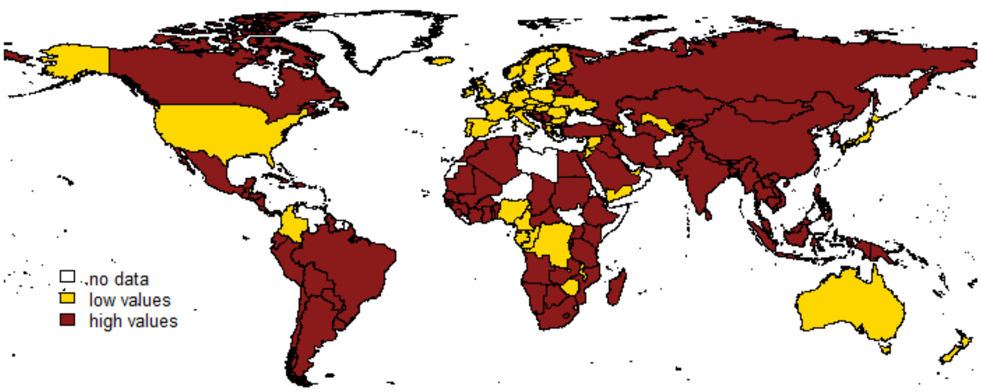

Fig. 5. The growth rate of CO_2 emissions in the World in the period of 1995-2018
Source: own elaboration

3. Empirical results

In the first step of the research, the long-term tendency in forming the processes is considered. Table 1 presents the estimation and verification results of the polynomial trend for all variables and the results of the LLC test.

For all variables, the first-degree trend was obtained. Moreover, a positive and statistically significant parameter α_1 signalizes that from 1995 to 2018, the level of all considered processes increased on average. The results of the LLC test show that in the processes filtered out from the non-stationarity (in the average), the unit root did not occur. Therefore, the convergence models were estimated for the stationary processes.

Table 2 presents the results of the estimation and verification of the absolute and conditional β-convergence panel data models.

In both models, the parameter $1+\beta_1$ is statistically significant and its estimate is less than one. It denotes that the CO_2 emissions per capita level between considered countries converged. Nevertheless, differences in the speed of convergence and half-life time statistics show that convergence with additional determinants influences air pollution to occur faster. Including these processes in the model, the time needed to reduce current inequalities by half decreased from almost six to just over two years. Estimates of parameters γ_1 and γ_3 confirm the negative impact of an increase in economic development and urbanization level on air pollution. In turn, the negative sign of the parameter γ_2 denotes that an increase in renewable energy use improved the ecological situation in the World.

The next part of the study began by dividing selected countries into two groups presenting a similar level of CO_2 emissions from 1995 to 2018 using cluster analysis. Figure 6 illustrates cluster membership of all analyzed regions obtained

Table 1. The results of the estimation and verification of the polynomial trend and the results of the LLC test

Parameter	Variable							
	CO_2		GDP		RE		URB	
	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value
α_1	0.0135	0.0000	0.0621	0.0000	0.0044	0.0000	0.0074	0.0000
Levin-Lin-Chu test								
z-score	-9.8953		-12.7115		-8.6466		-9.6962	
(p-value)	(0.0000)		(0.0000)		(0.0000)		(0.0000)	

Source: own elaboration

Table 2. The results of estimation and verification of the absolute and conditional β-convergence panel data models

Parameter	*Absolute convergence*		*Conditional convergence*	
	Estimate	p-value	Estimate	p-value
β_0	-0.0002	0.9294	0.0004	0.8218
$1+\beta_1$	0.8888	0.0000	0.7422	0.0000
γ_1	-	-	0.0650	0.0003
γ_2	-	-	-0.0911	0.0012
γ_3	-	-	0.2773	0.0150
b	0.1179		0.2981	
t_{hl}	5.8811		2.3253	

Source: own elaboration

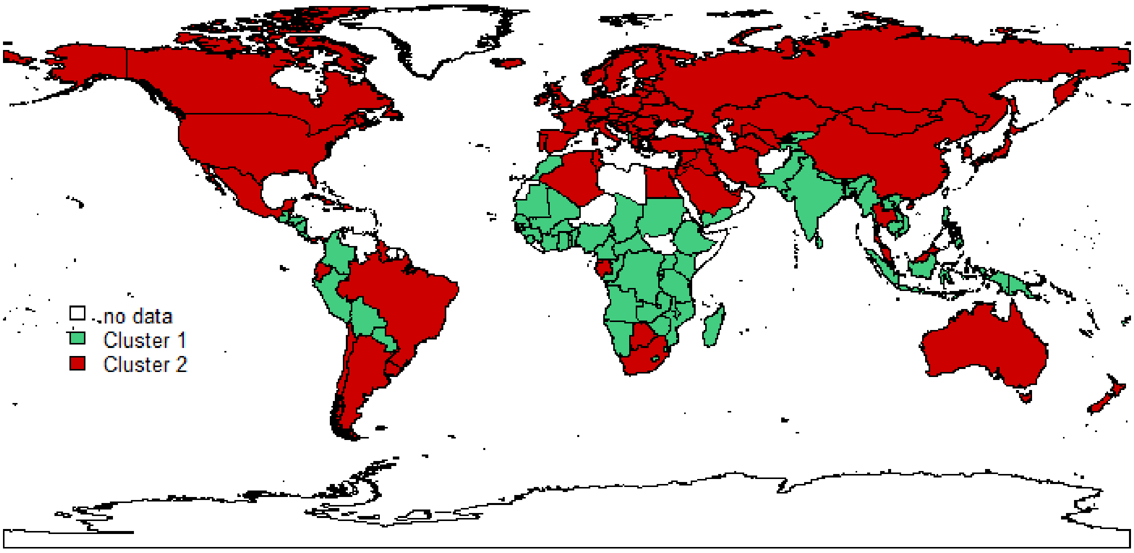

Fig. 6. Clusters membership of countries based on the CO_2 emissions similarity
Source: own elaboration

using the Ward method of clustering. The first cluster contains countries with a lower level of the considered process. African countries and some of the remaining Middle World states dominated this group. The second cluster comprises European, Northern American, most Asian and South American countries, and Australia.

Table 3 contains the results of the estimation and verification of the club-convergence panel data models. Clubs of countries correspond with clusters presented in figure 6. Such as in the previous case, two types of convergence were considered – absolute and conditional.

Parameters $1+\beta_{1,1}$ and $1+\beta_{1,2}$ are statistically significant in both cases – for absolute and conditional convergence approaches. Moreover, their estimates indicate that the convergence process occurs between the first and second clubs' countries. It is worth to be noted that in the first club (where the regions only with a positive growth rate of the analyzed process are located), the aligning of the CO_2 emissions progress slower. The faster growth rate of the considered variable in the regions with low values can be caused by their more rapid economic development and an increase in the percentage of the urban population, which have a negative impact on air pollution (positive and statistically significant parameters $\gamma_{1,1}$ and $\gamma_{3,1}$). In turn, for the second club, faster convergence of the CO_2 emissions (*half-life* time statistics is less than three years and one year for absolute and conditional convergence, respectively) is caused, among others, by the presence of countries with both positive and negative growth rates. Moreover, the regions are mostly recognized as well-developed and more stable than the others. Some of them have reached the level of development that allows improving the ecological situation despite further economic growth. It is the premise to enrich this study with the Ecological Kuznets Curve (EKC) approach.

The impact of the different processes determining the level of CO_2 emissions is the same as in the convergence analysis for selected countries without division into clubs. Further, the exact relation between absolute and conditional convergence speed is observed.

4. Conclusion

CO_2 emissions play a significant role from a current global perspective since their reduction is in the spotlight of sustainable development goals, which are an urgent call for action worldwide. This paper proved that there is a strong need for decreasing the level of CO_2 emissions as well as sustainable city planning and increasing the share of renewable energy use. Moreover, when countries are developing their economies, it can be observed that they produce more pollution to the environment. Therefore, the question for further analysis would be if there is a certain point of a country on its development when they turn from more to less CO_2 emissions, so it is precisely the point made by the so-called Kuznets Curve in its environmental

Table 3. The results of estimation and verification of the absolute and conditional club-convergence panel data models

Parameter	*Absolute convergence*		*Conditional convergence*	
	Estimate	**p-value**	**Estimate**	**p-value**
$\beta_{0,1}$	0.0129	0.0000	0.0106	0.0000
$1+\beta_{1,1}$	0.9035	0.0000	0.7951	0.0000
$\gamma_{1,1}$	-	-	0.0544	0.0000
$\gamma_{2,1}$	-	-	-0.1971	0.0000
$\gamma_{3,1}$	-	-	0.1323	0.0011
$\beta_{0,2}$	-0.0099	0.0000	-0.0078	0.0005
$1+\beta_{1,2}$	0.8419	0.0000	0.7041	0.0000
$\gamma_{1,2}$	-	-	0.0612	0.0000
$\gamma_{2,2}$	-	-	-0.0508	0.0000
$\gamma_{3,2}$	-	-	0.3089	0.0000
	Cluster 1	**Cluster 2**	**Cluster 1**	**Cluster 2**
b	0.1015	0.1721	0.2293	0.3508
t_{hl}	6.8281	4.0283	3.0225	1.9761

Source: own elaboration

approach. Observing certain tendencies in the spatial distributions of the processes, it is worth enriching models with the spatial and spatio-temporal tendencies and dependence in further analysis. Moreover, the Environmental Kuznets Curve framework in the CO_2 emissions convergence should be taken into consideration.

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