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Analysis of Spatial Effects in the Relationship between CO_2 Emissions and Renewable Energy Consumption in the Context of Economic Growth

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Abstract: The paper presents a spatial approach to the analysis of the relationship between air pollution, economic growth, and renewable energy consumption. The economic growth of every country is based on the energy consumption that leads to an increase in national productivity. Using renewable energy is very important for the environmental protection and security of the earth's resources. Promoting environmentally friendly operations increases awareness of sustainable development, which is currently a major concern of state governments. In this study, we explored the influence of economic growth and the share of renewable energy out of total energy consumption on CO_2 emissions. The study was based on the classical environmental Kuznets curve (EKC) and enriched with the spatial dependencies. In particular, we determined the spatial spillovers in the form of the indirect effects of changes in renewable energy consumption of a specific country on the CO_2 emissions of neighboring countries. A neighborhood in this study was defined by ecological development similarity. The neighborhood matrix was constructed based on the values of the ecological footprint measure. We used the spatio-temporal Durbin model, with which the indirect effects were determined in relation to the spatially lagged renewable energy consumption. The results of our study also show the strength of the effects caused by imitating actions from the states with high levels of environmental protection. The study was conducted using data for 75 selected countries from the period of 2013–2019. Cumulative spatial and spatio-temporal effects allowed us to determine (1) the countries with the greatest impact on others and (2) the countries that follow the leading ones.

Keywords: economic growth; environmental Kuznets curve; renewable energy; spatio-temporal Durbin model; spatial spillovers

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1. Introduction

Caring for the natural environment should be an integral part of the economic development policy of each country. Unfortunately, state authorities have devoted too little attention to this issue so far, and the degradation of the environment caused by the overexploitation of natural resources and an excessive desire to become wealthy has been extreme. High levels of consumption of non-renewable energy sources and environmental pollution cause an increase in greenhouse gas emissions, mainly carbon dioxide (CO_2). Increasingly more emissions have a negative effect on the composition of the atmosphere and global climate [1].

To protect nature, the concept of sustainable development was created, the goal of which is economic development with consideration for the well-being of the present and future generations [2]. The most popular definition of sustainable development is the one formulated by the Brundtland Commission, which describes it as meeting the needs of the present generation without limiting the possibilities of meeting them for future generations.

In particular, sustainable development addresses the problem of reducing the consumption of limited resources of the Earth as well as reducing environmental pollution [3].

The relationship between economic growth and the amount of environmental degradation is usually described by the environmental Kuznets curve (EKC) [4–7]. In the basic version, the curve expresses the dependence between these processes in the form of an inverted "U" shape, that is, an increase in the level of income of states leads to ever greater environmental degradation, and then, when wealth reaches a certain level, the relationship is reversed. In addition to economic development, renewable energy consumption also has an impact on the natural environment. Increases in the levels of renewable energy consumption, as well as its share of total energy consumption, promote environmental protection [8]. The influence of other factors on the state of the natural environment has also been considered in the literature, for example, the level of trade openness, fossil fuel energy consumption, and the degree of urbanization or population density [9–14].

In many countries, an increase in the share of energy from renewable sources out of the total energy consumption has been observed. Moreover, the actions of some countries in this direction have influenced changes to the structure of energy consumption in others. The improvement of environmental conditions resulting from the increase in using renewable energy sources causes an imitation effect.

The aim of this study was to explore the influence of economic growth and the share of renewable energy out of the total energy consumption on the CO_2 emissions for 75 selected countries of the world in the period of 2013–2019. Our concern, in particular, was the impact of changes in renewable energy consumption in a specific country on the air pollution in neighboring countries (the so-called spatial spillovers). In the investigation, we used the spatio-temporal Durbin model (STDM) as a re-specification of the equation based on the concept of the classical environmental Kuznets curve (EKC) and determined the indirect effects in relation to spatially lagged renewable energy consumption. A neighborhood in this study was defined by ecological development similarity. The neighborhood matrix was constructed based on the values of the ecological footprint measure.

The results of our study also show the strength of the effect caused by imitating actions from states with high levels of environmental protection. In particular, the study allowed us to determine the countries with the greatest impact on others as well as the countries that follow the leading ones.

In this study, the following research hypotheses were formulated: (1) The neighborhood, in the sense of ecological similarity, is significant for the analysis of dependence between CO_2 emissions, economic growth, and the consumption of energy from renewable sources. (2) The countries characterized by a high share of energy from renewable sources out of the total energy consumption have less of an impact on the state of the natural environment in other countries than those wealthier but with a lower use of renewable energy.

The paper is organized as follows. In Section 2, we present a review of the literature related to the subject of our research. Section 3 presents a discussion on the tools and models that were used in the empirical analysis performed. The data are discussed in Section 4, as are the spatial distributions of the variables considered. Section 5 contains the details of the empirical results, and Section 6 summarizes the main results and presents the general conclusions. Finally, suggestions for further studies are presented.

2. Literature Review

The relationship between energy consumption and the emissions of pollutants has been analyzed by many researchers. Issues related to the effects of increasing total energy consumption as well as increasing the share of energy consumption from renewable sources have been discussed. These studies show that increases in energy consumption result in increases in the emissions of pollutants. Özokcu and Özdemir [15] consider this relationship on the basis of the cubic Kuznets curve, which was estimated for two groups of countries—26 highly developed OECD countries and 52 developing ones. Other authors, such as Aydin and Esen [16], Piłatowska and Włodarczyk [17], Presno et al. [18], and

Yavuz and Yilanci [19] have also pointed out the negative impact of increased consumption energy on the environment. They used a nonlinear approach based on threshold analysis in their studies.

Studies that deal with the impact of renewable energy consumption on the environmental situation can be divided into two groups. The first group consists of studies in which the consumption of energy per capita was considered [20–23]; the second consists of those that considered the share of energy consumption from renewable sources [24]. In the work of Zoundi [25], 25 countries in the period of 1980–2012 were analyzed using the concept of co-integration. The same approach was presented by Zambrano-Monserrate et al. [26] with a discussion on the relationship in Brazil, by Jebli and Youssef [27], who considered the link between energy and the environment in Tunisia, as well as by Sahbi and Shahbaz [28], who focused on the countries of central-east and northern Africa. Similar analyses can be found in the works of Gill et al. [29], Sinha et al. [30], Dogan and Seker [31], and Bölük and Mert [32].

Despite the differences in the approaches to expressing energy consumption in the models used, the general results are the same. They show a positive effect of the increase in both the level and share of renewable energy consumption on the natural environment.

The research studies cited above were based on the environmental Kuznets curve, by which the role of the explanatory variable is played by an appropriate measure of economic growth. The models used were enriched with various additional explanatory variables. In a few works in this field, one can find a reference to the spatial connections between countries/regions. For example, Güçlü [33] incorporates spatial links into the Kuznets curve by analyzing the relationship between economic growth and environmental degradation for Turkish NUTS-3 regions in the years 2008–2013. The spatial environmental Kuznets curve was also used in the works by the following: Tan [34], Donfouet et al. [35], McPherson and Nieswiadomy [36], Burnett and Bergstrom [37], and Tevie et al. [38]. These researchers used simple spatial models, such as the spatial autoregressive model (SAR) and the spatial error model (SEM). In addition, Kang et al. [39], Wang et al. [40], Fong et al. [41], and Li et al. [42] used the spatial Durbin model (SDM). In their study, Li et al. [42] additionally determined the spatial direct and indirect effects resulting from changes in all explanatory variables included in the model.

In all of the above-mentioned studies, the significance of spatial connections for the relationship under investigation was indicated, and the authors formulated conclusions about the similarity of the environmental situation in the countries directly adjacent to each other. It should be emphasized that in these works, only the first-order neighborhood according to the common border criterion was considered.

3. Methodology

In the investigation, we used the models for pooled time series and cross-sectional data (TSCS), with particular reference to the spatial model. The basic space–time model was chosen, enriched only by spatial components, without any fixed or random effects that are characteristic of panel models. In this approach, we studied the heterogeneity of economies using the spatial trend, but for CO_2 emissions, it turned out to be statistically insignificant. We also considered the validity of using dynamic spatial models as well as dynamic spatial panel data models; however, given the insignificance of spatial effects and other diagnostics of these models, we decided to forgo them in further analysis. The justification for the use of the spatial models, that is, the models containing spatial lags of dependent or/and explanatory variables, comes from the specific interpretation of the parameters of these models, which measured the impact of changes in the variable values in neighboring observations/regions (i.e., y_j, x_{kj}) on the dependent variable observation y_i [43] (p. 34).

In classical terms, based on the concept of the environmental Kuznets curve in the variant of the quadratic function, the model describing the relationship between CO_2

emissions and GDP per capita as well as the share of energy consumption from renewable sources out of the total energy consumption takes the following form:

$$\ln(CO_2)_{i,t} = \beta_0 + \beta_1 \ln(GDP)_{i,t} + \beta_2(\ln(GDP))^2_{i,t} + \beta_3 \ln(RE)_{i,t} + \varepsilon_{i,t}, \quad (1)$$

where CO_2 denotes the carbon dioxide emissions per capita, GDP stands for the value of gross domestic product per capita, and RE is the share of renewable energy consumption. In turn, β_0, β_1, β_2, and β_3 are the structural parameters of the model, and ε is its random component. All the variables have been expressed in logarithms to stabilize the variance. Depending on the sign of the parameters β_1 and β_2, the Kuznets curve takes a different shape. Depending on their values, we explored the following situations:

(i) No relationship between GDP and CO_2 emissions ($\beta_1 = 0$ and $\beta_2 = 0$);
(ii) Linear relationship between GDP and CO_2 emissions ($\beta_1 \neq 0$ and $\beta_2 = 0$);
(iii) Inverse U-shaped relationship between GDP and CO_2 emissions ($\beta_1 > 0$ and $\beta_2 < 0$)—the classical Kuznets curve;
(iv) U-shaped relationship between GDP and CO_2 emissions ($\beta_1 < 0$ and $\beta_2 > 0$).

A turning point can be determined for the last two of the above-mentioned relationships, indicating the level of GDP per capita at which CO_2 emissions reach the maximum value (iii) or the minimum value (iv). It is determined according to the following formula:

$$GDP_{TP} = exp\left(-\frac{\beta_1}{2\beta_2}\right),\ \beta_2 \neq 0 \quad (2)$$

In order to verify the validity of introducing spatial connections to our analysis, first for all the variables considered in every year the values of Moran's I have been calculated, using the following formula [44,45]:

$$I = \frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \cdot \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}[y_i - \overline{y}][y_j - \overline{y}]}{\frac{1}{n}\sum_{i=1}^{n}[y_i - \overline{y}]^2} = \frac{n}{S_0} \cdot \frac{\mathbf{z}^T\mathbf{W}\mathbf{z}}{\mathbf{z}^T\mathbf{z}}, \quad (3)$$

where y_i denotes an observed value of the phenomenon in the region i, $\mathbf{z}$ means a column vector with elements $\mathbf{z}_i = y_i - \overline{y}$, $S_0 = \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}$ is a sum of the corresponding elements of the weights' matrix $\mathbf{W}$, and n stands for the number of regions. The matrix $\mathbf{W}$ of spatial connections in our study was defined based on the environmental development similarity of the countries.

The **W** matrix was derived from the 2017 ecological footprint value because this was the year for which the latest data was available. We decided to use the connectivity matrix constant in time due to the fact that in the period of 2013–2017, for the countries under consideration, there have been only minor changes in the ecological footprint values. Therefore, we concluded that this regularity was maintained in the following years. Thus, for the entire period of our study, the neighborhood structure remained unchanged.

The choice to use the ecological footprint as a criterion for determining the neighborhood of countries was dictated by its close relationship with the theory of sustainable development, in which special attention is paid to natural environmental protection. In addition, the level of CO_2 emissions, which was the subject of this study, is one of the main aspects of environmental pollution.

To construct the matrix **W,** we started by determining the distance between pairs of countries according to the following formula:

$$d_{ij} = \left|EF_i - EF_j\right|, \quad (4)$$

where EF_i and EF_j are indicators of the ecological footprint for countries ith and jth, respectively.

Then, the borderline level g of similarity between the countries was determined as the fifteenth percentile of all distances. This avoided the problem of excessive density in the neighborhood matrix. A matrix too dense would blur the actual relations between neighbors.

Subsequently, the non-zero elements of the distance matrix **D** were inverted as follows:

$$d_{ij}^{*} = \begin{cases} \frac{1}{d_{ij}}, & i \neq j \wedge d_{ij} < g \\ 0, & i = j \vee d_{ij} > g \end{cases} \quad (5)$$

and row-standardized to one. Finally, a block matrix of cross-sectional and temporal links between various countries in the field of environmental development was created.

In order to confirm the validity of introducing the spatial effects to model (1) the Lagrange multiplier tests (LM), in the basic and robust versions, were used. Thus, the following spatio-temporal Durbin model specification was considered:

$$\begin{aligned} \ln(CO_2)_{i,t} = \rho \textstyle\sum_{i \neq j} w_{ij,t} \ln(CO_2)_{j,t} + \alpha + \beta_1 \ln(GDP)_{i,t} + \beta_2 (\ln(GDP))_{i,t}^2 + \beta_3 \ln(RE)_{i,t} \\ + \theta \textstyle\sum_{i \neq j} w_{ij,t} \ln(RE)_{j,t} + \varepsilon_{i,t}. \end{aligned} \quad (6)$$

The models such as (6), thanks to the inclusion of spatial lags of the dependent variable and independent variables, allowed us to quantify the magnitude of the so-called direct and indirect effects in the short term [46] (p. 11). In this study, we were primarily interested in the indirect effects that were used to test the hypothesis whether in the area of the countries considered in terms of CO_2 emissions the spatial spillovers exist.

To see the way in which the mentioned effects were obtained, the general expression of the non-dynamic model was transformed into Equation (7)

$$\mathbf{Y}_t = \rho \mathbf{W} \mathbf{Y}_t + \alpha \boldsymbol{\iota}_N + \mathbf{X}_t \boldsymbol{\beta} + \mathbf{W} \mathbf{X}_t \boldsymbol{\theta} + \boldsymbol{\varepsilon}_t. \quad (7)$$

By transforming the equation to the form the following:

$$\mathbf{Y}_t = (\mathbf{I} - \rho \mathbf{W})^{-1} \alpha \boldsymbol{\iota}_N + (\mathbf{I} - \rho \mathbf{W})^{-1} (\mathbf{X}_t \boldsymbol{\beta} + \mathbf{W} \mathbf{X}_t \boldsymbol{\theta}) + (\mathbf{I} - \rho \mathbf{W})^{-1} \boldsymbol{\varepsilon}_t \quad (8)$$

and excluding from the matrix $\mathbf{X}_t$ the vector regarding the variable X_k, that is, $\mathbf{X}_{kt}$, the following equation was obtained:

$$\mathbf{Y}_t = (\mathbf{I} - \rho \mathbf{W})^{-1} \alpha \boldsymbol{\iota}_N + (\mathbf{I} - \rho \mathbf{W})^{-1} \left(\dot{\mathbf{X}}_t \boldsymbol{\beta} + \mathbf{W} \dot{\mathbf{X}}_t \boldsymbol{\theta} \right) + (\mathbf{I} - \rho \mathbf{W})^{-1} (\beta_k \mathbf{I}_N + \theta_k \mathbf{W}) \mathbf{X}_{kt} + (\mathbf{I} - \rho \mathbf{W})^{-1} \boldsymbol{\varepsilon}_t, \quad (9)$$

where $\dot{\mathbf{X}}_t$ stands for the matrix from which the $\mathbf{X}_{kt}$ has been removed.

The expression $(\mathbf{I} - \rho \mathbf{W})^{-1} (\beta_k \mathbf{I}_N + \theta_k \mathbf{W})$ allowed us to determine the direct and indirect effects of the kth explanatory variable X_k on the dependent variable Y. In our study, the indirect effects were determined in relation to the share of energy from renewable sources out of the total energy consumption in the neighboring regions.

The short-term effects were designated as the matrix of partial derivatives of Y with respect to the kth explanatory variable of **X** in spatial unit 1 up to unit N at a particular point in time, as shown in the following equation:

$$\left[\frac{\partial Y}{\partial x_{1k}} \cdots \frac{\partial Y}{\partial x_{Nk}} \right] = (\mathbf{I} - \rho \mathbf{W})^{-1} (\beta_k \mathbf{I}_N + \theta_k \mathbf{W}), \quad (10)$$

which denotes the effect of a change of a particular explanatory variable in a particular spatial unit on the dependent variable of all other units in the short term. Similarly, the long-term effects could be determined from the dynamic model, which takes into account the time delays of the dependent and/or independent variables [46] (p. 11).

The diagonal elements of the matrix $(\mathbf{I} - \rho \mathbf{W})^{-1} (\beta_k \mathbf{I}_N + \theta_k \mathbf{W})$ define the direct impacts of change in ith observation x_k (denoted by x_{ik}) on y_i, that is, on the values of the dependent variable in the same ith spatial unit. The average of the sum across the ith row of this matrix represents the average impact on the individual observation y_i resulting from changing the kth explanatory variable by the amount across all observations—the average impact to an observation. In turn, the average of the sum in the jth column of the matrix yields the average impact over all y_i observations from changing the kth explanatory variable by an amount in the jth observation—the average impact from an observation [43] (p. 37). To sum up, indirect effects as spatial spillovers were identified based on the non-diagonal elements of the matrix considered.

4. Data

The data used in the analysis came from three databases. First, the Our World in Data website (https://ourworldindata.org (accessed on 17 May 2021)) provided the data on CO_2 emissions per capita (CO_2) and the share of energy from renewable sources out of the total energy consumption (RE). Second, the World Bank (https://data.worldbank.org (accessed on 17 May 2021)) provided the GDP per capita (GDP). Third, the Global Footprint Network (https://data.footprintnetwork.org (accessed on 17 May 2021)) provided the ecological footprint by countries used to create a neighborhood matrix. All calculations and drawings were made in the program R-CRAN (version 4.0.2).

Figure 1 presents the spatial distributions of carbon dioxide per capita in 2013 and 2019. In both years, the CO_2 values were distributed almost identically in the studied area. The lowest CO_2 emission values can be observed in the countries of South America, the southern part of Asia (on the Indian Peninsula and Indonesia), as well as in Southern Europe and the countries of Northern Africa. The highest values can be observed in North America (the US and Canada), northern and eastern parts of Asia, in Arab countries, as well as in Australia and New Zealand. Mostly, they are the relatively high development countries, which have a great impact on the world economy.

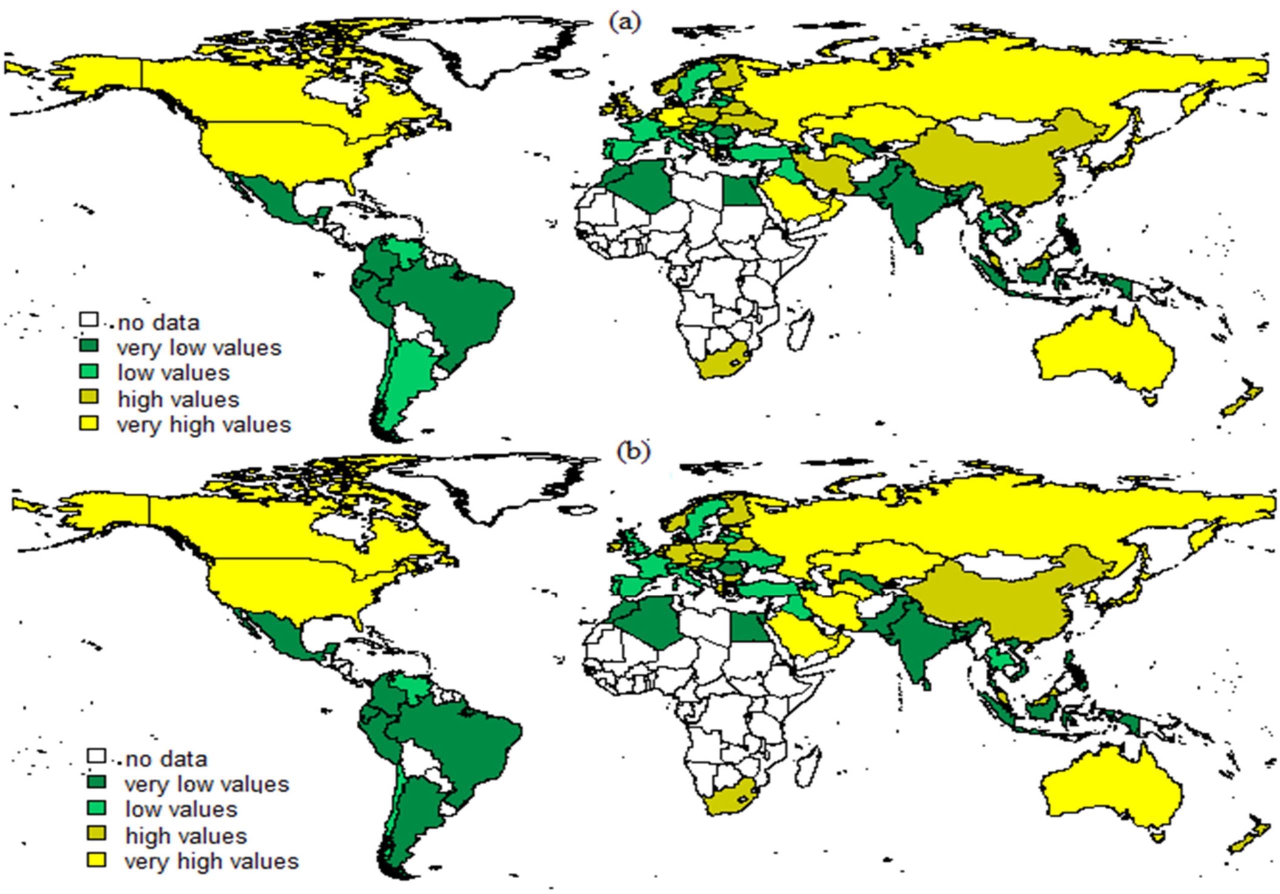

Figure 1. Spatial distribution of the per capita CO_2 emissions in (**a**) 2013 and (**b**) 2019.

Figure 2 shows the spatial distributions of the share of energy from renewable sources out of the total energy consumption in 2013 and 2019. The greatest share of renewable energy consumption characterized countries of both North and South America (excluding Mexico), most European countries (without Central and Eastern Europe), and China, Australia, and New Zealand. The lowest values were observed in Africa and in North and West Asia. By comparing the distributions of the variables under consideration in Figures 1 and 2, it can be assumed that there is an inverse relationship between renewable energy consumption and CO_2 emissions in the areas of the surveyed countries. An exception may be highly developed countries, such as Canada, the United States, Australia, and China (in these countries, both variables have relatively high values), as well as less developed countries, such as Egypt, Morocco, and Algeria (in these countries, both variables are characterized by relatively low values).

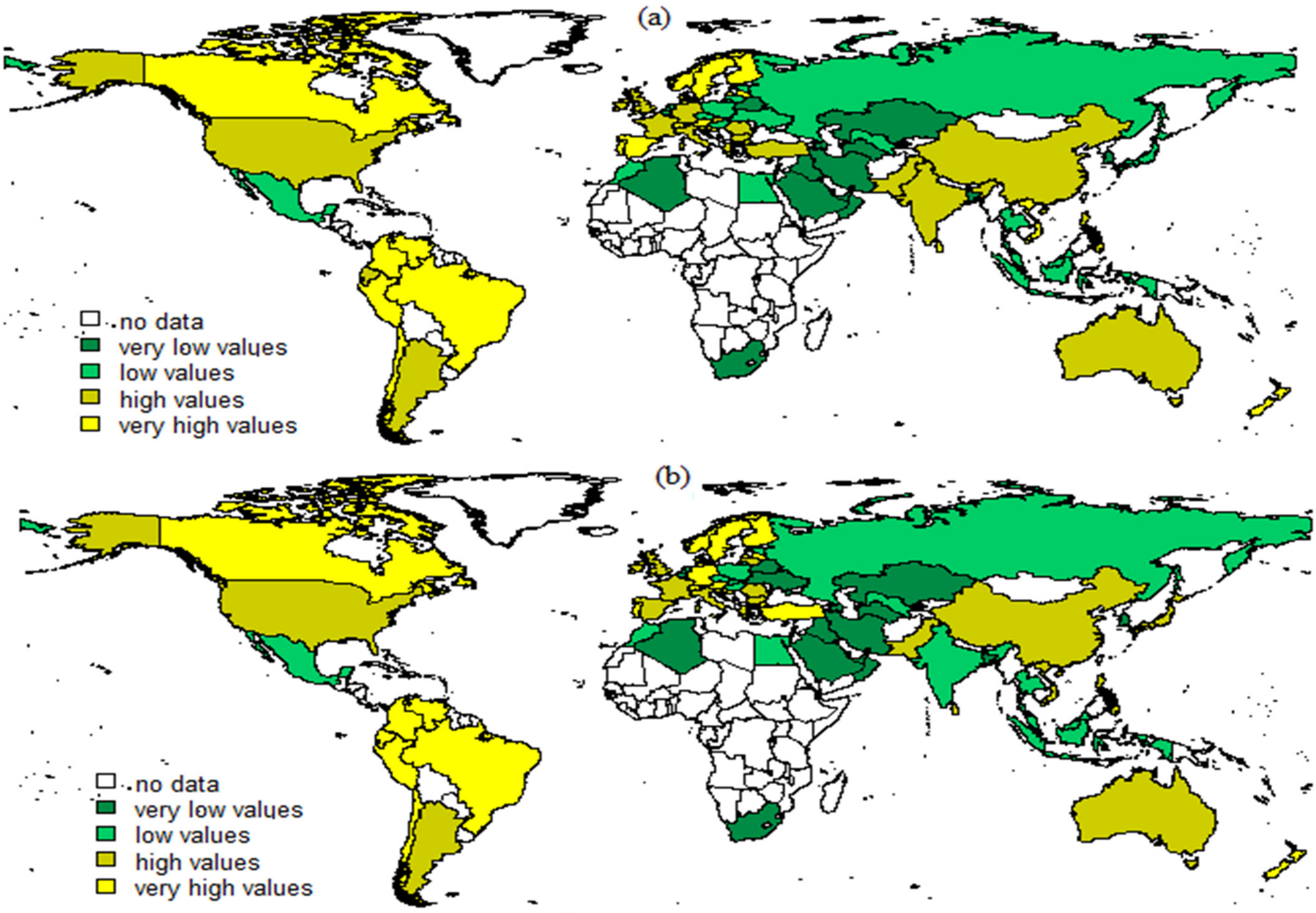

Figure 2. Spatial distribution of the share of energy from renewable sources in total energy consumption in (**a**) 2013 and (**b**) 2019.

5. Empirical Results

5.1. Spatial Autocorrelation

The empirical analysis began with testing the spatial autocorrelation for the variables under consideration with established connections between countries based on the level of environmental development (ecological footprint). The level of significance was 0.05. Table 1 presents the values of Moran statistic (Moran's *I*) and the assessment of its statistical significance in the years 2013–2019.

Table 1. Spatial autocorrelation tests for the variables considered in years 2013–2019.

Year	l_CO2		l_RE		l_GDP	
	Moran's *I*	*p*-Value	Moran's *I*	*p*-Value	Moran's *I*	*p*-Value
2013	0.6733	0.0000	−0.0747	0.2499	0.6298	0.0000
2014	0.6554	0.0000	−0.0749	0.2486	0.6316	0.0000
2015	0.6563	0.0000	−0.0719	0.2602	0.6282	0.0000
2016	0.6624	0.0000	−0.0840	0.2184	0.6270	0.0000
2017	0.6659	0.0000	−0.0885	0.2027	0.6282	0.0000
2018	0.6587	0.0000	−0.0801	0.2303	0.6295	0.0000
2019	0.6484	0.0000	−0.0810	0.2257	0.6291	0.0000

Positive and statistically significant values of the spatial autocorrelation coefficient for the per capita carbon dioxide emission and the per capita GDP (expressed in natural logarithms and marked as l_CO_2 and l_GDP, respectively) have been recorded for all the years. The positive spatial autocorrelation indicates similarity, in terms of CO_2 emissions as well as GDP, of countries with a similar level of environmental protection. The values of the Moran's *I* prove the strong links between countries with comparable levels of environmental development.

The situation is different in the case of the share of energy from renewable sources in total energy consumption (l_RE). The Moran statistics are statistically insignificant and indicate the lack of links, in this respect, between "neighboring" countries.

The results of spatial autocorrelation testing for the considered variables were the initial motivation for incorporating the spatial effects into the model of CO_2 emissions relative to GDP and renewable energy consumption using the Kuznets curve additionally.

5.2. Empirical Models

First, the space–time model (LM_pooled) in the form of Equation (1) was estimated and verified. The results obtained are presented in Table 2. The *p*-values for the parameters β_1 and β_2 indicate the significance of the impact of GDP per capita as well as its squares on CO_2 emissions. Moreover, the signs of the parameters ($\beta_1 > 0$ and $\beta_2 < 0$) allow us to conclude an inverse U-shaped relationship between GDP and CO_2 emissions. Thus, the considered relationship for selected countries of the world takes a classic shape of the Kuznets curve.

Table 2. The results of estimation and verification of the TSCS model for the squared Kuznets curve.

Parameter	Estimate	Std. Error	t-Statistic	*p*-Value
α	−12.5434	1.1672	−10.7470	0.0000
β_1	2.5715	0.2500	10.2840	0.0000
β_2	−0.1085	0.0133	−8.1750	0.0000
β_3	−0.1720	0.0081	−21.2050	0.0000
GDP_{TP}	139,658.40			
R^2	0.7472			
F	513.4000 (0.0000)			
JB	5.3284 (0.0697)			
Moran test	−0.0483 (0.0953)			
LM tests	LM_{SE}: 2.0105 (0.1562) LM_{SAR}: 12.2105 (0.0005) RLM_{SE}: 13.4241 (0.0002) RLM_{SAR}: 23.6242 (0.0000)			

Note: *JB* means the Jarque'a–Bery test (for normality of the distribution of residuals); figures in brackets refer to the *p*-values.

The negative and statistically significant value of the β_3 parameter indicates an inverse relationship between renewable energy consumption and CO_2 emissions. Thus, an increase in the share of energy consumption from renewable sources in individual countries leads to improvement in their environmental situation. Based on the estimated Kuznets curve, its turning point was determined, amounting to $139,658.40 per capita. Taking into account the values of GDP per capita, it should be stated that none of the countries reached this ceiling during the period considered. Therefore, all the countries are on the path leading to the turning point, which may indicate a greater focus on economic development than on care for the natural environment. Figure 3 shows the shape of the Kuznets curve determined on the basis of model (1).

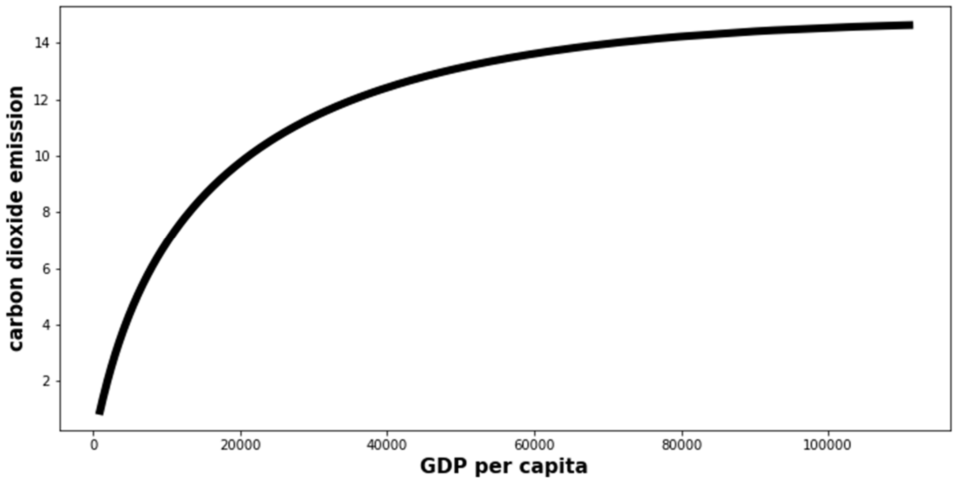

Figure 3. The shape of the Kuznets curve for the considered countries in the period of 2013–2019 (determined based on model (1)).

The Lagrange multiplier tests (the basic versions—LM_{SE}, LM_{SAR}, and the robust ones—RLM_{SE}, RLM_{SAR}) indicate the legitimacy of supplementing model (1) with spatial connections between the countries. Therefore, the spatio-temporal Durbin model was specified (see Equation (6)). The results of estimation and verification of the model are reported in Table 3.

Table 3. The results of estimation and verification of the spatio-temporal Durbin model for the squared Kuznets curve.

Parameter	Estimate	Std. Error	z-Statistic	*p*-Value
α	−13.1261	1.2111	−10.8380	0.0000
β_1	2.7745	0.2627	10.5607	0.0000
β_2	−0.1226	0.0138	−8.8546	0.0000
β_3	−0.1725	0.0076	−22.8059	0.0000
θ	−0.1042	0.0133	−7.8316	0.0000
		ρ : 0.0589 (0.0386)		
GDP_{TP}	82,138.04			
$pseudo - R^2$	0.7805			
Wald statistics	4.9215 (0.0265)			
Log likelihood	−242.2354			
JB	1.7206 (0.4230)			
Moran test	−0.0144 (0.3624)			

The values of the β_1 and β_2 parameters, as in the case of the model without spatial effects, indicate an inverse U-shaped relationship between GDP and CO_2 emissions. Importantly, these parameters are statistically significant. Moreover, the sign of the parameter β_3 has not changed, which, as in the previous model, indicates a positive impact of renewable energy consumption on carbon dioxide emissions. Likewise, a negative and statistically significant parameter θ describing the effects of changes in renewable consumption in "neighboring" countries (with a similar level of environmental development) shows that its increase results in lower CO_2 emissions in a given country.

Compared to model (1), the GDP value at which CO_2 emissions started to decline decreased. In this case, the threshold value was estimated at $82,138.04. This is further evidence of a positive influence of pro-ecological neighbors' behavior on the environmental situation in a given country. It is worth emphasizing that only two countries have reached the threshold point, namely Luxembourg and Norway. The shape of the Kuznets curve, determined based on model (6), is presented in Figure 4.

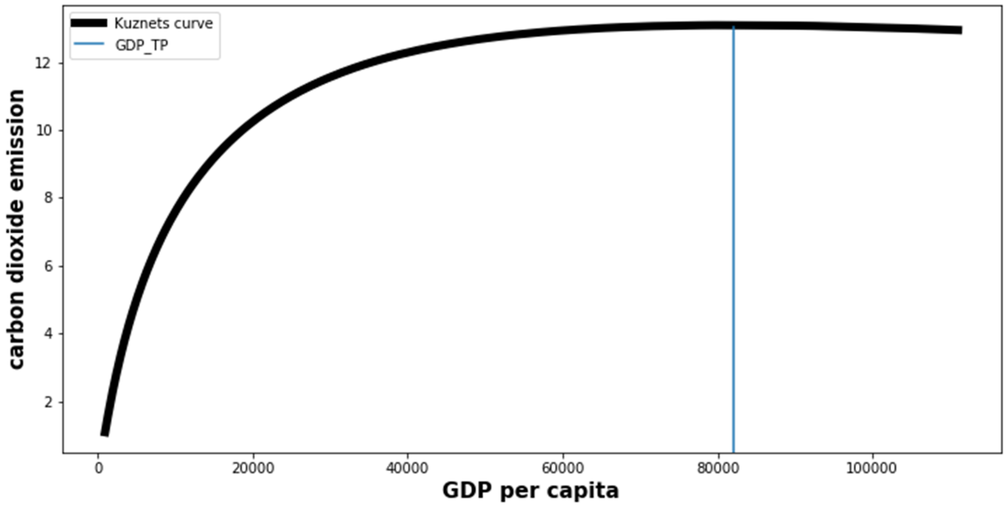

Figure 4. The shape of the Kuznets curve for the considered countries in the period of 2013–2019 (determined based on model (6)).

The positive and statistically significant value of the autoregression parameter ρ proves a similar level of CO_2 emissions in countries with a similar level of environmental development.

5.3. Spatial Spillovers

In this subsection, we present the results of the empirical indirect effects analysis for the years of the examined period, carried out on the basis of the following transformation of model (6), with respect to the spatially lagged renewable energy consumption, expressed in natural log $\mathbf{Wln}(\boldsymbol{RE})$, that is, as the following formula:

$$\begin{aligned}\mathbf{ln}(\boldsymbol{CO_2})_t = {} & (\mathbf{I}-\rho\mathbf{W})^{-1}\alpha\iota_N + (\mathbf{I}-\rho\mathbf{W})^{-1}\beta_1\mathbf{ln}(\boldsymbol{GDP})_t + (\mathbf{I}-\rho\mathbf{W})^{-1}\beta_2(\mathbf{ln}(\boldsymbol{GDP}))_t^2 \\ & +(\mathbf{I}-\rho\mathbf{W})^{-1}(\beta_3\mathbf{I}_N+\theta\mathbf{W})\mathbf{ln}(\boldsymbol{RE})_t\end{aligned} \quad (11)$$

The indirect effects were determined in the form of the average values in the cross-section of rows and, separately, in the cross-section of columns of the $(\mathbf{I}-\rho\mathbf{W})^{-1}(\beta_3\mathbf{I}_N+\theta\mathbf{W})$ matrix, excluding diagonal elements. In this way, measurements of the average impacts (in terms of the analyzed variables) of individual countries on a given country, and of a given country on other countries, respectively, were obtained. Due to the stability of the spatial connectivity matrix over time, the spillover effects were the same in each of the analyzed years.

Figure 5 presents spatial distributions of indirect effects obtained. The first map in Figure 5 shows the distribution of average inflows via the share of energy consumption from renewable sources out of the total energy consumption in individual countries on the CO_2 emissions in a given country.

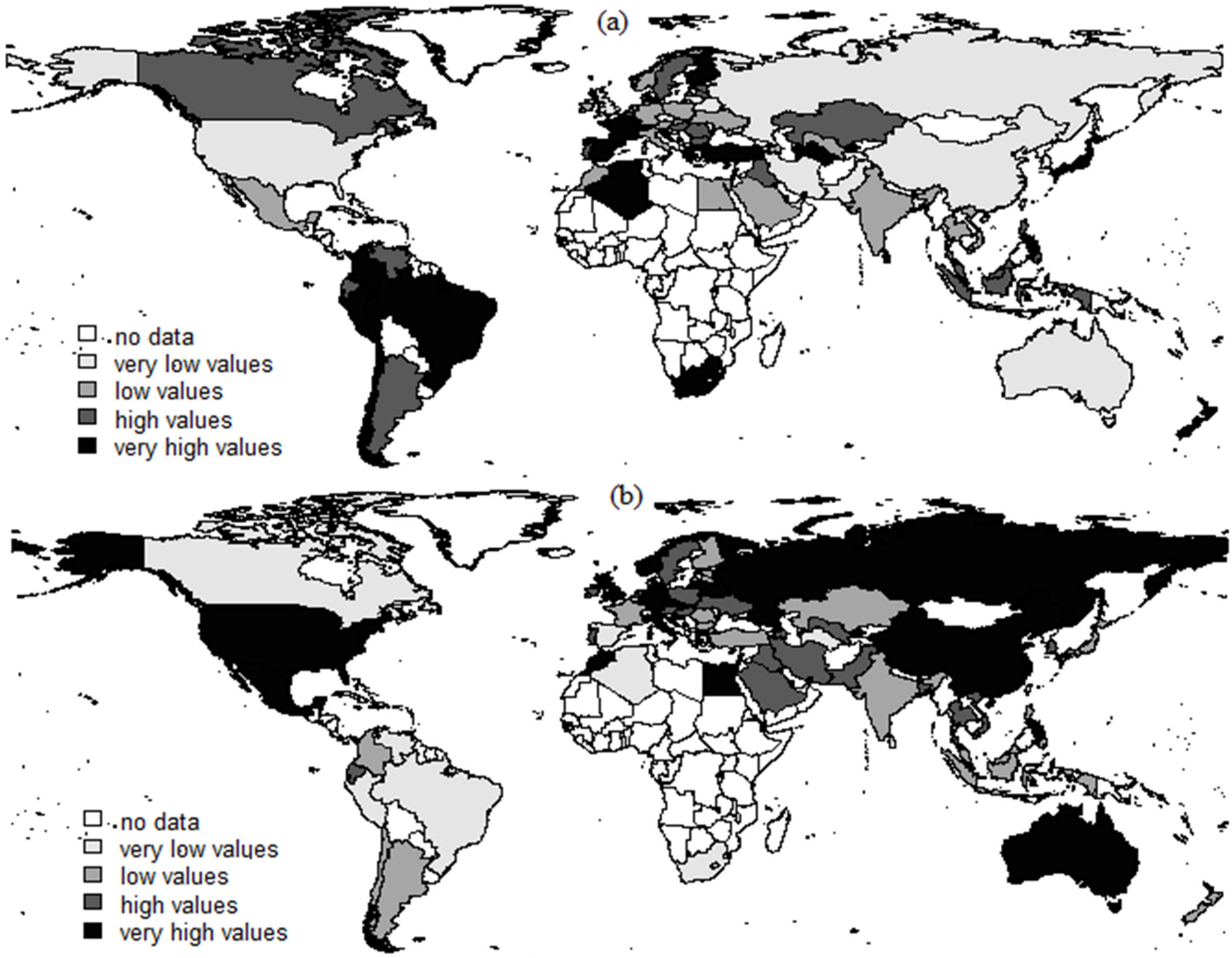

Figure 5. The distribution of the average impacts of (**a**) the spatially lagged renewable energy consumption on the CO_2 emissions in individual economies and (**b**) a change of the share of energy from renewable sources out of the total energy consumption in a particular economy on the CO_2 emissions in all other economies.

We can see that the countries of South America were among the ones that received transmission impulses from other countries with the highest strength. It should be noted that these countries were characterized by the lowest CO_2 emissions and the highest share of renewable energy consumption. The countries that were least affected by all other countries through the transmission of renewable energy consumption included the United States, China, Russia, and Australia—the relatively highly developed economies.

The second map in Figure 5 shows the distribution of the average impacts of a given country's share of energy from renewable sources out of the total energy consumption on the CO_2 emissions in all other economies. It is worth noting that countries that were the least influenced by others were the ones that most strongly affected other countries. Thus, renewable energy consumption in the United States, China, Russia, and Australia most strongly affected the CO_2 emissions in other countries. Among the economies whose impact on other economies was the largest, there were also those of Italy and Norway. On the other hand, among the countries whose impact (through changes in the structure of energy consumption) on environmental pollution in other countries was the lowest, were Brazil, Algeria, Peru, and Venezuela.

Figure 6 shows the impacts of two selected countries on other countries in the range of the variables considered. The maps in this figure present transmission impulse distributions resulting from changes in the structure of energy consumption in countries with the highest share of energy consumption from renewable sources, namely Norway and Brazil.

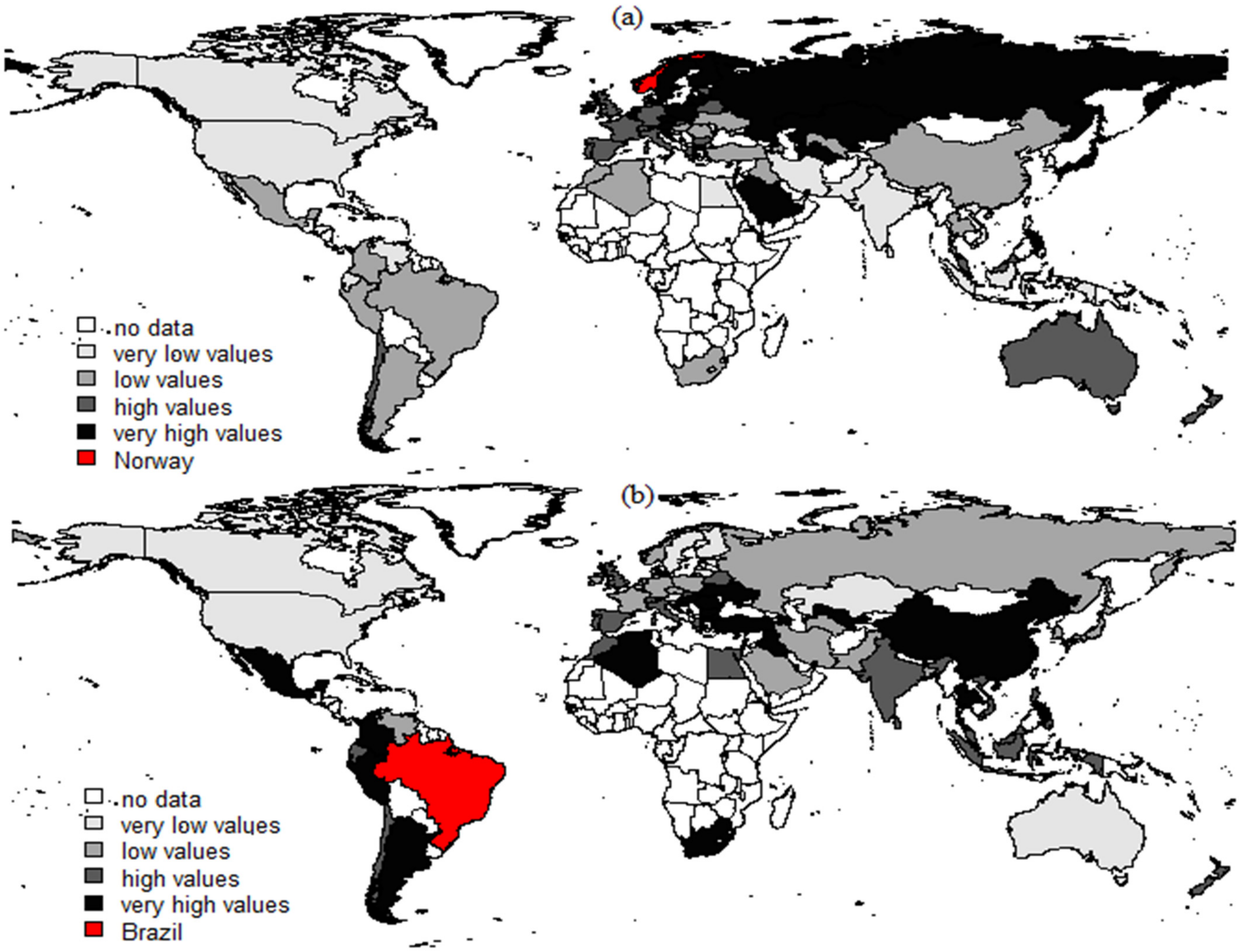

Figure 6. Dependence of the CO_2 emissions of all other countries on the share of energy from renewable sources out of the total energy consumption in (**a**) Norway and (**b**) Brazil.

A change in the share of renewable energy in Norway had the strongest impact on environmental pollution in other Scandinavian countries, as well as in Central European countries and Russia. It can be assumed that this was due to the high degree of energy dependence on Norway of countries located close to each other in geographical space. In contrast, the countries of both North and South America, as well as South Asia, were least influenced by the changes in Norway.

Changes in the share of renewable energy out of the total energy consumption in Brazil had the strongest impact on environmental pollution in most of other South American countries, China and Mexico, as well as in most Mediterranean countries. The reason for such dependencies may be the comparable, equatorial climate of the countries, where changes in the structure of energy consumption result in similar changes in terms of CO_2 emissions. The least sensitive (from the environmental aspect) to changes in renewable energy consumption in the country were the United States, Canada, Norway, and Finland.

Figure 7 presents the distributions of the average impacts of changes in the structure of energy consumption in countries with the strongest impact on others in terms of CO_2 emissions. Based on the results obtained, it was established that such countries were Italy and China.

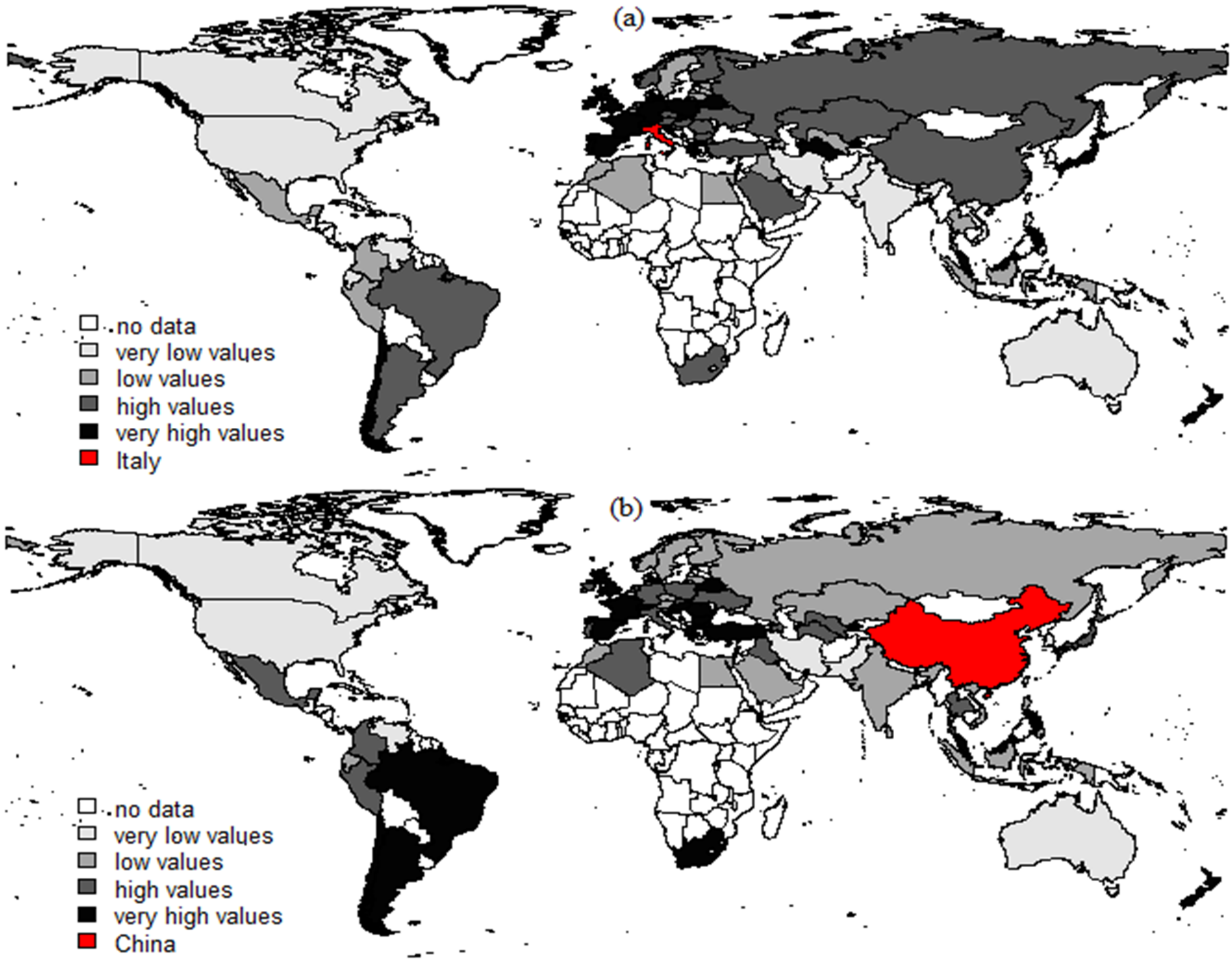

Figure 7. Dependence of CO_2 emissions of all other countries on the share of energy from renewable sources out of the total energy consumption in (**a**) Italy and (**b**) China.

In the cases analyzed, we found that a change in the share of renewable energy out of the total energy consumption in Italy had the strongest impact on the levels of CO_2 emissions in most of the European economies taken into account, as well as in Chile. The North and East Asia countries, as well as Brazil and Argentina, were among the ones slightly less affected by Italy, whereas the smallest transmission impulses from Italy were received by the United States, Canada, Australia, and India.

China, in turn, had the strongest impact on Argentina, Brazil, Malaysia, as well as on most of the European Mediterranean countries. As with the impulses from Italy, the group of countries least sensitive to changes in the structure of energy consumption in China included the United States, Canada, and Australia.

Finally, it is worth emphasizing the similarity of the strength of influence of Italy and China on environmental pollution in South American countries as well as in most European countries. It is also worth noting the weak dependence of the level of environmental protection in the United States on changes in the structure of energy consumption in other considered world economies.

6. Conclusions

The results of this study underline the role of changes in the structure of energy consumption in the world economies for the improvement of the environmental situation.

Environmental protection has become an increasingly important element of the economic development of countries, which is reflected in the contemporary concept of sustainable development. Its purpose is to improve the state of the national economy while reducing the consumption of scarce resources.

The Kuznets curve determined for the selected countries pointed to the inverse U-shaped relationship between the per capita GDP and CO_2 emission. Including the share of energy from renewable sources in the total energy consumption as an additional explanatory variable in the models constructed confirmed the conclusions of other researchers that with the increase in this share, there was an improvement in the environmental situation, that is, the carbon dioxide emissions were reduced. Moreover, the inclusion of spatially lagged variables (i.e., the CO_2 emissions and energy from renewable sources consumption in "neighboring" countries) in the final model showed to what extent the pro-ecological actions of some economies affect others. Additionally, it can be seen that the impact of these variables on the dependent variable is smaller than their impact within a given territorial unit.

The spatial indirect effects determined based on the spatio-temporal Durbin model allowed us to identify, firstly, the countries that are most susceptible to the influence of other countries, and secondly, those with the strongest impact on others.

It is worth noting that relatively highly developed countries were among those in which the change in energy from renewable sources consumption had the greatest impact on the CO_2 emissions in other countries. This is mainly due to the fact that most of the economies failed to reach the turning point, that is, the level of GDP per capita at which the CO_2 emissions start to decline. The economies are still at a stage where the main focus is on economic development.

At the same time, the highly developed countries were minorly influenced by other countries in terms of the variables under consideration. The case of the United States should be distinguished as an economy independent of most others.

Undoubtedly, the positive impact of the changes taking place in the countries with a higher level of environmental development on the state of the environment in other countries was observed. This thesis was confirmed by the decline in GDP per capita at the turning point when relationships between neighbors were incorporated into the model.

The analysis of the spatial distributions of the impact of changes in the structure of energy consumption in Norway, Italy, Brazil, and China on air pollution in other countries leads to interesting conclusions. The mentioned European countries have a major influence on the others within the same continent, whereas impulses from economies such as Brazil and China, located on other continents, have a wider geographical scope. The countries influenced by them are not located in one cohesive area.

The results of the research show the importance of pro-ecological activities not only within a given country. The spatial spillovers in this regard are also significant.

The spatio-temporal Durbin model used in our study is only one of the possible specifications that turned out to be useful for the analysis of the phenomenon under consideration. Other model specifications should be used in further studies. Additionally, the use of other connectivity matrices should be verified. It is also worth determining the indirect effects in relation to other explanatory variables and establishing appropriate spatial regimes with regard to the wealth of the analyzed economies.

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