Acta Sci. Pol., Administratio Locorum 23(4) 2024, 417–436.
https://czasopisma.uwm.edu.pl/index.php/aspal plISSN 1644-0749 eISSN 2450-0771 DOI: 10.31648/aspal.10717

ORIGINAL PAPER
Received: 23.10.2024 Accepted: 26.11.2024

# THE COURSE OF THE COVID-19 PANDEMIC IN POLAND IN RELATION TO THE LEVEL OF SUSTAINABLE DEVELOPMENT – MULTISCALE GEOGRAPHICALLY WEIGHTED REGRESSION ANALYSIS

Krzysztof Rząsa[1]✉, Mateusz Ciski[2]✉

[1] ORCID: 0000-0001-5215-7630
[2] ORCID: 0000-0002-4919-9570
[1, 2] University of Warmia and Mazury in Olsztyn
15 Romana Prawocheńskiego Street, 10-720 Olsztyn, **Poland**

## ABSTRACT

**Motives:** This article explores the relation between the course of the COVID-19 pandemic and the level of Sustainable Development of Polish counties. First, the data was collected to describe the level of Sustainable Development in terms of Social, Environmental and Economical indicators. In the second step, using data regarding the number of COVID-19 cases and the number of deaths caused by the pandemic, a regression model was built using Multiscale Geographically Weighted Regression (MGWR).
**Aim:** Authors decided to create a comprehensive model of the level of Sustainable Development. This approach made it possible to analyze the relations between the level of Sustainable Development and the course of the COVID-19 pandemic, as well as provided an opportunity to address the individual components of the model.
**Results:** The values of the coefficient of determination of the regression model indicate a high and very high fit. The MGWR model also made it possible to develop maps of local R-Squared values. These maps, by exploring spatially varying relationships between variables, further allowed to identify local anomalies of the phenomenon.

**Keywords:** COVID-19, pandemic, GWR, MGWR, Geographically Weighted Regression, Multiscale Geographically Weighted Regression

## INTRODUCTION

The first cases of COVID-19 were reported in Wuhan, capital of Hubei province, in December 2019 (Q. Li et al., 2020; Zhu et al., 2020). Over the next few years, the disease quickly spread to every province of China and to other countries across the world. On March 11, 2020, the World Health Organization announced the coronavirus outbreak as a pandemic (Di Gennaro et al., 2020). Although today the COVID-19 pandemic is no longer the most important topic, it has already changed the world and has become one of the greatest health challenges of the 21st century.

Today, researchers have the ability to analyze the course of the pandemic from a certain time perspective. An increasing amount of data is available to allow for broader and more diverse analyses, both of the course of the pandemic and of the factors that

✉krzysztof.rzasa@uwm.edu.pl; ✉mateusz.ciski@uwm.edu.pl

may have influenced its course. In the available scientific databases, one can find many articles related to the impact of the COVID-19 pandemic on the health and lives of people (Clemente-Suárez et al., 2021; S. Li et al., 2020; Linton et al., 2020; Marom et al., 2022; Meyer et al., 2020; Shekhar et al., 2021; Solomou & Constantinidou, 2020; C. Wang et al., 2020; Zhang et al., 2020; Zhang & Ma, 2020). This topic seems to have been most extensively studied by scientists from many countries. The impact of the pandemic on both physical and mental health has been highlighted. It has been confirmed that the pandemic has changed the lifestyles and behaviors of people around the world (Castañeda-Babarro et al., 2020; Gualano et al., 2020; Lesser & Nienhuis, 2020; Mazza et al., 2020; Md Iderus et al., 2022; Stanton et al., 2020; Suzuki et al., 2020; Taff et al., 2021).

Various factors that could have influenced the COVID-19 pandemic were also analyzed. These primarily involved demographic factors (Alves et al., 2021; Kodera et al., 2020; Starke et al., 2020). Among other things, it was confirmed that an important factor in the course of the pandemic appeared to be the age structure of the population. A number of studies also addressed the impact of environmental factors on the course of the pandemic (Coccia, 2020; Comunian et al., 2020; Johnson et al., 2021; Y. Ma et al., 2020; Q. Wang et al., 2017; Xie & Zhu, 2020). The effects of temperature and air pollution on the course of the pandemic were demonstrated (Baniasad et al., 2021; Jamshidi et al., 2020). Most of the studies related to economic factors were concerned with the impact of the COVID-19 pandemic on the economic itself (Ahundjanov et al., 2020; Cao et al., 2020; Ghiani et al., 2020; Navon et al., 2021; Sharif et al., 2020).

Geographic Information System (GIS) is a computer system used to input, collect, process, and visualize geographic data, with decision support as one of its functions (Ciski & Rząsa, 2021). GIS tools have proved extremely useful for analyzing the spatial patterns of the course of the COVID-19 pandemic. Building regression models in a GIS environment allows for a thorough study of the factors influencing the course of the pandemic. Regression models incorporating spatial determinants, such as Geographically Weighted Regression (GWR) and Multiscale Geographically Weighted Regression (MGWR), appear to be particularly useful (Brunsdon et al., 1996; Comber et al., 2022; Franch-Pardo et al., 2020; Mennis, 2006; Mohammad Sham et al., 2022; Permai et al., 2021; Rząsa & Ciski, 2022; S. Yu et al., 2022; Yue et al., 2022).

The available scientific databases lack articles that comprehensively analyze the impact of factors describing the relationship between the level of Sustainable Development and the COVID-19 pandemic. This article therefore undertakes such an analysis. Thus, the main purpose of the article was to investigate whether a relation could be demonstrated between the course of the COVID-19 pandemic, as described by the number of cases and the number of deaths caused by the pandemic, and the level of Sustainable Development of an area. Poland was chosen as the study area, and detailed analyses were carried out at the administrative level of counties.

The research objective formulated in this way was carried out in two stages. In the first, data were collected to describe the level of Sustainable Development of the studied counties in terms of social, environmental, and economical characteristics. In the second step, using data regarding the number of COVID-19 cases and the number of deaths caused by the pandemic, using Multiscale Geographically Weighted Regression, a regression model was built to determine whether and to what extent the characteristics describing the level of Sustainable Development explain the course of the pandemic.

The obtained results, on the one hand can provide further confirmation of the validity of the concept of Sustainable Development, on the other hand, could serve as an important element for decision-makers to use in the fight against the possible next pandemic.

✉krzysztof.rzasa@uwm.edu.pl; ✉mateusz.ciski@uwm.edu.pl

## MATERIALS AND METHODS

### Study area

Determining the level of sustainable development as well as analyzing the course of the COVID-19 pandemic was carried out for the counties of Poland, the second level of the country's administrative division. Poland is divided into 380 counties. The average county area is about 822 square kilometers. Among 380 counties, there are 66 cities with county rights – municipalities with city status, carrying out county duties. The smallest county is Swietochlowice city county with an area of 13 square kilometers, and the largest county (with an area of 2,975 square kilometers) is Bialystok county. Due to the rather small area of the analyzed polygons, the chosen degree of detail of the study will allow a thorough investigation of the phenomenon, while maintaining a relatively higher administrative level, which ensures greater availability of data. Also, the number of counties in Poland meets the requirements of the GWR and MGWR (over 160) (Devkota et al., 2014). Fig. 1 shows the study area – the borders of voivodeships and counties, the highest and the second highest level administrative division of Poland.

### Data source and processing

The first step in the research process was to describe the examined counties of Poland with the unified index of Sustainable Development. Polish law in the Environmental Protection Act defines Sustainable Development as "the socio-economic development integrating political, economic, and social actions, balanced with environmental protection


**Fig. 1**. Study area – counties of Poland
*Source*: own elaboration using ArcGIS Pro 3.2 by Esri.

krzysztof.rzasa@uwm.edu.pl; mateusz.ciski@uwm.edu.pl

and permanence of basic natural processes" (Act of 27 April 2001 Environmental Protection Law, 2001). The problem of measuring the level of sustainable development is an issue that many researchers have addressed in their studies. In previous studies, the authors have proposed a method for the classification of objects based on the natural breaks of Jenks in order to measure the level of sustainable development (Rząsa & Ciski, 2021). To study the impact of different factors on the course of the COVID-19 pandemic in this article, the authors decided to create a general statistical model. This approach made it possible, on the one hand, to comprehensively analyze the links between the level of Sustainable Development and the course of the COVID-19 pandemic, and, on the other hand, provided an opportunity to refer to and analyze the individual components of the model (three thematic groups: Social, Environmental, and Economical). The unified index was determined using data from Statistics Poland, a central government office for the collection and publishing of statistical information on most areas of public life. This data source is reliable, it is used in various scientific studies.

The level of sustainability was described with 30 factors, 10 of each related to social, environmental, and economical elements, respectively. Its selection was determined by an analysis of the subject literature (Azapagic & Perdan, 2000; Bossel, 1999; Drastichová, 2017; European Commission, 2015; Hák et al., 2016; Klopp & Petretta, 2017; Mori & Christodoulou, 2012; Morton et al., 2017; Schleicher-Tappeser, 2018; Shen et al., 2011; Spangenberg, 2015; United Nations, 2007, 2015) as well as the availability of data at the county level of detail. Sustainability studies conducted by different researchers for different case studies, such as countries, administrative parts of countries, etc., were also analyzed (Bąk & Cheba, 2018; Czermińska, 2002; Koszel & Bartkowiak, 2018; Moran et al., 2008; Mortensen, 2013; Stafford-Smith et al., 2017). Factors that relate to the level of various aspects of the development of social functions of area include: V1 – the number of housing units per 1,000 residents; V2 – the number of beneficiaries of community social assistance per 10,000 population; V3 – the number of cultural centers, houses and centers, clubs, and community centers; V4 – the number of beds in general hospitals; V5 – the number of stationary social assistance institutions; V6 – number of families granted social assistance due to poverty; V7 – average floor area of an apartment per 1 person; V8 – enrollment rate in elementary schools, defined as the ratio of the number of all residents studying at a given level to the total population of residents of the age nominally assigned to that level of education; V9 – expenditures incurred on social assistance; and V10 – infant deaths per 1,000 live births.

Factors that relate to the level of elements affecting the environment include: V11 – emission of gaseous pollutants; V12 – emission of particulate pollutants; V13 – population using wastewater treatment plants; V14 – the area of legally protected areas per capita; V15 – the amount of municipal wastewater treated per 100 $km^2$; V16 – the amount of total wastewater treated; V17 – the amount of industrial wastewater treated per 100 $km^2$; V18 – share of green areas in the total area; V19 – water consumption for economy and population; and V20 – total amount of municipal waste collected per year.

The level of economic development of the area was described by: V21 – income of county budgets; V22 – investment expenditures in enterprises per capita; V23 – number of registered economic entities per 1,000 population; V24 – number of registered motor vehicles and tractors; V25 – number of issued permits and notifications for construction of residential buildings; V26 – number of employed per 1,000 population; V27 – the amount of average monthly gross wages; V28 – the share of the area covered by valid local zoning plans in the total area (planning documents giving the right in Poland to change the zoning of area in a more intensive way); V29 – the value of housing units sold in market transactions; and V30 – expenditures of county budgets.

The next step of the research was to standardize the above indicators using Jenks' Natural Breaks classification method. Each variable has been separately classified using the Jenks optimization algorithm, with ArcGIS Pro 3.2 software. In order

✉krzysztof.rzasa@uwm.edu.pl; ✉mateusz.ciski@uwm.edu.pl

to correctly assign counties to classes, it was necessary to divide variables into stimulants and destimulants – variables whose increase in value indicates an increase in the level of Sustainable Development were selected as stimulants; and variables whose increase in value indicates a decrease in the level of Sustainable Development were selected as destimulants. Based on this division, using Jenks' Natural Breaks classification method, each variable was assigned a corresponding numerical value <0;10>. The following Table 1 lists the

**Table 1**. Selected factors

| Thematic Group | Variable | Symbol | Impact on Sustainable Development |
|---|---|---|---|
| Social | the number of housing units per 1,000 residents | V1 | Stimulant |
| | the number of beneficiaries of community social assistance per 10,000 population | V2 | Destimulant |
| | the number of cultural centers, houses and centers, clubs and community centers | V3 | Stimulant |
| | number of beds in general hospitals | V4 | Stimulant |
| | number of stationary social assistance institutions | V5 | Stimulant |
| | number of families granted social assistance due to poverty | V6 | Destimulant |
| | average floor area of an apartment per 1 person | V7 | Stimulant |
| | enrollment rate in elementary schools | V8 | Stimulant |
| | expenditures incurred on social assistance | V9 | Stimulant |
| | infant deaths per 1,000 live births | V10 | Destimulant |
| Environmental | emission of gaseous pollutants | V11 | Destimulant |
| | emission of particulate pollutants | V12 | Destimulant |
| | population using wastewater treatment plants | V13 | Stimulant |
| | area of legally protected areas per capita | V14 | Stimulant |
| | amount of municipal wastewater treated per 100 km$^2$ | V15 | Stimulant |
| | amount of total wastewater treated | V16 | Stimulant |
| | amount of industrial wastewater treated per 100 km$^2$ | V17 | Stimulant |
| | share of green areas in total area | V18 | Stimulant |
| | water consumption for economy and population | V19 | Destimulant |
| | total amount of municipal waste collected per year | V20 | Destimulant |
| Economic | income of county budgets | V21 | Stimulant |
| | investment expenditures in enterprises per capita | V22 | Stimulant |
| | number of registered economic entities per 1,000 population | V23 | Stimulant |
| | number of registered motor vehicles and tractors | V24 | Stimulant |
| | number of issued permits and notifications for construction of residential buildings | V25 | Stimulant |
| | number of employed per 1,000 population | V26 | Stimulant |
| | the amount of average monthly gross wages | V27 | Stimulant |
| | the share of the area covered by valid local zoning plans in the total area | V28 | Stimulant |
| | the value of housing units sold in market transactions | V29 | Stimulant |
| | expenditures of county budgets | V30 | Stimulant |

*Source*: own elaboration on the basis of data from Statistics Poland.

✉krzysztof.rzasa@uwm.edu.pl; ✉mateusz.ciski@uwm.edu.pl

selected variables broken down by thematic section, with appropriate symbol, and stimulant/ destimulant breakdown.

In such a way, Poland's counties were described by the unified Sustainable Development index. Such extracted data were later used for analysis using the MGWR method as explanatory variables.

From the database published by Michal Rogalski and Konrad Kalemba, the two main variables describing the course of the COVID-19 pandemic: "the number of SARS-CoV-2 cases" and "the number of deaths due to SARS-CoV-2 infection", were obtained (Michał Rogalski (@micalrg) / Twitter, 2022; Rogalski, 2022). Many studies on the COVID-19 pandemic issue in Poland use these trusted databases (Ciski & Rząsa, 2023; Duszyński et al., 2020; Kaczmarek & Mikuła, 2022; Lorent et al., 2021; Parysek & Mierzejewska, 2022; Śleszyński, 2020). These variables were used for analysis using the MGWR method as dependent variables.

Tabular data containing aforementioned variables were merged and combined with polygon data representing the administrative boundaries of counties of Poland from the polish National Register of Boundaries (NRB) (Główny Urząd Geodezji i Kartografii, 2023), an official polish spatial database.

## Research method

A null hypothesis had to be established and the statistical significance of all the variables analysed had to be tested to ensure that the results were not the result of chance before the regression model was developed. ArcGIS Pro 3.2 software was used to perform a spatial autocorrelation analysis (Global Moran's I). One of the most common ways to measure spatial autocorrelation is to calculate the Moran's I index (Gao et al., 2022; Han & Sui, 2019; Lichstein et al., 2002). Moran's $I = 0$ indicates no spatial autocorrelation, Moran's $I > 0$ indicates spatial autocorrelation, with positive and negative values indicating positive and negative autocorrelation, respectively. When the null hypothesis is rejected (i.e. the results of the study are not the result of chance), it is possible to conduct the study using Multiscale Geographically Weighted Regression (MGWR), the extended and advanced version of Geographically Weighted Regression (GWR). GWR is based on the assumption that all modeled processes occur at the same spatial scale; MGWR creates a separate and optimized bandwidth for each relationship in the model, therefore indicating how different relationships perform at different spatial scales, to provide more accurate local estimates (Fotheringham et al., 2017).

MGWR is used to analyze a variety of problems in geography, urban planning and other disciplines by investigating geographically varying relationships between dependent and explanatory variables (Chen & Luo, 2022; Geddes et al., 2021). Most importantly, the validity of using this method to model the course of the COVID-19 pandemic has been proven (Ciski & Rząsa, 2023; He et al., 2023; J. Ma et al., 2022; Mohammadi et al., 2023). MGWR extends GWR by examining relationships at different spatial scales using different bands instead of a single constant band. Different bandwidths allow MGWR to model a wider range of geographic phenomena than other regression models, providing better estimates, more accurate predictions and less multicollinearity (He et al., 2023; Oshan et al., 2019). MGWRs allow for the estimation of the effect of explanatory variables on the dependent variable, and the identification of counties where the effect of variables differs, for the purpose of studying and interpreting spatial non-stationarity. MGWR is expressed as:

$$y_i = \beta_0(u_i, v_i) + \sum_k^n \beta_{bwk}(u_i, v_i) x_{ik} + \varepsilon_i \quad (1)$$

where:

$y_i$ – the dependent variable of the $i$-th,
$x_{ik}$ – the explanatory variable of the $i$-th,
$u_i$ and $v_i$ – the spatial coordinates of the i-th (i.e., the centroid coordinates of the counties),
$\beta_{bwk}(u_i, v_i)$ – the estimated coefficient of the $k$-th explanatory variable for the $i$-th with the $b_w$ bandwidth,
$\varepsilon_i$ – the residual at the location $(u_i, v_i)$.

✉krzysztof.rzasa@uwm.edu.pl; ✉mateusz.ciski@uwm.edu.pl

A comparison of the magnitude of the MGWR-derived R-Squared index for all variables analyzed will allow conclusions to be drawn. RR-Squared is a measure of model performance and should be understood as the proportion of the variance in the dependent variable accounted for by the regression model, summarizing how well the estimated values match the observed values. The MGWR tool in ArcGIS Pro 3.2 enables the calculation of "Adjusted R-Squared", which reflects the complexity of the model (the number of variables) as it relates to the data. The Adjusted R-Squared value is the preferred and more accurate measure of the performance of the model (Fotheringham et al., 2006).

In addition, the maps of local R-Squared values generated with MGWR tool will allow the study of local anomalies in the analyzed phenomena, and is useful in identifying locations that have significant local parameter estimates to help focus attention on regions of interest (H. Yu et al., 2020).

A total of eight regression models were developed, all using MGWR, to assess the influence of the level of Sustainable Development of Poland's counties on the course of the COVID-19 pandemic:

1. The number of SARS-CoV-2 cases explained by the unified index of Sustainable Development (all 30 variables).
2. The number of deaths due to SARS-CoV-2 infection explained by the unified index of Sustainable Development (all 30 variables).
3. The number of SARS-CoV-2 cases explained by the Social group (V1-V10 variables).
4. The number of deaths due to SARS-CoV-2 infection explained by the Social group (V1-V10 variables).
5. The number of SARS-CoV-2 cases explained by the Environmental group (V11-V20 variables).
6. The number of deaths due to SARS-CoV-2 infection explained by the Environmental group (V11-V20 variables).
7. The number of SARS-CoV-2 cases explained by the Economical group (V21-V30 variables).
8. The number of deaths due to SARS-CoV-2 infection explained by the Economical group (V21-V30 variables).

All generated regression models were prepared using the Multiscale Geographically Weighted Regression tool in ArcGIS Pro 3.2 software.

## RESULTS

The first step in understanding the studied phenomenon is to analyze its spatial distribution. For this purpose, two maps were generated using the cartographic method of choropleth map, in ArcGIS Pro 3.2 software. The results are presented on Fig. 2 below.

Even such a simple study of the spatial distribution of a phenomenon can often shed light on its character. In the case of the two dependent variables, describing the course of the COVID-19 pandemic: the number of SARS-CoV-2 cases (Fig. 2a), and the number of deaths due to SARS-CoV-2 infection (Fig. 2b), it is difficult to see any characteristic spatial trends in the distribution of the phenomenon. In order to more accurately depict the two dependent variables, a hot spot analysis was carried out using the "Optimized Hot Spot Analysis" tool in ArcGIS Pro 3.2 software. The results are shown on maps in the Fig. 3 below.

Optimized Hot Spot Analysis executes the Hot Spot Analysis tool using parameters derived from characteristics of the input data, and reflects the distribution of hot and cold spots. In the case of the variable "the number of SARS-CoV-2 cases" (Figure 3a), a significant hot spot cluster was recorded in the vicinity of Poland's capital, Warsaw. Map for the second variable „the number of deaths due to SARS-CoV-2 infection" (Fig. 3b) demonstrates, in turn, a large hot spot in the Silesian Voivodeship, and a smaller one in several counties of the Masovian Voivodeship.

### Null hypothesis

The Spatial Autocorrelation (Global Moran's I) tool in ArcGIS Pro 3.2 was used for the assessment of the probability that the null hypothesis is true or false. This tool measures spatial autocorrelation on the basis of feature values and locations; and evaluates whether the pattern of the data is clustered, dispersed,

✉krzysztof.rzasa@uwm.edu.pl; ✉mateusz.ciski@uwm.edu.pl

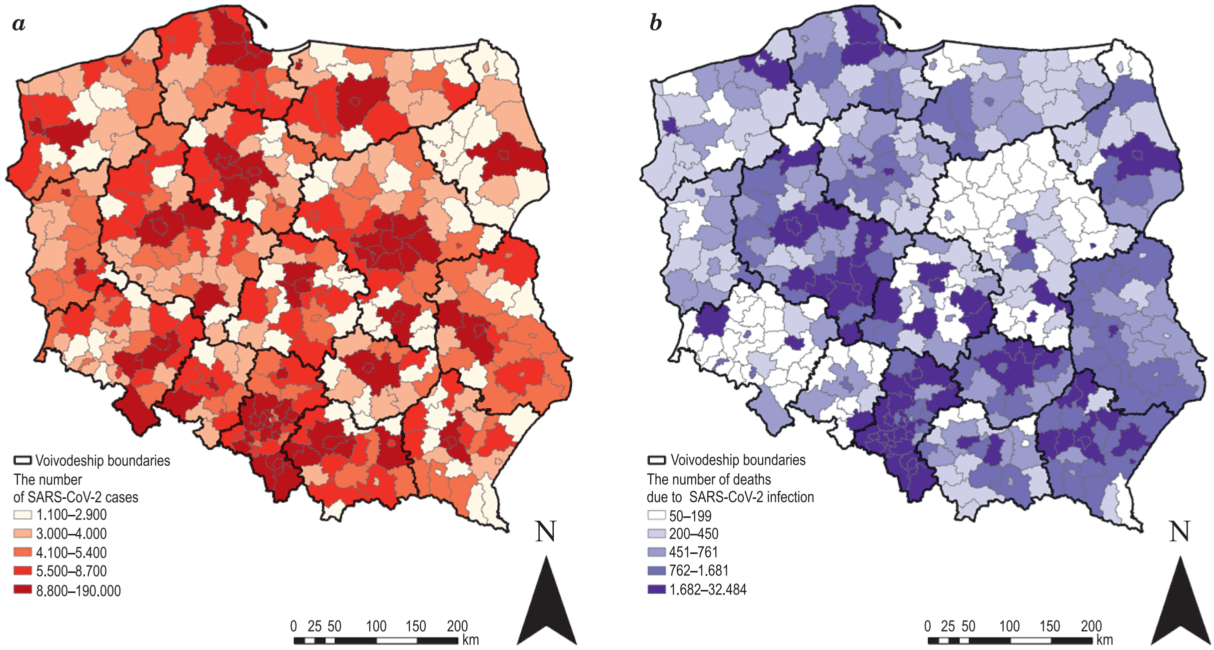


**Fig. 2**. Spatial distribution of two dependent variables, describing the course of the COVID-19 pandemic: the number of SARS-CoV-2 cases (a), and the number of deaths due to SARS-CoV-2 infection (b)
*Source*: own elaboration using ArcGIS Pro 3.2 by Esri.

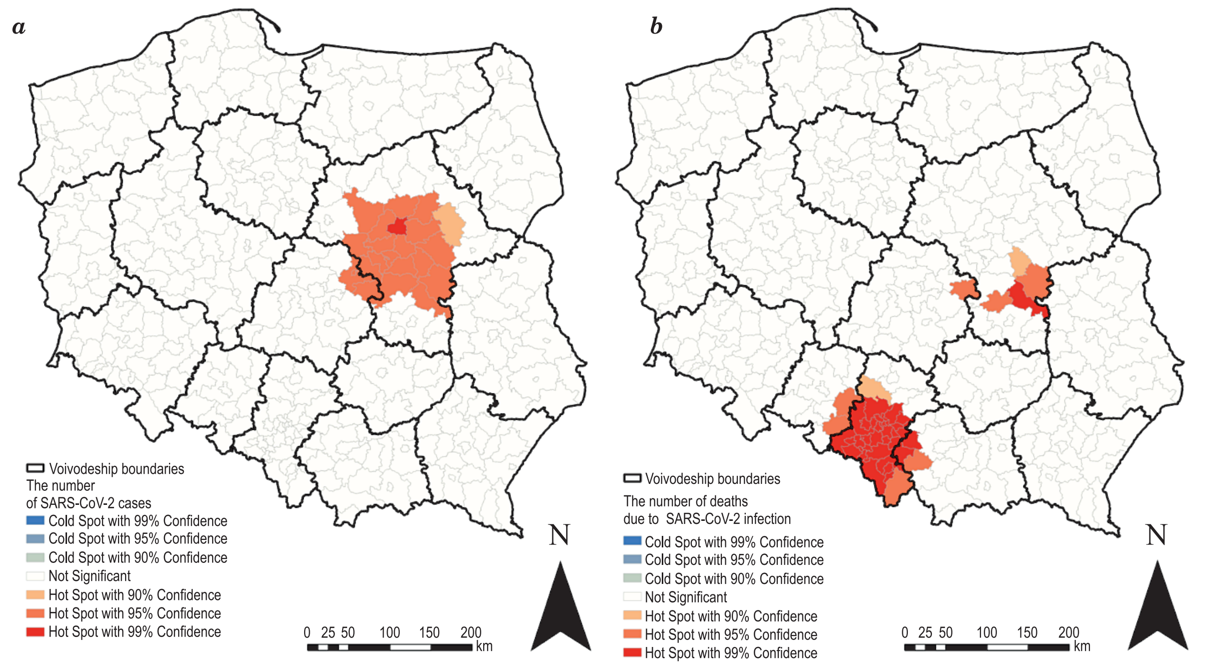


**Fig. 3**. Hot Spot analysis of two dependent variables, describing the course of the COVID-19 pandemic: the number of SARS-CoV-2 cases (a), and the number of deaths due to SARS-CoV-2 infection (b)
*Source*: own elaboration using ArcGIS Pro 3.2 by Esri.

✉krzysztof.rzasa@uwm.edu.pl; ✉mateusz.ciski@uwm.edu.pl

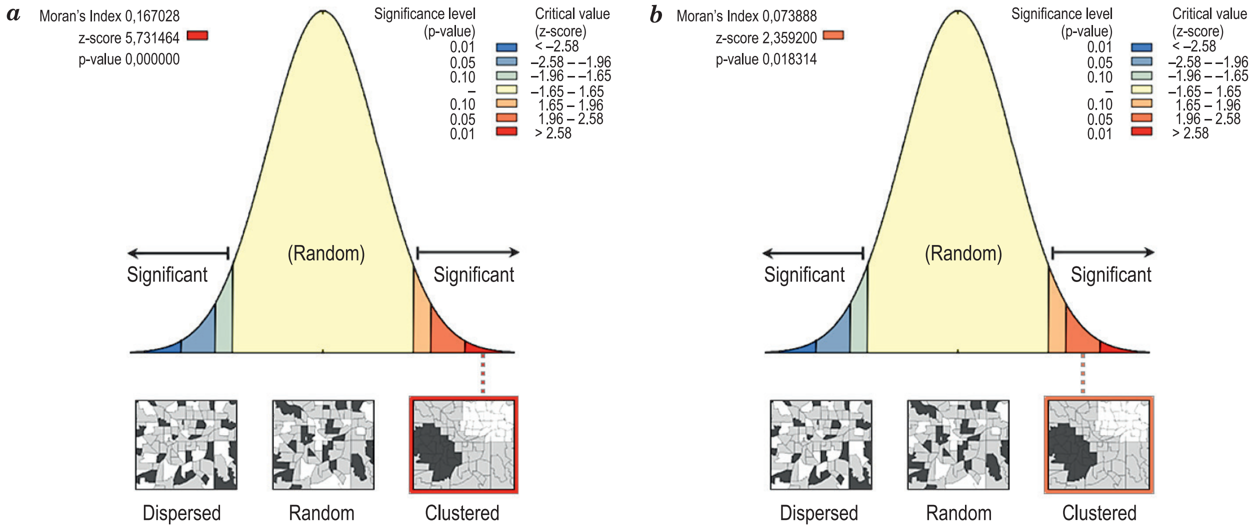


**Fig. 4**. Spatial Autocorrelation reports of two dependent variables, describing the course of the COVID-19 pandemic: the number of SARS-CoV-2 cases (a), and the number of deaths due to SARS-CoV-2 infection (b)
*Source*: own elaboration using ArcGIS Pro 3.2 by Esri.

or random. "Inverse distance squared" was selected as the "Conceptualization of Spatial Relationships" parameter, with closest nearby neighboring counties having a larger influence on the computations for a target county than features that are far away. The chosen parameter of the tool reflects and models the analyzed phenomenon to the highest degree. All the study variables were analyzed in this way; Fig. 4 presents Spatial Autocorrelation reports of two dependent variables: the number of SARS-CoV-2 cases (a), and the number of deaths due to SARS-CoV-2 infection (b). Due to the large number of variables, reports on the explanatory variables can be found in Supplementary Materials.

Detailed analysis of the results of Spatial Autocorrelation (Global Moran's I) makes it possible to estimate the spatial pattern of the studied variables. A positive value of Moran's I indicates a clustering tendency, while a negative value of Moran's I indicates a dispersion tendency, when the z-score or p-value indicates statistical significance. The following Table 2 shows the results of this measure, with indication if analyzed data has a tendency to form clusters or to be disparate.

An autocorrelation analysis showed that almost all variables tend to form clusters (except for variables V4 and V8, "number of beds in general hospitals" and "enrollment rate of elementary schools" respectively). The p-value indicates that all variables are statistically significant. Results allow rejecting the null hypothesis and proceeding with the rest of the study.

**Table 2**. Summary of the spatial autocorrelation

| Variable | p-value | z-score | Spatial pattern |
|---|---|---|---|
| 1 | 2 | 3 | 4 |
| the number of SARS-CoV-2 cases | 0.00 | 5.73 | Clustered |
| the number of deaths due to SARS-CoV-2 infection | 0.02 | 2.36 | Clustered |
| V1 | 0.00 | 4.71 | Clustered |
| V2 | 0.00 | 14.82 | Clustered |
| V3 | 0.03 | 2.17 | Clustered |
| V4 | 0.00 | -5.13 | Dispersed |

✉krzysztof.rzasa@uwm.edu.pl; ✉mateusz.ciski@uwm.edu.pl

cont. **Table 2**

| 1 | 2 | 3 | 4 |
|---|---|---|---|
| V5 | 0.00 | 8.04 | Clustered |
| V6 | 0.00 | 3.80 | Clustered |
| V7 | 0.00 | 10.93 | Clustered |
| V8 | 0.00 | -11.66 | Dispersed |
| V9 | 0.04 | 2.10 | Clustered |
| V10 | 0.05 | 1.93 | Clustered |
| V11 | 0.02 | 2.28 | Clustered |
| V12 | 0.03 | 2.24 | Clustered |
| V13 | 0.00 | 9.98 | Clustered |
| V14 | 0.00 | 12.67 | Clustered |
| V15 | 0.00 | 3.32 | Clustered |
| V16 | 0.05 | 1.99 | Clustered |
| V17 | 0.00 | 8.32 | Clustered |
| V18 | 0.00 | 2.82 | Clustered |
| V19 | 0.01 | 2.68 | Clustered |
| V20 | 0.00 | 3.79 | Clustered |
| V21 | 0.00 | 3.38 | Clustered |
| V22 | 0.00 | 3.41 | Clustered |
| V23 | 0.00 | 14.56 | Clustered |
| V24 | 0.00 | 3.39 | Clustered |
| V25 | 0.00 | 6.75 | Clustered |
| V26 | 0.01 | 2.56 | Clustered |
| V27 | 0.00 | 7.63 | Clustered |
| V28 | 0.00 | 19.51 | Clustered |
| V29 | 0.01 | 2.44 | Clustered |
| V30 | 0.00 | 3.47 | Clustered |

*Source*: own elaboration with ArcGIS Pro 3.2 by Esri.

## Calculating the level of Sustainable Development of polish counties, and its influence on the dependent variables

The next step of the study was to assess the impact of the level of Sustainable Development of Poland's counties on the course of the COVID-19 pandemic, represented by the number of SARS-CoV-2 cases, and the number of deaths due to SARS-CoV-2 infection. For this purpose, all the explanatory variables studied were used to build a two regression models (using the MGWR tool in ArcGIS Pro 3.2 software). In addition, six separate regression models were built from variables in the subsequent three groups (Social, Environmental, and Economical) to examine changes in the impact of specific thematic groups.

When explanatory variables are correlated, they share mutual information and the regression model cannot distinguish between the effects of the variables, so multicollinearity has a negative impact on coefficient estimation and optimal neighborhood. MGWR tool in ArcGIS Pro 3.2 highlights potential problems with multilinearity – none were found in the 8 developed regression models.

The indicator values for these models are shown in Table 3 below. Tables with complete regression results and autocorrelation reports of Adjusted R-Squared can be found in Supplementary Materials.

The values of the Adjusted R-Squared index indicate a high and very high fit of the model to the dependent variables. The explanatory variables explain the variable "the number of SARS-CoV-2 cases_ much



✉krzysztof.rzasa@uwm.edu.pl; ✉mateusz.ciski@uwm.edu.pl

**Table 3**. The level of goodness of fit of the 8 regression models, expressed by the coefficient of determination – Adjusted R-Squared index

| | Coefficient of determination, Adjusted R-Squared | |
|---|---|---|
| | The number of SARS-CoV-2 cases | The number of deaths due to SARS-CoV-2 infection |
| Sustainable Development level | 0.8737* | 0.7061* |
| Social group | 0.7469* | 0.6005* |
| Environmental group | 0.7574* | 0.5708* |
| Economical group | 0.8250* | 0.6882* |

Note: *—statistically significant at the $p < 0.01$ level
*Source*: own elaboration with ArcGIS Pro 3.2 by Esri.

better, the values of the Adjusted R-Squared index here are in the range of approximately 0.75–0.88. Less fit are the models explaining the variable "the number of deaths due to SARS-CoV-2 infection", in this case, the Adjusted R-Squared values are about 0.57–0.71. Of all the models, the highest value of the Adjusted R-Squared index was recorded for the unified level of Sustainable Development explaining the variable "the number of SARS-CoV-2 cases" – approximately 0.88.

In addition, the extracted models for each thematic group are characterized by different levels of model fit. Economical group explains the explanatory variables best, at a level of around 0.83 and 0.69. The other groups explain the explanatory variables to a lesser extent. The variable "the number of SARS-CoV-2 cases" is worst explained by the Social group model, while the variable "the number of deaths due to SARS-CoV-2 infection" – by the Environmental group model (respectively around 0.75 and 0.57).

The MGWR tool allows the creation of maps of local R-Squared values. These maps provide a better picture of such a complex phenomenon as the COVID-19 pandemic, and are useful in identifying locations that have significant local parameter estimates (H. Yu et al., 2020). Comparison of the content of maps is only viable if uniform classification is used (Ciski et al., 2019). The classification of the maps was standardized to allow comparison of the local R-Squared distribution for the models explaining the variables "number of SARS-CoV-2 cases" and "number of deaths due to SARS-CoV-2 infection". This way, each class on each map for variables "the number of SARS-CoV-2 cases" and "the number of deaths due to SARS-CoV-2 infection" matches the same values. This allows to draw the correct conclusions without any spatial classification bias, that can occur when trying to compare data visualized using different class intervals.

The following Fig. 5, 6, 7, and 8 presents the local R-Squared values for the models of Sustainable Development level, Social group, Environmental group, and Economical group.

The use of a unified cartographic classification allows the comparison of local R-Squared maps. While the impact of the explanatory variables varies (which is strongly noticeable by comparing the intensity of the symbolization of the classes of the maps), the general trend of the spatial distribution of the phenomenon is quite similar – a notable separation of the eastern and western parts of the country is evident. This trend is more pronounced in the map for the variable "the number of deaths due to SARS-CoV-2 infection" (Fig. 5b). In the case of the map for the variable "the number of SARS-CoV-2 cases" (Fig. 5a), one can see lower values of local R-Squared for counties in the eastern part of Poland, and more distinctly higher values of local R-Squared for the central part of the country.

The local R-Squared map for the "Social" thematic group for the variable "the number of SARS-CoV-2 cases" (Fig. 6a) shows a very unified picture of the phenomenon – all counties in the country are described by only two adjacent classes. A completely opposite picture is presented by the map for the variable "the number of deaths due to SARS-CoV-2 infection" (Fig. 6b) – a similar spatial trend can be observed here as in the corresponding map in Figure 5, with a stronger emphasis on the northeastern part of the country. A very unusual situation is the occurrence of counties with opposite classes (marked in red

✉krzysztof.rzasa@uwm.edu.pl; ✉mateusz.ciski@uwm.edu.pl

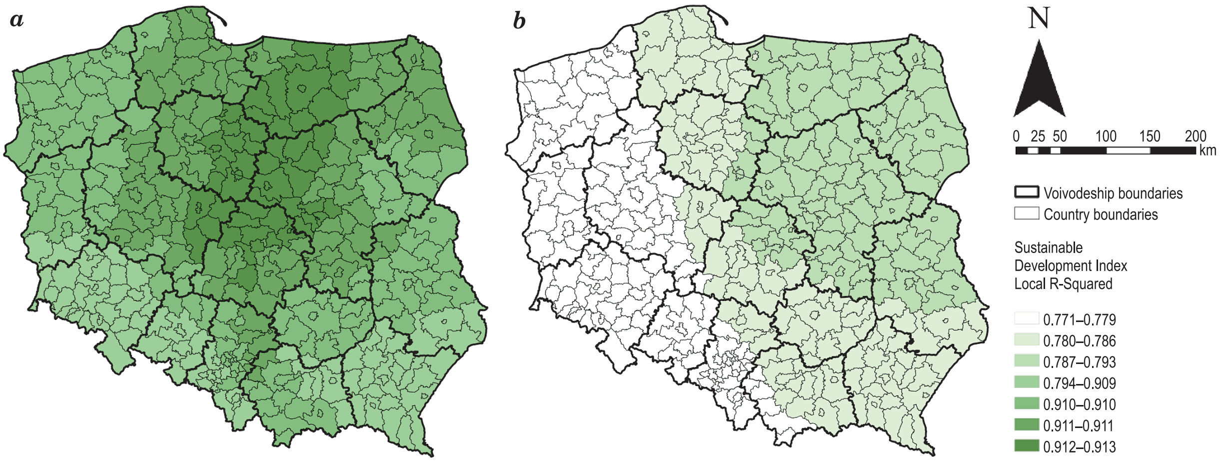


**Fig. 5**. Local R-Squared maps – unified Sustainable Development index for variables "the number of SARS-CoV-2 cases" (a) and "the number of deaths due to SARS-CoV-2 infection" (b)
*Source*: own elaboration using ArcGIS Pro 3.2 by Esri.

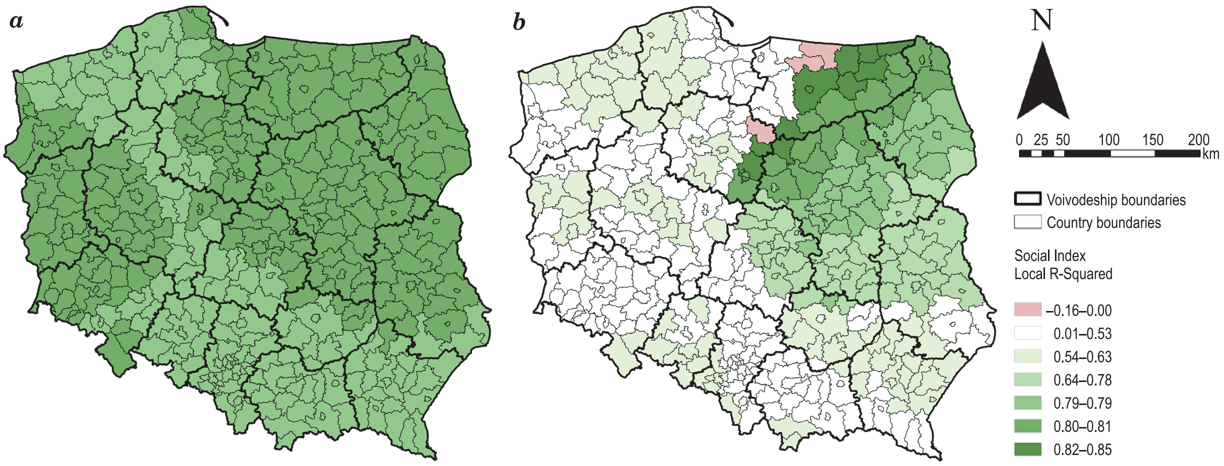


**Fig. 6**. Local R-Squared – Social Index for variables "the number of SARS-CoV-2 cases" (a) and "the number of deaths due to SARS-CoV-2 infection" (b)
*Source*: own elaboration using ArcGIS Pro 3.2 by Esri.

and green) in close proximity. This indicates the presence of very large local anomalies in the studied phenomenon in this area, namely the northern part of the Warmian-Masurian Voivodeship and the north-eastern part of the Kuyavian-Pomeranian Voivodeship.

As outlined in the previous figure, the phenomenon of the occurrence of extreme values of local R-Squared in neighboring counties is much more evident in the map for the Environmental group. Very unusual is the occurrence in a number of places of strong negative values of the R-Squared index (marked in red on all maps) alongside a strong positive values. Large clusters of such incidences can be seen in the northeastern and southwestern parts of the country.

The spatial distribution of the local R-Squared environmental group for the explained variable "the number of deaths due to SARS-CoV-2 infection" (Fig. 7b) is almost identical to that of the previous group – Social (Fig. 6b). Again, the extreme values

✉krzysztof.rzasa@uwm.edu.pl; ✉mateusz.ciski@uwm.edu.pl

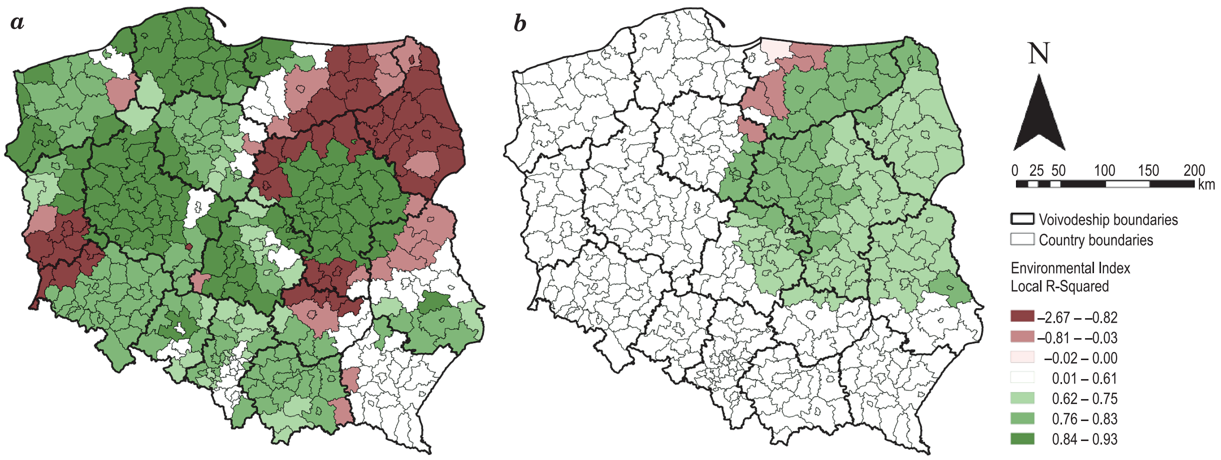


**Fig. 7.** Local R-Squared – Environmental Index for variables "the number of SARS-CoV-2 cases" (a) and "the number of deaths due to SARS-CoV-2 infection" (b)
*Source*: own elaboration using ArcGIS Pro 3.2 by Esri.

of the local R-Squared are found in the northern part of the Warmian-Masurian Voivodeship and the north-eastern part of the Kuyavian-Pomeranian Voivodeship. In the case of this group, this phenomenon is even more strongly outlined – the differences in local R-Squared class values are greater in this case than in the case of the Fig. 6b.

The spatial trends presented in Fig. 8 are remarkably similar to those observed in Fig. 7. The map describing the variable "the number of SARS-CoV-2 cases" (Fig. 8a) shows a similar phenomenon of the widespread occurrence of negative values of the local R-Squared, and the cooccurrence of extreme values. However, the large cluster of negative values in the northeastern part of the country has disappeared. As with the map for the unified Sustainable Development index, the overall trend of the spatial distribution of the phenomenon shows a significant separation of the eastern and western parts of the country.

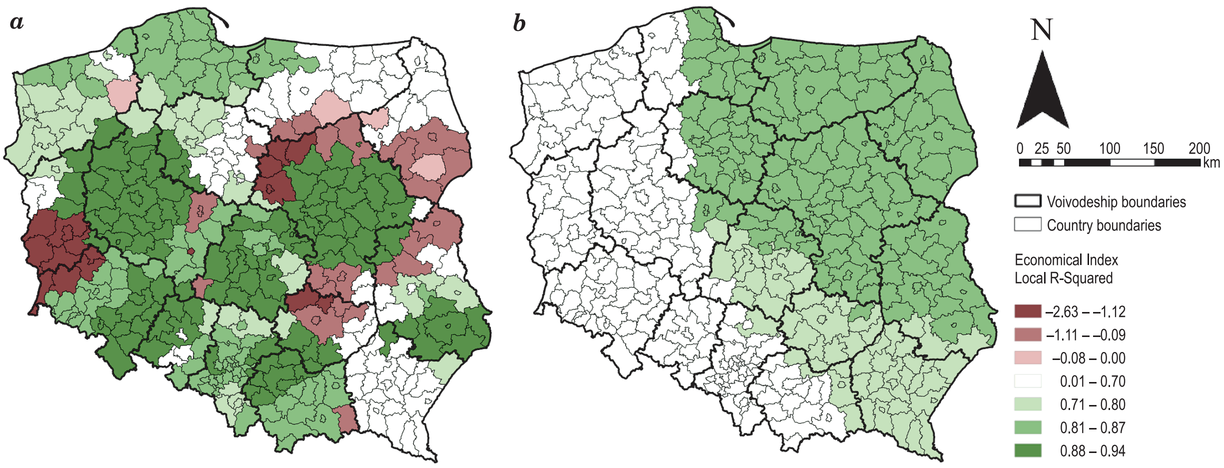


**Fig. 8.** Local R-Squared – Economical Index for variables "the number of SARS-CoV-2 cases" (a) and "the number of deaths due to SARS-CoV-2 infection" (b)
*Source*: own elaboration using ArcGIS Pro 3.2 by Esri.

✉krzysztof.rzasa@uwm.edu.pl; ✉mateusz.ciski@uwm.edu.pl

## Residual spatial autocorrelation

To assess the performance of the regression model, the presence of residual spatial autocorrelation was analysed. The residual spatial autocorrelation was measured using the Spatial Autocorrelation tool (Global Moran's I). The results of this analysis are presented in Table 4 below.

**Table 4**. Spatial autocorrelation results for MGWR residuals

| | z-score | |
|---|---|---|
| | The number of SARS-CoV-2 cases | The number of deaths due to SARS-CoV-2 infection |
| Sustainable Development level | -0.52* | 0.62* |
| Social group | -0.25* | -0.03* |
| Environmental group | -1.79** | -0.10* |
| Economical group | 0.75* | 1.50* |

Note: * – random spatial pattern, ** – weak dispersed spatial pattern
*Source*: own elaboration with ArcGIS Pro 3.2 by Esri.

The distribution of the residuals does not appear to be significantly different from random when considering the z-scores – out of the 8 regression models, only one z-score value indicate a weak dispersed pattern, confirming the validity of using the MGWR model.

## CONCLUSIONS

The main purpose of the article was to investigate whether a relationship can be demonstrated between the course of the COVID-19 pandemic, as described by the number of cases and the number of deaths caused by the pandemic, and the level of Sustainable Development of an area. The study showed that such a relationship exists, and the magnitudes of the Adjusted R-Squared index indicate a high and very high fit of the model to the dependent variables. The variable "the number of SARS-CoV-2 cases" is explained to a greater extent (Adjusted R-Squared here is in the range of about 0.75–0.88) than the variable "the number of deaths due to SARS-CoV-2 infection" (Adjusted R-Squared here are in the range of about 0.57–0.70). The highest value of Adjusted R-Squared occurs for the unified level of Sustainable Development explaining the variable "the number of SARS-CoV-2 cases", and reached almost 0.88. These values confirm the very high relationship between the level of Sustainable Development of the area and the course of the COVID-19 pandemic.

Analyzing the Adjusted R-Squared values for each thematic group comprising the unified level of Sustainable Development, it can be found that all of them explain the variables "the number of SARS-CoV-2 cases" and "the number of deaths due to SARS-CoV-2 infection" to a high degree. The lowest Adjusted R-Squared value was obtained for the Environmental group explaining "the number of deaths due to SARS-CoV-2 infection" and it equaled 0.5708. The highest Adjusted R-Squared value was 0.8259, and it was recorded for the Economical group explaining "the number of SARS-CoV-2 cases" Among all three subject groups, higher Adjusted R-Squared values were obtained for the variables explaining the dependent variable "the number of SARS-CoV-2 cases". This may indicate that the variable "the number of deaths due to SARS-CoV-2 infection" was influenced by other factors (not related to the level of Sustainable Development) that were not included in the regression model.

While the article focuses on indicators related to Sustainable Development, the obtained Adjusted R-Squared values indicate that the two analyzed dependent variables may have been influenced by other factors not included in the regression models. It can be speculated that these factors could have included: climate factors (e.g., temperature), demographic factors (e.g., population density), factors related to emergency management and policy (e.g., local government decisions to fight the pandemic), and even factors related to the population's approach to the pandemic (e.g., pandemic denialism).

The development of local R-Squared maps enabled the study of spatially varying relationships between variables. In addition, further allowed to identify local

✉krzysztof.rzasa@uwm.edu.pl; ✉mateusz.ciski@uwm.edu.pl

anomalies of the phenomenon. Maps for the "Environmental" and "Economical" thematic groups, describing the dependent variable "the number of SARS-CoV-2 cases" display high concentrations of anomalies on the outskirts of the Masovian Voivodeship, and in the west of the country on the border of the Lubusz and Lower Silesian Voivodeships. Maps describing the variable "the number of deaths due to SARS-CoV-2 infection" show fewer anomalies, confined to single counties: the Bartoszyce county, the Lidzbark Warmiński county, the Ostróda county, the Iława county (in the Warmian-Masurian Voivodeship), and the Brodnica county (in the Kuyavian-Pomeranian Voivodeship).

Areas with anomalies indicated in the local R-Squared maps may require additional research due to high deviations from the regression model. This may be relevant and helpful to local authorities and decision-makers, due to the abnormalities in the results, and should pay special attention to these areas.

**Author contributions:** The authors have approved the final version of the article. The authors have contributed to this work as follows: K.R. and M.C. developed the concept and designed the study, K.R. and M.C. collected the data, K.R. and M.C. analyzed and interpreted the data, K.R. and M.C. drafted the article, K.R. and M.C. revised the article critically for important intellectual content.

## REFERENCES


Ahundjanov, B. B., Akhundjanov, S. B., & Okhunjanov, B. B. (2020). Information search and financial markets under COVID-19. *Entropy*, *22*(7), Article 791. https://doi.org/10.3390/e22070791

Alves, V. P., Casemiro, F. G., De Araujo, B. G., De Souza Lima, M. A., De Oliveira, R. S., De Souza Fernandes, F. T., Gomes, A. V. C., & Gregori, D. (2021). Factors associated with mortality among elderly people in the COVID-19 pandemic (SARS-CoV-2): A systematic review and meta-analysis. *International Journal of Environmental Research and Public Health*, *18*(15), Article 8008. https://doi.org/10.3390/ijerph18158008

Azapagic, A., & Perdan, S. (2000). Indicators of Sustainable Development for Industry: A General Framework. *Process Safety and Environmental Protection*, *78*(4), 243–261. https://doi.org/10.1205/095758200530763

Bąk, I., & Cheba, K. (2018). Syntetyczna ocena dysproporcji zrównoważonego rozwoju krajów Unii Europejskiej [Synthetic assessment of disparities in sustainable development of European Union countries]. *Wiadomości Statystyczne* [*Statistical News*], *5*(684), 37–55.

Baniasad, M., Mofrad, M. G., Bahmanabadi, B., & Jamshidi, S. (2021). COVID-19 in Asia: Transmission factors, re-opening policies, and vaccination simulation. *Environmental Research*, *202*, Article 111657. https://doi.org/10.1016/j.envres.2021.111657

Bossel, H. (1999). *Indicators for sustainable development: theory, method, applications*. International Institute for Sustainable Development.

Brunsdon, C., Fotheringham, A. S., & Charlton, M. E. (1996). Geographically Weighted Regression: A Method for Exploring Spatial Nonstationarity. *Geographical Analysis*, *28*(4), 281–298. https://doi.org/10.1111/J.1538-4632.1996.TB00936.X

Cao, K. H., Li, Q., Liu, Y., & Woo, C. K. (2020). COVID-19's adverse effects on a stock market index. *Applied Economics Letters*, *28*(14), 1157–1161. https://doi.org/10.1080/13504851.2020.1803481

Castañeda-Babarro, A., Coca, A., Arbillaga-Etxarri, A., & Gutiérrez-Santamaría, B. (2020). Physical Activity Change During COVID-19 Confinement. *International Journal of Environmental Research and Public Health*, *17*(18), Article 6878, 1–10. https://doi.org/10.3390/ijerph17186878

Chen, Y., & Luo, Z. (2022). Hedonic Pricing of Houses in Megacities Pre- and Post-COVID-19: A Case Study of Shanghai, China. *Sustainability*, *14*(17), Article 11021. https://doi.org/10.3390/su141711021

Ciski, M., & Rząsa, K. (2021). Threats to Cultural Heritage Caused by the Global Sea Level Rise as a Result of the Global Warming. *Water*, *13*(18), Article 2577. https://doi.org/10.3390/W13182577

Ciski, M., & Rząsa, K. (2023). Multiscale Geographically Weighted Regression in the Investigation of Local COVID-19 Anomalies Based on Population Age Structure in Poland. *International Journal of Environmental Research and Public Health*, *20*(10), Article 5878. https://doi.org/10.3390/ijerph20105875

Ciski, M., Rząsa, K., & Ogryzek, M. (2019). Use of GIS tools in sustainable heritage management-the


✉krzysztof.rzasa@uwm.edu.pl; ✉mateusz.ciski@uwm.edu.pl

importance of data generalization in spatial modeling. *Sustainability*, *11*(20), Article 5616. https://doi.org/10.3390/su11205616

Clemente-Suárez, V. J., Navarro-Jiménez, E., Jimenez, M., Hormeño-Holgado, A., Martinez-Gonzalez, M. B., Benitez-Agudelo, J. C., Perez-Palencia, N., Laborde-Cárdenas, C. C., & Tornero-Aguilera, J. F. (2021). Impact of COVID-19 Pandemic in Public Mental Health: An Extensive Narrative Review. *Sustainability*, *13*(6), Article 3221. https://doi.org/10.3390/su13063221

Coccia, M. (2020). How (Un)sustainable Environments Are Related to the Diffusion of COVID-19: The Relation Between Coronavirus Disease 2019, Air Pollution, Wind Resource and Energy. *Sustainability*, *12*(22), Article 9709, 1–12. https://doi.org/10.3390/su12229709

Comber, A., Brunsdon, C., Charlton, M., Dong, G., Harris, R., Lu, B., Yihe, L., Murakami, D., Nakaya, T., Wang, Y., & Harris, P. (2022). A Route Map for Successful Applications of Geographically Weighted Regression. *Geographical Analysis*, *55*(1), 155–178. https://doi.org/10.1111/GEAN.12316

Comunian, S., Dongo, D., Milani, C., & Palestini, P. (2020). Air pollution and COVID-19: The Role of Particulate Matter in the Spread and Increase of COVID-19's Morbidity and Mortality. *International Journal of Environmental Research and Public Health*, *17*(12), 1–22. https://doi.org/10.3390/ijerph17124487

Czermińska, M. (2002). Zastosowanie metod taksonomicznych w klasyfikacji krajów Unii Europejskiej z punktu widzenia poziomu ich rozwoju gospodarczego [Application of taxonomic methods in the classification of European Union countries from the point of view of their level of economic development]. *Zeszyty Naukowe Akademii Ekonomicznej w Krakowie* [*Scientific Journals of the Cracow University of Economics*], *575*(284), 149–161.

Devkota, M., Hatfield, G., & Chintala, R. (2014). Effect of Sample Size on the Performance of Ordinary Least Squares and Geographically Weighted Regression. *British Journal of Mathematics & Computer Science*, *4*(1), 1–21. https://doi.org/10.9734/bjmcs/2014/6050

Di Gennaro, F., Pizzol, D., Marotta, C., Antunes, M., Racalbuto, V., Veronese, N., & Smith, L. (2020). Coronavirus Diseases (COVID-19) Current Status and Future Perspectives: A Narrative Review. *International Journal of Environmental Research and Public Health*, *17*(8), Article 2690. https://doi.org/10.3390/ijerph17082690

Drastichová, M. (2017). Measuring Sustainability of the EU Countries with the Selected Indices. In M. Pech (Ed.), *The International Scientific Conference INPROFORUM 2017* (pp. 87–101). Faculty of Economics, University of South Bohemia in České Budějovice.

Duszyński, J., Afelt, A., Ochab-Marcinek, A., Owczuk, R., Pyrć, K., Rosińska, M., Rychard, A., & Smiatacz, T. (2020). Zrozumieć COVID-19 [Understanding COVID-19]. *ACADEMIA. Magazyn Polskiej Akademii Nauk [ACADEMIA. The Magazine of the Polish Academy of Sciences]*, *4*(64), 1–80.

European Commission: Directorate-General for Environment. (2015). Indicators for sustainable cities. *Science for Environment Policy*. Publications Office. https://doi.org/10.2779/61700

Fotheringham, A. S., Brunsdon, C., & Charlton, M. (2006). *Geographically Weighted Regression: The Analysis of Spatially Varying Relationships*. Wiley.

Fotheringham, A. S., Yang, W., & Kang, W. (2017). Multiscale Geographically Weighted Regression (MGWR). *Annals of the American Association of Geographers*, *107*(6), 1247–1265. https://doi.org/10.1080/24694452.2017.1352480

Franch-Pardo, I., Napoletano, B. M., Rosete-Verges, F., & Billa, L. (2020). Spatial analysis and GIS in the study of COVID-19. A review. *Science of The Total Environment*, *739*, Article 140033. https://doi.org/10.1016/J.SCITOTENV.2020.140033

Gao, Y., Zhao, J., & Han, L. (2022). Exploring the spatial heterogeneity of urban heat island effect and its relationship to block morphology with the geographically weighted regression model. *Sustainable Cities and Society*, *76*, Article 103431. https://doi.org/10.1016/J.SCS.2021.103431

Geddes, A., Fotheringham, A. S., Libby, G., & Steele, R. J. C. (2021). Colorectal cancer screening participation: Exploring relationship heterogeneity and scale differences using multiscale geographically weighted regression. *Geospatial Health*, *16*(1). https://doi.org/10.4081/gh.2021.967

Ghiani, E., Galici, M., Mureddu, M., & Pilo, F. (2020). Impact on Electricity Consumption and Market Pricing of Energy and Ancillary Services During Pandemic of COVID-19 in Italy. *Energies*, *13*(13), Article 3357. https://doi.org/10.3390/en13133357

Główny Urząd Geodezji i Kartografii. (2023). *Państwowy Rejestr Granic*. https://www.geoportal.gov.pl/dane/panstwowy-rejestr-granic

✉krzysztof.rzasa@uwm.edu.pl; ✉mateusz.ciski@uwm.edu.pl

Gualano, M. R., Lo Moro, G., Voglino, G., Bert, F., & Siliquini, R. (2020). Effects of COVID-19 Lockdown on Mental Health and Sleep Disturbances in Italy. *International Journal of Environmental Research and Public Health*, *17*(13), Article 4779. https://doi.org/10.3390/ijerph17134779

Hák, T., Janoušková, S., & Moldan, B. (2016). Sustainable Development Goals: A need for relevant indicators. *Ecological Indicators*, *60*, 565–573. https://doi.org/10.1016/j.ecolind.2015.08.003

Han, F., & Sui, F. (2019). Effect of Global Moran's I and space-time permutation scanning method in shanghai metro traffic based on ecological transportation system. *Ekoloji Dergisi*, *28*(107), 4295–4303.

He, Y., Seminara, P. J., Huang, X., Yang, D., Fang, F., & Song, C. (2023). Geospatial Modeling of Health, Socioeconomic, Demographic, and Environmental Factors with COVID-19 Incidence Rate in Arkansas, US. *ISPRS International Journal of Geo-Information*, *12*(2), Article 45. https://doi.org/10.3390/ijgi12020045

Jamshidi, S., Baniasad, M., & Niyogi, D. (2020). Global to USA County Scale Analysis of Weather, Urban Density, Mobility, Homestay, and Mask Use on COVID-19. *International Journal of Environmental Research and Public Health*, *17*(21), Article 7847. https://doi.org/10.3390/ijerph17217847

Johnson, D. P., Ravi, N., & Braneon, C. V. (2021). Spatiotemporal Associations Between Social Vulnerability, Environmental Measurements, and COVID-19 in the Conterminous United States. *GeoHealth*, *5*(8). https://doi.org/10.1029/2021GH000423

Kaczmarek, T., & Mikuła, Ł. (2022). Presidential Elections in Poland During the COVID-19 Pandemic: An Unexpected Challenge for Political Actors and the Relationship Between Central Government and Local Government. In C. Nunes Silva (Ed.), *Local Government and the COVID-19 Pandemic. Local and Urban Governance* (pp. 451–479). Springer, Cham. https://doi.org/10.1007/978-3-030-91112-6_18

Klopp, J. M., & Petretta, D. L. (2017). The urban sustainable development goal: Indicators, complexity and the politics of measuring cities. *Cities*, *63*, 92–97. https://doi.org/10.1016/j.cities.2016.12.019

Kodera, S., Rashed, E. A., & Hirata, A. (2020). Correlation Between COVID-19 Morbidity and Mortality Rates in Japan and Local Population Density, Temperature, and Absolute Humidity. *International Journal of Environmental Research and Public Health*, *17*(15), Article 5477. https://doi.org/10.3390/ijerph17155477

Koszel, M., & Bartkowiak, P. (2018). Taksonomiczna miara zrównoważonego rozwoju obszarów metropolitalnych w Polsce [Taxonomic measure of sustainable development of metropolitan areas in Poland]. *Zeszyty Naukowe Uniwersytetu Ekonomicznego w Krakowie* [*Scientific Journals of the Cracow University of Economics*], *3*(975), 83–100. https://doi.org/10.15678/znuek.2018.0975.0306

Lesser, I. A., & Nienhuis, C. P. (2020). The impact of COVID-19 on Physical Activity Behavior and Well-Being of Canadians. *International Journal of Environmental Research and Public Health*, *17*(11), Article 3899. https://doi.org/10.3390/ijerph17113899

Li, Q., Guan, X., Wu, P., Wang, X., Zhou, L., Tong, Y., Ren, R., Leung, K. S. M., Lau, E. H. Y., Wong, J. Y., Xing, X., Xiang, N., Wu, Y., Li, C., Chen, Q., Li, D., Liu, T., Zhao, J., Liu, M., … Feng, Z. (2020). Early Transmission Dynamics in Wuhan, China, of Novel Coronavirus–Infected Pneumonia. *New England Journal of Medicine*, *382*(13), 1199–1207. https://doi.org/10.1056/NEJMOA2001316

Li, S., Wang, Y., Xue, J., Zhao, N., & Zhu, T. (2020). The Impact of COVID-19 Epidemic Declaration on Psychological Consequences: A Study on Active Weibo Users. *International Journal of Environmental Research and Public Health*, *17*(6), Article 2032. https://doi.org/10.3390/ijerph17062032

Lichstein, J. W., Simons, T. R., Shriner, S. A., & Franzreb, K. E. (2002). Spatial autocorrelation and autoregressive models in ecology. *Ecological Monographs*, *72*(3), 445–463. https://doi.org/10.1890/0012-9615(2002)072[0445:SAAAMI]2.0.CO;2

Linton, N. M., Kobayashi, T., Yang, Y., Hayashi, K., Akhmetzhanov, A. R., Jung, S. M., Yuan, B., Kinoshita, R., & Nishiura, H. (2020). Incubation Period and Other Epidemiological Characteristics of 2019 Novel Coronavirus Infections with Right Truncation: A Statistical Analysis of Publicly Available Case Data. *Journal of Clinical Medicine*, *9*(2), Article 538. https://doi.org/10.3390/jcm9020538

Lorent, D., Nowak, R., Roxo, C., Lenartowicz, E., Makarewicz, A., Zaremba, B., Nowak, S., Kuszel, L., Stefaniak, J., Kierzek, R., & Zmora, P. (2021). Prevalence of Anti-SARS-CoV-2 Antibodies in Poznań, Poland, after the First Wave of the COVID-19 Pandemic. *Vaccines*, *9*(6), Article 541. https://doi.org/10.3390/VACCINES9060541

Ma, J., Zhu, H., Li, P., Liu, C., Li, F., Luo, Z., Zhang, M., & Li, L. (2022). Spatial Patterns of the Spread

✉krzysztof.rzasa@uwm.edu.pl; ✉mateusz.ciski@uwm.edu.pl

of COVID-19 in Singapore and the Influencing Factors. *ISPRS International Journal of Geo-Information*, *11*(3), Article 152. https://doi.org/10.3390/ijgi11030152

Ma, Y., Zhao, Y., Liu, J., He, X., Wang, B., Fu, S., Yan, J., Niu, J., Zhou, J., & Luo, B. (2020). Effects of temperature variation and humidity on the death of COVID-19 in Wuhan, China. *Science of the Total Environment*, *724*, Article 138226. https://doi.org/10.1016/j.scitotenv.2020.138226

Marom, P., Zalcman, B. G., & Dankner, R. (2022). Association between Self-Classification of COVID-19 Risk Levels and Adverse Lifestyle Changes among Physically Active Older Adults Following the Coronavirus Outbreak. *International Journal of Environmental Research and Public Health*, *19*(12), Article 7039. https://doi.org/10.3390/ijerph19127039

Mazza, C., Ricci, E., Biondi, S., Colasanti, M., Ferracuti, S., Napoli, C., & Roma, P. (2020). A Nationwide Survey of Psychological Distress Among Italian People during the COVID-19 Pandemic: Immediate Psychological Responses and Associated Factors. *International Journal of Environmental Research and Public Health*, *17*(9), Article 3165. https://doi.org/10.3390/ijerph17093165

Md Iderus, N. H., Lakha Singh, S. S., Mohd Ghazali, S., Yoon Ling, C., Cia Vei, T., Md Zamri, A. S. S., Ahmad Jaafar, N., Ruslan, Q., Ahmad Jaghfar, N. H., & Gill, B. S. (2022). Correlation between Population Density and COVID-19 Cases during the Third Wave in Malaysia: Effect of the Delta Variant. *International Journal of Environmental Research and Public Health*, *19*(12), Article 7439. https://doi.org/10.3390/ijerph19127439

Mennis, J. (2006). Mapping the Results of Geographically Weighted Regression. *Cartographic Journal*, *43*(2), 171–179. https://doi.org/10.1179/000870406X114658

Meyer, J., McDowell, C., Lansing, J., Brower, C., Smith, L., Tully, M., & Herring, M. (2020). Changes in Physical Activity and Sedentary Behavior in Response to COVID-19 and Their Associations with Mental Health in 3052 US Adults. *International Journal of Environmental Research and Public Health*, *17*(18), Article 6469. https://doi.org/10.3390/ijerph17186469

Michał Rogalski (@micalrg). (2022). *Twitter profile*. https://twitter.com/micalrg

Mohammad Sham, N., Anual, Z. F., & Shaharudin, R. (2022). GIS based interpolation method to urinary metal concentrations in Malaysia. *Food and Chemical Toxicology*, *163*, Article 112949. https://doi.org/10.1016/J.FCT.2022.112949

Mohammadi, A., Pishgar, E., Fatima, M., Lotfata, A., Fanni, Z., Bergquist, R., & Kiani, B. (2023). The COVID-19 Mortality Rate Is Associated with Illiteracy, Age, and Air Pollution in Urban Neighborhoods: A Spatiotemporal Cross-Sectional Analysis. *Tropical Medicine and Infectious Disease*, *8*(2), Article 85. https://doi.org/10.3390/tropicalmed8020085

Moran, D. D., Wackernagel, M., Kitzes, J. A., Goldfinger, S. H., & Boutaud, A. (2008). Measuring sustainable development – Nation by nation. *Ecological Economics*, *64*(3), 470–474. https://doi.org/10.1016/j.ecolecon.2007.08.017

Mori, K., & Christodoulou, A. (2012). Review of sustainability indices and indicators: Towards a new City Sustainability Index (CSI). *Environmental Impact Assessment Review*, *32*(1), 94–106. https://doi.org/10.1016/j.eiar.2011.06.001

Mortensen, L. F. (2013). Measuring sustainable development. In M. A. Quaddus, & M. A. B. Siddique (Eds.), *Environmental Management in Practice: Instruments for Environmental Management* (pp. 39–60). Edward Elgar Publishing. https://doi.org/10.4337/9780857932167.00009

Morton, S., Pencheon, D., & Squires, N. (2017). Sustainable Development Goals (SDGs), and their implementation. *British Medical Bulletin*, *24*(1), 81–90. https://doi.org/10.1093/bmb/ldx031

Navon, A., Machlev, R., Carmon, D., Onile, A. E., Belikov, J., & Levron, Y. (2021). Effects of the COVID-19 Pandemic on Energy Systems and Electric Power Grids—A Review of the Challenges Ahead. *Energies*, *14*(4), Article 1056. https://doi.org/10.3390/en14041056

Oshan, T. M., Li, Z., Kang, W., Wolf, L. J., & Stewart Fotheringham, A. (2019). MGWR: A Python Implementation of Multiscale Geographically Weighted Regression for Investigating Process Spatial Heterogeneity and Scale. *ISPRS International Journal of Geo-Information*, *8*(6), Article 269. https://doi.org/10.3390/ijgi8060269

Parysek, J. J., & Mierzejewska, L. (2022). Cities in the epidemic, the epidemic in cities: Reconstruction of COVID-19 development in Polish cities. *Cities*, *125*, Article 103676. https://doi.org/10.1016/J.CITIES.2022.103676

Permai, S. D., Christina, A., & Santoso Gunawan, A. A. (2021). Fiscal decentralization analysis that affect

✉krzysztof.rzasa@uwm.edu.pl; ✉mateusz.ciski@uwm.edu.pl

economic performance using geographically weighted regression (GWR). *Procedia Computer Science*, *179*, 399–406. https://doi.org/10.1016/J.PROCS.2021.01.022

Rogalski, M. (2022). *Archiwum danych powiatowych raportowanych przez Ministerstwo Zdrowia* [*Archive of county data reported by the Ministry of Health*]. https://bit.ly/covid19_archiwumMZ

Rząsa, K., & Ciski, M. (2021). Determination of the level of sustainable development of the cities – a proposal for a method of classifying objects based on natural breaks. *Acta Scientiarum Polonorum Administratio Locorum*, *20*(3), 215–239. https://doi.org/10.31648/ASPAL.6701

Rząsa, K., & Ciski, M. (2022). Influence of the Demographic, Social, and Environmental Factors on the COVID-19 Pandemic—Analysis of the Local Variations Using Geographically Weighted Regression. *International Journal of Environmental Research and Public Health*, *19*(19). https://doi.org/10.3390/ijerph191911881

Schleicher-Tappeser, R. (2018). Sustainable development in the European Union – Monitoring Report On Progress Towards The Sdgs In An Eu Context. *Greener Management International*, *2001*(36), 50–66.

Sharif, A., Aloui, C., & Yarovaya, L. (2020). COVID-19 pandemic, oil prices, stock market, geopolitical risk and policy uncertainty nexus in the US economy: Fresh evidence from the wavelet-based approach. *International Review of Financial Analysis*, *70*, Article 101496. https://doi.org/10.1016/J.IRFA.2020.101496

Shekhar, R., Sheikh, A. B., Upadhyay, S., Singh, M., Kottewar, S., Mir, H., Barrett, E., & Pal, S. (2021). COVID-19 Vaccine Acceptance among Health Care Workers in the United States. *Vaccines*, *9*(2), Article 119. https://doi.org/10.3390/vaccines9020119

Shen, L. Y., Jorge Ochoa, J., Shah, M. N., & Zhang, X. (2011). The application of urban sustainability indicators – A comparison between various practices. *Habitat International*, *35*(1), 17–29. https://doi.org/10.1016/j.habitatint.2010.03.006

Śleszyński, P. (2020). Prawidłowości przebiegu dyfuzji przestrzennej rejestrowanych zakażeń koronawirusem SARS-CoV-2 w Polsce w pierwszych 100 dniach epidemii [Spatial Diffusion Patterns of Recorded SARS-CoV-2 Coronavirus Infections in Poland in the First 100 Days of the Epidemic]. *Czasopismo Geograficzne* [*Geographical Journal*], *91*(1–2), 5–18.

Solomou, I., & Constantinidou, F. (2020). Prevalence and Predictors of Anxiety and Depression Symptoms during the COVID-19 Pandemic and Compliance with Precautionary Measures: Age and Sex Matter. *International Journal of Environmental Research and Public Health*, *17*(14), Article 4924. https://doi.org/10.3390/ijerph17144924

Spangenberg, J. H. (2015). Indicators for sustainable development. In G. Lawrence (Ed.), *The Way Forward*. Routledge. https://doi.org/10.4324/9780429197383-18

Stafford-Smith, M., Griggs, D., Gaffney, O., Ullah, F., Reyers, B., Kanie, N., Stigson, B., Shrivastava, P., Leach, M., & O'Connell, D. (2017). Integration: the key to implementing the Sustainable Development Goals. *Sustainability Science*, *12*, 911–919. https://doi.org/10.1007/s11625-016-0383-3

Stanton, R., To, Q. G., Khalesi, S., Williams, S. L., Alley, S. J., Thwaite, T. L., Fenning, A. S., & Vandelanotte, C. (2020). Depression, Anxiety and Stress during COVID-19: Associations with Changes in Physical Activity, Sleep, Tobacco and Alcohol Use in Australian Adults. *International Journal of Environmental Research and Public Health*, *17*(11), Article 4065. https://doi.org/10.3390/ijerph17114065

Starke, K. R., Petereit-Haack, G., Schubert, M., Kämpf, D., Schliebner, A., Hegewald, J., & Seidler, A. (2020). The age-Related Risk of Severe Outcomes Due to COVID-19 Infection: A Rapid Review, Meta-Analysis, and Meta-Regression. *International Journal of Environmental Research and Public Health*, *17*(16), Article 5974. https://doi.org/10.3390/ijerph17165974

Suzuki, Y., Maeda, N., Hirado, D., Shirakawa, T., & Urabe, Y. (2020). Physical Activity Changes and Its Risk Factors Among Community-Dwelling Japanese Older Adults During the COVID-19 Epidemic: Associations with Subjective Well-Being and Health-Related Quality of Life. *International Journal of Environmental Research and Public Health*, *17*(18), Article 6591. https://doi.org/10.3390/ijerph17186591

Taff, B. D., Rice, W. L., Lawhon, B., & Newman, P. (2021). Who Started, Stopped, and Continued Participating in Outdoor Recreation During the COVID-19 Pandemic in the United States? Results From a National Panel Study. *Land*, *10*(12), Article 1396. https://doi.org/10.3390/land10121396

United Nations Department of Economic and Social Affairs. (2007). *Indicators of Sustainable Development: Guidelines and Methodologies*. United Nations. https://doi.org/10.1016/j.cirpj.2010.03.002

United Nations. (2015). *Transforming Our World: The 2030 Agenda for Sustainable Development*.

✉krzysztof.rzasa@uwm.edu.pl; ✉mateusz.ciski@uwm.edu.pl

Ustawa z dnia 27 kwietnia 2001 r. Prawo ochrony środowiska [Act of 27 April 2001 Environmental Protection Law, 62 Polish Journal of Law (2001)], Dz.U. 2001/62, item 627 (2001) (Poland). https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=wdu20010620627

Wang, C., Pan, R., Wan, X., Tan, Y., Xu, L., Ho, C. S., & Ho, R. C. (2020). Immediate Psychological Responses and Associated Factors during the Initial Stage of the 2019 Coronavirus Disease (COVID-19) Epidemic among the General Population in China. *International Journal of Environmental Research and Public Health*, *17*(5), Article 1729. https://doi.org/10.3390/ijerph17051729

Wang, Q., Dai, H. N., & Wang, H. (2017). A Smart MCDM Framework to Evaluate the Impact of Air Pollution on City Sustainability: A Case Study from China. *Sustainability*, *9*(6), Article 911. https://doi.org/10.3390/su9060911

Xie, J., & Zhu, Y. (2020). Association between ambient temperature and COVID-19 infection in 122 cities from China. *Science of The Total Environment*, *724*, Article 138201. https://doi.org/10.1016/J.SCITOTENV.2020.138201

Yu, H., Fotheringham, A. S., Li, Z., Oshan, T., Kang, W., & Wolf, L. J. (2020). Inference in Multiscale Geographically Weighted Regression. *Geographical Analysis*, *52*(1), 87–106. https://doi.org/10.1111/gean.12189

Yu, S., Ye, Q., Zhao, Q., Li, Z., Zhang, M., Zhu, H., & Zhao, Z. (2022). Effects of Driving Factors on Forest Aboveground Biomass (AGB) in China's Loess Plateau by Using Spatial Regression Models. *Remote Sensing*, *14*(12), Article 2842. https://doi.org/10.3390/RS14122842

Yue, H., Duan, L., Lu, M., Huang, H., Zhang, X., & Liu, H. (2022). Modeling the Determinants of PM2.5 in China Considering the Localized Spatiotemporal Effects: A Multiscale Geographically Weighted Regression Method. *Atmosphere*, *13*(4), Article 627. https://doi.org/10.3390/atmos13040627

Zhang, Y., & Ma, Z. F. (2020). Impact of the COVID-19 Pandemic on Mental Health and Quality of Life Among Local Residents in Liaoning Province, China: A Cross-Sectional Study. *International Journal of Environmental Research and Public Health*, *17*(7), Article 2381. https://doi.org/10.3390/ijerph17072381

Zhang, Y., Zhang, H., Ma, X., & Di, Q. (2020). Mental Health Problems during the COVID-19 Pandemics and the Mitigation Effects of Exercise: A Longitudinal Study of College Students in China. *International Journal of Environmental Research and Public Health*, *17*(10), Article 3722. https://doi.org/10.3390/ijerph17103722

Zhu, N., Zhang, D., Wang, W., Li, X., Yang, B., Song, J., Zhao, X., Huang, B., Shi, W., Lu, R., Niu, P., Zhan, F., Ma, X., Wang, D., Xu, W., Wu, G., Gao, G. F., & Tan, W. (2020). A Novel Coronavirus from Patients with Pneumonia in China, 2019. *New England Journal of Medicine*, *382*(8), 727–733.

✉krzysztof.rzasa@uwm.edu.pl; ✉mateusz.ciski@uwm.edu.pl