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Five waves of the COVID-19 pandemic and green–blue spaces in urban and rural areas in Poland

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ABSTRACT

Several waves of COVID-19 caused by different SARS-CoV-2 variants have been recorded worldwide. During this period, many publications were released describing the influence of various factors, such as environmental, social and economic factors, on the spread of COVID-19. This paper presents the results of a detailed spatio-temporal analysis of the course of COVID-19 cases and deaths in five waves in Poland in relation to green−blue spaces. The results, based on 380 counties, reveal that the negative correlation between the indicator of green−blue space per inhabitant and the average daily number of COVID-19 cases and deaths was clearly visible during all waves. These relationships were described by a power equation (coefficient of determination ranging from 0.83 to 0.88) with a high level of significance. The second important discovery was the fact that the rates of COVID-19 cases and deaths were significantly higher in urban counties (low values of the green–blue space indicator in m^2/people) than in rural areas. The developed models can be used in decision-making by local government authorities to organize anti-COVID-19 prevention measures, including local lockdowns, especially in urban areas.

1. Introduction

A novel coronavirus (SARS-CoV-2) that emerged in the Chinese city of Wuhan in December 2019 causes COVID-19. The virus quickly spread around the world, resulting in the declaration of a pandemic by the WHO in March 2020 (WHO, 2020). From the time of the first reports of COVID-19 until the end of July 2022, there were approximately 570 million confirmed cases worldwide, including over 6.3 million deaths (WHO, 2022).

Numerous publications on the incidence of COVID-19 indicate a clear influence of a variety of geographical, environmental, social and economic factors and government responses on the magnitude and spread of COVID-19 (Cohen, 2020; Bański et al., 2021; Bontempi and Coccia, 2021; Bontempi et al., 2021; Coccia, 2022a, c). One of the most important factors determining the transmission of SaRS-CoV-2 among people is population density. This relationship has been widely debated in scientific articles. Strong, positive relationships between density and COVID-19 incidence have been observed in many countries worldwide (cf. Bhadra et al., 2021; Coşkun et al., 2021; Kubota et al., 2020; Lee et al., 2021; Pascoal and Rocha, 2022). As the pandemic progressed, an increasing number of publications provided a literature review on the interaction between the natural environment and COVID-19 (Shakil et al., 2020; Facciolà et al., 2021; Núñez-Delgado et al., 2021; Labib et al., 2022; Rahimi et al., 2021; Han et al., 2023) or focused on the analysis of the correlation between various components of the natural environment (atmosphere, hydrosphere, lithosphere, biosphere) and COVID-19 in specific geographical regions or countries (Bashir et al., 2020b; Sobral et al., 2020; Zhu et al., 2020; Song et al., 2022). A large impact on the spread of the virus as well as the number of infections was most often attributed to climatic factors (Ahmadi et al., 2020; Islam et al., 2021; Werner et al., 2021; Akan, 2022). The international scientific literature emphasizes the key role of air quality and pollution (i.e., particulate matter, carbon monoxide, nitrogen dioxide, sulfur dioxide, ozone) in the spread and severity of COVID-19 in various world regions (Kowalski et al., 2021; Maleki et al., 2021; Carballo et al., 2022; Perone, 2022). Pollutants influence the immune system of susceptible individuals and may enhance the risk of severe and fatal COVID-19. Higher concentrations of fine particulate matter and other pollutants have a positive correlation with cases and deaths caused by COVID-19 (Bashir et al., 2020a; Comunian et al., 2020; Magazzino et al., 2020; Yao et al., 2020; Wu et al., 2020; Wang et al., 2020; Konstantinoudis et al., 2021; Meo et al., 2021; Zoran et al., 2022a, b). Extensive studies

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have explored the role of meteorological elements in COVID-19 transmission. Low wind speed (especially in areas with high concentrations of air pollutants) promotes a longer stay and permanence of SARS-CoV-2 particles in the air and the dispersion of the virus and generates a higher number of COVID-19 infections (Coccia, 2021b). A similar negative association between wind speed and COVID-19 cases was found in the studies by Ahmadi et al. (2020), Islam et al. (2021), and Grigsby-Toussaint and Shin (2022). Hovewer, other manuscripts showed that COVID-19 spreads more in windy weather (Coşkun et al., 2021). In most cases, experimental studies indicate a statistically significant negative correlation of ambient temperature and relative humidity with COVID-19 (Prata et al., 2020; Qi et al., 2020; Şahin, 2020; Wang et al., 2020, 2021). However, some studies reported that increased daily relative humidity was associated with an increased number of new COVID-19 cases and deaths (Pani et al., 2020; Sarkodie and Owusu, 2020; Zoran et al., 2022a, b). The significant relationship between meteorological factors and COVID-19 transmission can be affected by season, geospatial scale and latitude (Walrand, 2021; Li et al., 2022).

A type of link between the components of the natural and socio-economic environments is green space (Nowak et al., 2013; Rui et al., 2018; Diener and Mudu, 2021), which is closely related to air quality and plays an important role in improving local "aerosanitary" conditions. Many scientists argue that green areas provide numerous health benefits (Rigolon et al., 2021), including relief of respiratory diseases (Soyiri and Alcock, 2018), and play a key role during the pandemic by providing ecosystem services relevant to recreation and temporarily limiting public life (Noszczyk et al., 2022). In addition, these areas improve mental health, and reduce the severity of disease and even mortality (Gascon et al., 2016; Vienneau et al., 2017; Rojas-Rueda et al., 2019; Andersen et al., 2021; Kasdagli et al., 2021; Labib et al., 2021; Peng et al., 2022). A literature review identified some recent ecological studies that showed that the green space ratio was associated with reduced COVID-19 incidence and mortality (Klompmaker et al., 2021; Russette et al., 2021; Spotswood et al., 2021; Falco et al., 2022). Additionally, a greater exposure to green spaces (especially forests and urban parks) and a small distance of green space from human settlements may mitigate the risk of COVID-19 infection (Johnson et al., 2021) and mortality (Jiang et al., 2022; Yang et al., 2022), although the specific mechanism of the interaction between greenness and virus activity remains unknown. The strongest protective relationship of greenness with COVID-19 incidence was in urbanized areas with lower population densities (Ciupa and Suligowski, 2021; Lee et al., 2021; Peng et al., 2022).

Waves are a characteristic feature of the pandemic (Porta, 2014). The seasonal variability of environmental factors contributes to the formation of the basic parameters of COVID-19 waves, i.e., their duration and height. The start and end dates of a local wave are identified based on the total number of confirmed cases of infection computed for a weekly incidence rate of, for example, 70 new cases per 100,000 people in Chile (Ayala et al., 2021) and 30 new cases per 100,000 people in South Africa (Jassat et al., 2021). However, due to the high complexity of the course of the pandemic (multiple waves), the criteria for identifying individual waves in Western Europe and the Americas were based on nonlinear regression and information criteria to obtain a statistical model (Zhai et al., 2021; de Lima Gianfelice et al., 2022).

In the international scientific literature, there are only a few publications on the relationship between the geographical environment and COVID-19 in Poland that include meteorological and bioclimatic factors (Kowalski et al., 2021; Werner et al., 2021) and green−blue space (Ciupa and Suligowski, 2021). Our research fits into the contemporary trend, showing the need to demonstrate the impact of the environment on the course of the COVID-19 pandemic (Han et al., 2023).

The aim of this study is to present the association between green−blue spaces and COVID-19 cases and deaths in all urban and rural counties in Poland during the five pandemic waves.

2. Material and methods

2.1. Study area and data

The study area covered Poland, which has a total area of 312.7 thousand km^2 and 38.4 million inhabitants. The detailed analysis included 380 counties, grouped into 16 provinces, of which 66 were city counties, and the remaining 316 were land counties (Fig. 1). The counties are highly diversified in terms of size. Their areas range from 13.3 km^2 (Świętochłowice) to 517.2 km^2 (Warsaw) for the city counties and from 158.1 km^2 (Bieruń-Lędziny) to 2976.4 km^2 (Białystok) for the land counties. Population density varies in city counties from 207.3 people per km^2 (Świnoujście) to 3723 people per km^2 (Świętochłowice) and in land counties from 19 people per km^2 (Bieszczady) to 673.6 people per km^2 (Pruszków), with the average for Poland at the level of 122.8 people per km^2 (Statistics Poland, 2022).

This study used daily data on the number of COVID-19 cases and deaths in particular counties (380), published in the Instant Atlas reports and provided by the Ministry of Health of the Republic of Poland (https://www.gov.pl/web/koronawirus). They covered a period of 800 days, i.e., from the beginning of the pandemic (March 4, 2020) until May 11, 2022.

The source of quantitative data referred to in this study regarding green−blue spaces was the database of the Local Data Bank (Statistics Poland, 2022), which includes data on geodetic areas in particular counties according to 24 uses. It is the most detailed collection of information on the forms of land use and development used in Poland for statistical purposes. This database was developed based on materials and data from national geodetic and cartographic resources as well as on the results of photogrammetric measurements (with a spatial resolution of 0.1 ha).

2.2. Measures of variables

This study focused on the following measures:

- the number of COVID-19 cases/deaths ($I_{covid\text{-}19}$; people/100 km^2 per day) in five waves of the pandemic and during the whole study period (March 2020 to May 2022)
- green−blue space area per inhabitant (GB; m^2/person) calculated with the following formula:

$$GB = \sum_{i=1}^{N}\left(\frac{\sum A_{\mathrm{Green}} + \sum A_{\mathrm{Blue}}}{P}\right) \tag{1}$$

where: A_{Green}, and A_{Blue} indicate the areas of green and blue spaces (in m^2), respectively, and P indicates the number of inhabitants.

The green spaces consisted of forests, woody and bushy lands, orchards, permanent meadows and pastures, recreational and rest areas (recreation centers, children's playgrounds, beaches, landscaped parks, squares, lawns, and sports areas) and other areas (arable land, which is biologically active during the growing season). The blue spaces included lakes and artificial water reservoirs, rivers, ecological areas and internal waters (Ciupa and Suligowski, 2021).

2.2.1. Models and data analysis procedure

Statistical methods were used to determine optimal relationships between two variables: the green−blue space area per inhabitant (GB) and the average daily number of cases/deaths in particular waves, along with their significance levels. The relationships were analyzed by simple regression models (power, logarithmic) estimated with the least squares method. The model R-squared, and adjusted R-squared values, standardized coefficients of regression values, 95% confidence intervals, root mean square error (RMSE) and p values were reported. These optimal relationships are illustrated by graphs. All of the analyses were performed using Statistica software ver. 14.0 (TIBCO Statistica®, 2020).

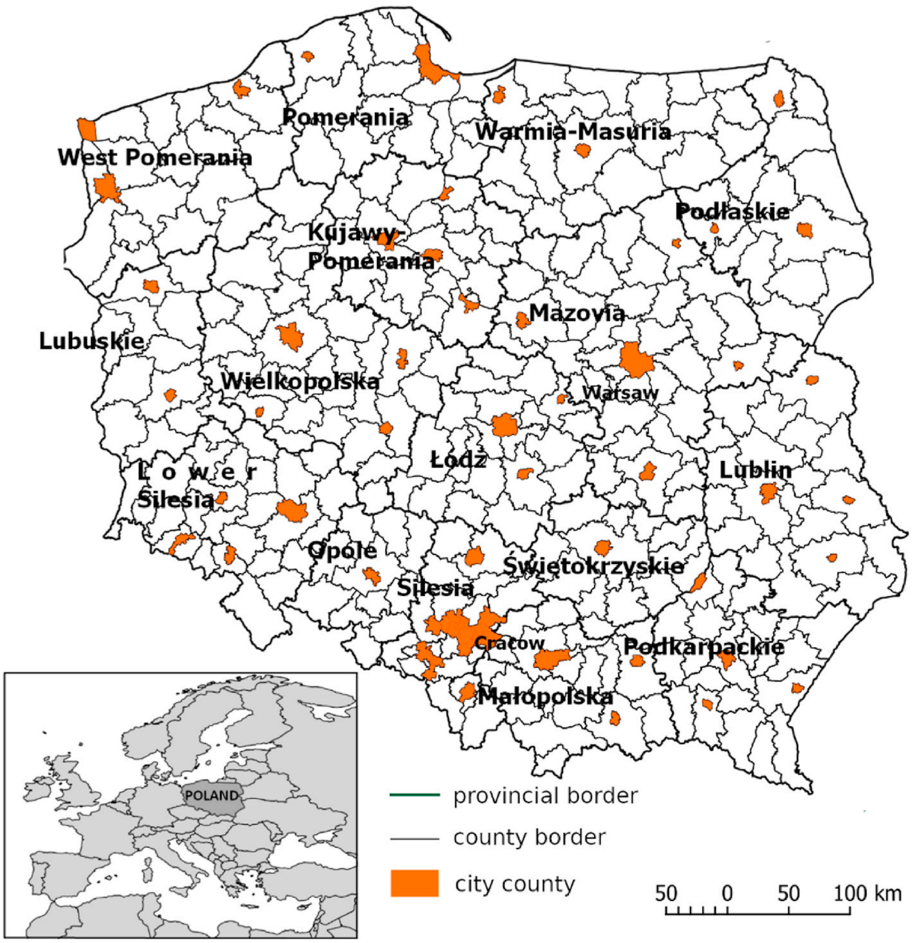


Fig. 1. Study area.

The calculations were presented on thematic maps using Quantum GIS ver. 3.22 (http://qgis.org).

In the first step of the procedure, five (5) waves of COVID-19 cases and deaths in Poland were identified. This number was reported by the Ministry of Health in Poland, and the duration of the waves was determined based on a graphical analysis of their 7-day moving average. This approach allowed most of the random changes (lower numbers of cases on Saturdays and Sundays, resulting from the mode of their registration) to be "suppressed" and have no significant impact on the course of the average. As the shape of the analyzed waves closely resembled the shape of flood waves in riverbeds, the authors decided to separate them using a method commonly applied in hydrology (Linsley et al., 1982; Belete, 2009). The beginning/end of the wave was at the inflection point of the ascending/descending curve, where an intense increase/decrease in cases/deaths began (Fig. S1). In this way, the dates of the beginning, peak and end of each wave were determined, as well as the number of cases/deaths during that time. The above resulted in creating graphs that illustrated the course of cases and deaths during 800 days of the pandemic against the background of the number of vaccinations in this period (Fig. 2). In the next step, based on Equation (1) the green−blue space indicator (m^2 per person) within 380 counties was calculated, and its regional spatial variation was presented. Finally, using regression models the relationships between variables in all waves were analyzed.

3. Results and discussion

3.1. Course and characteristics of COVID-19 waves in Poland

The first case of infection from SARS-CoV-2 in Poland was confirmed on March 4, 2020, in Zielona Góra, and the first death was confirmed a week later in Poznań; both cities are located in the western part of the country (Poland Reports First Coronavirus Case – Health Minister, 2020). A state of epidemic was called in Poland on March 20, 2020 (Pinkas et al., 2020; Regulation of the Minister of Health, 2020) despite the low total number of cases and deaths at the time (423 and five, respectively), in contrast to numbers in Western European countries (e.g., France: 453,700 and 31,300 and Italy: 47,300 and 4100, respectively) (WHO, 2020). In the same month, a pandemic was declared by the World Health Organization.

Particular waves of cases in Poland lasted from 90 (the fifth wave) to 134 days (the second wave) and an average of 117 days, whereas the duration of all death waves varied from 102 (the fifth wave) to 157 days (the second wave) and approximately 130 days on average (Table S1). The length of all waves of deaths was longer than that of waves of cases by approximately two weeks on average.

The first wave of cases in Poland, which started on March 12, 2020, and lasted 109 days (until June 28), was definitely different from subsequent waves. It was poorly developed and flattened with a vague low maximum of 599 people (Fig. 2), which was due to the initial phase of pandemic development (Alpha variant). The number of daily cases remained at a stable level of 312 people (Table S1). The total number of cases was approximately 34,000. The first wave of COVID-19 infection in Poland did not provide a real picture of the epidemic's development, because diagnostics were performed only on the most symptomatically advanced cases. The wave of deaths, which started on March 29 and ended on July 17 and lasted 111 days, had similar features. It was the only wave of the pandemic during which the maximum level of deaths (April 29, 2020) was observed earlier than that of cases (June 8, 2020).

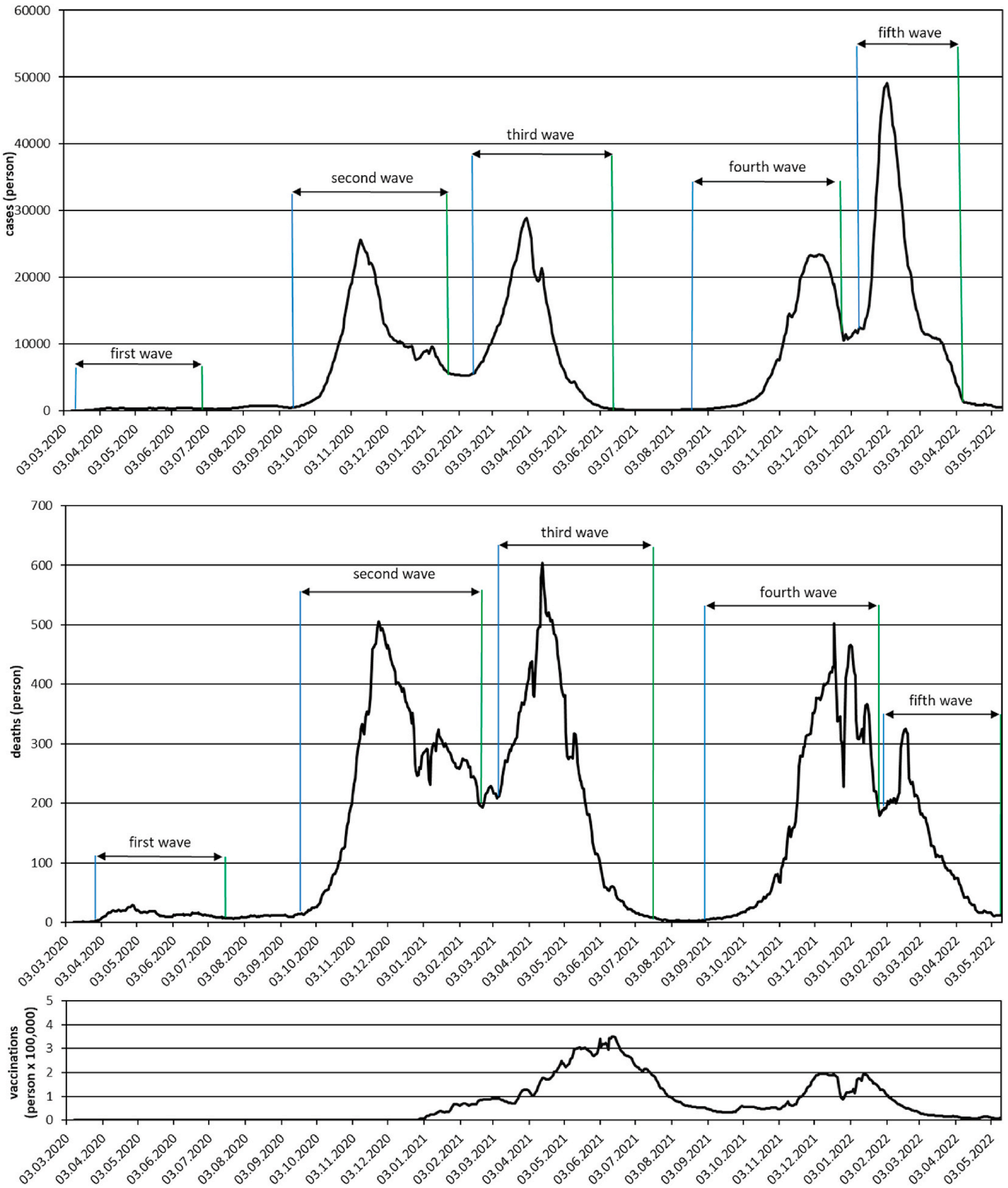


Fig. 2. Daily cases (A) and deaths (B) caused by COVID-19 (including the five separate pandemic waves) against the background of the pandemic course and number of vaccinations (C) in Poland.

The analysis of the development of the pandemic in Poland, in spatial terms (in counties), in the first two months was presented by Raciborski et al. (2020) and in the first six months by Śleszyński (2021).

The next four waves of the pandemic were already fully developed and resembled waves associated with natural phenomena. The second wave of cases and deaths began in mid-September 2020 (Fig. 2, Table S1). At that time, a more than twofold increase in cases and deaths was observed in Poland (Michalski and Szymańska, 2021). This was probably because that COVID-19 tests started to be used on a massive scale (from September 2020), i.e., the SARS-CoV-2 RNA test, antigen test and serological tests. Additionally, the loosening of restrictions during the summer season and the return of children and adolescents to school contributed to these results.

The second wave of infections lasted until the third week of January 2021 and was the longest (134 days) of all the waves (Fig. 2). Its peak occurred in mid-November (7-day moving average of 25,580 people and absolute maximum of 27,875 people). The second wave of deaths reached its maximum at the end of November (7-day moving average of 506 people and absolute daily maximum of 674 people). This wave of the COVID-19 pandemic looked similar in many Western European countries (Bontempi, 2021) except for Italy, where a much lower number of COVID-19 cases was recorded, likely due to containment measures applied to constrain the COVID-19 pandemic over March–May 2020 (Coccia, 2021a). Poland was then ranked fifth among the countries with the highest incidence rate and fourth regarding deaths (Gruszczynski et al., 2021). The disease dynamics in Poland's largest cities in October and November 2020 were also impacted by different social and political phenomena (anti- and pro-abortion protests), despite the social distancing strategies in place (Kowalski et al., 2021; Werner et al., 2022). The vaccination program against COVID-19 started in Poland on December 27, 2020, and in the following weeks (until the end of January 2021), a gradual decrease in the number of cases (approximately 5000 per day) and deaths (approximately 150 per day) was documented (Fig. 2). Many scientists (cf. Bernal et al., 2021; Saban et al., 2022) clearly emphasized that COVID-19 vaccines are effective in reducing the number of confirmed cases and deaths of COVID-19, and even presented optimal dose levels in particular countries (i.e., Coccia, 2022b, d). The total number of cases during the second wave in Poland reached 1.378 million, and 35,000 deaths occurred (Table S1).

Over a dozen days after the end of the second wave, the development of the next wave—the third wave (from mid-February 2021 for the wave of cases; from March 8 for the wave of deaths) was recorded at a high baseline level (approximately 5700 cases and 200 deaths). Cases and deaths caused by the predominant Delta coronavirus variant showed a steady upward trend until reaching their maxima, i.e., cases at the beginning of April (7-day moving average of 28,920 people and absolute maximum of 35,251 people), and deaths 2 weeks later (Table S1). At that time, the documented number of deaths caused by COVID-19 reached the highest number during the whole pandemic in Poland (7-day moving average of 604 and absolute daily maximum of 954). The total number of cases in these waves exceeded 1.27 million, and the number of deaths exceeded 29.9 thousand, which translated into the highest average values of daily rates among all waves analyzed: 10,481 cases/day and 227 deaths/day. Poland during the third wave of COVID-19 had one of the EU's highest rates of COVID-19 deaths, yet until the end of April 2021, only 7.8 percent (2.9 million people) of the population was fully vaccinated (first dose 23.5%; 8.9 million people). The spread of the virus in Poland at the time is associated with mass visits to the country before Christmas by thousands of Poles from Great Britain (Stach, 2021). The Delta variant has a higher transmissibility than the original SARS-CoV-2 (Choi et al., 2022). The analysis of the graph (Fig. 3) shows that the end of the third waves of cases and deaths coincided with the beginning of the summer season (mid-June and July, respectively) and was at a very low level (215 cases and seven deaths). At the same time, notably the period of dynamic decline in the number of cases and deaths in the third wave coincided with the maximum daily number of vaccinations (650,000 people/day; June 2, 2021). In Poland as a whole, 48.3 percent of people were fully vaccinated by the end of July (https://www.gov.pl/web/koronawirus).

At the end of the holiday period in the third week of August 2021, the fourth wave of cases began (from a level of 212 new cases), and in early September, the fourth wave of deaths began (5 people). Both waves, caused by the Delta coronavirus variant, characterized by high transmissibility, were marked by a clear asymmetry, i.e., a long increase time (cases, 110 days, deaths, 109 days) compared to the decrease time (20 and 37 days, respectively). At that time, an exceptionally high ratio of deaths to new cases was recorded, which at the peak of the fifth waves was 1:47. These waves, similar to the autumn and winter waves of the previous year, ended on a high note: there were 10,920 cases/day and 183 deaths/day (Table S1). After several days, the fifth wave of the COVID-19 pandemic began to take shape in Poland. There was then a very dynamic increase in cases, which within three weeks reached a record level (7-day moving average of 48,220 cases/day and absolute daily maximum of 57,659 cases/day). Although this was the shortest-lasting wave (90 days), the total number of cases exceeded 1.75 million, which translated into a daily average of 19,488 cases. The obtained results confirmed the large increase in total COVID-19 infections during the cold season in Northern Hemisphere countries (Liu et al., 2021). Low air temperature impacts the high occurrence of COVID-19 (Nottmeyer and Sera, 2021). This state in Poland may also be related to the lower uptake of widespread vaccination (great uncertainty/skepticism about vaccines) and the higher infectivity of Omicron (BA.5 variant of SARS-CoV-2) and the lower virulence, milder symptoms and course of the disease (Wang and Han, 2022).

At the same time, the fifth wave of deaths was the shortest observed and had the lowest numbers (7-day moving average of 322 deaths/day and absolute daily maximum of 540 deaths/day). The course of this wave of deaths was the most complex, which is probably due to the influence of vaccination as well as the characteristics of Omicron, which were less likely to lead to deaths than the previously dominant Delta variant. The effectiveness of vaccinations against COVID-19 in Poland was reported by Kasperska-Dębowska et al. (2021). This translated into a relatively low value of the calculated ratio of the quotient of the daily average number of deaths and cases in the fifth wave (1:171), which means that it was almost four times lower than in all other waves. The fifth wave (cases and deaths) ended at a low level in spring 2022, as did the third wave (2021) (1220 and 6 people/day, respectively). As of May 15, 2022, a state of epidemic (Regulation of the Council of Ministers, 2022) was no longer in force in Poland. The calculated excess deaths in Poland for the COVID-19 pandemic period (2020–2021) were one of the largest in the world (Levitt et al., 2022).

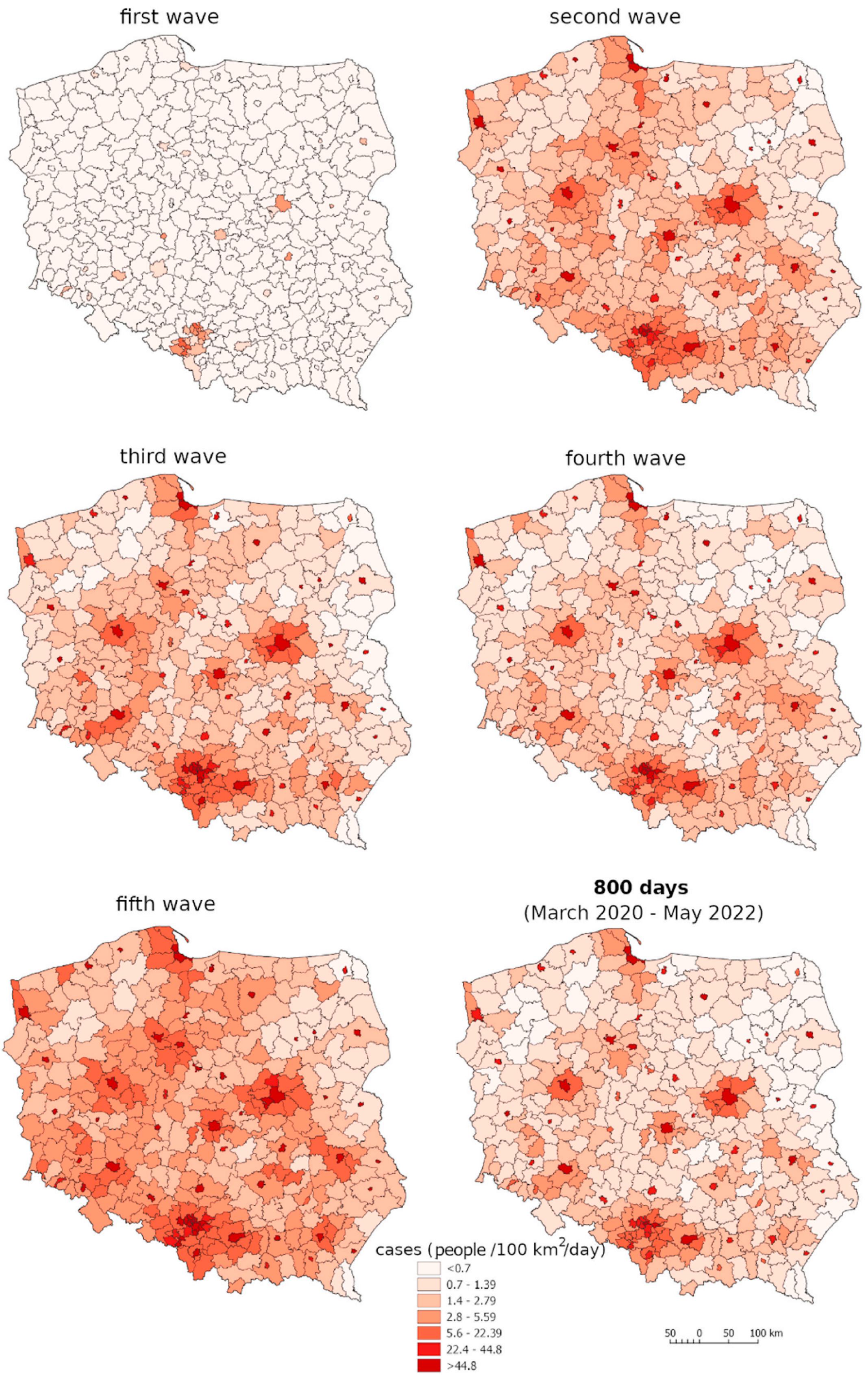
It is very interesting to note the incidence and mortality patterns in successive waves of the pandemic within particular counties. The analysis of the cases and death rates (people/100 km^2) presented in the graphs (Fig. S2 – Supplementary Material) shows that there was a totally different course of cases and deaths in city (66) and land (314) counties. In most of the city counties, in all waves, the values of the calculated indicator were several times higher than those observed in land counties. This started to be noticeable even during the first and a-typical wave. Arranged in an ascending sequence, the average values of cases and deaths in land counties in the waves of the pandemic showed a dynamic increase in the value of the indicator in successive units, and the graphical effect was a convex–concave course of the upper envelope of the bar graphs representing successive counties (Fig. S2). In the case of most land counties, the analyzed values of the indicator were low, which determined the concave shapes of the envelopes. Considering this phenomenon during the four well-developed pandemic waves (2–5), it is characteristic that the highest values of the case rate in the group of city counties were always recorded in the capital city and in the group of land counties were recorded in Pruszków, a satellite city of the Warsaw agglomeration. The greatest variation in the value of this indicator occurred during the fifth wave of cases, and the maximum was recorded in a city county (Warsaw, 23,942 people/100 km^2) and in the land county of Pruszków (5277 people/100 km^2). During the fifth wave of deaths, the maximum value of the analyzed indicator was 7.4 times higher in a city county (Świętochłowice in Silesian Province) than in a land county (Pruszków in Mazovia Province) (Fig. S2).

3.2. Spatial distribution of COVID-19 case waves in Poland

A characteristic feature of the spatial distribution of the rate of cases per 100 km^2 per day was its high variability (Fig. 3). During the first wave, the first clusters of the incidence rate were visible in the largest agglomeration (Upper Silesian urban area) and cities in Poland (e.g., Warsaw, Łódź, Wrocław, Gdańsk). The conditions of the first wave of the COVID-19 epidemic in Poland were presented by Parysek and Mierzejewska (2021) and in Silesian Province by Krzysztofik et al. (2021).

In subsequent waves, new cases were recorded in all counties. The value of the indicator ranged from 0.3 people/100 km^2 per day in the third wave (Suwałki County) to 266 people/100 km^2 per day (Warsaw) in the fifth wave. The highest values were observed in metropolitan centers (Warsaw, Upper Silesia, Cracow, Tricity, Łódź, Poznań, Wrocław), which became surrounded by rings formed of the counties with high indicator values (Fig. 3). High indicator values ($>$45 people/100 km^2 per day) during all waves occurred only in cities (second wave, 31 cities; third wave, 38 cities; fourth wave, 29 cities; and fifth wave, 55 cities). Urbanized regions were the foci of pandemic outbreaks. During the last wave, this indicator was also exceeded in one land county, Pruszków. Low values of the indicator ($<$0.7 people/100 km^2 per day) occurred in counties with the lowest population densities and high forest cover (eastern Poland) as well as in the wetter Pomorskie and Mazurskie Lake Districts (Ciupa and Suligowski, 2021).

During the second wave, low values were recorded in seven counties; in the third wave, low values were recorded in 27 counties; in the fourth wave, low values were recorded in 32 counties; and in the fifth wave, low values were recorded in three counties. Extremely low values of the



first wave

second wave

third wave

fourth wave

fifth wave

800 days
(March 2020 - May 2022)

Fig. 3. Average daily number of COVID-19 cases (people/100 km^2/day) in successive waves and since the beginning of the pandemic (March 2020–May 2022).

indicator occurred in the counties of Bieszczady (Podkarpackie Province), Suwalski and Sejneński (Podlaskie Province). Rural residents have fewer opportunities for contact with nonnative people and limited access to health care. The obtained results confirmed the findings in many studies in which a statistically significant relationship was found between population density and the development of the COVID-19 pandemic, e.g., in Turkey (Coşkun et al., 2021), India (Bhadra et al., 2021), and even in other regions of the world (Kubota et al., 2020; Diao et al., 2021; Sutton et al., 2022).

3.3. Spatial distribution of COVID-19 death waves in Poland

The spatial distribution of the indicator values of the number of deaths per 100 km^2 per day also showed great variation in all waves (Fig. 4). Deaths occurred in 48.4% of all counties but predominated in city counties, 77.2%, whereas in land counties they accounted for only 42.3%.

The highest values of this indicator in the first wave occurred in medium-sized and large cities (Radom, 0.78 people/100 km^2 per day, Kalisz, 0.77 people/100 km^2 per day, Bytom, 0.5 people/100 km^2 per day). COVID-19 deaths in all counties were recorded from the second wave onward, but values in a separate class above 1 person/100 km^2 per day occurred only in urban counties (in the second wave in 34 counties, in the third wave in 43 counties, in the fourth wave in 23 counties, and in the fifth wave in 4 counties out of the total of 66 counties). The highest values in successive waves were recorded in the cities of the Upper Silesia urban area (in the second wave in Chorzów with 2.6 people/100 km^2 per day and in the third, fourth, and fifth waves in Świętochłowice with 2.6, 2.1, and 1.5 people/100 km^2 per day, respectively). Upper Silesia is the most industrialized region and has the highest population density in Poland. This results in poor air quality and substantial exceedances of permissible standards of particulate matter (PM2.5, PM10) and other pollutants (Moździerz et al., 2011; Kobza et al., 2018; Łowicki, 2019). The lowest values of the rate of deaths were always recorded in land counties: Ostrołęka, with 0.011 people/100 km^2 per day (second wave), Gryfino, with 0.008 people/100 km^2 per day (third wave), Choszczno, with 0.006 people/100 km^2 per day (fourth wave), and Łosice with 0.002 people/100 km^2 per day (fifth wave). These are counties with an agroforestry landscape characterized by a high proportion of green−blue spaces exceeding 92% of their total area (Statistics Poland, 2022).

Notably, the fifth wave of the pandemic (despite the highest rate of COVID-19 cases) was characterized by a sharp decrease in the rate of deaths. This phenomenon occurred in all waves and counties. This was related to the total number of people who were vaccinated against COVID-19 and had milder symptoms of the disease (Omicron variant).

The above map analysis shows that there is an exceptionally clear spatial relationship between COVID-19 cases and death rates in Poland in each wave and the green−blue space indicator and population density (Ciupa and Suligowski, 2021).

3.4. Green–blue spaces in Poland

There is a large regional spatial variation in the green−blue space indicator (m^2 per person) within the 380 counties (Fig. 5A).

The range of variation in green−blue space was from 81 m^2 per person (Chorzów and Świętochłowice; Silesian Province) to 50,697 m^2 per person (county of Bieszczady in Podkarpackie Province). As many as 202 counties, including all city counties, were below the national average (10,895) (Fig. 5B). The average value of this indicator in this group of administrative units was 465 m^2 per person, and the maximum was 3938 (Świnoujście in West Pomerania Province) (Fig. 5B). A value below 1000 m^2 per person (class intervals in Fig. 5A) was found only in city counties (60), mainly concentrated in Silesian Province. In turn, the value of >24,000 m^2 per person (class intervals in Fig. 5A) was documented only in land counties (25) located mainly in northern and eastern Poland (Masurian and Pomeranian Lake Districts) and in mountainous areas (Bieszczady). There are large, dense forest complexes that play an essential role in photosynthesis/assimilation of CO_2, absorb greenhouse gases (Poland's National Inventory Report, 2018) and absorb particulate matter. These processes are conducive to improving air quality, which has proven particularly valuable during the COVID-19 outbreak. The availability and the diversity of green spaces are crucial elements of sustainability (Wolch et al., 2014) and livability (Ruth and Franklin, 2014; Shen et al., 2017; Bolleter and Ramalho, 2020).

3.5. Relationships between COVID-19 cases and deaths and green–blue spaces

The relationships between the rate of green−blue space per inhabitant (m^2 per person) and the average daily number of cases and deaths in each of the five waves of the COVID-19 pandemic (people/100 km^2/day) recorded in all (380) Polish counties are presented in Fig. 6. These relationships were described by a power-regression model (except for the first wave) with negative values of the exponent, indicating a decrease in the value of the average daily number of cases/deaths with an increase in the area of green−blue space per inhabitant. The values of the adjusted R-squared (coefficient of determination) of the established relationships were very high, ranging from 0.833 (the fifth wave) to 0.882 (the fourth wave) for cases, with a significance level of $p = 0.001$ (Fig. 6); for deaths, the values ranged from 0.837 (the fourth wave) to 0.873 (the second wave). These relationships were also evaluated for the first, still atypical waves of the pandemic (cases and deaths). They were described by logarithmic equations with a low R^2 (cases, 0.237; deaths, 0.199) with a significance level of 0.01.

A similar association between the decrease in the number of cases/deaths of COVID-19 and the increasing share of green areas (defined as the total area of vegetation within a boundary) was observed in a few countries, especially in the USA, for example, in 989 urban areas (You and Pan, 2020), in 3089 counties (Klompmaker et al., 2021), and in 486 urban areas across 17 states (Spotswood et al., 2021) (Table S4). The results by You and Pan (2020) show that the partial linear regression coefficient between urban vegetation and cumulative COVID-19 cases suggests that each 1% increase in the percentage of urban green space will lead to a 2.6% decrease in cumulative COVID-19 cases. Klompmaker et al. (2021) indicated a 6% reduction in the COVID-19 incidence rate, and Spotswood et al. (2021) indicated a 4% per 0.1 unit increase in the normalized difference vegetation index (NDVI). In turn, Russette et al. (2021) proved that COVID-19 mortality was negatively associated with leaf area index (LAI). Peng et al. (2022) described the high association of the NDVI with COVID-19 incidence in 266 cities in China during two months of the pandemic (a 0.1 unit increase in the NDVI with a 7.6% decrease in COVID-19 incidence). These associations were stronger in cities with lower population densities and lower urbanization rates. Research in South Korea (Lee et al., 2022) showed that a higher rate of natural greenness (forests and grasslands) is associated with lower COVID-19 incidence rates, while there is no relationship between built greenness and COVID-19 incidence rates. A higher share of public green areas was significantly associated with a low number of COVID-19 hospitalizations, and deaths in Italy and Spain (Falco et al., 2022). A very interesting relationship was also presented by Lu et al. (2021). Four types of green spaces (forest, grassland, open space in developed areas, shrub and scrub) were significantly, negatively associated with the racial disparity in SARS-CoV-2 infection. Our findings complement and detail a previous study in Poland (Ciupa and Suligowski, 2021). During the first year of the pandemic in Poland (March 2020–February 2021), an increase in the percentages of green–blue spaces caused a decrease in the numer of COVID-19 cases (adj. $R^2 = 0.81$) and deaths (adj. $R^2 = 0.80$), according to the logarithmic model. Completely different results were presented by You et al. (2020). However, it is necessary to note that they studied the early stage of the COVID-19 pandemic in Wuhan, when

Fig. 4. Average daily number of COVID-19 deaths (people/100 km^2/day) in successive waves and since the beginning of the pandemic (March 2020–May 2022).

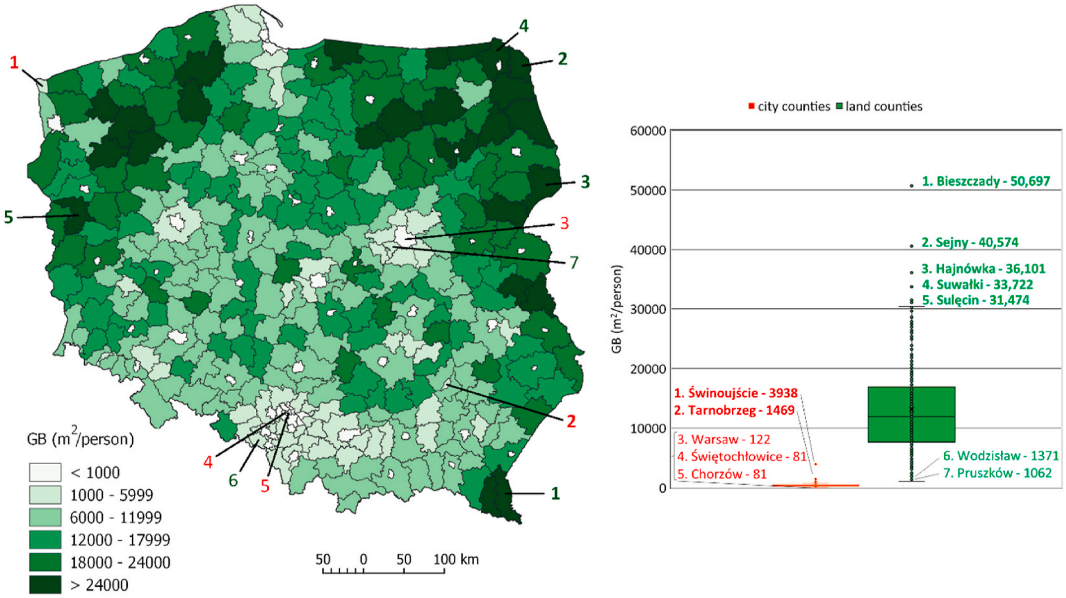


Fig. 5. Green–blue spaces per inhabitant in Polish counties (m^2 per person): (**A**) spatial distribution, (**B**) box and whisker plot of city and land counties.

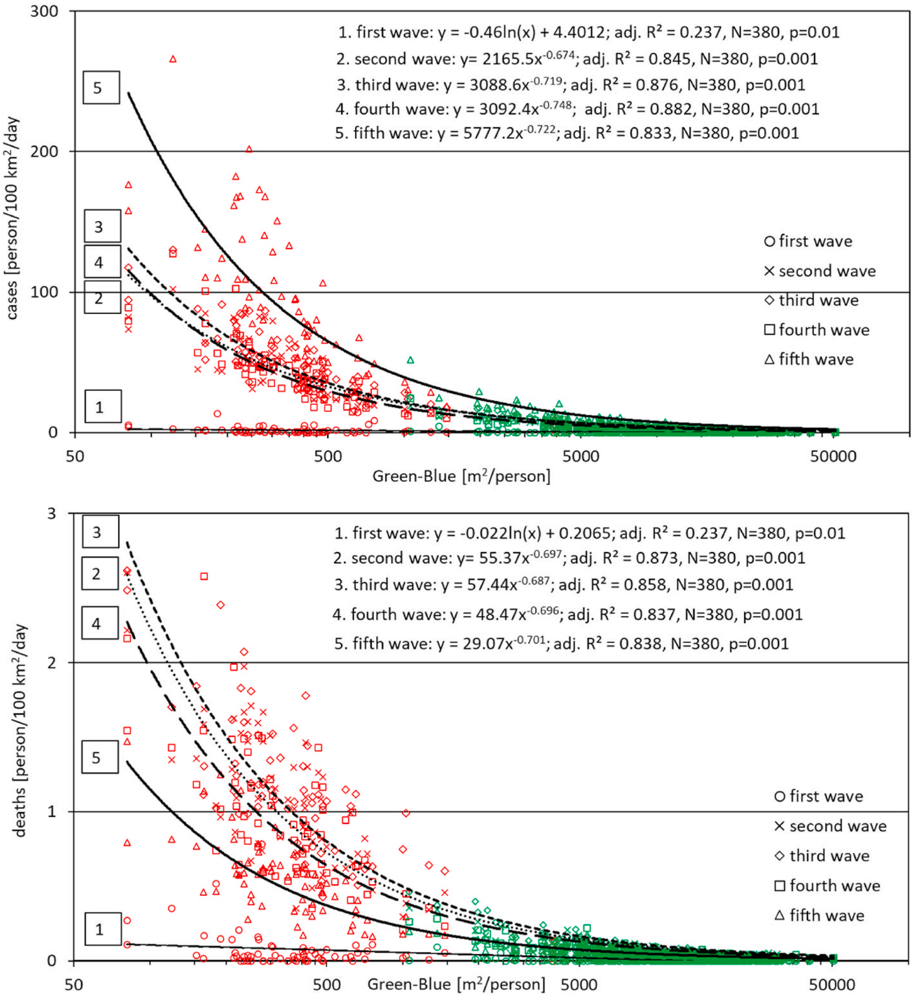


Fig. 6. Relationship between the rate of green–blue space per inhabitant (m^2 per person) in all Polish counties and the average daily number of cases (**A**) and deaths (**B**) in the five waves of the COVID-19 pandemic (people/100 km^2/day). Green represents land counties, and red represents city counties.

people were allowed to do some outdoor activities in public green spaces. Consequently, the high levels of close contact caused many SaRS-CoV-2 infections.

Interestingly, although the coronavirus variants that appeared in Poland in 2020–2022 and determined the course of successive waves of the pandemic were different, there were similarities in the course of the extracted curves (Fig. 6).

The curves representing the second, third and fourth waves of cases (autumn-winter) had similar but relatively low values of the exponent and were almost consistent in their graphical representation. This led to the flattening of these curves. In contrast, the curve for the fifth wave had higher values of the exponent than those discussed above as a result of a more dynamic increase in the number of cases in the winter-spring season.

Considering the relationship between the green−blue space indicator and the average daily number of deaths in the four major waves of the pandemic, there were also clear similarities in the course of the autumn-winter curves (the second, and third, and fourth waves). In contrast, the curve representing the fifth wave (spring 2022) were noticeably different and were very far apart (Fig. 6B). As noted earlier, the fifth wave of deaths was characterized by a low death rate, indicating the influence of other determinants (in addition to green−blue spaces) that had a considerable impact on the shape of this curve (e.g., vaccination, Omicron traits).

Notably, irrespective of the COVID-19 wave analyzed, the points representing city counties (points marked in red) cluster along the left branch of the curve and the points representing land counties (marked in green) cluster along the right branch, with a small amplitude of change in the rates of cases and deaths (Fig. 6). This indicates that the range of values of the indicator characterizing both cases and deaths is many times greater in the city counties. From the analysis of the curves, in the administrative units under consideration where green−blue spaces occupy less than 1000 m^2 per person, there is a sharp increase in the rates of both COVID-19 cases and deaths, which is characteristic of city counties. People living in rural areas have more contact with greenery, which influences natural resistance against infections (Maas et al., 2006). Relatively low COVID-19 incidence rates in rural versus urban counties (putting aside the benefits of greenness) may also be associated with limited access to health care.

An analogous analysis was carried out in relation to districts located in two provinces: Silesia (trans-industrial region, highest population density and most polluted air in Poland) and Mazovia (largest area and number of inhabitants, includes the capital city). The calculated coefficients of determination of the relationships between the indicator of green−blue space per inhabitant and the average daily number of cases and deaths in the four main waves of the COVID-19 pandemic were higher than their counterparts for Poland (Fig. S3). They indicated an even better match of the data, both in terms of estimating the numbers of cases (Silesia: 0.874–0.933; Mazovia: 0.898–0.965) and deaths (0.787–0.939, 0.861–0.976, respectively). All the extracted models were statistically significant at the $p = 0.001$ level.

4. Conclusion and implications

Irrespective of the spatial (counties in Poland, provinces) and temporal (five waves) scales of this study, the relationships between the area of green−blue spaces per inhabitant and the values of the indicators of new cases and deaths were clearly visible. Certain relationships (statistically significant and with high values of the coefficient of determination) make it possible to forecast, with high probability, the daily COVID-19 incidence rates in relation to the area of individual counties in Poland. The obtained results have some limitations. First, the current study only concerns Poland. Additionally, we did not take into account other natural (including meteorological) and socioeconomic variables. Several factors, such as population size, economy, human behavior, and immunity, may severely confound the influence of environmental variables on COVID-19 (Bontempi and Coccia, 2021). Future research may therefore be focused on looking for more complex relationships that would take these contexts into account. Second, the inclusion of detailed vaccination data from rural and urban areas would be an interesting research contribution allowing for a comprehensive assessment of their relationship with the COVID-19 pandemic, especially at certain times of the year. Our research results indicate that the course of the 4th and 5th waves of COVID-19 deaths was slightly different from the previous ones, which is probably the result of the wave of mass vaccinations carried out in Poland several months earlier. Further research in this direction may yield valuable discoveries that will help to reduce the effects of the pandemic, as already pointed out by Coccia (2021).

Individual countries have introduced different response policies to prevent the rapid transmission of COVID-19 (Coccia, 2022a). Future policy responses to contain the COVID-19 pandemic should take into account restrictions, especially in areas with a high risk of COVID-19 outbreaks (Coccia, 2021). The research results obtained in this study indicate that these include areas with low values of green–blue space indicators. In light of the presented results, it was a mistake to limit access to green areas. An example is Poland, where during the lockdown in the first wave of the COVID-19 pandemic, a short-term but complete ban on access to forests and parks was introduced. Staying in these areas could have contributed to a reduction in the number of COVID-19 cases and deaths. The obtained results indicate the potential of green spaces in promoting health and their importance will increase during future pandemic waves.

Finally, since green areas are of great importance, they should be included in a comprehensive assessment of the impact of environmental conditions on the course of COVID-19 and should be considered in different epidemiological models. The use of the developed models would help to design effective crisis management strategies aimed at dealing with the new waves of the COVID-19 pandemic at the local level (e.g., in counties).

Overall, our study is a useful addition to encourage regulatory bodies to promote green spaces in environmental policies to reduce the harmful effects of COVID-19 and help to control the spread of new variants of SARS-CoV-2. For urban planners, the implications are particularly clear. Planners must consider the potential of greenery in view of future pandemics and work toward assuring access to urban green spaces in close proximity for all.

Additionally, including green areas in a country's health policy can be used as an effective strategy to prevent future pandemic threats similar to COVID-19.

Author statement

Roman Suligowski: Conceptualization, Methodology, Formal analysis, Writing – original draft preparation, Writing – review & editing. Tadeusz Ciupa: Conceptualization, Methodology, Formal analysis, Writing – original draft preparation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.envres.2022.114662.

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