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Assessment of Spatial and Temporal Variation in NO_2 Levels over Tourist Reception Areas in Poland

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Featured Application: Recognizing the temporal and spatial variation in NO_2 pollution will allow more effective management of tourist reception areas.

Abstract: Air quality in tourist reception areas can be a significant health concern. It also plays an increasingly important role when it comes to choosing tourist destinations. NO_2 is a harmful gas that can cause an increased number of cancer or respiratory diseases. The development of satellite remote sensing techniques now enables a much broader spectrum of air quality analysis than mere point measurements at environment monitoring stations. In the study, the spatial diversity of nitrogen dioxide air pollution over tourist reception areas in Poland was assessed. The lowest pollution was found in national parks and tourist regions. The most polluted air was found in tourist reception areas located near industrial regions and large urban agglomerations. Temporal variation—annual and monthly—and spatial variation were determined (for the period 2019–2021). The highest concentrations, exceeding the WHO recommended value (40 µmol/m^2), occurred in the winter and autumn. Low pollution was found in most reception areas in the summer (except cities). In 2020, due to restrictions related to the SARS-CoV-2 epidemic, the NO_2 pollution decreased (10–20%). In the cold half of the year (October–April), NO_2 concentrations greater than 40 µmol/m^2 occurred for about 20% of national parks, 50% of health resorts, 30% of tourist regions, and 100% of provincial capitals.

Keywords: air pollution; protected areas; health risk; tourism; wellbeing

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1. Introduction

Air pollution occurs when substances that may have a negative environmental impact are introduced into the atmosphere. They originate from anthropogenic sources associated with organised forms of human activity (e.g., transport, residential heating, and industrial plants) or natural sources resulting from natural processes (e.g., volcanic eruptions, forest fires, and sandstorms). These can be substances that do not naturally occur in the atmosphere as well as those occurring in the environment in quantities that clearly exceed the geochemical background [1–3].

According to the European Environment Agency (2021), the biggest problem for the quality of the air today is pollution with particulate matter (PM_{10} and $PM_{2.5}$), tropospheric ozone (O_3), and nitrogen dioxide (NO_2). It is estimated that in 2019, nearly 400,000 people in the European Union, including about 43,000 in Poland, died prematurely due to air pollution [4]. The International Agency for Research on Cancer has classified outdoor air pollution in general, including particulate matter and diesel exhaust, as carcinogenic [5,6]. This has been confirmed by the results of numerous studies [7,8]. Elevated atmospheric concentrations of nitrogen oxides, reflecting pollution generated by fuel combustion, have been associated with an increased risk of certain cancers and higher mortality rates [9–11]. The exposure of pregnant mothers to elevated concentrations of nitrogen oxides results in a higher risk of cancer in their children in early childhood [12]. The human body's response to air pollution can vary [13]:

- acute, caused by a single introduction of a large dose of a substance into the body,
- chronic, caused by the prolonged introduction of small doses of a substance into the body,
- latent, when the effects of introducing certain doses of a toxic substance into the body can emerge only after a long period of time.

A review study by Nazar and Niedoszytko [14] indicates that air pollution in Poland increases the total number of deaths and deaths related to respiratory diseases, as well as the incidence of respiratory diseases, including asthma, lung cancer, and COVID-19-related infections. The authors point out that, according to the World Bank, 36 of the world's 50 most polluted cities are located in Poland [15].

The negative health effects of air pollution, as outlined above, indicate the importance of their accurate spatial detection. Direct measurements can be carried out at a limited number of sites. One of the tools that can be an important source of information in this regard are satellite data, particularly those collected via the Sentinel-5P satellite with the TROPOMI multispectral imaging spectrometer. This allows the transition from the point data to the area data. This is important in the context of recreational areas, within which the network of measurement stations is limited. Although satellite observations of air pollution have been carried out since 1978, starting with the study of the so-called ozone layer and aerosols, these missions were not dedicated to such applications [16]. The Sentinel-5P satellite is markedly different from other satellites and has been dubbed a forerunner in air pollution research thanks to the new technological solutions which allow many applications [17–19]. For a detection of: (a) the impact of anthropogenic emissions on industrial plants, power plants, heating plants, district heating systems, transport, and mines [20]; (b) volcanic gases [21]; and (c) fires [22].

The data on air quality in Poland originate mostly from measurements carried out at the State Environmental Monitoring stations, which measure the content of sulphur dioxide (SO_2), carbon monoxide (CO), benzene (C_6H_6), ozone (O_3), nitrogen dioxide (NO_2), particulate matter PM_{10}, and $PM_{2.5}$ [23] (http://powietrze.gios.gov.pl). According to these data, the greatest threat to human health in Poland was posed by PM_{10}, particularly in the Upper Silesian Conurbation and the agglomerations of Kraków and Rybnik–Jastrzębie-Zdrój [24]. Another significant threat is the concentration of nitrogen dioxide which exceeds the applicable limits most often in the Upper Silesian Conurbation and the agglomerations of Kraków, Warsaw, and Wrocław. Increased levels are also evident along the transport routes between cities. NO_2 emissions are, to some extent, regulated by the increasingly strict Euro standards for newly manufactured vehicles and the introduction of zones in cities restricting the movement of cars with excessive exhaust emissions. In Poland, however, the number of older cars is still high: the average age of a car in Poland is 15.5 years.

The main sources of nitrogen oxides in Poland include road transport (particularly diesel engines), district heating systems, and high-temperature technological processes. The toxic effect of nitrogen dioxide manifests itself in the weakening of the defenses of the lungs and disruption of their ventilation, a reduction in blood oxygen saturation, a decrease in the self-cleaning capacity of the respiratory tract, and thus, a reduced resistance to bacterial infections of the lower respiratory tract. Nitrogen oxides play an important role in the formation of acid rain, winter smog, and summer (photochemical) smog [13].

In this study, the spatial variation as well as the annual and seasonal variation in air quality in tourist reception areas in Poland was assessed, and the national parks, landscape parks, tourist regions, health resorts, and large cities were studied. These areas serve recreation and wellbeing; hence, they should have the lowest possible levels of air pollution. Knowledge about air quality in these areas will enable taking appropriate measures to improve it. At the same time, the state of air quality can be an important factor in the choice of a place for recreation. The findings made it possible to determine the extent of the health risk to tourists posed by the presence of nitrogen dioxide in the air. The data for the years

2019, 2020, and 2021 were analysed. Studies on the temporal and spatial variation in NO_2 content in the air based on the satellite data have already been conducted in Poland in the context of the impact of the coronavirus pandemic [25]. However, no analysis has been carried out for tourist areas in Poland yet. Studies conducted around the world have not specifically addressed these issues either.

2. Materials and Methods

The tourist reception areas analysed in the study include 23 national parks, 126 landscape parks, 21 tourist regions, 46 health resorts, and 16 provincial capitals. The spatial distribution of these areas is shown in Figure 1. They are concentrated in the southern (health resorts and national parks) and northern (tourist regions) parts of Poland. They constitute reception areas for mass tourism (tourist regions), nature and cognitive tourism (national and landscape parks), cultural tourism (cities), and spa tourism (health resorts). A total of more than 22 million tourists used registered accommodation facilities in Poland in 2021. Ten million tourists visit national parks in Poland every year. Health resort services are used by around 850,000 people per annum, including circa 50,000 foreign tourists. It should be noted that national parks, landscape parks, and health resorts are located within tourist regions.

The source of the data used in this study were the observations made using the TROPOMI spectrometer (TROPOspheric Monitoring Instrument, Airbus Defence and Space Nederland, Leiden, The Netherlands) of the Sentinel-5P satellite, launched on 13 October 2017 as part of the Copernicus Programme. Its task is to measure air quality as well as monitor and forecast climate change. To do so, it uses passive remote sensing techniques, mainly by measuring reflected solar radiation in the ultraviolet and visible light (270–500 nm), near-infrared (675–775 nm), and short-wave infrared (2305–2385 nm) ranges. Sentinel-5P products are made available by the European Space Agency. Level-2 data products encompass: (a) columns of total ozone (O_3), sulphur dioxide columns (SO_2), nitrogen dioxide columns (NO_2), carbon monoxide (CO), formaldehyde (HCHO), and methane (CH_4); (b) tropospheric ozone columns (O_3) and nitrogen dioxide columns (NO_2); and (c) cloud cover and aerosols. Studies using the data collected via the TROPOMI sensor on NO2 have been conducted in many places around the world and show good correlation between the satellite data and the ground-based measurements [26–29].

In the present study, annual and monthly means for the tropospheric nitrogen column were used, based on the data downloaded from the provider's website [30] (https://s5phub.copernicus.eu/dhus). The borders of protected areas were retrieved from the Geoportal of the General Directorate for Environmental Protection [31]. Health resort data and death statistics were obtained from the Local Data Bank [32].

Tropospheric NO_2 levels for the individual areas were calculated by averaging the values occurring within their boundaries (the horizontal resolution of the data was 5.5 × 3.5 km). Single measurement data with the highest quality (QA value of more than 0.75) were extracted, processed to a newly defined $0.01° \times 0.01°$ grid and visualised in a GIS environment (QGIS). Annual means (2019, 2020, 2021) and monthly means were calculated for the following months: February 2019, April 2019, July 2019, and October 2019. Due to the small amount of data available (weather conditions) for January, the data for February were used.

No nitrogen dioxide threshold values have yet been developed for units in which the satellite data are available. WHO provides values in $\mu g/m^3$ while the satellite data are given in $\mu mol/m^2$. Therefore, we recalculated the values based on the calculated relationship (linear regression) between the terrestrial (x) and satellite (y) data for the same points. Measurement data from 37 ground stations were used, and calculations were carried out for the annual means in 2019 and 2020. Analyses were performed without taking into account stations close to sources of local NO_2 emissions (cities and roads). The correlation obtained in both cases was very similar (Figure 2). The one from 2020 was chosen because of its higher R^2 value: y = 1.689x + 22,932 (R^2 = 0.71). A similar level of agreement between the ground and satellite station data was obtained by Ialongo et al. [33], Goldberg et al. [20], and Lee et al. [34].

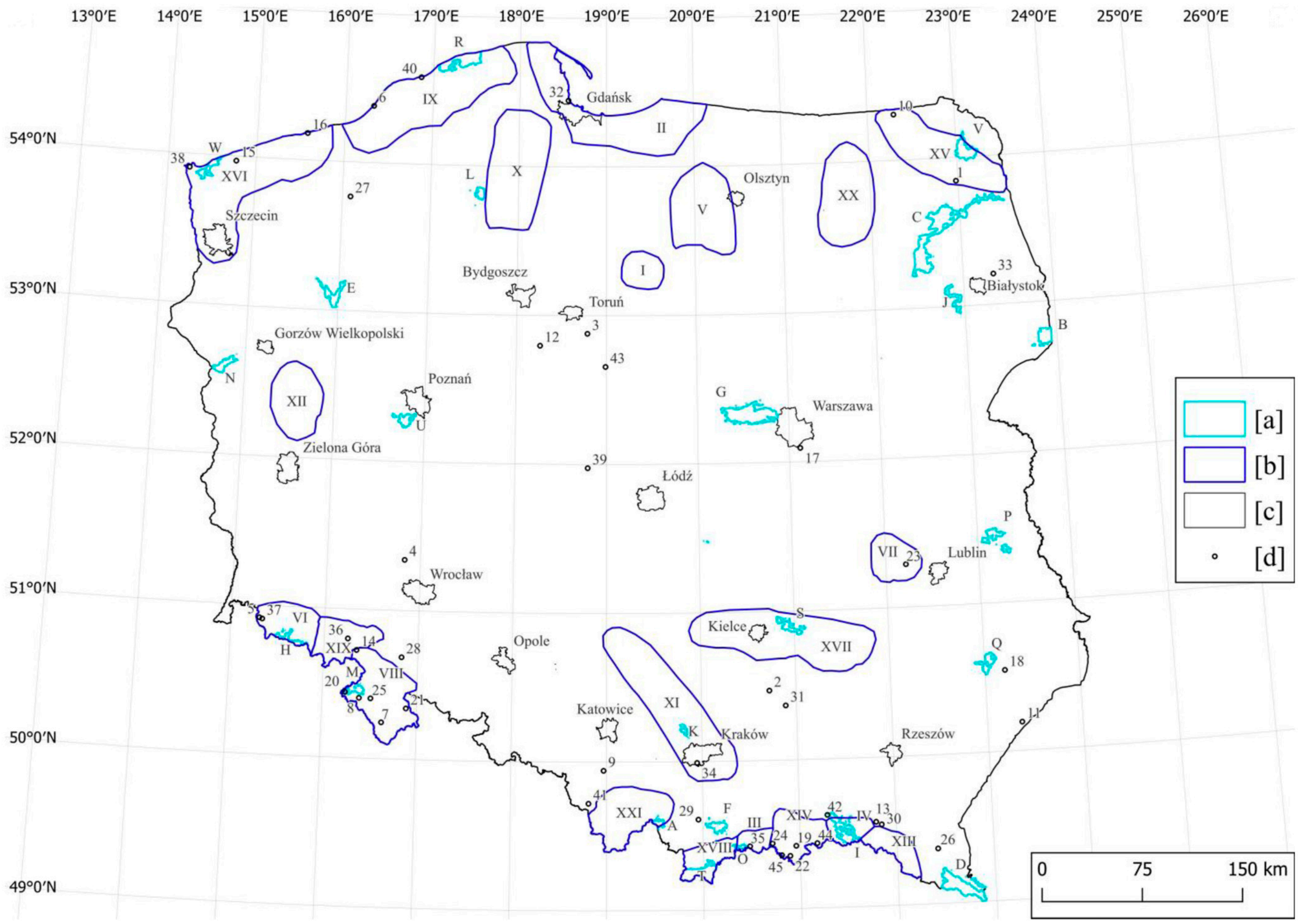

Figure 1. Location of tourist reception areas. (a) National parks: A—Babiogórski, B—Białowieski, C—Biebrzański, D—Bieszczadzki, E—Drawieński, F—Gorczański, G—Kampinoski, H—Karkonoski, I—Magurski PN, J—Narwiański, K—Ojcowski, L—Bory Tucholskie, M—Gór Stołowych, N—Ujście Warty, O—Pieniński, P—Poleski, Q—Roztoczański, R—Słowiński, S—Świętokrzyski, T—Tatrzański, U—Wielkopolski, V—Wigierski, and W—Woliński. (b) Tourist regions: I—Brodnica, II—Gdańsk, III—Gorce–Lubań, IV—Gorlice, V—Iława–Ostróda, VI—Jelenia Góra, VII—Kazimierz Dolny–Nałęczów, VIII—Kłodzko, IX—Kołobrzeg, X—Kościerzyna–Kartuzy, XI—Kraków–Częstochowa, XII—Łagów, XIII—Rymanów-Zdrój, XIV—Nowy Sącz, XV—Suwałki–Augustów, XVI—Szczecin, XVII—Świętokrzyskie, XVIII—Tatra–Podhale, XIX—Wałbrzych, XX—Great Mazurian Lakes, and XXI—Żywiec. (c) Provincial capitals. (d) Health resorts: 1—Augustów, 2—Busko-Zdrój, 3—Ciechocinek, 4—Cieplice, 5—Czerniawa-Zdrój, 6—Dąbki, 7—Długopole-Zdrój, 8—Duszniki-Zdrój, 9—Goczałkowice-Zdrój, 10—Gołdap, 11—Horyniec-Zdrój, 12—Inowrocław, 13—Iwonicz-Zdrój, 14—Jedlina-Zdrój, 15—Kamień Pomorski, 16—Kołobrzeg, 17—Konstancin-Jeziorna, 18—Krasnobród, 19—Krynica-Zdrój, 20—Kudowa-Zdrój, 21—Lądek-Zdrój, 22—Muszyna, 23—Nałęczów, 24—Piwniczna-Zdrój, 25—Polanica-Zdrój, 26—Polańczyk, 27—Połczyn-Zdrój, 28—Przerzeczyn-Zdrój, 29—Rabka-Zdrój, 30—Rymanów-Zdrój, 31—Solec-Zdrój, 32—Sopot, 33—Supraśl, 34—Swoszowice, 35—Szczawnica, 36—Szczawno-Zdrój, 37—Świeradów-Zdrój, 38—Świnoujście, 39—Uniejów, 40—Ustka, 41—Ustroń, 42—Wapienne, 43—Wieniec-Zdrój, 44—Wysowa-Zdrój, and 45—Żegiestów-Zdrój.

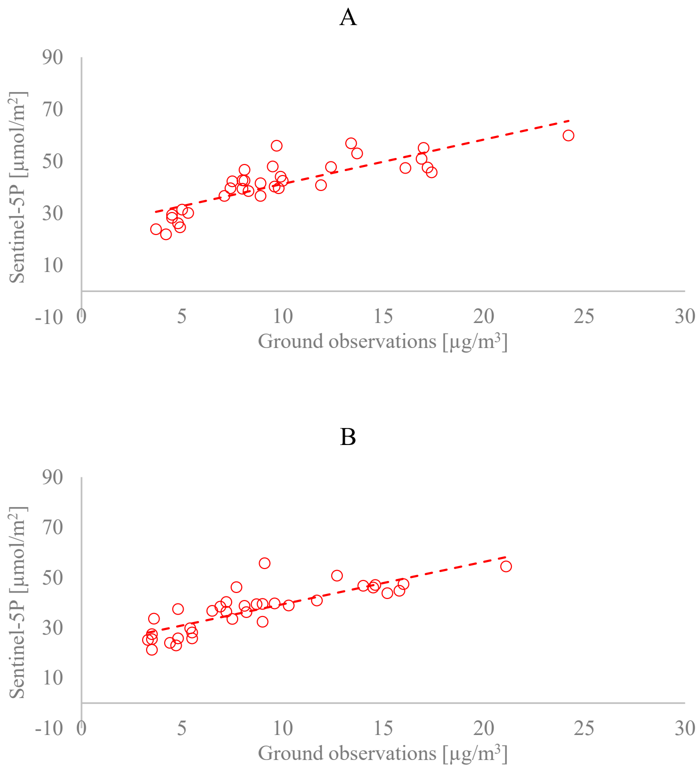

Figure 2. Relationship between the satellite and ground data (annual averages): (**A**)—2019, (**B**)—2020.

The annual mean NO_2 concentration limit, 40 µg/m^3 (2008/EC/50), set by the EU and GIOŚ [35], corresponds to 91 µmol/m^2 (satellite data). In turn, research by Mele et al. [36] suggests that the effect of NO_2 on COVID-19 mortality was already evident at the level of about 20 µg/m^3, which corresponds to about 57 µmol/m^2 for the satellite data. Even lower values were indicated in September 2021 by the World Health Organization, according to which the mean NO_2 concentration should not exceed 10 µg/m^3 [37]. This corresponds to 40 µmol/m^2 in the case of satellite data. In the analyses carried out in the present study, we referred to this concentration as a limit. At this point, it should be noted that, according to a study by Ialongo et al. [33], TROPOMI sensor data are slightly underestimated compared to ground-based measurements in the case of high pollution. The adoption of lower concentrations as a limit is justified from this point of view. In addition to assessing the spatial and temporal variation in NO_2 content in tourist reception areas, an attempt was also made to evaluate the impact of the amount of nitrogen dioxide air pollution on the number of deaths.

3. Results

3.1. General Variation in Pollution

The spatial distribution of the annual average NO_2 concentrations in the air above Poland varies strongly. The lowest concentrations occur in southern Poland (the Carpathian Mountains), and in northern Poland (lake districts and coastal areas). Low levels also occur in Eastern Poland (Figure 3). In contrast, high concentrations, exceeding 40 µmol/m^2, occur in central Poland and parts of southern Poland. The highest pollution occurs in the vicinity of the Bełchatów Power Plant and the Upper Silesian Conurbation (approx. 80 µmol/m^2), as well as in the agglomerations of Kraków and Warsaw (approx. 70 µmol/m^2). High levels occur in the air over the agglomerations of Wrocław, Opole, Łódź, Poznań, and Tarnów (50–60 µmol/m^2). Power plants at Kozienice, Turów, and the German Jänschwalde (border area west of Zielona Góra) also have a similar impact on air pollution with NO_2. Lower but still noticeable pollution (40–50 µmol/m^2) occurs in Szczecin, the Trójmiasto, Radom, the Płock refinery, the Głogów and Legnica copper works, and the Konin and Połaniec power plants. As a result of lockdown restrictions, the year 2020 saw quite a marked reduction in areas with the highest concentrations of NO_2 in the air. It was particularly noticeable in the case of the Bełchatów power plant, the Upper Silesian Conurbation, and the agglomerations of Warsaw and Kraków. By contrast, in the following year, the areas with the highest concentrations (>60 μmol/m^2) were larger than before the pandemic (Figure 3).

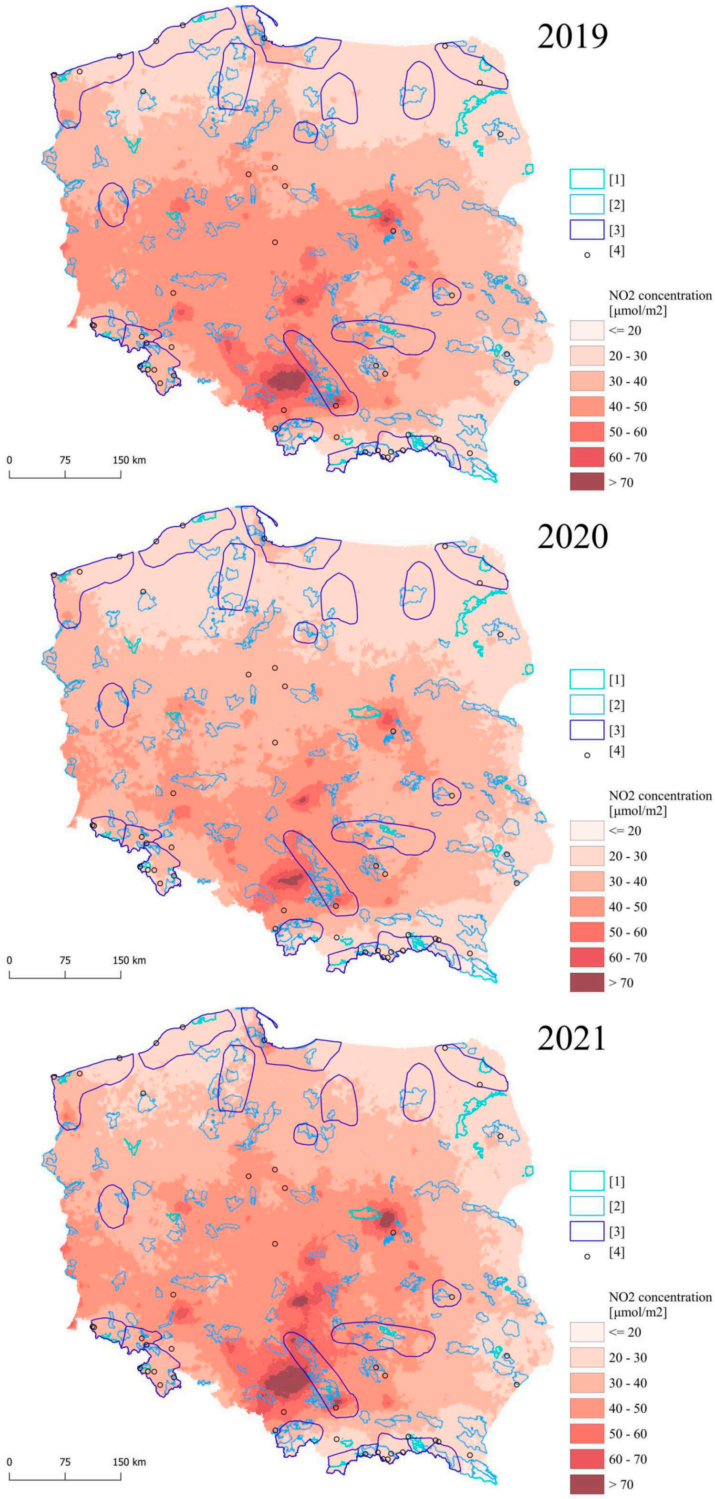

Figure 3. Spatial diversity of the mean annual NO_2 concentrations in the air over Poland in 2019, 2020, and 2021: 1—national parks, 2—landscape parks, 3—tourist regions, and 4—health resorts.

Over the course of the year, there is significant variation in the monthly mean NO_2 concentrations in the air. They are the highest in February and October, and the lowest in July (Table 1). The maximum levels recorded in Poland in months other than June and September are above 80 µmol/m^2, and they are greater than 140 µmol/m^2 in February.

Table 1. Monthly variation in nitrogen dioxide concentrations over Poland in 2019 [µmol/m^2].

Month	Mean	Median	Standard Deviation	VC [%]	Maximum
January	39.48	32.56	30.21	76.5	383.55
February	56.46	56.86	16.80	29.7	145.42
March	37.03	35.95	12.68	34.3	126.86
April	33.26	31.86	9.61	28.9	105.33
May	27.54	26.53	7.89	28.7	94.76
June	25.45	24.89	5.05	19.9	78.36
July	24.05	23.52	6.63	27.5	88.46
August	27.40	26.68	6.71	24.5	83.60
September	31.92	31.01	7.59	23.8	74.45
October	48.57	48.34	11.46	23.6	130.77
November	50.34	49.21	13.85	27.5	115.29
December	55.08	54.39	17.10	31.0	132.39

The lowest mean annual concentrations occurred in national parks and tourist regions, followed by health resorts and landscape parks (Figure 4). In provincial capitals, they were 50% greater than in the other areas. It was found that the amount of pollution in tourist reception areas in 2020 decreased by 5% in national parks, 7.7% in health resorts, and 7.8% in provincial capitals. In 2021, by contrast, there was an increase by 1.2–2.0% in national parks, landscape parks, and health resorts; by 3% in tourist regions; and by 6% in provincial capitals, in relation to 2019 (Figure 4).

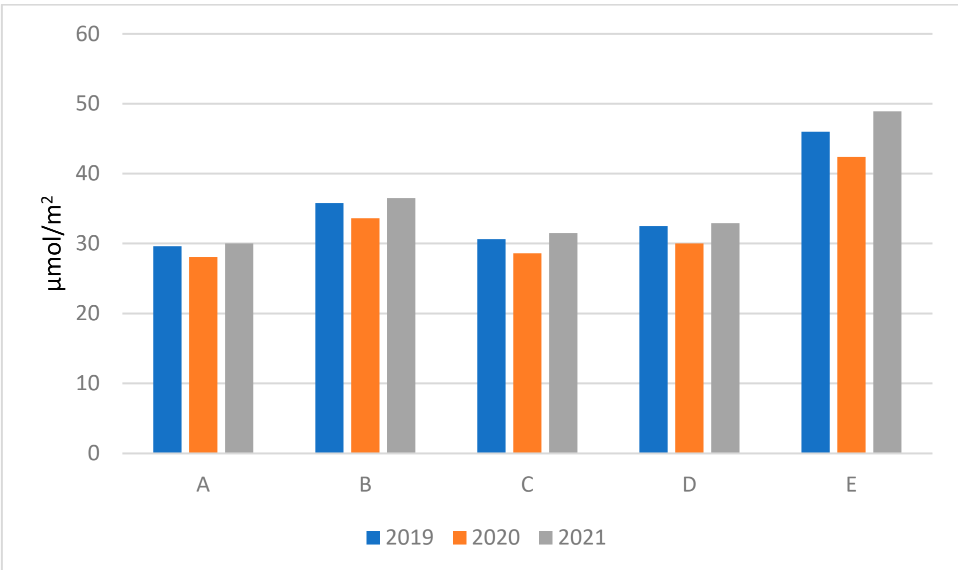

Figure 4. Mean annual NO_2 concentrations by type of tourist reception area for 2019–2021: A—national parks, B—landscape parks, C—tourist regions, D—health resorts, and E—provincial capitals.

3.2. Variation in Air Quality in Tourist Reception Areas

The mean annual concentrations for all national parks were changing from 28.4 µmol/m^2 (2020) to 30.1 µmol/m^2 (2021) in the period under study. In three parks, it exceeded 40 µmol/m^2. The following national parks had the greatest NO_2 content in the air (in 2021): Kampinowski (48 µmol/m^2), Ojcowski (46 µmol/m^2), Ujście Warty (41 µmol/m^2), Wielkopolski (40 μmol/m^2), and Świętokrzyski (37 μmol/m^2). The best quality of the air occurred in the following national parks: Bieszczadzki (18 μmol/m^2), Tatrzański (23 μmol/m^2), Babiogórski (24 μmol/m^2), Wigierski (24 μmol/m^2), and Słowiński (24 μmol/m^2). The trends for 2019 and 2020 are the same, but the values are slightly lower. Compared to 2020, the greatest increase in mean values in 2021 occurred in the following national parks: Bory Tucholskie (22%), Kampinowski (18%), Gór Stołowe (16%), Ojcowski (15%), and Świętokrzyski NP (12%). The greatest decrease in NO_2 concentration occurred in Poleski (7%), Roztoczański (7%), and Wielkopolski (2%) national parks. When comparing the 2021 data with the data for 2019, the decreases for these national parks range from 8 to 16%, with the biggest being in Wielkopolski NP, whereas the declines in 2020, in relation to 2019, exceed 10% (3–5 μmol/m^2) for Magurski, Ojcowski, Wielkopolski, and Góry Stołowe national parks.

The mean annual NO_2 concentration for all landscape parks ranged from 34 μmol/m^2 (2020) to 36 μmol/m^2 (2020). It exceeded 40 μmol/m^2 in the case of 40 parks. In 2021, it ranged from 20 to 60 μmol/m^2.

The mean annual NO_2 content for all tourist regions changed from 28.6 μmol/m^2 (2020) to 31.5 μmol/m^2 (2021). It exceeded 40 μmol/m^2 in only two regions. The highest NO_2 concentrations occurred in the following tourist regions: Kraków–Częstochowa (55 μmol/m^2), Świętokrzyski (42 μmol/m^2), Wałbrzych (38 μmol/m^2), Kazimierz Dolny–Nałęczów (37 μmol/m^2), and Łagów (37 μmol/m^2). The lowest concentrations were found in the following regions: Rymanów-Zdrój (22 μmol/m^2), Tatra–Podhale (24 μmol/m^2), Gorlice (24 μmol/m^2), Gorce–Lubań, and Suwałki–Augustów (25 μmol/m^2). The highest increase (in 2021 compared to 2020) was found in the following regions: Kościerzyna–Kartuzy and Iława–Ostróda (17%), Kraków–Częstochowa, Brodnica, and Wałbrzych (15%). A 1% to 4% increase occurred in the Żywiec, Rymanów-Zdrój, Łagów, and Gorce–Lubań regions. In 2021, mean NO_2 content in these regions fell by 4% to 8% in relation to 2019. In 2020, a decrease by more than 10% (in relation to 2019) occurred in the Nowy Sącz, Rymanów-Zdrój, Gorlice, and Kłodzko regions. No increase occurred in any of these regions in that period.

The lowest mean annual NO_2 content for all health resorts was 30 μmol/m^2 (2020) and the highest was 33 μmol/m^2 (2021). In 2021, it exceeded 40 μmol/m^2 in 11 health resorts. The highest NO_2 concentration in 2021 occurred in the following resorts: Swoszowice (59 μmol/m^2), Goczałkowice-Zdrój (56 μmol/m^2), Konstancin-Jeziorna (53 μmol/m^2), Inowrocław (45 μmol/m^2), and Cieplice (45 μmol/m^2). The lowest concentrations (22–23 μmol/m^2) occurred in the following health resorts: Piwniczna-Zdrój, Polańczyk, Krynica-Zdrój, Gołdap, and Rymanów-Zdrój. In 2021, the highest increase in relation to 2019 occurred in Sopot (21%), Horyniec-Zdrój (16%), Busko-Zdrój (14%), Wieniec-Zdrój (12%), and Polańczyk (10%). A 10% decrease in pollution was found in Dąbki, Krynica-Zdrój, Piwniczna-Zdrój, Rabka-Zdrój, and Żegiestów-Zdrój. In 2020, which saw the pandemic-related restrictions, a decline of more than 20% in relation to 2019 (by about 5 μmol/m^2) occurred in the following health resorts: Żegiestów-Zdrój, Wysowa-Zdrój, Ciechocinek, Krynica-Zdrój, and Lądek-Zdrój. A 2% to 6% increase was recorded in Kamień Pomorski, Polańczyk, Cieplice, and Busko-Zdrój.

In 2021, the highest NO_2 concentrations were found in the following cities: Katowice (79 μmol/m^2), Warszawa (70 μmol/m^2), Kraków (64 μmol/m^2), Wrocław (61 μmol/m^2), and Łódź (60 μmol/m^2). In only four cities—Lublin, Rzeszów, Olsztyn, and Białystok—40 μmol/m^2 was not exceeded. In 2021, the greatest increase in relation to 2019 occurred in Olsztyn and Gdańsk (16%), as well as Warsaw, Szczecin, and Łódź (11%). Lublin, Opole, Poznań, and Zielona Góra, on the other hand, experienced a 1–5% decline. In 2020, restrictions related to COVID-19 resulted in a more than a 10% decrease (6–10 μmol/m^2) in NO_2 concentration in relation to 2019 in Łódź, Bydgoszcz, Poznań, Kraków, Katowice, Opole, and Toruń.

3.3. Temporal Variation

For monthly averages, the seasonal variation in NO_2 concentration was very similar for all types of areas. The highest monthly average NO_2 concentrations occur from October to February, while the lowest in June and July (Figures 5 and 6). The difference between the lowest and highest mean value is usually almost 50%. It should be noted that monthly threshold values were not introduced. Therefore, when it comes to monthly variation, we relate these values to the annual average. The 40 $\mu mol/m^2$ level is exceeded from the months of February to October in all types of reception areas (Figure 5). During the summer season, from June to August, for all types of areas, the average is less than 40 $\mu mol/m^2$. The temporal distribution of NO_2 pollution is primarily due to the changes in emissions associated with the burning of fossil fuels. The data for January 2019, due to weather conditions making it difficult to acquire a large number of good quality satellite scenes, are less reliable.

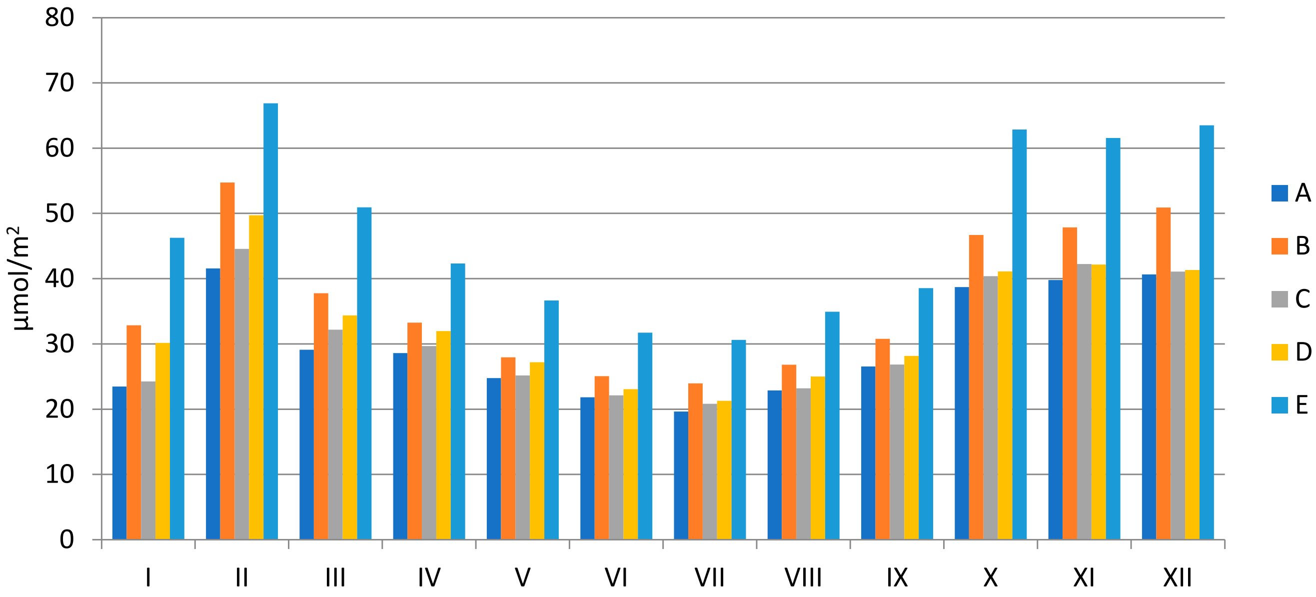

Figure 5. Mean monthly NO_2 concentrations in the specific types of areas: A—national parks, B—landscape parks, C—tourist regions, D—health resorts, and E—provincial capitals.

In April, the number of national parks with a monthly average >40 $\mu mol/m^2$ was about 50% lower than in February and October, and a similar relationship occurred for tourist regions. In contrast, for landscape parks and the health resorts, the differences were smaller. In autumn and winter, the value of 40 $\mu mol/m^2$ is exceeded for more than 50% of tourist reception areas (except for national parks) (Table 2).

Table 2. Share of reception areas with NO_2 concentration above 40 $\mu mol/m^2$.

Reception Areas	February 2019	April 2019	July 2019	October 2019
National parks	48%	21%	0%	43%
Landscape parks	77%	50%	2%	82%
Tourist regions	54%	28%	0%	71%
Health resorts	71%	42%	0%	55%
Provincial capitals	88%	94%	23%	100%

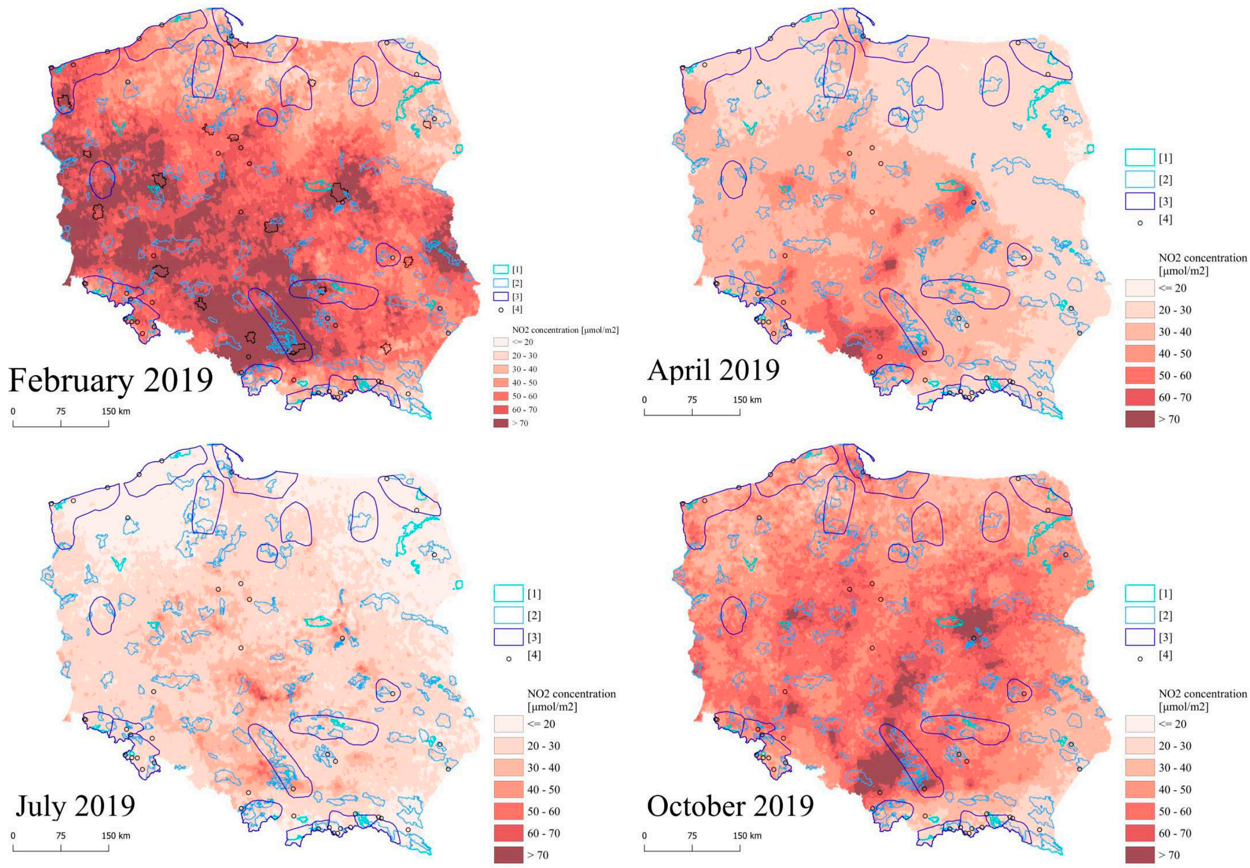

Figure 6. Spatial diversity of the mean monthly NO_2 concentrations in the specific types of areas: 1—national parks, 2—landscape parks, 3—tourist regions, and 4—health resorts.

3.3.1. February 2019

The NO_2 level of 40 µmol/m^2 was higher in the air of nine national parks. The following national parks were the most polluted: Ojcowski (79 µmol/m^2), Ujście Warty (74 µmol/m^2), and Wielkopolski (74 µmol/m^2) (Figure 6). The lowest levels (<20 µmol/m^2) occurred in Bieszczadzki and Tatrzański NPs. NO_2 content in the air was greater than 40 µmol/m^2 in 108 landscape parks and greater than 75 µmol/m^2 in three parks, and it was not lower than 20 µmol/m^2 in any park. The highest NO_2 concentrations were found for the following health resorts: Swoszowice (103 µmol/m^2), Goczałkowice (87 µmol/m^2), and Świnoujście (68 µmol/m^2). The NO_2 concentration was higher than 40 µmol/m^2 in 32 health resorts (Table 2). The lowest concentrations (<20 µmol/m^2) occurred in the following health resorts: Polańczyk, Augustów, and Gołdap. The NO_2 level was higher than 40 µmol/m^2 in 12 tourist regions (Figure 6). The following tourist regions were among the most polluted: the region of Kraków–Częstochowa (85 µmol/m^2), Świętokrzyski (68 µmol/m^2), and Łagów (68 µmol/m^2). The highest NO_2 concentrations occurred in Katowice (117 µmol/m^2), Kraków (108 µmol/m^2), and Warszawa (88 µmol/m^2). It was not lower than 40 µmol/m^2 in Białystok and Olsztyn

3.3.2. April 2019

The highest NO_2 concentrations occurred in the following national parks: Kampinoski (54 µmol/m^2), Karkonoski (48 µmol/m^2), Ojcowski (46 µmol/m^2), Świętokrzyski (46 µmol/m^2), and Ujście Warty (45 µmol/m^2) (Figure 6). Concentrations lower than 20 µmol/m^2 occurred in two national parks: Bieszczadzki and Tatrzański. The level of 40 µmol/m^2 was exceeded in 64 landscape parks and it was below 20 µmol/m^2 in only two parks. The highest concentrations occurred in the following health resorts: Goczałkowice-Zdrój (70 µmol/m^2), Konstancin-Jeziorna (61 µmol/m^2), and Inowrocław (60 µmol/m^2). In 19 health resorts, the level of

40 μmol/m^2 was exceeded, while in two—Krynica-Zdrój and Wysowa-Zdrój—it was below 20 μmol/m^2. The level of NO_2 was greater than 40 μmol/m^2 in six tourist regions, where the highest was in Kraków–Częstochowa (54 μmol/m^2), Wałbrzych (46 μmol/m^2), and Jelenia Góra (46 μmol/m^2). It was not lower than 20 μmol/m^2 in any of these regions (Figure 4). The highest concentrations occurred in Katowice (90 μmol/m^2), Warsaw (78 μmol/m^2), and Opole (75 μmol/m^2). It was lower than 40 μmol/m^2 only in Zielona Góra.

3.3.3. July 2019

The concentrations were lower than 40 μmol/m^2 in all national parks. The highest concentrations were found in Kampinoski NP (33 μmol/m^2), Woliński NP, and Ojcowski NP (29 μmol/m^2) (Figure 6). In 11 national parks, it was below 20 μmol/m^2. The mean monthly NO_2 content in the air was greater than 40 μmol/m^2 in three landscape parks, while it was below 20 μmol/m^2 in 26 parks. It was lower than 40 μmol/m^2 in all tourist regions. The same was true in health resorts (Figure 5). The highest concentrations occurred in Sopot (38 μmol/m^2) and Goczałkowice-Zdrój (36 μmol/m^2), while the lowest were observed in Muszyna (13 μmol/m^2), Krynica-Zdrój, and Żegiestów-Zdrój (14 μmol/m^2). The NO_2 level of 40 μmol/m^2 was exceeded in the air of four provincial capitals: Katowice (48 μmol/m^2), Warsaw (45 μmol/m^2), Kraków (40 μmol/m^2), and Łódź (40 μmol/m^2). The lowest concentration occurred in Zielona Góra (21 μmol/m^2).

3.3.4. October 2019

The level of 40 μmol/m^2 was exceeded in 10 national parks, and it was the highest in Ujście Warty NP (60 μmol/m^2), Woliński NP (56 μmol/m^2), and Wielkopolski NP (52 μmol/m^2). The lowest levels were recorded in Bieszczadzki NP (34 μmol/m^2), Tatrzański NP (30 μmol/m^2), and Gorczański NP (31 μmol/m^2) (Figure 6). The mean monthly NO_2 content in the air was greater than 40 μmol/m^2 in 105 landscape parks, with the highest level being 85 μmol/m^2, and the lowest being 26 μmol/m^2. The level of 40 μmol/m^2 was exceeded in 15 tourist regions: it was the highest in the region of Kraków–Częstochowa (60 μmol/m^2) and Świętokrzyskie (55 μmol/m^2), while the lowest level occurred in the region of Rymanów-Zdrój (28 μmol/m^2). The level of 40 μmol/m^2 was exceeded in 26 out of 46 health resorts (Figure 6). It was the highest in Swoszowice (87 μmol/m^2), Goczałkowice-Zdrój (73 μmol/m^2), and Sopot (70 μmol/m^2), and it was the lowest in Rymanów-Zdrój (28 μmol/m^2) and Polańczyk (29 μmol/m^2). The level of 40 μmol/m^2 was exceeded in all provincial capitals. It was the highest in Katowice (92 μmol/m^2), Warsaw (84 μmol/m^2), and Kraków (78 μmol/m^2), and it was the lowest in Białystok (45 μmol/m^2).

The analysis of the relationship between the level of nitrogen dioxide air pollution and the number of deaths demonstrated a clear correlation for cancer and, to a slightly lesser extent, for the total deaths. Such a correlation did not occur for deaths from respiratory diseases (Table 3). This may indicate an indirect effect of the pandemic on deaths related to more difficult access to health care and not directly deaths from respiratory diseases.

Table 3. Pearson correlation coefficients between the level of NO_2 pollution and the number of deaths in the districts' demographic data [31].

	Total Deaths per 100,000 Inhabitants	Total Deaths from Cancer per 100,000 Inhabitants	Total Deaths from Respiratory Diseases per 100,000 Inhabitants
Mean 2020 (all districts, n = 380)	0.18	0.32	−0.19
Mean 2020 (districts with >150,000 inhabitants, n = 50)	0.44	0.54	−0.12
December 2020 (all districts, n = 380)	0.09	0.25	−0.19
December 2020 (districts with >150,000 inhabitants, n = 50)	0.38	0.51	−0.14

4. Discussion

The issue of nitrogen dioxide limits, which, if exceeded, have harmful effects on human health, has not been fully resolved yet. However, there has recently been a trend towards lowering these limits. The investigations carried out within this study indicate the occurrence of harmful air pollution (>40 μmol/m^2) in the air of some tourist reception areas in Poland. For mean annual levels, this harmful pollution occurs in: (i) two tourist regions (9.5%): Kraków–Częstochowa and Świętokrzyski; (ii) three national parks (14%): Kampinoski, Ojcowski, and Ujścia Warty; (iii) 11 health resorts (24%): the highest levels being in Swoszowice, Goczałkowice-Zdrój, Konstancin-Jeziorna, Inowrocław, and Cieplice; (iv) 40 landscape parks (31%); and (v) 12 provincial capitals (75%): the highest levels being in Katowice, Kraków, Warsaw, and Łódź.

The extent to which the limits were exceeded varied significantly over time. In January, the limits were exceeded in 53% of national parks, 75% of landscape parks, 57% of tourist regions, 50% of health resorts, and 100% of provincial capitals. In other months, it was clearly smaller:

(a) April: national parks (22%), landscape parks (51%), tourist regions (27%), health resorts (41%), and provincial capitals (94%)
(b) July: national parks (0%), landscape parks (2%), tourist regions (0%), health resorts (0%), and provincial capitals (25%)
(c) October: national parks (48%), landscape parks (83%), tourist regions (65%), health resorts (56%), and provincial capitals (100%)

During the summer months, i.e., in periods of the highest tourist traffic, nitrogen dioxide air pollution is basically non-existent. However, for more than half a year, from October to April, the annual threshold value is exceeded in 20% of the national parks, more than half of the landscape parks, 30% of the tourist regions, 40% of the health resorts, and nearly 100% of the provincial capitals. The greatest pollution occurs in tourist reception areas close to major cities. These are areas where tourism and recreation take place all year round (weekend trips). The most polluted national parks in 2019 experienced the following levels of tourist traffic: Woliński (1.5 million), Kampinoski (1 million), Wielkopolski (1 million), Ojcowski (440,000), Świętokrzyski (120,000), and Ujście Warty (58,000).

The spatial and temporal distribution of NO_2 content is related to meteorological conditions to some extent. The study of these relationships was not the objective of the study, but some relationships can be seen as related to the average wind speeds, for example. Lower pollution occurred in areas with higher speeds—the mountainous areas and the Baltic coast. A more important factor, however, was the location in relation to emission sources. It is higher in the winter and autumn months and spatially concentrated in cities and industrial centres.

The COVID-19-related restrictions introduced in Poland in 2020 resulted in a reduction in NO_2 concentrations in the air of tourist reception areas. For February, October, and November, the monthly averages for Poland were 20–30% lower in 2020 than in 2019 (Figure 7). This is due to less car traffic, one of the main sources of pollution. According to Filonchyk et al. [25], during the lockdown period in Poland, car traffic decreased by 25–50%. In 2021, however, the pollution returned to pre-pandemic levels in Poland. Similar data are provided by studies conducted in other parts of the world [38–42]. Studies of pollution variability are much rarer, but the regularities found there are similar. Periods of lockdown improve the state of the air; however, it worsens much more when tourists return [43].

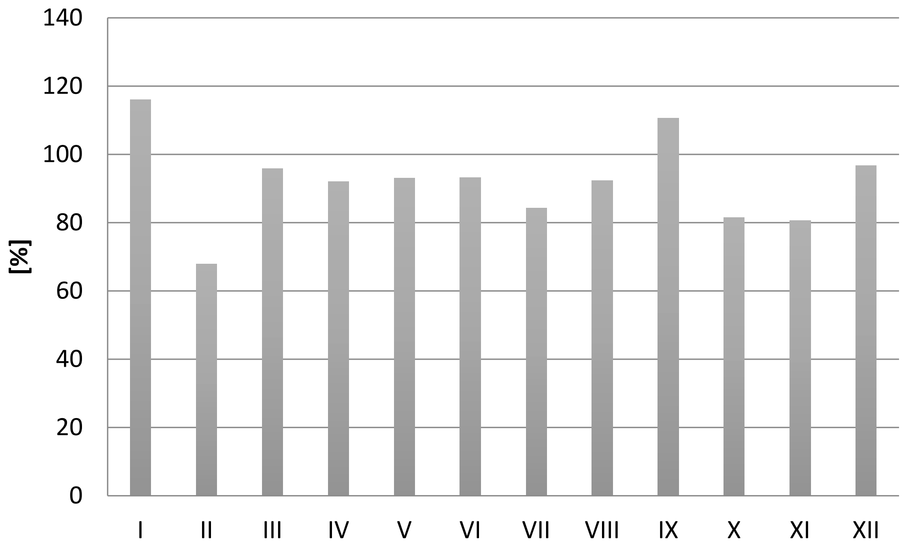

Figure 7. Relation of NO_2 monthly concentrations in 2020 to 2019.

Some health resorts with high levels of nitrogen dioxide pollution are identified as facilities where people with pulmonary, ENT, or cardiovascular diseases can be treated. These resorts include Goczałkowice Zdrój, Konstancin, and Inowrocław, located in close proximity to large cities. However, the air in most health resorts with this treatment profile has the lowest NO_2 levels. These resorts are located in mountainous areas, mainly in the Carpathians, namely Piwniczna, Polańczyk, Rymanów, and Krynica Zdrój. Health resorts are most often frequented by elderly people suffering from various illnesses, hence the harmful impact of NO_2 is particularly strong in their case, particularly because health resorts with a high concentration of nitrogen dioxide also suffer from pollution with dust and other harmful substances [44].

Staying in areas with elevated nitrogen dioxide levels can have negative health effects. Ongoing research confirms the relationship between NO_2 in the air and the number of cancer deaths [9,10,12,45]. Studies conducted in Poland also indicate the influence of the amount of pollution on the frequency of asthma attacks (hospitalisations) [46] or an increase in mortality linked to COVID-19 [47]. However, the studies conducted thus far have not been based on the satellite data, hence the need to undertake this type of research. In the absence of data on deaths and illnesses in tourist reception areas, it was not possible to accurately estimate the impact of elevated NO_2 concentrations on the health of their residents and visitors. We therefore conducted an assessment of the impact of NO_2 concentrations extracted from the satellite data for the entire country. Our analyses demonstrate the existence of a correlation between nitrogen dioxide content and the total number of deaths and the number of deaths from cancer (0.44 and 0.54). The correlation was particularly noticeable in the case of urban districts, with more than 150,000 inhabitants. Similar correlations between the number of deaths and NO_2 levels in the air were found by Musiałek and Nosowicz [47] ($\rho = 0.60$, $p < 0.05$) and by Semczuk-Kaczmarek et al. [48] for deaths related to COVID-19 ($R^2 = 0.319$).

The levels of air pollution can be an important factor in decisions about choosing particular tourist destinations [49,50]. Increased pollution, particularly in cities, results in a reduction in the number of tourists visiting them [51–53]. The quality of the environment can thus have a direct impact on the economy in addition to its effects on health. Therefore, this factor should be taken into account by policymakers. In the case of Polish tourists, however, the researchers highlight the discrepancy between declarations about the significant impact of air quality on the choice of travel destinations and the actual awareness of pollution levels [50].

The standards for NO_2 content in the air currently applicable in the Polish legal system are clearly higher than those suggested by the WHO. In addition, in both cases, they rely on units different from those obtained from the satellite measurements. Therefore, for the time being, it is impossible to take concrete action based on such results. However, they provide important information on the spatial variation in NO_2 content and indicate potentially vulnerable areas where further research, including ground-based monitoring, should be carried out.

The use of satellite data opens up another chapter of research into the state of pollution, including in areas that have not been covered by monitoring to date due to the lack of ground-based measurement stations. It is also possible to study the impact of local conditions on the amount of pollution and its migration routes. With point measurements, this was not possible. The data obtained enables better management of the environmental condition in tourist reception areas and takes action where NO_2 pollution levels exceed acceptable standards. These may primarily concern measures to reduce the volume of automobile traffic.

5. Conclusions

Air pollution of NO_2 over tourist reception areas in Poland shows great spatial and seasonal variation. It is lowest in tourist regions and national parks. However, the problem is that annual limits are exceeded in 25% of health resorts and 75% of larger cities. In the former case, it is particularly dangerous due to the fact that the patients are elderly people suffering from various diseases.

The lowest concentrations of NO_2 occur in spring and summer. In contrast, they are twice as high in autumn and winter. These regularities apply to all tourist reception areas. This is a positive phenomenon because the highest volume of tourist traffic takes place in spring and summer. Therefore, it seems that the health risk for tourists is negligible during this period.

Pandemic-related restrictions have resulted in a temporary improvement in air quality, but in 2021, the NO_2 concentrations in the air were higher than in 2019. The drop in pollution during the winter months was an exceptional phenomenon and was due to a significant reduction in car traffic.

Directly demonstrating the impact of elevated NO_2 concentrations in tourist reception areas on the health of visitors is very difficult. It can only be inferred through studies for larger populations and over a longer period of time. The analysis performed in this study shows a positive relationship between both the overall number of deaths and the number of cancer deaths in Poland and the NO_2 concentrations in the air.

In the study, we used the threshold value proposed in 2021 by WHO (40 $\mu mol/m^2$). However, further detailed research on nitrogen dioxide air pollution is necessary to determine the level from which its harmful health effects begin. This will allow for a better management of tourist areas in the future, including measures aimed at improving air quality in particularly polluted areas.

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