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Monitoring Nitrogen Dioxide (NO_2) in Environment of Ukraine based on Satellite Data

Abstract: Air pollution (especially near industrial enterprises that are located mainly in densely populated regions) is one of the most significant problems of modern ecology. The purpose of this research is to study nitrogen dioxide air pollution over Ukraine, which has a negative impact on human health. As part of the research over the territory of Ukraine, the real planar distribution of nitrogen dioxide (NO_2) as well as its local emissions (which make the main contribution to this distribution) were revealed using the materials of the remote sensing of the Earth from the AURA satellite. The results were calculated for the multi-year period of 2005 through 2021 and separately for 2022, which characterized the full-scale war in Ukraine and which made it possible to identify priority polluters; namely, industrial enterprises (thermal power plants, heavy metallurgy enterprises, etc.). For 17 years, the average value of NO_2 was $160.78 \cdot 10^9$ molecules/mm^2; in 2022, its concentration decreased to $126.93 \cdot 10^9$ molecules/mm^2. The war manifested itself due to the shutdown of industrial enterprises, which were (and remain) priority polluters in Ukraine (particularly in large cities).

Keywords: remote sensing, nitrogen dioxide, air pollution, Ukraine

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1. Introduction

The modern anthropogenic load on the biosphere significantly disrupts the balance mechanisms of the natural environment and creates environmental problems. The environmental security of any region (in this case, the territory of Ukraine) is one of the conditions for ensuring the economic security of the state. Carrying out the environmental safety diagnostics of the territory allows us to detect the degrees of action of the pollutants that are contained in the air, identify the sources of the pollution, conduct cause-and-effect relationships, assess the safety of the region, and create countermeasures against any anticipated factors in a timely manner regarding the impact of the pollution on people and the existing ecological systems.

Atmospheric air is a peculiar mediator of the anthropogenic pollution of all other elements of nature; it contributes to the spread of pollutants over considerable distances. The problem of anthropogenic and technogenic pollution is most acute in large cities with high concentrations of industrial enterprises, transport, and populations.

The development of industry and increasing the number of modes of transport are directly proportional to reducing the quality of the air. Some important pollutants (such as nitrogen dioxide) have a negative effect on human health and the environment. NO_2 is a harmful gaseous compound that is secreted by vehicles, power plants, and industrial facilities that are selected to characterize human anthropogenic activity. Anthropogenic sources emit up to 20 million tons of nitrogen every year in the form of oxides. The main combustion processes of fossil fuel at the CHP (up to 6.5 million tons/year) and in the internal combustion engines of cars (up to 5.5 million tons/year) are the most powerful sources of the analyzed substance and the cause of photochemical smog [1].

Many scientific works and reports are devoted to the problem of researching the content of nitrogen dioxide in the atmosphere as well as its role in air pollution.

The researchers conducted a long-term observation of air pollution in the industrial region in the northeast section of Bulgaria (the Devnya industrial region) during the period of 2000–2015. It was noted that, with the introduction of available technologies, effective waste-gas treatment plants and strict control over harmful substances (particularly NO_2) significantly decreased the concentrations of pollutants [2]. The analysis of air pollution in some industrial areas that was calculated using AERMOD allowed us to obtain a high-precision result of both daily and hourly NO_2 concentrations [3]. Researchers have developed a system of monitoring industrial air pollution to increase safety and health as well as stable working environments using the QFD approach for improving it [4]. An analysis of atmospheric pollution problems in the urban areas of Greece was a serious environmental problem, which was related to the rapid urbanization of cities, anarchic housing without basic infrastructures, increases in vehicles in the urban regions, and the formation of the notorious brownish-yellow "Nefos" in Athens. This review covers the most important results from the air pollution trends in large cities, cites the results of the economic crisis when using fuels with biomass, and shows the adverse effects on the health of the population and the increasing mortality in urban areas [5]. A study of the environmental pollution of a large industrial zone near Cairo (Egypt) was carried out with the help of neutron activation analysis; this also indicated that pollution can be dangerous for the people who were living in the studied area [6]. The United States Environmental Protection Agency (U.S. EPA) has identified the main criteria for air pollutants (including NO_2) and their harmful effects on the state of the environment [7]. The risks of air pollution by NO_2 dioxides were evaluated due to the activities of the metallurgical enterprises of Annaba (Algeria) and Kryvyi Rih (Ukraine). A risk-assessment map regarding nitrogen dioxide has been created. The obtained results were used for the effectiveness of the preventive measures regarding the health of the children in these cities [8]. Vietnamese researchers developed an assessment model of harmful health from air pollution in the career-development area. The results of the calculations showed that the damage that was caused to the health of the people was estimated to be about $15.03 million [9]. An analysis of the characteristics of industrial sources of emissions into the atmosphere in Beijing–Tianjin–Hebei (China) and adjacent areas used intellectual data analysis and statistics on a different time scale. It has been proven that intellectual data analysis and statistics on different time scales can be used to analyze the characteristics of industrial sources of emissions that are emitted into the atmosphere and can also be applied in support systems for environmental decision-making to make the management of air pollution more objective, reliable, and efficient [10]. With the help of the OLS model, researchers investigated the connection between the concentrations of air pollutants of nitrogen dioxide (NO_2) daily time series, economic activity, and meteorology in the cities of Austria [11]. Simultaneous observations of nitrogen dioxide, formaldehyde, and ozone in the Indo-Gangetic plain was conducted and obtained using multi-axis differential optical absorption spectroscopy (MAX-DOAS) and ground-based observations during the monsoon period. The analysis showed that mixed coefficients of NO_2 can be transported over long distances from thermal power plants during the monsoon period [12]. The mapping of nitrogen dioxide pollution of the urban atmosphere in the northern part of Algeria using satellite and ground data was also conducted. The results of this study helped inform Algerian air pollution policymakers regarding air pollution mitigation and also served as a step toward air pollution monitoring, acid rain risk assessment, and negative local and regional impacts [13]. A regional-scale environmental-impact-assessment model was developed in the West Taiwan Strait area, which included pollution sources, pollution stress, and assessment results; it also assessed the environmental impact (particularly of NO_2) from three perspectives: regional integration, different energy consumption sectors, and different cities [14]. The systematics of monitoring the atmospheric environment of China with the help of satellite remote sensing has been carried out. Products that are widely used for monitoring the atmospheric environment in China were analyzed [15]. Satellite observations of nitrogen dioxide over Turkey were also carried out. The relationship between tropospheric NO_2 and population density over Turkey was investigated via the recently launched Sentinel-5 Precursor (a low-orbit atmospheric air-pollution-monitoring mission that was equipped with the Tropomi [Tropospheric Monitoring Instrument] spectrometer). The results showed a significant correlation above 0.72 between population density and maximum NO_2 values [16].

Pollution is a serious environmental threat in the atmospheres of the industrial cities of Ukraine. Intensive mining and industrial activity, power and heating plants, and construction enterprises have contributed to the increase in the number of sources of atmospheric pollution. The researchers made an assessment of NO_2 pollution in the Dnipropetrovsk region; this was carried out using a new GIS system and meteorological data from stationary networks of the Dnipropetrovsk Regional Hydrometeorological Center. Over the last five years, increased concentrations of nitrogen dioxide have been observed in the atmospheres of this region (1.25–2.25 times the maximum-permissible limit) [17]. The ecological situation of the Azov region (particularly the problem of air pollution) was considered using the example of the city of Mariupol. A significant excess of the maximum-allowable concentrations of nitrogen dioxide was detected [18]. Research on the impact of the machine-building complex on the state of the atmosphere was conducted using the example of JSC Zaporizhabrazyv [19]; the state of the atmospheric air in the city of Kherson was analyzed [20]. The analysis of NO_2 nitrogen dioxide pollution was carried out on the example of Kyiv (Ukraine) during the period of 2018–2019. According to satellite data, the obtained result of the NO_2 concentration distribution showed that the average annual concentration of NO_2 was $134.58 \cdot 10^9$ molecules/mm^2 in 2018; this number rose to $157.51 \cdot 10^9$ molecules/mm^2 in 2019 and was $153.27 \cdot 10^9$ molecules/mm^2 over the first six months of 2020. The average values of NO_2 concentration for the first six months of 2018, 2019, and 2020 were determined: 2018 – $123.12 \cdot 10^9$ molecules/mm^2; 2019 – $144.15 \cdot 10^9$ molecules/mm^2; and 2020 – $153.27 \cdot 10^9$ molecules/mm^2. The increase in the NO_2 concentration values between 2018 and 2019 was $21.03 \cdot 10^9$ molecules/mm^2, and between 2019 and 2020 – $9.12 \cdot 10^9$ molecules/mm^2 [21]. The remote monitoring of the state of the atmospheric environment on the territory of Ukraine during the period of the quarantine restrictions of COVID-19 was conducted. A real planar spread in the atmosphere of anthropogenic emissions was found: NO_2. The results of the conducted studies showed that quarantine restrictions contributed to a reduction of NO_2 due to the decline of industry and transport activity [22].

Within the framework of this research over the territory of Ukraine, the aim is to identify the real plane spread of nitrogen dioxide (NO_2) for many years (from 2005 to 2022) using data from the Earth's remote sensing.

2. Materials and Methods

The general conceptual basis of the sequence of the diagnostic evaluation of nitrogen dioxide (NO_2) above the territory of Ukraine consisted of several basic stages (given in Figure 1).

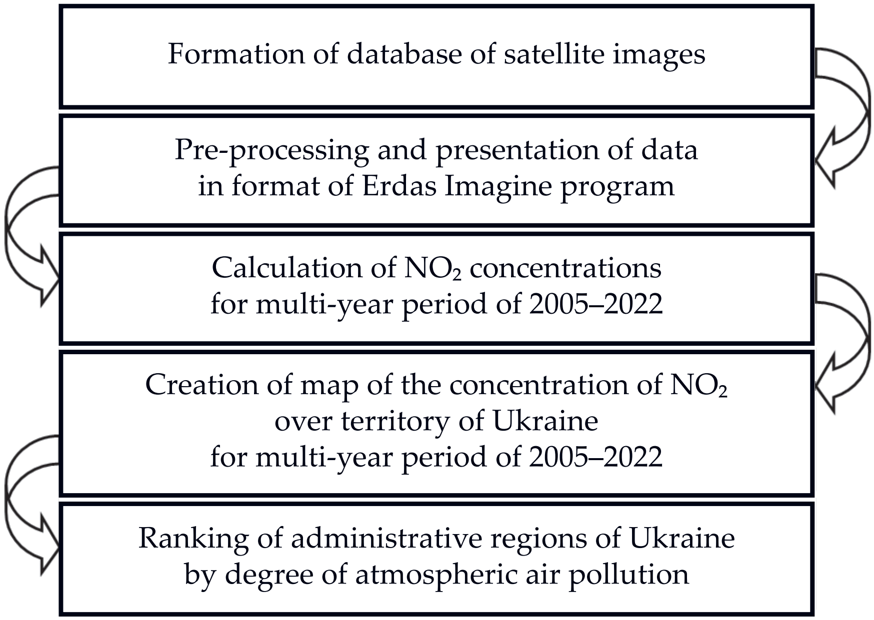

Fig. 1. Technological scheme of using data from AURA satellite to determine content of nitrogen dioxide (NO_2) over territory of Ukraine. Monthly data on NO_2 concentration from the AURA satellite was used in the work

For the period of 2005–2022, 216 images of monthly NO_2 concentration values were processed (with a spatial resolution of 11 km).

The data processing was carried out in the Erdas Imagine space-image-processing program. The experience of using the Erdas Imagine program for solving problems that are related to the monitoring of the state of the atmosphere is given [23, 24]. Thus, a technique for processing the Earth's remote sensing data using Erdas Imagine was developed using the available experience and the received nitrogen dioxide (NO_2) input data:

1. Since the input data on the concentration of NO_2 was received in the *.csv format, it needed to be converted to the *.grd format (with the help of additional lines that contained the values of the total number of columns and rows of an image as well as the latitude and longitude coordinates).
2. Using the Erdas Imagine program's Import function, the file was converted from the *.grd format to the *.img format.
3. The geographic coordinate system in degrees was set using the Add/Change Projection function of the Erdas Imagine program.
4. For more convenient data processing, a 12-channel image was created for each year (where each channel was assigned to a corresponding month). Thus, 18 images were created that corresponded to each year using the Layer Stack function of the Erdas Imagine program.

5. With the help of the developed models in the Model Maker editor, the average values of NO_2 concentration were calculated for each year as well as for all 18 years of the research (Fig. 2).
6. The territory of Ukraine was highlighted using vector data "Ukraine 500" via the Subset function of the Erdas Imagine program.
7. Using the Reproject function of the Erdas Imagine program, the metric coordinate system was set – UTM/WGS 84/zone36.

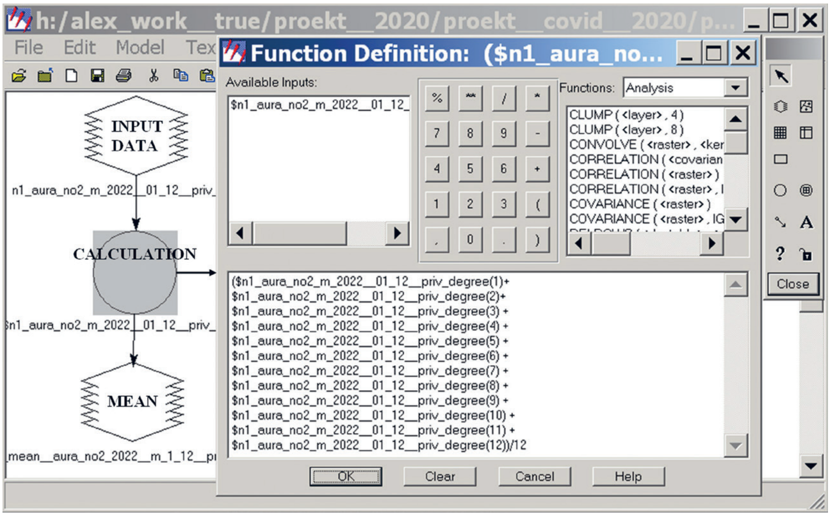

Fig. 2. Example of model for calculating average concentration of nitrogen dioxide (NO_2) for 2022 in Model Maker editor of Erdas Imagine program

After all of the data to determine the concentration of NO_2 from the AURA satellite was transformed according to the specified approach for the regional scale (the entire territory of Ukraine and its administrative regions), the average values of the concentration were calculated for the multi-year period (from 2005 through 2022) as well as separately for each year. To determine the local levels of pollution (industrial enterprises), their coordinates were determined using GIS (the MapInfo Professional program), and a vector layer was made (using the Erdas Imagine program); also, quantitative indicators of nitrogen dioxide (NO_2) were taken for the 18 years.

3. Results and Discussion

A theoretical analysis of the research of domestic and foreign scientists as well as the authors' own research showed that, in recent years, the influence of the anthropogenic factors of air pollution began to exceed the natural factors, becoming global in nature. This also applies to the territory of Ukraine, in the ecology of which significant corrections have been made by a full-scale war.

Figure 3 shows the dynamics of the NO_2 concentrations during the following periods: I – 2005–2009; II – 2010–2014; III – 2015–2019; IV – 2020–2022.

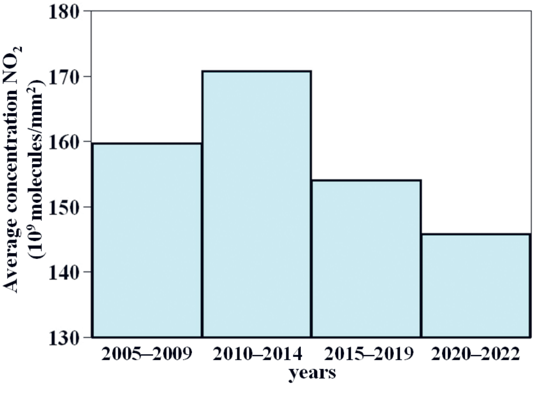

Fig. 3. Average values of concentration of nitrogen dioxide (NO_2) over territory of Ukraine according to AURA satellite data over 18 years for periods of 2005–2009, 2010–2014, 2015–2019, and 2020–2022

The obtained results showed that, since 2005 (when the monitoring of the state of NO_2 concentration in the atmosphere began), a gradual increase in the NO_2 content could be observed over the 18 years according to the data from the AURA satellite. During the period of 2005–2009, the concentration of NO_2 was $159.70 \cdot 10^9$ molecules/mm^2, and during the period 2010–2014, this was $170.77 \cdot 10^9$ molecules/mm^2; the increase between these periods was $11.07 \cdot 10^9$ molecules/mm^2. This can be explained by the fact that, during this period, heavy industrial enterprises were operating at full capacity in the country (Arcelor Mittal Kryvyi Rih, the Mariupol Metallurgical Plant named after Ilyich, MK Azovstal, etc.) Starting from the period of 2015–2019, NO_2 emissions dropped to $154.08 \cdot 10^9$ molecules/mm^2. Such a reduction was due to the fact that, after 2014 (when the annexation of the territory of Ukraine began), the invasion of Donbas (the largest industrial region of Ukraine) began to lead to the decline of industrial production and, accordingly, the decline in the dynamics of the nitrogen dioxide in the air. Over the past three years (2020–2022), the NO_2 concentration was $145.84 \cdot 10^9$ molecules/mm^2; the difference from the previous period was $8.25 \cdot 10^9$ molecules/mm^2. This period included a year of full-scale war in the country throughout the territory – especially in those territories where the main industrial enterprises were concentrated (the Dnipropetrovsk, Zaporizhzhia, Kharkiv, Donetsk, and Luhansk oblasts), where the direct active hostilities took place, or regular the artillery strafing's took place (aviation and long-range systems). For the 18 years of observations, the period with the maximum increase in NO_2 (2010–2014) was chosen for comparison. When compared to Period I (2005–2009), the increase was 6.48%; starting from Period III, a 9.77% decrease in NO_2 concentration began to be observed; and from Period IV, a 14.6% decrease could be observed relative to the base. In order to understand the quantitative characteristics of the changes in the air quality on a regional scale, the values of the concentrations of NO_2 in the atmosphere were calculated for the years of 2005–2021 and separately for 2022 (full-scale war in Ukraine) based on the data from the AURA satellite (Fig. 4).

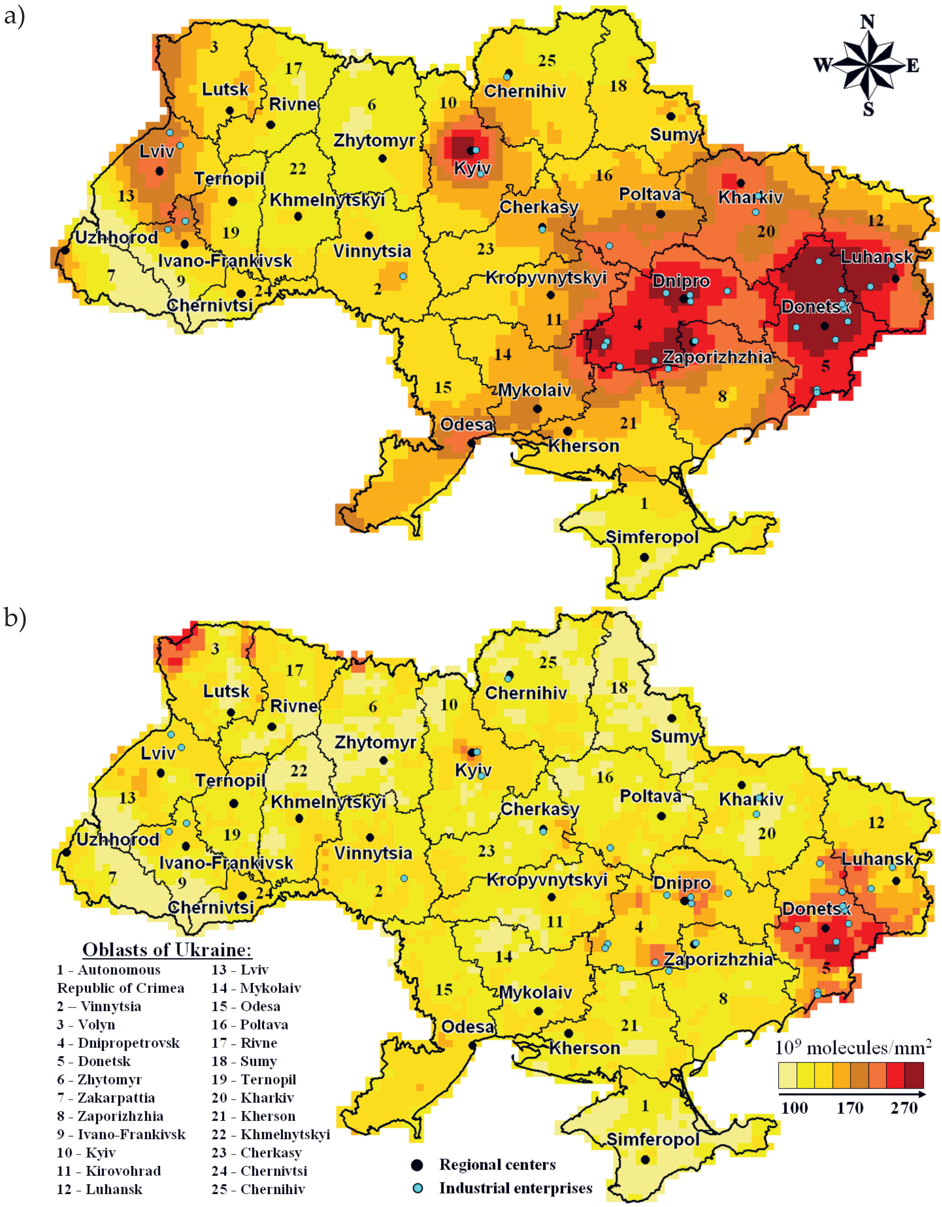

Fig. 4. Distribution of NO_2 concentrations over territory of Ukraine according to AURA satellite data: a) 2005–2021; b) 2022

In the territory of Ukraine, the average value of NO_2 concentration for the period of 2005–2021 was $160.78 \cdot 10^9$ molecules/mm^2; in 2022, this was $126.93 \cdot 10^9$ molecules/mm^2. The NO_2 concentration fell by 1.27 times (which was 21.5%). In 2022, the range of the air pollution by nitrogen dioxide did not change, but there were significant changes in the areas of each gradation. Table 1 calculates the areas of NO_2 pollution of the territory and defines four gradations of air pollution: slightly polluted, sufficiently polluted, heavily polluted, and excessively polluted.

Table 1. Areas of nitrogen dioxide (NO_2) pollution for various gradations for 2005–2021 and 2022 over territory of Ukraine

Gradations of pollution	Average value of NO_2 [$\cdot 10^9$ molecules/mm^2]	Area [km^2]			
		2005–2021		2022	
Slightly polluted	50–100	21,503	125,002	97,930	339,294
	100–125	103,499		241,364	
Sufficiently polluted	125–145	174,253	291,609	141,985	215,603
	145–170	117,356		73,618	
Heavily polluted	170–190	57,018	117,404	20,543	40,319
	190–225	60,386		19,776	
Excessively polluted	225–270	40,365	68,085	6642	6884
	270–380	27,720		242	

In 2022, there were significant decreases in the areas of three gradations: sufficiently polluted areas decreased by 1.36 times as compared to all of the previous years of the study; heavily polluted areas decreased by 2.91 times; and excessively polluted areas decreased by 9.89 times. At the same time, the areas of lightly polluted areas increased by 2.71 times. It should be noted that, in 2022, lightly polluted areas were spread throughout Ukraine (even in the industrial regions). The war, which has been going on for a year, did not manifest itself directly through hostilities but manifested itself through the shutdown of industrial enterprises, which were priority air polluters in Ukraine (particularly in large cities).

According to the spatial distribution of NO_2 concentration for the period of 2005–2021 (Fig. 4), industrial regions are shown to be up: Eastern (the Donetsk, Luhansk, and Kharkiv oblasts), Dnipro (the Dnipropetrovsk and Zaporizhzhia oblasts), Capital (the Kyiv and Chernihiv oblasts as well as the city of Kyiv), and Western (the Lviv and Ivano-Frankivsk oblasts). A ranking of the administrative oblasts of Ukraine was carried out by the degree of nitrogen dioxide (NO_2) pollution for the period of 2005–2021.

The next step was conducting the ranking of the administrative regions of Ukraine according to the determined gradations of pollution for the period of 2005–2021 (Table 2). This allowed us to determine the NO_2 contribution of each oblast to the air pollution in a regional aspect.

Table 2. Results of ranking of administrative regions of Ukraine for 2005–2021 by degree of NO_2 pollution according to AURA satellite data

No.	Oblasts of Ukraine	Average concentration of NO_2 [$\cdot 10^9$ molecules/mm^2]	No.	Oblasts of Ukraine	Average concentration of NO_2 [$\cdot 10^9$ molecules/mm^2]
1	Donetsk	277.85	14	Cherkasy	150.35
2	Dnipropetrovsk	246.05	15	Ternopil	135.35
3	Luhansk	205.64	16	Chernihiv	135.24
4	Kharkiv	193.12	17	Sumy	134.48
5	Zaporizhzhia	189.61	18	Vinnytsia	132.02
6	Poltava	169.38	19	Ivano-Frankivsk	127.11
7	Kirovohrad	167.57	20	Rivne	122.71
8	Mykolaiv	166.17	21	Chernivtsi	121.43
9	Kyiv	164.70	22	Khmelnytskyi	120.76
10	Kherson	158.30	23	Autonomous Republic of Crimea	117.30
11	Lviv	155.29	24	Zhytomyr	115.37
12	Odesa	152.24	25	Zakarpattia	101.54
13	Volyn	151.88			

The results of the data in Table 2 allowed us to group the administrative oblasts of Ukraine into four groups: Group 1 (2 oblasts), Group 2 (3 oblasts), Group 3 (14 oblasts), and Group 4 (6 oblasts). This made it possible to show a quantitative assessment of the total contribution of each of the groups over 17 years: for Group 1, the total contribution was $106{,}874 \cdot 10^9$ molecules/mm^2; for Group 2 – $120{,}028.70 \cdot 10^9$ molecules/mm^2; for Group 3 – $428{,}416.73 \cdot 10^9$ molecules/mm^2; and for Group 4 – $142{,}615.18 \cdot 10^9$ molecules/mm^2. This shows that the oblasts that were included in Groups 3 and 4 (which generally did not have enterprises with the "excessive pollution" gradations when taking the entire areas of the territories of the oblasts into account) had the greatest NO_2 contributions to the air pollution.

To assess the local NO_2 contribution to the air pollution over the entire territory of Ukraine, 33 enterprises that emitted the most pollutants into the atmosphere were taken according to the State Statistics of Ukraine (http://ukrstat.gov.ua). Of these, nine were located in the Donetsk oblast, eight in the Dnipropetrovsk oblast, two enterprises each in the Zaporizhzhia, Ivano-Frankivsk, Lviv, Kyiv, Luhansk, and Kharkiv oblasts, and one enterprise each in the Chernihiv, Cherkasy, Vinnytsia, and Poltava oblasts. Each of the listed enterprises was placed on the map according to its coordinates for the visualization (Fig. 4). Based on the satellite data, the quantitative values of the emissions of the average concentrations of nitrogen dioxide that were emitted by the industrial enterprises were calculated; these were the largest polluters (thermal power stations [TPS] and heavy industry enterprises), which are ranked by the degree of pollution and are listed in Table 3.

Table 3. Industrial enterprises of Ukraine that are largest polluters of environment in terms of NO_2 emissions into atmosphere

No.	Name of enterprise (by type)	Average concentration of NO_2 [$\cdot 10^9$ molecules/mm^2]	No.	Name of enterprise (by type)	Average concentration of NO_2 [$\cdot 10^9$ molecules/mm^2]
Thermal power stations (TPSs)					
1	Vuhlehirs'ka TPS	333.22	10	Kryvoriz'ka TPS	237.23
2	Slov'yans'ka TPS	332.40	11	Trypil's'ka TPS	224.40
3	Starobeshivs'ka TPS	318.95	12	Zmiyivs'ka TPS	205.71
4	Kurakhivs'ka TPS	310.92	13	Dobrotvirs'ka TPS	189.89
5	Zuyivs'ka TPS	301.5	14	Burshtyns'ka TPS	189.11
6	Prydniprovs'ka TPS	283.96	15	Kalus'ka TPS	177.33
7	Luhans'ka TPS	270.68	16	Ladyzhyns'ka TPS	154.94
8	Darnyts'ka CHP	269.15	17	Chernihivs'ka TPS	143.95
9	Zaporiz'ka TPS	251.54			
Enterprises of heavy industry					
1	Yenakiyeve Iron and Steel Works	331.07	9	Zaporizhzhia Metallurgical Combine "Zaporizhstal"	269.57
2	Avdiivka Coke Plant	324.34	10	PJSC Illich Steel and Iron Works	264.75
3	Dniprostal	310.01	11	PJSC Azovstal Iron and Steel Works	264.75
4	Dnieper Metallurgical Combine	307.77	12	Pavlohradvuhillya	232.13
5	Nikopol Ferroalloy Plant	304.28	13	Ukrtatnafta	205.48
6	Southern Mining and Processing Plant	289.00	14	LLC DV Oil and Gas Production Company	205.05
7	PJSC ArcelorMittal Kryvyi Rih	283.60	15	Shakhta Stepova	192.13
8	Alchevsk Metallurgical Complex	273.88	16	Cherkas'ke khimvolokno	167.82

According to the obtained results, almost all of the listed enterprises belong to the two classes of gradations (strong and excessive pollution); this allows us to state that the industry itself is the main polluter of NO_2 in the territory of Ukraine. Within these two gradations, the enterprises themselves were ranked according to their contributions to direct-point pollution. First of all, 17 thermal power stations (TPS) stood out based on the characters of their production; of these, 5 TPSs were singled out for their contributions to pollution that had maximum levels of pollution that were above $300 \cdot 10^9$ molecules/mm^2, 7 – from 200 to $300 \cdot 10^9$ molecules/mm^2 and 5 – from 140 to $200 \cdot 10^9$ molecules/mm^2. A significant contribution to nitrogen dioxide air pollution was made by 16 heavy metallurgy enterprises, which can be divided into two groups: Group 1 – 5 industrial enterprises with pollution levels that were above $300 \cdot 10^9$ molecules/mm^2, and Group 2 – 11 enterprises with levels from 167 to $300 \cdot 10^9$ molecules/mm^2. Considerations of the NO_2 pollution contributions of enterprises at the local level made it possible to understand the character of the regional nitrogen dioxide pollution.

4. Conclusions

In this research, an assessment of nitrogen dioxide was carried out using satellite monitoring (namely, on the basis of materials from the AURA satellite) at different scale levels from regional (territory of Ukraine) to local (industrial enterprises) for the multi-year period of 2005–2022. The obtained results made it possible to identify periods of growth and the decline in the concentration of NO_2. During the period of 2005–2009, the concentration of NO_2 was $159.70 \cdot 10^9$ molecules/mm^2, and during the period of 2010–2014, this was $170.77 \cdot 10^9$ molecules/mm^2; the increase between these periods was $11.07 \cdot 10^9$ molecules/mm^2. During the period of 2015–2019, the reduction of NO_2 emissions began – $154.08 \cdot 10^9$ molecules/mm^2 – and over the last three years (2020–2022), the concentration of NO_2 was $145.84 \cdot 10^9$ molecules/mm^2 the difference from the previous period was $8.25 \cdot 10^9$ molecules/mm^2.

Maps of the spatial distribution of NO_2 concentration were compiled within Ukraine for 2005–2021 and 2022. The maps were made using the same primary materials, which allowed us to compare the different regions of the country. The presentation of the materials in numerical form made it possible to use various mathematical methods for their processing as well as to combine the obtained results with the materials of other types of research.

The maps of the distributions of NO_2 concentration over the territory of Ukraine showed the uneven character of its distribution over the area, which was consistent with the distribution of the industrial and energy facilities within the country. Both composite maps show that particularly polluted areas within the country are located from west to east, with an advantage in the southeast.

The significant differences in nitrogen dioxide concentrations on the maps for 2005–2021 and 2022 were undoubtedly related to the military operations on the territory of the country. As a result of the war, many industrial enterprises and energy facilities stopped working.

Determining the distribution of NO_2 concentration at the level of oblasts was the cleanest on both maps: these were the Zakarpattia, Lviv, and Ivano-Frankivsk oblasts (which include the Carpathian Mountains and adjacent territories) as well as Crimea. Most of the Rivne, Volyn, Ternopil, Khmelnytskyi, and Vinnytsia oblasts were areas with low concentrations of nitrogen dioxide. This is clearly visible when both of the maps are compared. Moreover, the areas with low nitrogen dioxide contents increased on the 2022 map when compared to the 2005–2022 map; the only reason for this was the military operations. The Donetsk, Luhansk, Kharkiv, and Dnipropetrovsk oblasts, parts of the Zaporizhzhia, Kirovohrad, Poltava, and Mykolaiv oblasts, and the Lviv and Ivano-Frankivsk oblasts belong to the territories that were most polluted by NO_2 during the pre-war period. As is known, the largest industrial enterprises and thermal power stations of significant capacity are located within the specified oblasts; they are sources of nitrogen dioxide emissions.

Within the boundaries of most of the oblasts, the centers were characterized by elevated values of nitrogen dioxide content (as should be expected). During the pre-war period, the city of Kyiv and its surrounding area stood out; according to their values, the NO_2 concentrations were not inferior to the most polluted areas in the southeast of the country. According to data for 2022, the areas with low nitrogen oxide contents increased significantly within all of the oblasts; without a doubt, this was caused by the reduction of industrial work and the subsequent reduction of emissions. The NO_2 anomaly in the northwest part of the Volyn oblast (on the border with Poland and small in area and intensity) should be considered in particular. The anomaly is well-displayed on both maps; moreover, it is displayed more clearly on the 2022 map than on the 2005–2021 map. According to the available data, however, there are no industrial and energy facilities within the boundaries of the Volyn oblast that could cause the appearance of such anomalies. At that time, industrial enterprises were located in the territory of neighboring Poland; these were probably the sources of the pollution. Thus, the compiled map indicates the possibility of fixing the transboundary movement of pollution.

To determine the local anomalies in the nitrogen dioxide content, nitrogen dioxide emissions by industrial enterprises were calculated. Positive anomalies of nitrogen dioxide content that was emitted by enterprises coincided with the cities where they are located: Odesa, Lviv, and Ivano-Frankivsk. At the same time, cities such as Kharkiv, Dnipro, Donetsk, Zaporizhzhia, and Luhansk (which are located in the territory with a significant level of pollution) were not singled out separately. In 2022, all of these selected anomalies manifested themselves much less clearly but were still reflected (albeit by rather weak increases in NO_2 concentration values). According to the materials from the AURA satellite, it was generally established that stationary industrial sources play primary roles in the polluted effects on the atmospheric air in the cities and administrative oblasts as well as the entire territory of Ukraine.

Thus, the proposed satellite monitoring makes it possible to quickly control the content of harmful substances (particularly nitrogen dioxide) in the air. The obtained results can be used as additional information for decision-making, to prevent an increase in the level of pollution, and with the aim to improve the quality of atmospheric air and avoid its negative impact on public health. The data that was obtained in the research give us reasons to classify some areas of the territory of Ukraine (namely, the east) as critical in terms of atmospheric air quality. In these areas, it is necessary to create appropriate sanitary and protective zones and increase the levels of greening in the urban ecosystems. It is also necessary to modernize and improve systems for cleaning the gases that are emitted by industrial enterprises by replacing air filters in a timely manner.

Author Contributions

Lesya Yelistratova: conceptualization, investigation and methodology, supervision, formal analysis, data curation and visualization, writing – original draft, writing – review & editing.

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Artur Khodorovskyi: conceptualization, investigation and methodology, formal analysis, data curation and visualization, writing – original draft, writing – review & editing.

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