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Convergence between Increased Light Pollution and Urban Sprawl Dynamic in Poland (2012–2022)

Abstract: Urban sprawl is a nuisance – both economically and ecologically speaking. Among the causes of this nuisance is light pollution; both the scale of the light pollution and the spatial expansion of suburbs in Poland increased significantly during the period 2012–2022. The most significant light pollution occurs in urbanized areas in general; however, the scattered developments of suburbs make the problem of light pollution in these areas disproportionate to the population density as compared to cities. The research that is described below analyzed changes in the amounts of light that were emitted into the sky (radiance) as were calculated on the basis of observational data from the Suomi NPP meteorological satellite as well as housing production dynamics. Data regarding both radiance and housing production was acquired for communes and then aggregated to larger areas depending on the urban, suburban, or rural character of each commune. Then, the agglomeration areas were analyzed – distinguishing between urban centers and non-urban agglomeration areas (suburbs). Two convergence indices were analyzed: Spearman's rank correlation coefficient, and coefficient of determination R^2. It turns out that, in suburban areas, both indices returned much higher convergence rates between light pollution and housing construction than in the cases of the cities. The causes of this phenomenon need further research; nevertheless, two possible top-down solutions of this problem may be lighting masterplans and the modernization of lighting fixtures.

Keywords: light pollution, urban sprawl, nighttime lighting, urban light emission, data aggregation, housing production

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1. Introduction

Light pollution is another cost that is incurred due to urban sprawl. Urban sprawl generates both economic [1, 2] and ecological [2, 3] costs; in the latter case, we are talking about air, water, and soil pollution. These, in turn, are related to the broadly understood anthropogenic pressure that is caused by construction development in new areas [4, 5] and the emissions that are related to the daily commuting of suburban residents to city centers [6].

The convergence of light pollution and urban sprawl is already the subject of scientific research. Primarily, it has been pointed out that more urbanized areas means more outdoor light sources, which translates into increased amounts of light that are emitted at nighttime [7]. An analysis of the light pollution phenomenon that compares data from the end of the 20th and beginning of the 21st century showed that a significant increase in the brightness of the night sky concerns, among others, suburbs [8]. This is directly related to the development of residential construction in these areas; in turn, this is related to urbanization and the accompanying increase in light emissions [9]. The dynamic development of cities significantly affects the intensity of light pollution, which is a challenge for researchers who study the impact of urbanization on the natural environment.

Previous studies on light pollution have largely focused on either analyses of entire regions or analyses that have been limited to the administrative borders of cities; the problem of comparing the scale of this pollution between urban and suburban areas remains an underdeveloped topic in the literature. The studies by Zhou et al. [10] and Zhao et al. [11] omitted suburbs due to the difficulties in accurately measuring the levels of light pollution in these areas. This problem resulted from the limitations of the measuring instruments that were used and not from the assumption of the different characteristics of the phenomenon itself in cities and suburbs.

Other studies have suggested taking either smaller territorial units or entire metropolitan areas into account, which would allow for the more precise monitoring of the impact of urbanization on light pollution [12]. Analyses of night satellite images are also indirect indicators of the rate of urbanization, because the increases in light emissions into the atmosphere strongly correlate with the developments of buildings and infrastructure density [13].

During the COVID-19 pandemic, a reduction in light emissions was recorded due to reduced human activity in general [14]; the spread of suburbs is an obvious component of this human activity [15].

In 2023, the Light Pollution Think Tank (LPTT) published a report on light pollution in Poland [14], which stated that this phenomenon was common in the country and that its scale was increasing. The same report confirmed the abovementioned research results [15] regarding the decrease of light emissions during the pandemic period.

Light pollution itself is the emission of light that is emitted in a direction, amount, and time that are inappropriate to the lighting task [16]. One form of light pollution is the artificial illumination of the night sky that is caused by both the direct and indirect escape of light into the sky [17].

However, light pollution is not only the artificial illumination of the night sky; other forms of light pollution are as follows (Fig. 1):

– light trespassing (inappropriate direction to lighting task);
– over-illumination (inappropriate amount to lighting task);
– light clutter (excessive and competing bright lights in area that can cause visual confusion or distraction);
– glare (harsh brightness from light source that can cause discomfort or reduced visibility).

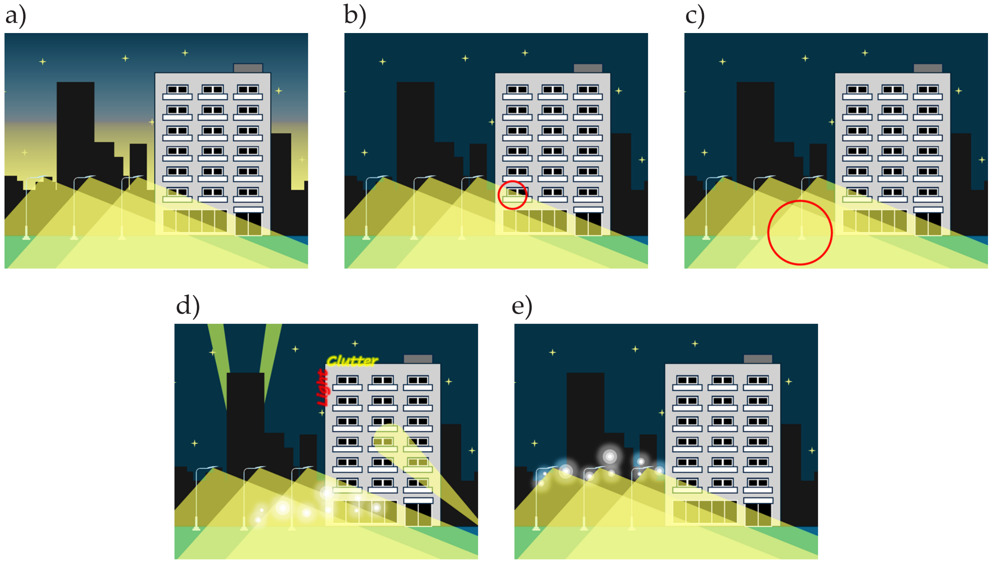

Fig. 1. Forms of light pollution:
a) urban glow; b) light trespassing; c) over-illumination; d) light clutter; e) glare

Therefore, light pollution does not only take the form of urban glow and make astronomical observations difficult [18, 19]; it also disrupts the circadian rhythms that regulate the functioning of living organisms [17]. Therefore, urban sprawl interferes with the natural environment in more than the obvious way (i.e., by occupying previously undeveloped areas); it is also the reason for the increased light emissions that negatively affect the inhabitants of the surrounding areas [20].

In the United States, for example, there is a visible trend of wealthier residents moving to the suburbs. By contributing to light pollution more intensively than poorer city dwellers (thus creating an even burden of light pollution), they deepen social inequalities [21].

As it turns out, not all types of buildings contribute equally to light pollution. Residential buildings are among those with a greater share of the emission of this pollutant [22]. According to the research results of Zheng et al. [23], residential buildings contribute more to light pollution in developed countries than other types of buildings do.

According to the research of Huang et al. [24], light pollution in suburbs is on a scale that is disproportionate to their population densities as compared to their adjacent cities. Despite the higher densities of population and buildings, more attention has been paid to lighting solutions in cities than in suburbs; as a result, the size and effects of light pollution are limited [24]. A larger amount of public space in cities with its clear boundaries and denser development makes the problem of light pollution in cities more controlled. Of course, the greatest pollution occurs in urbanized areas in general [25]; however, the scattered developments of suburbs means that the problem of light pollution takes on more dispersed forms there [24].

The European Statistical Office (Eurostat) analyzes the local administrative units in terms of population density and then divides them into three types: cities, towns and suburbs, and rural areas [26]. In the case of Poland, the local administrative units that are subject to the above typology are its communes. A comparison of the yearly data that was collected for Poland from the period of 2012–2022 showed the trend of the changes in the proportions between the individual types.

In 2012, 34.8, 24.6, and 40.6% of the population lived in cities, suburbs, and rural areas, respectively; by 2022, these shares changed by −0.3, +4.8, and −4.5 percentage points, respectively (Fig. 1). Greater differences were noted in the cases of the areas that were occupied by each of the three typological units. In the cases of towns and suburbs, there was an increase of 7.5 percentage points (Fig. 2); in the cases of cities and rural areas, however, there was no increase in the share in the country's area (or it decreased). Taking Eurostat's methodology in assigning municipalities to one of three types of spatial units into account [27], it can be concluded that suburbanization was a common phenomenon in Poland during the period of 2012–2022.

The typology of space that divides territorial units into cities, suburbs, and rural areas is also used by Statistics Poland (GUS). In 2022, FUAs (i.e., functional urban areas) were designated [28]; on their basis, the rural areas were then delimited [29]. In turn, agglomeration and non-agglomeration rural areas were distinguished, and both categories were then divided into those with high and low population densities.

Pollution emissions take on different characteristics in cities and suburbs. Air pollution varies depending on the availability of public transport and the share of network heating in a given area [30, 31]. It was assumed that light pollution can also take various forms and sizes depending on the types and densities of buildings. The research that resulted in this article examined the convergence and relationship between the phenomenon of light pollution (in the form of light emissions into the sky) and housing production. Both phenomena were analyzed separately in each of the typological units that were defined by GUS.

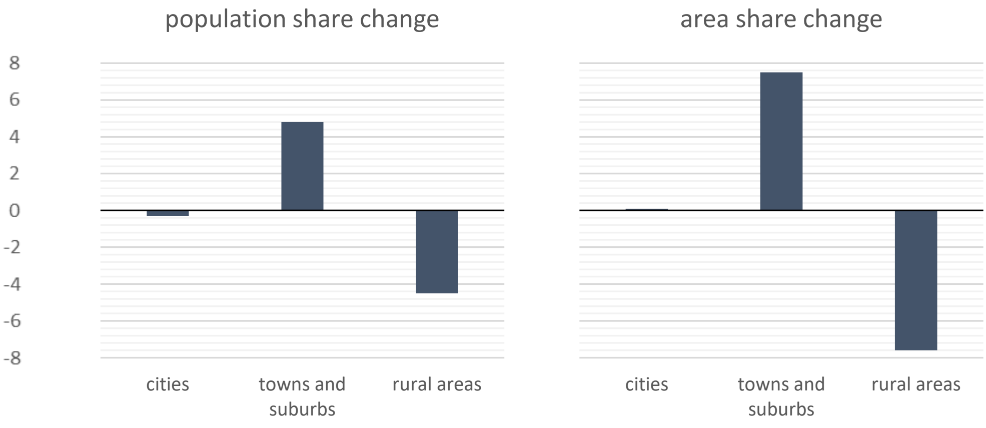

Fig. 2. Changes in shares of typological units in country's population and area (percentage points)

Source: own work based on Eurostat data

This paper is innovative in that it quantitatively compares light pollution levels in cities and suburbs and verifies the convergence of changes in light pollution levels with housing production.

The structure of the article is as follows: this introduction is followed by a part that describes the methodology of research, and it is further divided into the acquisition and processing of input data (i.e., data on light emissions and housing construction statistics in individual communes) and a description of the calculation process. Processing the data concerned aggregations to larger areas and determinations of housing production indicators, while the calculations focused mostly on the methods of comparing light emission data and housing construction statistics. Then, the comparison results are presented.

Finally, a discussion about prior research was included, followed by the conclusions that resulted from the research outcome. Possible directions for a deeper analysis of the issue were also proposed.

2. Methodology

2.1. Data

The 2023 LPTT report [14] analyzed two radiometric values that were seen as indicators of light pollution: radiance (the amount of light that was emitted into the sky), and luminance (the brightness of the night sky). The radiance values were calculated based on observational data from the Suomi NPP meteorological satellite, which is equipped with VIIRS (Visible Infrared Imaging Radiometer Suite) [14].

Based on the first of the values mentioned above, the change in the intensity of the light emissions into the sky was calculated; this compared the value from 2022 with the average value from the period of 2012–2021.

This change was calculated for each commune in Poland and then assigned to one of five classes:

– statistically significant decrease (below −20%);
– statistically significant decrease (−20 to −5%);
– statistically insignificant change (−5 to +5%);
– statistically significant increase (+5 to +20%);
– statistically significant increase (above +20%).

Due to the availability of only classified data, it was decided to aggregate the absolute minimum values of the intervals into larger units (as is described in the Calculations subsection).

In 2022, GUS designated functional urban areas (FUAs); these included cities and their commuting zones where the labor market was integrated with the urban centers. The integration of suburban areas with a city was evidenced by a minimum of 15% of the working people commuting to work in the city [28]. Based on the FUAs, GUS developed a typology of local administrative units (communes); i.e., the delimitation of rural areas (DOW) [29].

In DOW, GUS indicated six typological units: (I) large cities (voivodeship seats and other cities with more than 150,000 inhabitants); (II) other cities; (III) high-density agglomeration areas; (IV) low-density agglomeration areas; (V) high-density non-agglomeration areas; and (VI) low-density non-agglomeration areas. For the purposes of research, the topological units that were proposed by GUS were provided with acronyms and arranged in the following order (Table 1).

Table 1. Typological units according to delimitation of rural areas (DOW)

Typological unit	Description
dow1	Non-agglomeration areas – low density
dow2	Non-agglomeration areas – high density
dow3	Agglomeration areas – low density
dow4	Agglomeration areas – high density
dow5	Cities with fewer than 150,000 inhabitants
dow6	Large cities and seats of voivodeships

Source: own work based on GUS

Suburbanization occurs primarily in agglomerations [2, 32]; hence, the non-agglomeration areas (dow1 and dow2) were excluded from further considerations.

GUS also collects data on housing production; this can be expressed, for example, in the number of housing units that are put into use. In the Local Data

Bank (BDL), GUS divides the apartments that are put into use, among others, due to investor groups: individual, cooperative, for sale and rent, municipal, social rental, and company. In Poland, apartments that are intended for sale or rent are being produced (put into use) primarily by developers; hence, this category of investors will be called 'developers' in the following sections of this article.

The groups that were proposed by GUS can be divided in various ways. Two divisions of groups of investors are proposed below: (I) due to the investor's legal form (i.e., individual and institutional investors); and (II) due to the investor's business expectations (whether they intend to sell housing unit put into use or not; i.e., commercial and non-commercial investors) (Table 2).

Table 2. Investors' groups due to their legal forms and business expectations

Division I: individual/ institutional	individual	cooperatives, developers, municipal, social rental, company
Division II: commercial/ non-commercial	cooperatives, developers	individual, municipal, social rental, company

Source: own work based on GUS

Of the six groups of investors that were proposed by GUS, two delivered totals of 95–98% of the housing production during the period 2012–2022: individuals, and developers [33]. Referring to the above table (Table 2), these two groups of investors are at different poles of the classification: individual/non-commercial, and institutional/commercial. Therefore, the total housing production was analyzed; i.e., for all investor groups jointly, and separately for the individual investors and developers.

The described research analyzed, among others, the phenomenon of urban sprawl – a component of which was the housing development in suburbs [34–37]. According to the BDL data, within the administrative boundaries of cities during the period of 2012–2022 three out of four residential units were built in multi-family buildings. In rural areas, only every 12th apartment was built in multi-family buildings, while the remaining residential units were in single-family buildings. Based on the proportions that were described above, it was also analyzed whether any of the two basic types of residential buildings were related to the phenomenon of light pollution.

Taking the groups of investors and building types that were mentioned above into account, the following sections of this paper describe the analyses of five categories of housing production (Table 3).

Table 3. Housing production categories

Category	Description
all_total	all analyzed investor groups; all analyzed buildings types
all_SF	all analyzed investor groups; single-family buildings
all_MF	all analyzed investor groups; multi-family buildings
ind_total	group of individual non-commercial investors; all analyzed building types
dev_total	group of commercial institutional investors; all analyzed building types

2.2. Calculations

The data from the LPTT report [14], which concerned the changes in the radiance levels in the communes between 2022 and the average for the period of 2012–2021, was classified into five ranges in the source material; this is why the research that is described below did not have absolute data for each commune separately. Therefore, it was decided to aggregate the data for the individual communes into larger spatial units.

With the classified data, the minimum change in each class was assumed for each commune; i.e., −20, −5, 0, 5, and 20%. The aggregation of the light pollution data was executed in the following manner: the spatially continuous areas were identified in accordance with the definitions of the typological units that were proposed by GUS (Table 1); then, the weighted averages of the minimum radiance changes that were recorded in the communes that were located inside these areas were calculated in each area. The weight in this case was the area of each commune (Fig. 3).

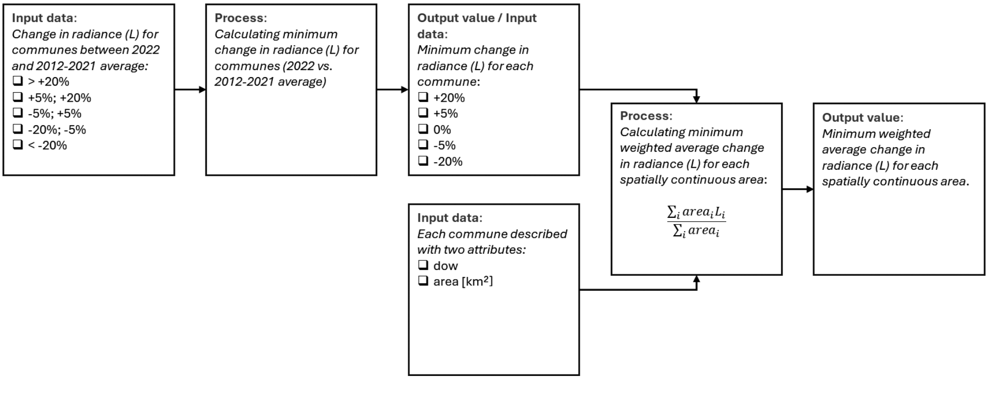

Fig. 3. Procedure of calculating weighted average radiance for each continuous region

Aggregated in this manner, the data was the input for further research on the correlation and determination indicators. As the light pollution data was first classified and then aggregated, removing any potential outliers could not be justified. Also, there was no prior proof whether the relationship between light pollution and housing production is monotonic, so Spearman's rank correlation coefficient was calculated for examining the correlation (as it is not sensitive to the above-mentioned issue). This also allowed for measuring both the direction and degree of correlation. In turn, the R^2 determination indicator showed how much one phenomenon is dependent on the other.

In order to compare the quantitative changes in the light pollution with the quantitative changes in the housing production in the individual typological units, four indicators of housing production were proposed.

The number of residential units that were completed in each of the above-mentioned housing construction categories was obtained (all_total, all_SF, all_MF, ind_total, dev_total). Then, the housing production index was calculated, comparing the result for 2022 with the average for the period of 2012–2021.

The fact that such an indicator may have been unreliable was taken into account. Especially in rural communes, the numbers of housing units that were put into use fluctuated significantly over the considered years; therefore, we risked the result being biased by relating the result from 2022 to the average from the period of 2012–2021. A low average result from 2012–2021 may have shown a disproportionately high percentage increase in 2022; conversely, a very low result from 2022 may have shown a disproportionately steep percentage decrease when compared to the period of 2012–2021.

Therefore, it was decided to calculate another indicator – the difference between the value from 2022 and the average from the period of 2012–2021. Then, two more indicators were calculated (i.e., the two that were described above divided by the surface area). Finally, four housing production indicators were analyzed: *delta_%*, *delta_%_area*, *delta_abs*, and *delta_abs_area*.

Indicator *delta_%*, i.e. percentage difference between value from 2022 and average from period of 2012–2021, is expressed by formula:

$$delta\_\%_{ij} = \frac{X_{n_{ij}}}{X_{m_{ij}}} - 1 \tag{1}$$

Indicator *delta_%_area*, i.e. percentage difference between value from 2022 and average from period of 2012–2021 divided by surface area, is given by:

$$delta\_\%\_area_{ij} = \frac{X_{n_{ij}} / X_{m_{ij}} - 1}{S_i} \tag{2}$$

Indicator *delta_abs*, i.e. absolute difference between value from 2022 and average from period of 2012–2021, is expressed by formula:

$$delta\_abs_{ij} = X_{n_{ij}} - X_{m_{ij}} \tag{3}$$

Indicator *delta_abs_area*, i.e. absolute difference between value from 2022 and average from period of 2012–2021 divided by surface area, is given by:

$$delta\_abs\_area_{ij} = \frac{X_{n_{ij}} - X_{m_{ij}}}{S_i} \tag{4}$$

where i is i-th DOW area, j – j-th housing production category, X_n – value for 2022, X_m – average value for period of 2012–2021, and S_i – surface area of i-th DOW area.

In the first phase of comparing the results of the changes in the values of the light pollution indicators with the housing production indicators, the correlation of the two mentioned variables was examined. This was intended to examine the strength and direction of the convergence of the two variables.

The typological units (dow3, dow4, dow5, and dow6) were arranged in ascending order: first, in terms of the value of the light pollution index, and then, in terms of the volume of the construction production in each of the five analyzed categories. Based on the data that was prepared in this manner, Spearman's rank correlation coefficient was calculated for each housing production category and each housing production indicator.

This coefficient is used to describe the strength of the correlation between variables; it takes values from −1 to +1 inclusive, where a result of −1 means that an increase in the value of one of the variables always results in a decrease in the value of the other variable, while a result of +1 means that an increase in the value of one of the variables results in an increase in the value of the other. A Spearman's rank correlation coefficient value of 0 means that no correlation is detected [38].

Spearman's rank correlation coefficient was calculated based on the following formula:

$$r_S = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2 - 1)} \tag{5}$$

where d_i is the difference between the ranks of the variables for the i-th observation, and n is the number of observations.

Spearman's rank correlation coefficient can be calculated on a set of values that do not have a normal distribution and within which there are outliers [38]. Hence, the coefficient values were calculated on the raw data; i.e., data that had not undergone any transformation.

In addition to Spearman's rank correlation coefficient, the coefficient of determination was also calculated; however, this required values of the variable whose distribution was close to the normal distribution. The vast majority of the input data (both the data that described the change in the radiance and the data regarding the development of the housing construction) was not normally distributed. In the vast majority of the cases, a more-or-less right-skewed distribution of the variable values could be observed.

A very popular method of data transformation that eliminates the right--skewness of a distribution is natural logarithm transformation; however, it has no use in the case of a set of values that includes those that are equal to or less than 0. When transforming data that contains values that are less than 0, the very popular BoxCox transformation [39] is also inapplicable.

Due to above-mentioned conditions, another method of data transformation was used to bring their distribution closer to a bell curve; i.e., Yeo-Johnson transformation. In this case, the fact that some of the values were less than 0 did not prevent the use of this transformation [40]. Yeo-Johnson transformation was performed in line with the following formulas:

$$y_i^{(\lambda)} = \begin{cases} \dfrac{\left((y_i+1)^{\lambda}-1\right)}{\lambda} & \text{where } y \geq 0,\ \lambda \neq 0 \\ \ln(y_i+1) & \text{where } y \geq 0,\ \lambda = 0 \\ -\dfrac{(-y_i+1)^{2-\lambda}-1}{2-\lambda} & \text{where } y < 0,\ \lambda \neq 2 \\ -\ln(-y_i+1) & \text{where } y < 0,\ \lambda = 2 \end{cases} \tag{6}$$

After normalizing the data, the coefficient of determination R^2 was calculated; its value indicated to what extent the dependent variable was determined by the examined independent variables [38]. In the calculations, the value of the light pollution index served as the dependent variable, and the values of the housing production indices served as the independent variables.

The coefficient of determination R^2 ranged from 0 to 1; the closer the value was to 1, the greater was the dependence of the dependent variable on the independent variable (38). This was calculated based on the following formula:

$$R^2 = 1 - \frac{SS_{res}}{SS_{tot}} \tag{7}$$

where SS_{res} is the sum of squares of residuals, and SS_{tot} is the total sum of the squares (proportional to the variance of the data).

Both coefficients' calculations were performed in MS Excel.

3. Results

The figure below (Fig. 4) shows the Spearman's rank correlation coefficient values. The correlation was calculated between the value of the light pollution index and the values of the housing production indices.

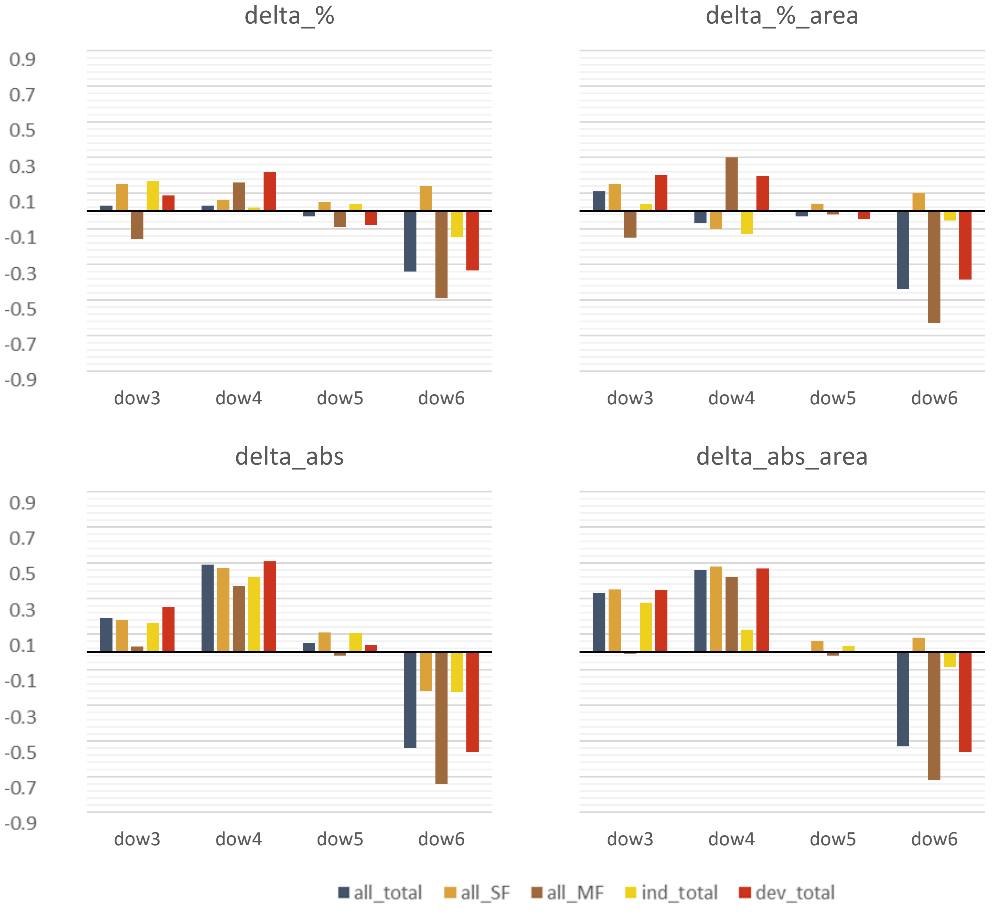

Fig. 4. Spearman's rank correlation coefficient values

Using the classification of correlation intensity according to Stanisz [41][2], those categories and indicators where at least a moderate correlation could be observed were searched for (i.e., $|r| > 0.3$).

In the case of the *delta*_% indicator, no results were obtained that showed a clear correlation. Only in the cases of the largest cities (dow6 topological unit) could moderate negative correlations be observed between the changes in the intensities of the light emissions into the sky and the dynamics of the housing productions. This could be observed in three categories: all_total, all_MF, and dev_total; in the other cases, however, the correlation was less significant.

[2] Degrees of correlation: $|r| = 0$ – no correlation; $0 < |r| \leq 0.1$ – very weak correlation; $0.1 < |r| \leq 0.3$ – weak correlation; $0.3 < |r| \leq 0.5$ – moderate correlation; $0.5 < |r| \leq 0.7$ – strong correlation; $0.7 < |r| < 1.0$ – very strong correlation; $|r| = 1$ – full correlation.

In the case of the *delta_%_area* indicator, the results similarly showed only moderate (in the all_total and dev_total categories) or strong (in the all_MF category) negative correlations in those areas with the largest cities.

The *delta_abs* indicator (the absolute difference in the number of residential units) returned results that indicated a clearer correlation of the two variables. In the case of the largest cities, there was a moderate negative correlation in three categories (all_total, all_MF, and dev_total). In the high-density agglomeration areas, there was a strong positive correlation for the dev_total category and a moderate positive correlation for the other four construction categories.

Also in the case of the *delta_abs_area* indicator, coefficient values that indicated a clear correlation could be observed. The housing production in the largest cities was negatively correlated with the increases in radiance; strong (total_total and dew_total) and very strong (total_MW) correlations could be observed. In the cases of the high-density agglomeration areas (dow4), a moderate positive correlation could be observed (all_total, all_SF, all_MF, and dev_total). A moderate positive correlation could also be observed for the low-density agglomeration areas (dow3) (all_total, all_SF, and dev_total).

The table below (Table 4) presents the average values of Spearman's rank correlation coefficient calculated on the basis of all four of the housing production indicators; those that returned $|r|$ values > 0.3 are shown in bold. The following investor categories turned out to be the most correlated: all_MF, dev_total, and all_total. According to the results below, these correlated negatively with the increases in light pollution in the largest cities yet positively in the suburbs. It is also worth noting that single-family buildings in general (all_SF) were more correlated with increases in light pollution than the buildings that were erected by individual investors for their own needs (ind_total) – also single-family buildings.

Table 4. Average values of Spearman's rank correlation coefficient

	all_total	all_SF	all_MF	ind_total	dev_total	all_total
del3	0.17	0.21	−0.07	0.16	0.22	0.17
del4	0.23	0.23	**0.31**	0.11	**0.35**	0.23
del5	−0.00	0.07	−0.04	0.04	−0.02	−0.00
del6	**−0.46**	0.03	**−0.65**	−0.13	**−0.46**	**−0.46**

The figure below (Fig. 5) shows the values of the coefficient of determination R^2. Its values were calculated by taking the value of the light pollution index as the dependent variable, and the independent variables were the values of the housing production indices.

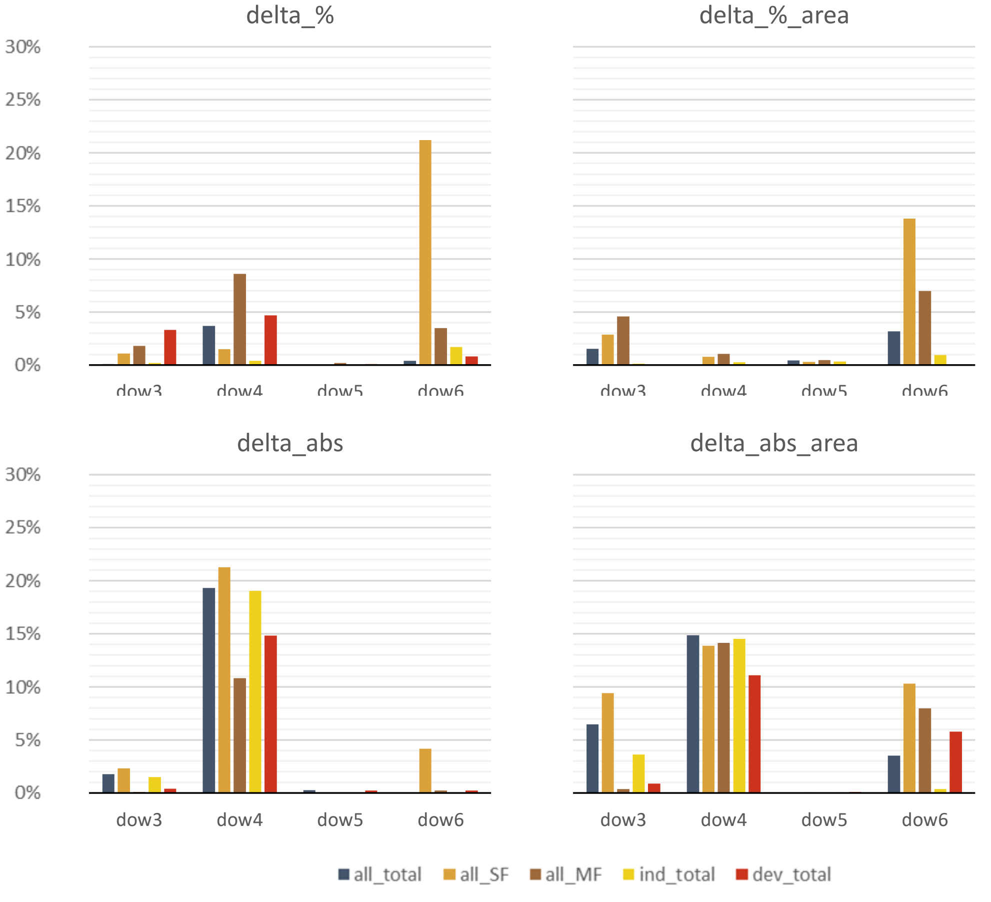

Fig. 5. Coefficient of determination (R^2) values

In the case of the *delta_%* housing production index, very low values of the R^2 determination coefficient were recorded; one exception, however, was the all_SF investor category in the dow6 topological unit. Here, the coefficient value exceeded 20%. The value of the coefficient exceeded 5% in only one other case (category: all_MF; unit: dow4).

In the case of the *delta_%_area* indicator, the coefficient of the determination values was even lower. The highest one was recorded in the same category and the same spatial unit as the *delta_%* indicator; the difference this time, however, was that the value of the determination coefficient did not even exceed 15%.

As in the case of Spearman's rank correlation coefficient, the *delta_abs* and *delta_abs_area* indicators returned significantly higher values. In the case of the dow4 topological unit, the coefficient of determination R^2 had the highest values; i.e., 10–21% for the *delta_abs* index, and 11–15% for the *delta_abs_area* index.

An impact above 5% on the changes in the level of light pollution in the dow3 typological units was recorded for the *delta_abs_area* indicator, in the all_total and all_SF categories, and in the dow6 typological units for the same indicator in the all_SF, all_MF, and dev_total categories.

4. Discussion and Conclusions

The research results indicated an average and above-average correlation between light pollution and housing production. In his research, Lamphar [12] stressed that there was a close relationship between light pollution and urbanization in general. He also pointed out that further analyses should be conducted on metropolitan or municipal levels (as was done in this paper).

Some researchers pointed out overestimations of light emissions in suburbs that were caused by data that was acquired from DMSP-OLS observations. In Zhou et al.'s research [10], suburbs were excluded from further considerations at the very beginning. In turn, Zhao [11] pointed out the so-called blooming effect, which caused light emissions to appear more extensive and brighter than was truly evident in suburbs. In the same paper, the authors concluded that it was the DMSP-OLS drawback to not refer to it in the same way as with the VIIRS data. In this paper, the latter's data was used.

A positive correlation (i.e., when one value increases [here, the value of the light pollution index], the other one increases [here, the housing production]) was especially visible in the suburban areas. A negative correlation could also be observed in the largest cities. It can therefore be concluded that ongoing housing production in suburban areas and, therefore, suburbanization leads to more light pollution. The above conclusion is consistent with the research results (Huang, Ye, Jin, and Liang, among others [24]).

For all of the housing production indicators that were analyzed, the positive correlation with light pollution in the suburbs (dow4 and dow3 typological units) outweighed the negative correlation. Those indicators for avoiding biased results indicated the particularly clear positive correlation of the two analyzed values. Also, the average values of the Spearman's rank correlation coefficient levels were the highest for the suburban areas.

The smaller share of public spaces than in cities as compared to private and semi-private spaces means that the phenomenon of light intrusion into areas that should not be lit is less controlled in the suburbs [42]. Also, less-developed areas (built up not as densely as cities) then require a larger number of light sources (i.e., risking more light to be emitted) or lighting fixtures with wider light distributions; the latter generates the risk of the so-called ULOR (upward light output ratio) (i.e., light emissions above the lamps into the sky) [43, 44].

The largest cities (typological unit dow6) recorded the highest housing production and relatively low increases in the light pollution index. This was probably related to the fact that, in recent years, local governments have been paying special attention to solutions that have allowed them to reduce the light pollution problem (e.g., lighting masterplans) [45]. In many cities, old high-pressure sodium lighting fixtures have been massively replaced with LEDs [46]. It is also important that the VIIRS instrument does not detect visible radiation that is shifted toward ultraviolet – an important component of some LED sources [14]. This requires further research.

Assuming the development of housing in suburban areas as one of the components of suburbanization processes, we can conclude that suburbanization contributes to increases in light pollution. Possible top-down initiatives that would help reduce the light pollution scale could be strategic documents like lighting masterplans [45]. Another way to reduce light pollution is modernizing the lighting fixtures – as some research has shown that simple improvements of fixture geometries can significantly reduce the occurrence of excess light [47].

There are several possible directions for further analyses of the issue of the convergence between light pollution indicators and housing production indicators (as are presented below):

- The described analyses compared the data from 2022 with the average from the period of 2012–2021. In many communes, housing production is subject to significant annual fluctuations; data aggregation to larger areas would certainly smooth these out, but it would be best to compare two longer periods (both in terms of light pollution indicators and housing production indicators); e.g., 2012–2016 and 2017–2021.
- The delimitation of the study area that was proposed by GUS (i.e., the delimitation of rural areas) was used. These could be further divided into areas with the highest dynamics of housing production within the suburbs; thus, those areas where housing production was actually on the largest scale would be identified.
- The research results showed that the single-family buildings that were constructed by all types of investors combined were more correlated with the increase in light pollution than those buildings that were constructed by individual investors (probably exclusively single-family buildings). It is therefore worth analyzing the impact of this type of development separately for individual and institutional investors.
- Finally, it should be noted that the data on light pollution levels certainly deserves further research. This could be carried out based on the data from several research instruments; i.e., based on VIIRS data supplemented with data from another instrument that recognizes short-length visible radiation.

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Declaration of Competing Interest

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Data availability

All input data analyzed in this paper are publicly accessible.

Use of Generative AI and AI-assisted Technologies

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