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THE DEGREE OF GREENERY IN LODZ CITY, POLAND – CLEARING UP DISCREPANCIES BETWEEN OFFICIAL STATISTICS AND SATELLITE DATA

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ABSTRACT

Motives: According to public statistics guidelines, areas officially classified in Lodz city as urban greenery include only forests, parks, lawns, squares and cemeteries. Areas of so-called unsealed greenery are omitted, which, however, have a great positive impact on improving the living conditions of the population. By taking information from satellite images and comparing them with official data, we have received a closer to the reality picture of the city, which is much more better than it would appear from official statistical data. Another dimension which the study addresses is the uneven distribution of greenery of a certain quality in individual units of the city.
Aim: Comparing these data with the fact that the distribution of places of residence is also uneven, an attempt was made to assess the accessibility of green areas for the inhabitants of Lodz city.
Results: There are much more green spaces, similar in terms of vegetation abundance to the official green spaces. That means the city is underestimated when talking about the degree of greenery.

Keywords: NDVI; urban greenery; Landsat; urban development

INTRODUCTION

Greenery is an important component of urban space, as it performs a number of very important functions, such as protection against air pollution, maintaining air humidity, mitigating extreme temperatures, reducing noise, while also producing a positive aesthetic impression (Białobok, 1976; Haber & Urbański, 2005; Łukasiewicz A. & Łukasiewicz S., 2016). Green areas also increase the level of satisfaction from living in their vicinity (Wu et al., 2019). Unfortunately, however, there is less and less high-quality greenery in urban areas (DeFries et al., 2010; Konijnendijk, 2003). Nowadays, despite the fact of increasing prices for the space in cities, local governments are more aware of the need for ensuring adequate open space for public use (Sustainable Development Goals). Those areas should be covered by the greenery.

According to currently binding legal acts in Poland, urban green areas are areas within the boundaries of arranged green space performing public functions, such as parks, lawns, promenades, boulevards, botanical gardens, zoos, playgrounds and historic gardens, cemeteries, greenery accompanying roads

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in developed areas, squares, historic fortifications, buildings, landfills, airports, railway stations and industrial facilities (Act, 2004). Such areas are included in official statistics, with the surface area being the main measure of the amount of green resources in a city. In practice, however, it appears that the adopted method of determining the degree of greenery in cities does not fully reflect the actual state of affairs, as there are many green objects in the urban fabric that are not taken into account, and yet perform a number of important functions related to greenery. This is the greenery found in developed plots, industrial and post-industrial areas (Cudny, 2011), along roads and watercourses, and others. What is more – the official data takes different aspect when it came to the classification (e.g function, majority land cover).

The aim of our study is to assess the size of greenery resources (in terms of surface area and quality) in the area of Lodz city (Łódź in Polish, the capital of province and also the 3rd largest city in terms of number of inhabitants in Poland) using publicly available satellite data from the Landsat 8 mission and the NDVI index derived from it, and to compare them with official urban greenery statistics. Based on the NDVI distributions, characteristic boundaries of the range of values for this index were calculated for areas considered as parks, lawns, forests etc. In this way, the different functional areas of the city have been characterised in terms of their greenery and population density. These areas were compared with the whole city, and then the differences between the individual types of areas were presented.

LITERATURE REVIEW

In many scientific works, the NDVI, Normalized Difference Vegetation Index (Deering, 1978; Jackson & Huete, 1991) was used as a measure of the degree of vegetation development in the studied areas. An important feature of the NDVI is its relationship with both the quantity and quality of greenery in a given area (Jarocińska & Zagajewski, 2008; Jarocińska, 2011). If the pixel of an image consists of objects of different reflectance (e.g. buildings, roadway with asphalt or concrete surface, tree crowns, gardens and lawns), then the NDVI is the resultant of the NDVI coefficients of the individual features, weighted by their share in the pixel area (Wirth et al., 1987). To some extent, the NDVI also reacts to the vertical structure of plant complexes – it is higher in areas with extensive, multi-storey vegetation (Krukowski, 2018). The NDVI can be used in analysing both aerial and satellite images, in assessing the amount of plant biomass at different spatial scales, from individual arable fields to global vegetation zones (Tucker, 1979; Wang et al., 2011), recognition of vegetation (Wang et al., 2009) and its condition (Lhermitte et al., 2010; Kopańczyk & Fitrzyk, 2016), crop maturity analysis (Jackson & Huete, 1991; Panda et al., 2010), the LAI – Leaf Area Index (Colombo et al., 2003), the amount of radiation absorbed by plants through photosynthesis (Badgley et al., 2017), biomass, phenological studies (Lüdecke et al., 1996; Zarzecki & Pasierbiński, 2009; Yan et al., 2018), water stress (Niedzielko et al., 2012), and many others. Nouri et al. (2014) used high resolution satellite images from WorldView-2 mission to determine the relationship of the intensity of field evaporation (evapotranspiration) between areas classified as urban green areas and green areas designated on the basis of the NDVI index, consequently determining the level of water stress for classified green areas and those designated on the basis of satellite images. The NDVI allows to differentiate land cover within agglomerations, which could often be considered (in other studies) as homogeneous, such as meadows (Kosiński et al., 2008; 2012; Kosiński & Kozłowska, 2003), which indicates high sensitivity of the index to plant cover diversity. These results are to some extent linked to the observation that the variability of the NDVI in an area covered by natural vegetation shows a greater correlation with climatic conditions than in areas of intensive human use (Musiał, 2009). The above-mentioned features of NDVI mean that it is often used in urban space studies (Gupta et al., 2012).

Different authors define the NDVI limits in different ways in order to distinguish vegetation-covered areas from others located in Poland. Kubalska

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and Preuss (2014) used digital aerial photographs (with 10 cm spatial resolution) and aerial laser scanning data (density 15 points m^{-2}) to take stock of green areas in Wrocław city, Poland. They adopted a minimum value of NDVI≥0.1 calculated from the pixels of an orthophotomap made with the use of an infrared channel (the so-called CIR – Color InfraRed). Krukowski et al. (2016) and Krukowski (2018) used IKONOS 2 images and decided to separate two classes of urban greenery: high and low. The first step was to adopt the NDVI>0.2 threshold to separate the vegetation, then the training fields for the two previously mentioned classes were determined and a supervised classification of green areas was performed. They observed higher values of the index for high vegetation, therefore they corrected the threshold discriminating this vegetation to the value of NDVI=0.35. Będkowski and Bielecki (2017) evaluated the availability of greenery based on the NDVI calculated from the Landsat 8 image. A large part of the city was characterised by index values between 0.2–0.3. It has been found that these are areas of the city where development is accompanied by well-developed greenery. Worm et al. (2019) adopted a low NDVI threshold of 0.1 for the purpose of distinguishing plant cover in the city of Lodz on the basis of a CIR aerial orthophotomap. The same boundaries in the study of urban vegetation in the Ursynów district of Warsaw were adopted by Pyra and Adamczyk (2018). For the purposes of analysing vegetation, understood as an element of the Green and Blue Infrastructure, Pluto-Kossakowska et al. (2018) assumed that the optimum range of NDVI values is <0.2, 1> when using an aerial CIR orthophotomap, and <0.5, 1> for Sentinel-2 images. Michałowska and Hejmanowska (2008), on the other hand, calculated the NDVI differences between 1979 (Landsat MSS) and 2000 (Landsat +ETM) to show changes in plant cover in the area of the Słowiński National Park, and concluded that the value in the range of -0.41 to +0.41 means areas with minor changes. Tomaszewski et al. (2011) assumed that MODIS pixels with an NDVI value lower than 0.3 represent areas without vegetation, while those with a value above 0.7 represent areas with intensive vegetation. Values in the range 0.3 < NDVI ≤ 0.7 are related to partial plant cover.

NDVI values are generally calculated with precision to two decimal places – e.g. Walker et al. (2012) in their study if green cover in North American and Eurasian Arctic transects, Robinson et al. 2017 in their study of the variability of NDVI values over 30 years based on image data from three different Landsat missions (5, 7 and 8).

The experience of many authors shows that it is not possible to indicate unambiguously how to interpret a given NDVI level, or with which forms of land cover it can be associated. It is necessary to check the applicable threshold values experimentally each time, in order to distinguish between plant cover and other forms, and to demonstrate the diversity within the vegetation.

In addition the NDVI indicator can be used as one of the image channels along with selected other images, e.g. for classification purposes (Pyra & Adamczyk, 2018). Supervised and unsupervised classification based on pixels in Pléiades images were tested by Trisakti (2017), who achieved high accuracy using a combination of the NDVI vegetation index and blue channel, while Sulma et al. (2016), based on NDVI spectral indices, NDWI (Normalized Difference Water Index) and MSAVI (Modified Soil Adjusted Vegetation Index), distinguished vegetation covered areas from other urban areas of Jakarta (Indonesia) with an overall accuracy of 86%.

NDVI can be calculated on the basis of image data from many satellite systems. Due to the different spatial, spectral and radiometric resolution of these systems, as well as to the variability of natural conditions between sometimes even close dates of images, variability of the index values determined is inevitable. This is particularly true for comparisons of individual observations, but as shown (Turlej, 2009), the differences between the results averaged over certain time periods are insignificant (approximately 0.1 NDVI). This gives rise to the use, if necessary, of different systems (after appropriate transformation of their resolution parameters).

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The share of green areas can be one of the important indicators (environmental dimensions) used, in addition to social and economic dimensions, in analytical analyses of the sustainable development of a city (Szarek-Iwaniuk, 2021).

MATERIALS

Land use and land cover databases used in Poland

The most important repositories presenting geospatial data in Poland are: Land and Property Register (EGiB), Topographic Object Database (BDOT), General Geographic Object Database (BDOO) and thematic maps created by local geodesy centres, e.g. greenery map according to the Lodz Centre of Geodesy – ŁOG (Table 4). Databases are a public resource, representing the type of land use in terms of functions.

Unfortunately, these databases are not consistent. Data from individual sources use different classification systems and are inconsistent in spatial terms (e.g. recreational areas in the LPR base, forest or bush areas in the TOD base or a park in the LCG urban greenery map that cover the same fragment of terrain but differ in terms of individual boundaries – Fig. 1).

The study used data from the Lodz Centre of Geodesy (LCG), as well as the LPR database, satellite images and demographic data from the voter registry.

Data of the Lodz Centre of Geodesy (LCG)

As part of its tasks, the Lodz Centre of Geodesy creates cartographic studies showing green areas within the administrative boundaries of the city of Lodz.

The geodetic data are the basis for statistics on the size of green areas reported in the state statistics, i.e. in the yearbooks of the Statistics Poland and in the Local Data Base (Fig. 2).

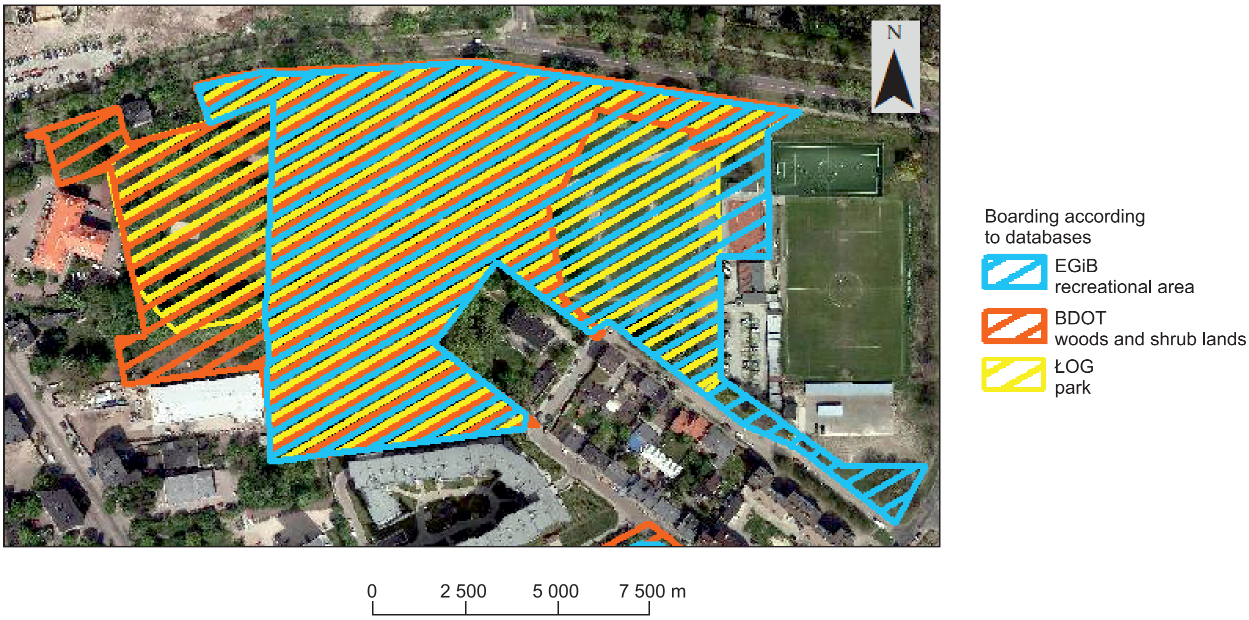

Fig 1. Comparison of boundaries of green areas according to different databases (EGiB = Land and Property Register, BDOT = Topographic Object Database, ŁOG = Lodz Centre of Geodesy)
Source: own preparation based on BDOT.

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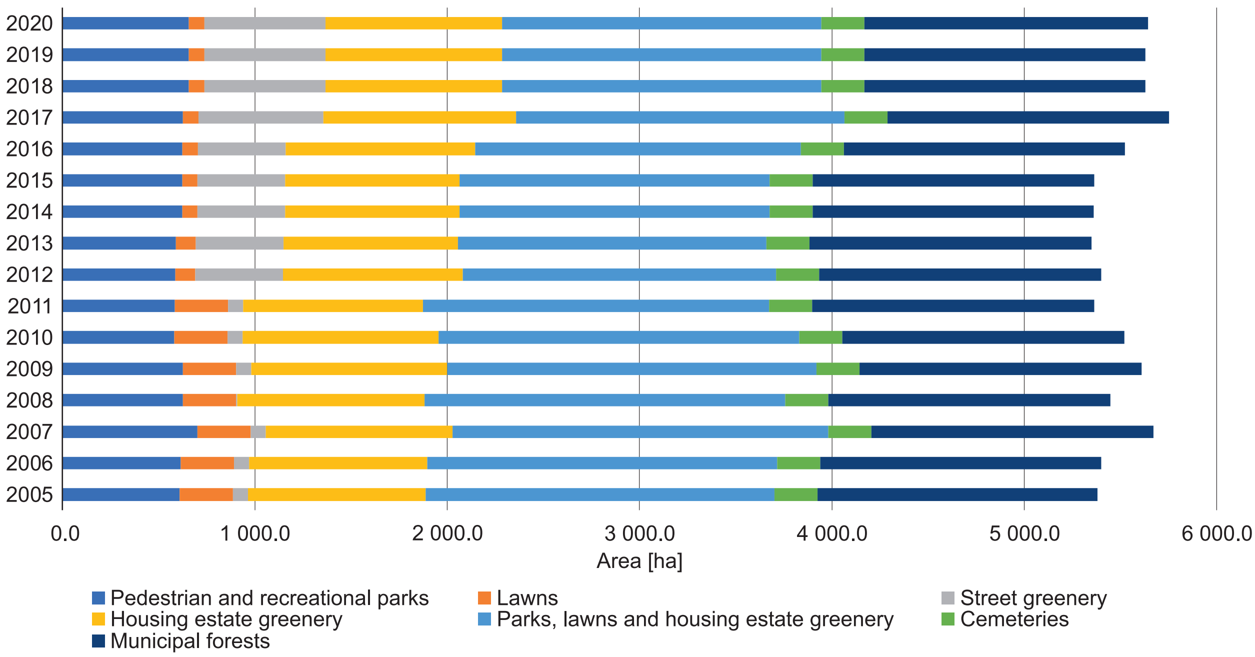

Fig. 2. Greenery in Lodz in 2005–2020 according to the Statistics Poland (Local Data Bank)
Source: own preparation based on CSO data.

Land and Property Register (LPR)

The LPR database primarily contains information on properties collected using terrain or photogrammetric surveying (Borsa et al., 2017). It is used in the performance of tasks in the field of economic planning, spatial planning, tax and benefit assessment, marking properties in land and mortgage registers, public statistics, and property management. The LPR data are used, among others, by tax authorities, as well as local government units (municipalities) for the purpose of spatial inventory of the area they cover (Notice, 2019). The LPR includes information on the location, boundaries, surface area and types of land use (Table 1).

Table 1. Types of land use according to LPR, their area and share in the city of Lodz

Type of use according to LPR	Surface area [km^2]	% of the city
1	2	3
Residential areas	46.17	16.00
Industrial areas	13.02	4.51
Other built-up areas	24.36	8.44
Urbanised undeveloped areas or under development	10.24	3.55
Built-up agricultural land	6.34	2.20
Recreational areas	10.95	3.79
Roads	30.84	10.69
Ecological use	0.91	0.31
Mining land use	1.07	0.37
Forests	24.69	8.55
Wooded and bushed land	3.77	1.31
Wooded and bushed land on agricultural land	0.11	0.04
Wasteland	1.23	0.43

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cont. Table 1

1	2	3
Pastures	6.66	2.31
Arable land	92.60	32.08
Orchards	2.57	0.89
Other communication areas	2.78	0.96
Railway areas	7.11	2.46
Land reserved for the construction of public roads or@railway lines	1.08	0.37
Miscellaneous land	0.34	0.12
Land under ditches	0.27	0.09
Land under surface water flowing	1.21	0.42
Land under surface water still	0.14	0.05
Land under ponds	0.19	0.06

Source: Lodz Centre of Geodesy (2018).

Population data

The population data necessary to carry out this study comes from the electoral register of voters of 30 June 2016 (UMŁ).

The distribution of the population was calculated as follows:

1. On the basis of vector layers of the Land and Property Register and information about the area of building outlines and the number of floors, the total area of all floors of each residential building in the city was determined.
2. The number of inhabitants in each of the 36 administrative auxiliary units of the city of Lodz was determined. Necessary data came from the Lodz Centre of Geodesy (vector data containing the boundaries of auxiliary units) and from the register of voters the Lodz City Hall (number of inhabitants per individual housing estate).
3. The size of the housing space per capita in individual administrative auxiliary units was calculated. The obtained values ranged from 35.06 m^2 to 115.57 m^2 per capita[1].
4. On the basis of the index value set out in point 1 and point 3, the approximate number of inhabitants of each residential building was determined.

The allocation of the number of inhabitants to the primary fields was made taking into account the relevant shares of buildings contained therein. Based on the above calculations, the map shows the distribution of population in Lodz (Fig. 3), and as a consequence, the spatial ratio of population distribution to areas designated as greenery on the basis of satellite images is also presented.

Satellite data

We use the Landsat 8 satellite scene from 3 July 2015 (path 189, row 024), obtained from the US Geological Survey (EarthExplorer). At the time the study was being carried out, it was the latest available image from the full vegetation season, on which the area of Lodz was not covered by a layer of clouds. Spectral bands 4 (Red) and 5 (NIR) were used to calculate the NDVI (Rouse et al., 1973), showing both the quantity and quality of greenery (Forster, 1982) in a given location, according to a classic formula:

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{Red}}{\mathrm{NIR} + \mathrm{Red}}$$

Since the image of the city of Lodz was entirely within the scope of the scene and no comparisons with other cities were planned, no sun and atmospheric correction of the images was made. The data down-

[1] For comparison, in 2002, the average floor area of an apartment in Lodz was 60.7 m^2 (20.5 m^2 floor area per capita). One flat was inhabited by 2.95 people and one chamber by 0.84 people (Parysek, 2004). In the years 2011–2016, according to the Central Statistical Office (Yearbook, 2015), the average floor area of a flat in Lodz was 53–54 m^2, with 27–28 m^2 per person. When comparing the indicators, one should remember about changes in the number of inhabitants of the city (725,055 in 2011 and 696,503 in 2016).

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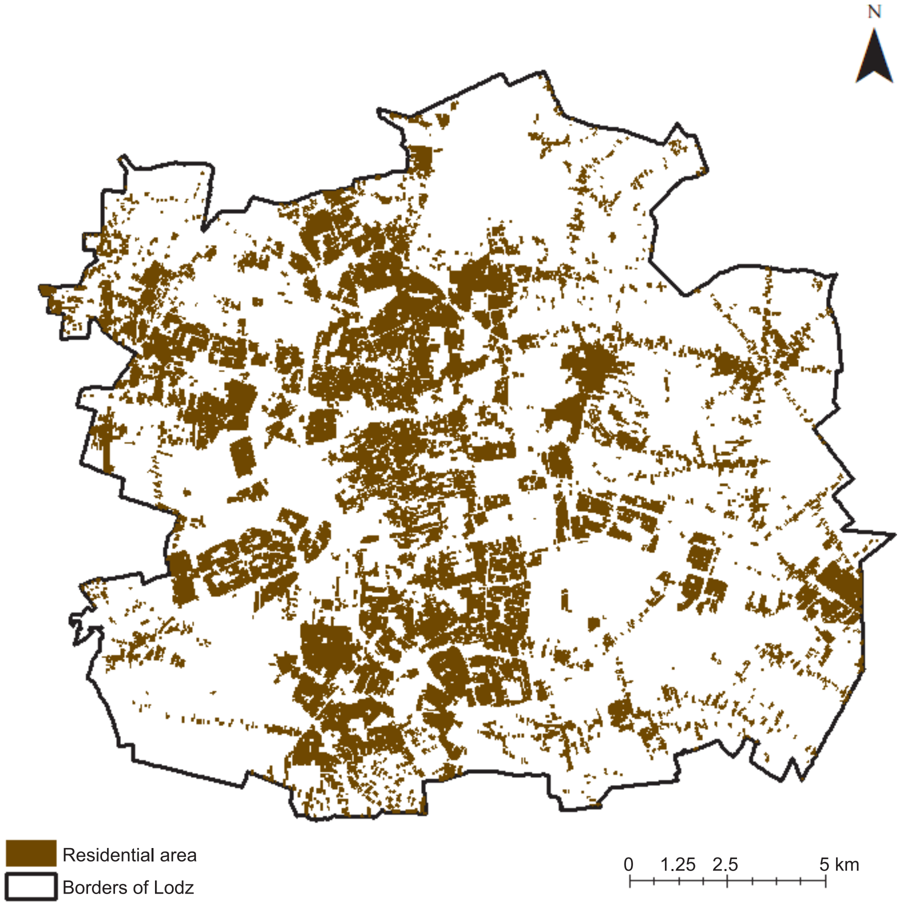

Fig. 3. Population distribution in Lodz
Source: own preparation based on the electoral register of voters (2016).

loaded using the Earth Explorer USGS browser has a topographic correction (USGS, 2020). The calculated NDVI values were between -0.18 and 0.63 (Fig. 4).

In an area covered by a single pixel, there are usually many different forms of land cover/development, not just greenery (Wirth et al., 1982; Kressler et al., 2000). In this case, the recorded NDVI value is the weighted average of the index value of all objects in the pixel area, with the weight being the share of the area of these objects in the pixel area (Figures 5–6):

$$\mathrm{NDVI} = \sum_{i=1}^{n} a_i \mathrm{NDVI_i}$$

$$\sum_{i=1}^{n} a_i = 1$$

where:

a_i – the share of the i-th object in the pixel area,
$NDVI_i$ – NDVI value of the i-th object located in the pixel,
n – number of forms of land cover/use.

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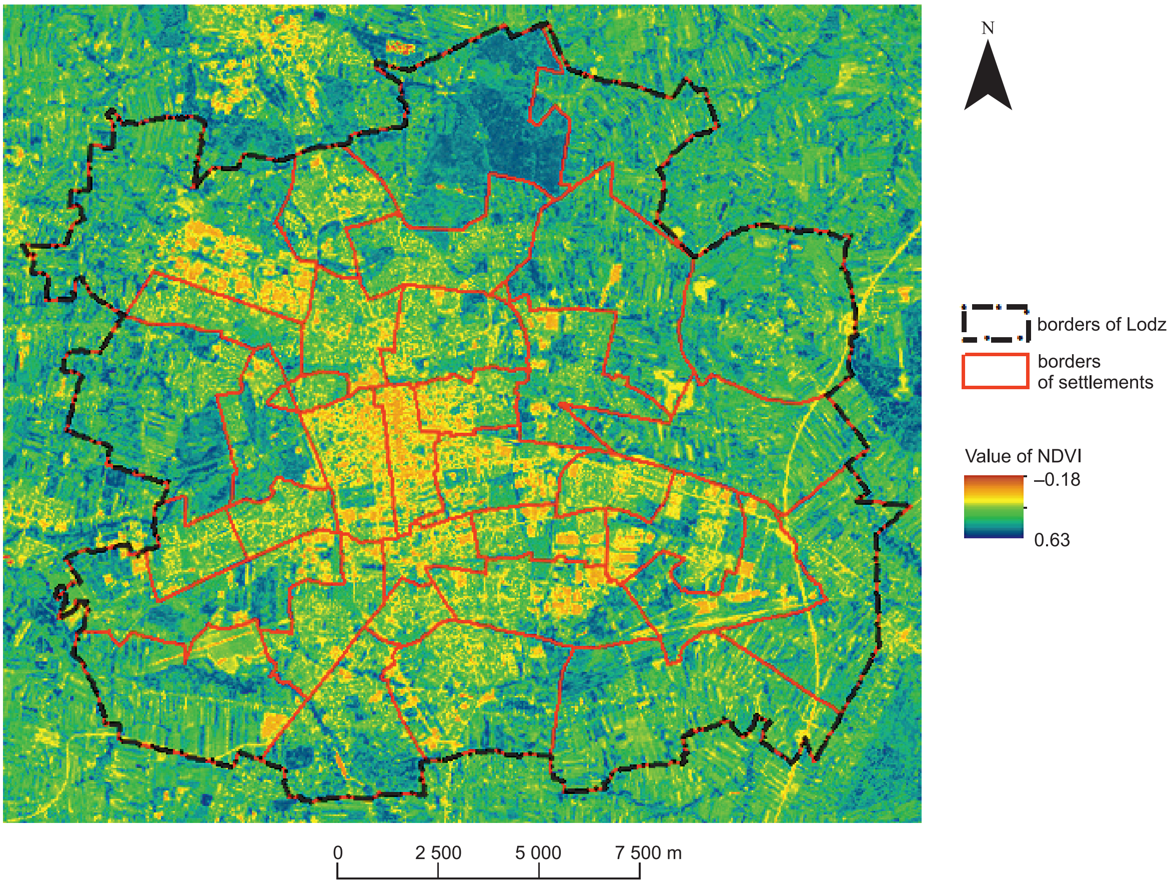

Fig. 4. NDVI for the area of the city of Lodz in the raster 30 × 30 m
Source: own preparation based on Landsat 8 image.

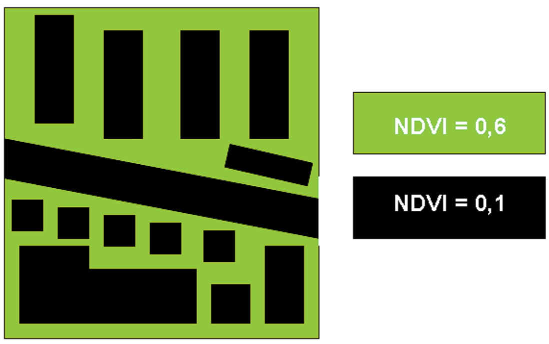

Fig. 5. Method of establishing NDVI values for areas composed of objects with different NDVI values. If the share of built-up areas and green areas are equal (50% each), the NDVI for the whole area is 0.35
Source: own preparation.

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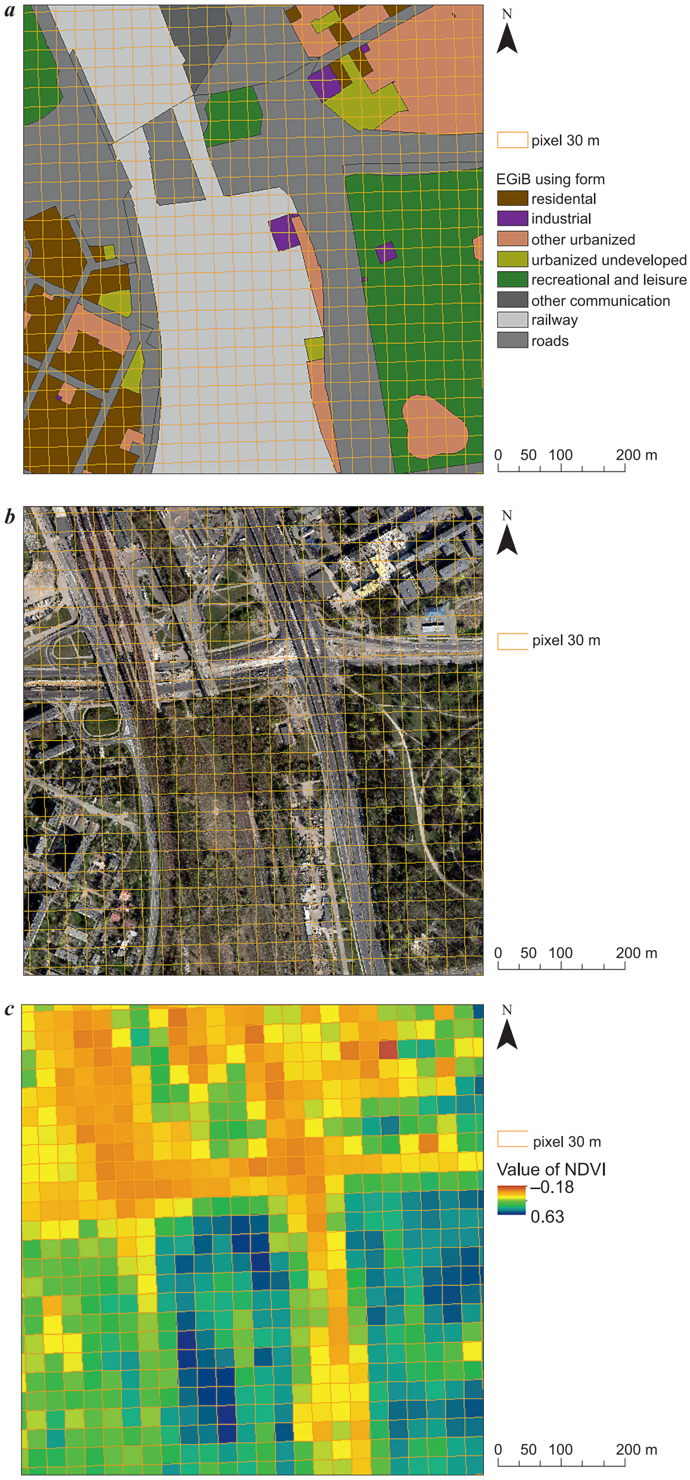

Fig. 6. Forms of land cover and registered NDVI values in pixels 30 × 30 m: a) objects according to LPR database, b) fragment of RGB composition of orthophotomap and grids of Landsat 8 image (30 × 30 m), c) calculated NDVI values

Source: own preparation based on EGiB, orthophotomap and Landsat 8 image.

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METHODS

NDVI of selected functional areas of the city

Areas classified as green areas we focused on, include forests, parks, squares, lawns and cemeteries (Fig. 7, Table 2). The share of these green areas in the total city area is 10.50% (30.77 km^2). They are largely covered with vegetation, but not fully, which is reflected in their average NDVI values (Fig. 8).

Table 2. The green areas in Lodz

Name	Area [km^2]	Share in the city area [%]
Forests	20.19	6.89
Parks	7.41	2.53
Lawns	0.94	0.32
Cemeteries	2.05	0.70
Squares	0.18	0.06
Total greenery	30.77	10.50

Source: own preparation based on LCG data.

Apart from the official greenery, there are many other areas with well-developed vegetation in the city, which successfully perform many important functions. For the precise characterisation of greenery resources, it is therefore necessary to also take into account the vegetation associated with undeveloped areas, i.e. areas called open according to Cieślak (2006) and residential and industrial development, traffic routes, watercourses, post-industrial wastelands, mines, etc. For a full balance, greenery associated with agricultural land (orchards, meadows, arable land) cannot be omitted, as the crops grown also fulfil many positive environmental functions (Lutz & Felici, 2008). According to Trzaskowska (2011) in analyzes of urban greenery, spontaneous, natural and synanthropic vegetation are rarely taken into account. It is most often not accepted by the society due to low aesthetic values and deteriorating sense of security. Nevertheless, it plays an important role, as it complements the spatial continuity of the urban greenery system and for this reason it should be used in the development of urban development strategies

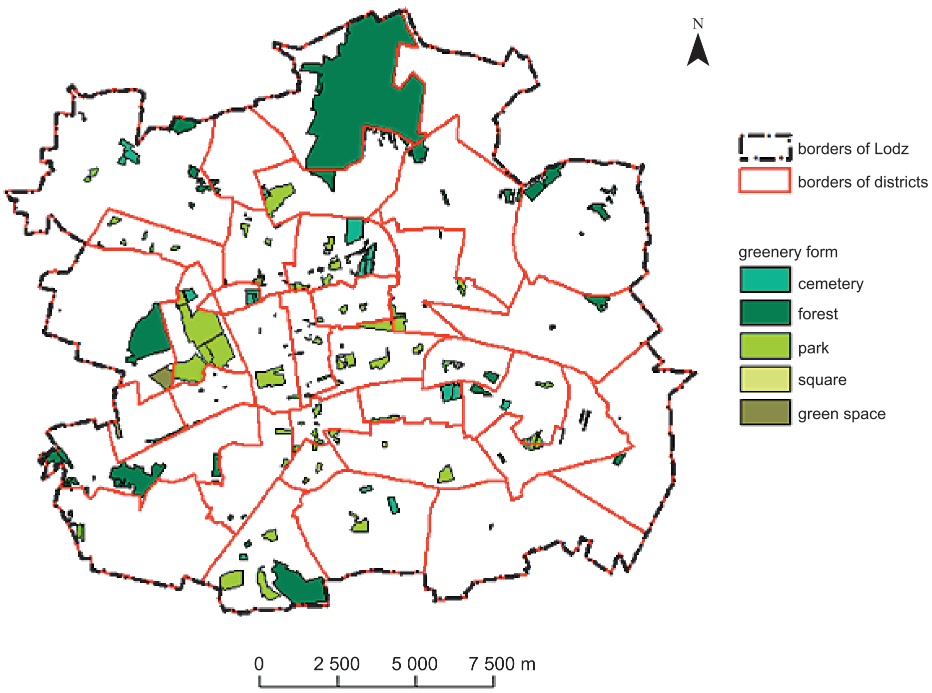

Fig. 7. Green areas in Lodz
Source: own preparation based on LCG data.

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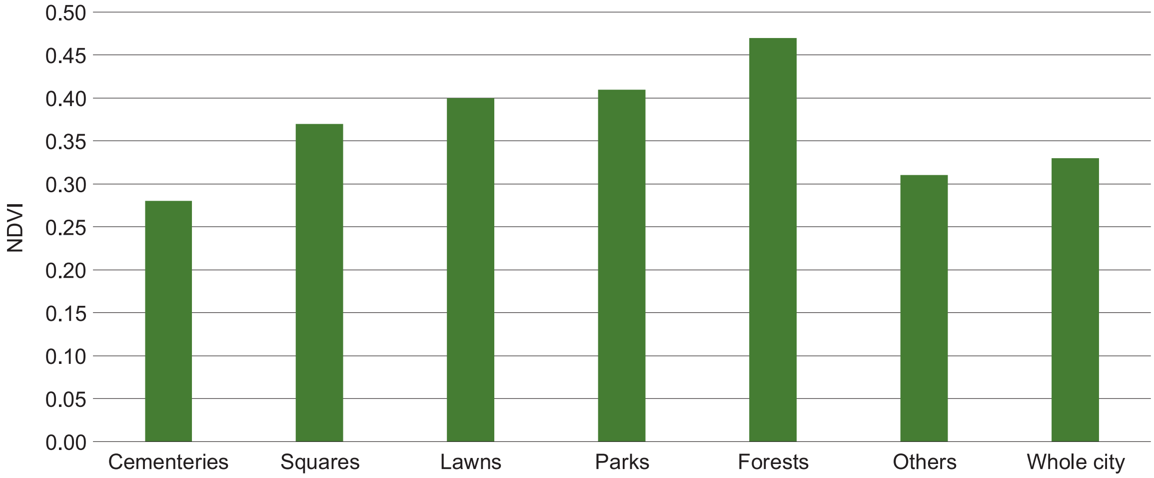

Fig. 8. Average NDVI values of selected functional areas of the city of Lodz
Source: own preparation based on LCG data.

in accordance with the principles of sustainable development.

The presence of greenery is expressed in the NDVI value calculated for each pixel of the satellite image. The distribution of NDVI values (Figures 9–11) is a good characteristic of the variability of vegetation in individual parts of the city. On the basis of NDVI distributions, typical ranges of values for this index were established for areas considered as greenery. These limits have been determined by establishing the modal value for the area under analysis and then including in the range the successive ranges the values adjacent to the modal value until the required percentage of the area is reached. Since such a procedure does not achieve a value exactly equal to the assumed value (68% of pixels in this case), its completion was decided when the next range was included and the number closest to 68% was reached (with the lowest possible undervalue or excess). The adopted method of determining the range for NDVI is similar to that of the mean value and standard deviation, which is, however, more appropriate for variables with distributions close to normal distribution (Wasilewska, 2009).

The established NDVI ranges have been used to designate areas of the city which, although not officially classified as green areas, have the same values of this index. In other words, areas with a level of greenery development similar to known forms: forests, parks, lawns, squares and cemeteries were indicated, so one can expect that in a given location there are similar developed vegetation complexes (Table 3, Figures 12–13).

Green areas and population distribution

In order to assess the living conditions and quality of life of the city's residents, it is important for the city's green spaces to be located in the areas they live in. For the analysis of spatially variable factors of the urban environment, it is recommended to use a network of basic fields, with a hexagonal grid being the best. However, there are no clear guidelines as to their size (Szarek-Iwaniuk, 2020). We have adopted 90 × 90 m grid, corresponding to groups of 9 (3 × 3) pixels of Landsat 8 satellite image as residential areas. The rationale for choosing this size of the primary field was the desire to take into account the condition of vegetation in the place of residence and its immediate surroundings. It was assumed that the immediate surrounding means a space contained within a circle with a 50 m radius, whose area is approximately equivalent to a square of 90 × 90 m. Consequently, the NDVI values determined had to be converted, by averaging, from a grid of pixels to a grid of 90 × 90 m primary units (Fig. 9). This operation

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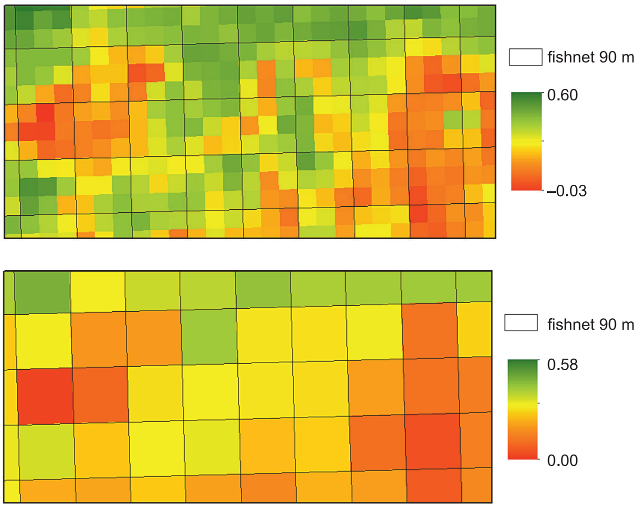

Fig. 9. Conversion of NDVI from a 30 × 30 m pixel grid of the Landsat 8 image into a 90 × 90 m grid of primary fields
Source: own preparation based on Landsat 8 image.

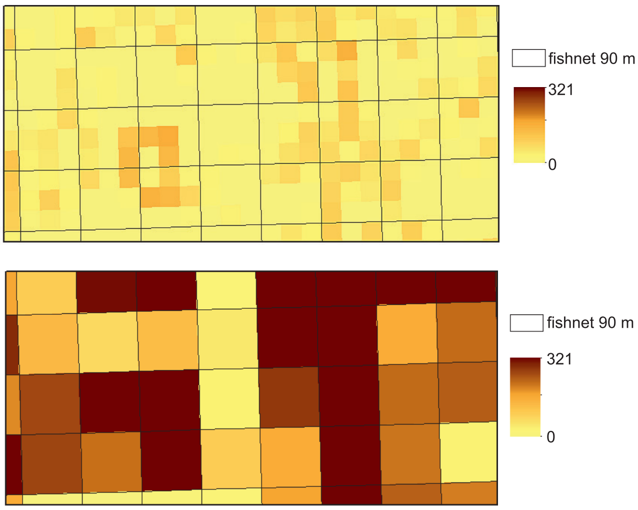

Fig. 10. Population distribution in the grid of 90 m × 90 m primary fields. *Source*: own preparation based on the electoral register of voters (2016)
Source: own preparation.

only slightly changed the range of the index to values from -0.11 to 0.60.

For the purpose of the planned analyses, the number of people living was determined for each of the primary fields of a square grid of 90 × 90 m, corresponding, as was the case with the NDVI value, to the size and range of 9 pixels of the satellite image.

The grid schematically divides the city space, including individual housing estates and individual buildings, into smaller sections. The way of calculating the approximate number of inhabitants in the individual primary fields was presented in the chapter Population data.

Tabular lists were prepared (Table 3).

RESULTS

The distribution of NDVI values for many functional areas of the city clearly shows that in some areas the share of greenery in the coverage of these areas is large. The NDVI even reaches values typical of forests and parks in many places (such as wastelands).

The average value of NDVI for the whole Lodz is 0.33 and takes values from -0.18 (surface waters) to 0.63 (forests). The distribution of NDVI values within the city limits is close to the normal distribution with a predominance of areas with a low NDVI (Fig. 11a).

When comparing the NDVI distribution of individual forms of land use, it can be seen that in most cases there is no specific level of greenery for particular areas (Fig. 12).

However, there are land use types that are in practice limited to a narrow spectrum of NDVI values, such as forests. The grid size of 90 × 90 m, as well as the high fragmentation of land use, means that in many cases the NDVI value represents more than one form of land cover (utility function). The analysis shows that as much as 32% of land use in LPR has an area equal to or less than 900 m^2, i.e. less than one image pixel. However, it should not be forgotten that the functions of greenery are not limited to the area it occupies, but also very important for adjacent areas.

An analysis of the distribution of NDVI values for urban-specific land use forms (residential, industrial and wasteland), not associated with greenery, was also carried out. The selected areas vary considerably in terms of the distribution of NDVI values. Residential areas show a distribution close to normal, with the median established for NDVI=0.3 (Fig. 13a). The graph for industrial areas (Fig. 11b) with a high prevalence

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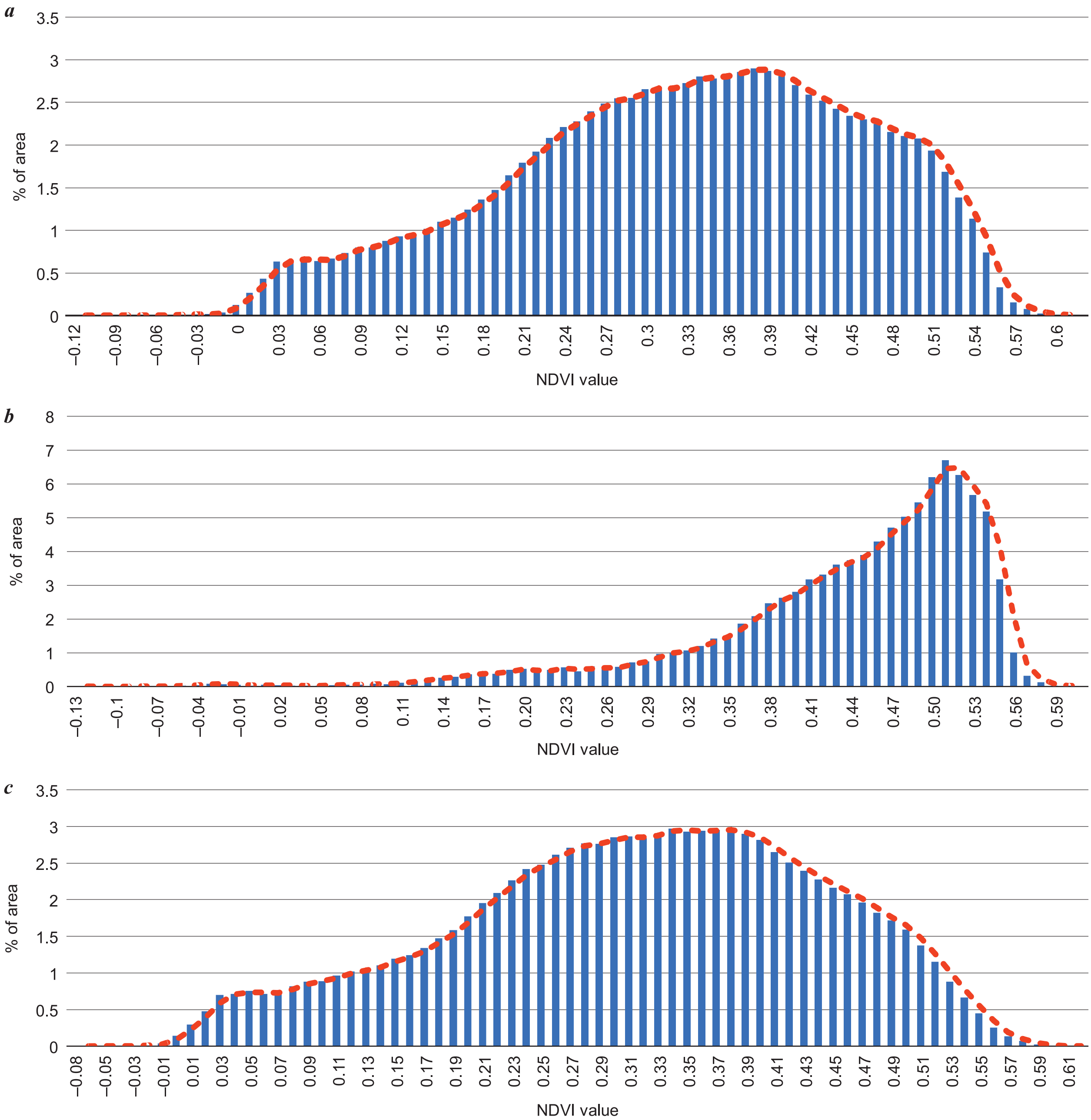

Fig. 11. NDVI distributions in the range ΔNDVI = 0.01 for: a) the whole city, b) areas officially classified as green areas (forests, parks, lawns, squares, cemeteries), c) other areas not including green areas
Source: own preparation based on Landsat data.

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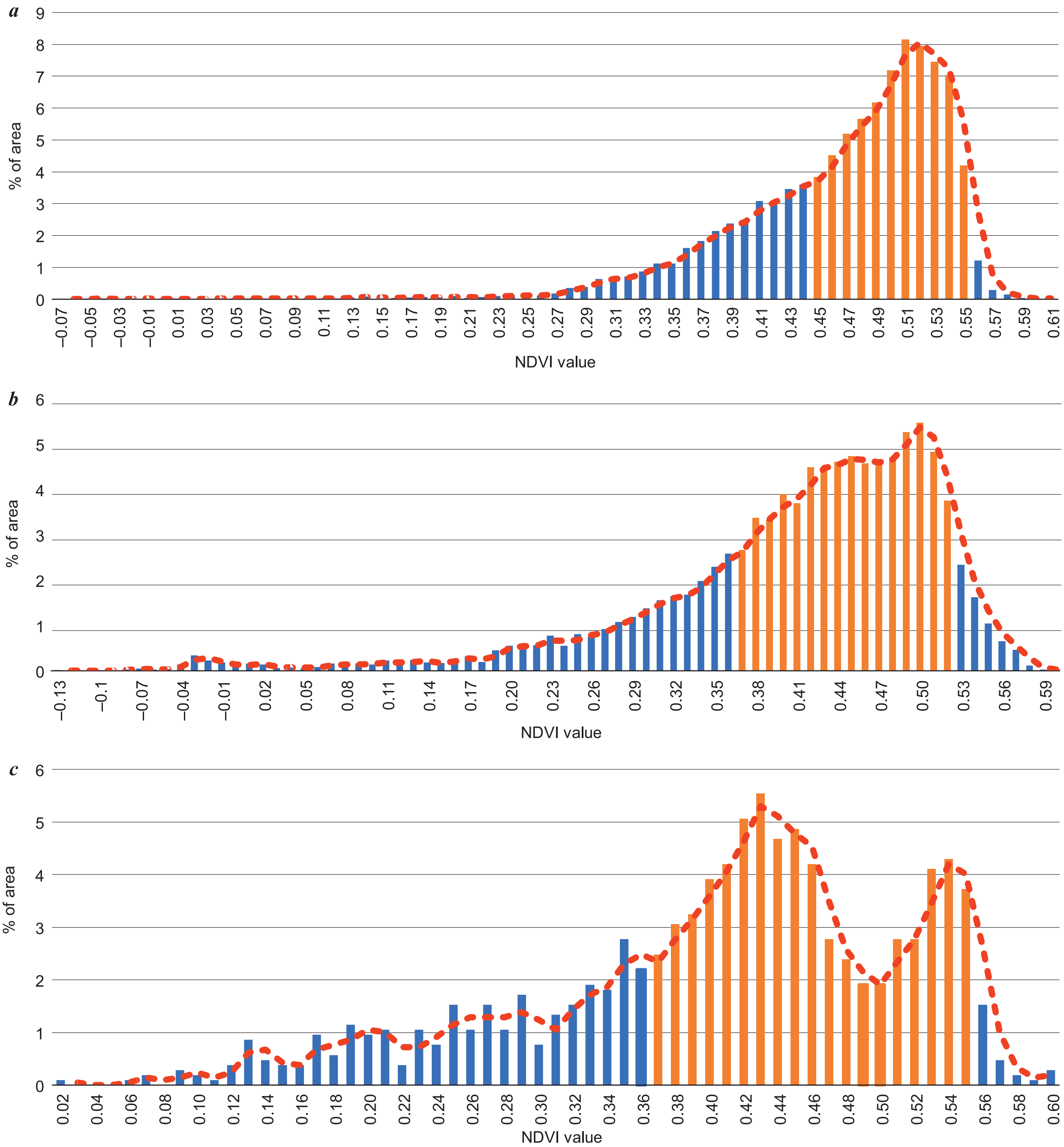

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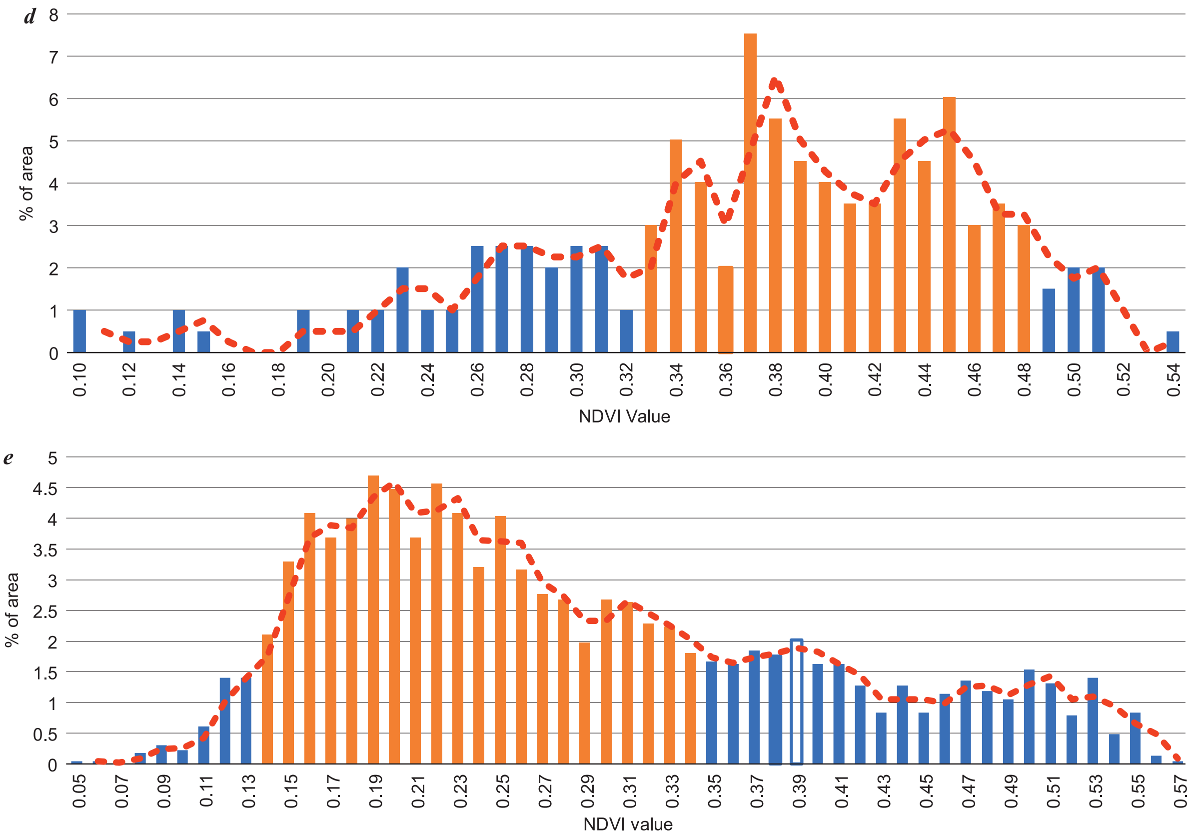

Fig. 12. NDVI distributions in ranges of ΔNDVI = 0.01 for areas officially recognised as green areas in Lodz: a) forests, b) parks, c) lawns, d) squares, e) cemeteries. Red is for the range of typical (68%) NDVI values

Source: own preparation based on Landsat data.

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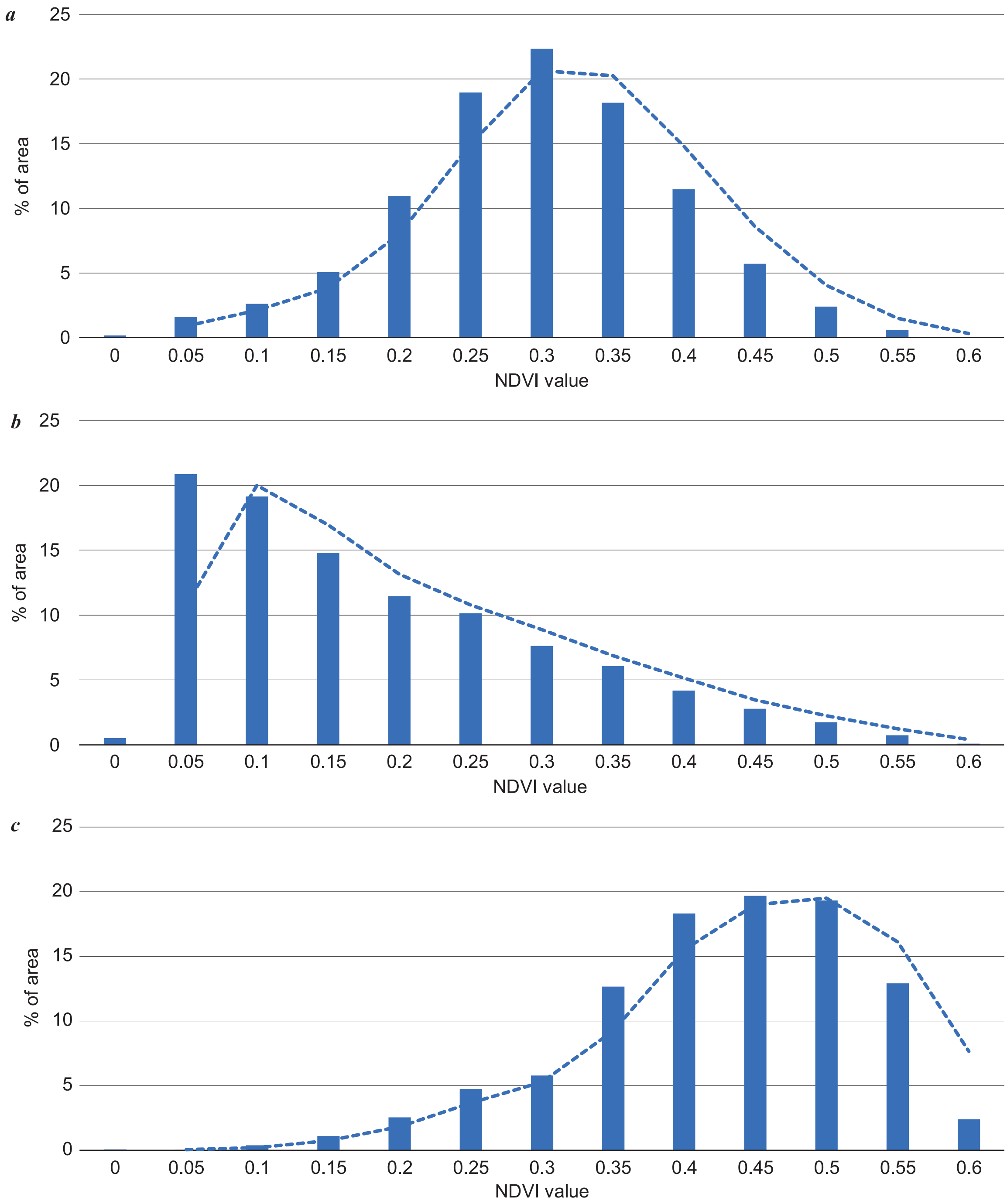

Fig. 13. NDVI distributions within ΔNDVI = 0.05 for areas of Lodz not classified as green areas: a) residential areas, b) industrial areas, c) wastelands
Source: own preparation based on Landsat data.

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of low values and a median = 0.05 clearly shows that greenery is very rare in these areas. The situation in wastelands, where the distribution of NDVI values (Fig. 11c) resembles the distribution for green areas, is the opposite. This is because, after some time, vegetation enters such areas through spontaneous succession (Rostański, 2000).

Based on the determined characteristic NDVI values for individual types of green areas in Lodz, maps were drawn of areas within the borders of Lodz, where the density and quality of vegetation is similar to the specific forms of land use (Figures 14–15), i.e. the NDVI value is within the above mentioned ranges.

The data thus collected were compared with information on the number of inhabitants living in specific characteristic areas (Table 3).

Table 3. Share in the city's area of areas where the NDVI value corresponds to ranges typical for green areas

Typical NDVI range for particular green areas		City area where NDVI is comparable to typical NDVI range		Number of inhabitants	
Object	NDVI range	[km^2]	[%]	[thousands]	[%]
Forests	0.45-0.55	56.11	19.16	3.72	0.57
Parks	0.37-0.52	110.73	37.81	26.99	4.14
Lawns	0.37-0.55	118.78	40.56	27.04	4.14
Cemeteries	0.14-0.39	169.47	57.87	502.85	77.06
Squares	0.33-0.48	137.43	46.93	94.68	14.51
Total greenery	0.42-0.55	77.78	26.56	7.46	1.14

Source: own preparation based on Landsat data.

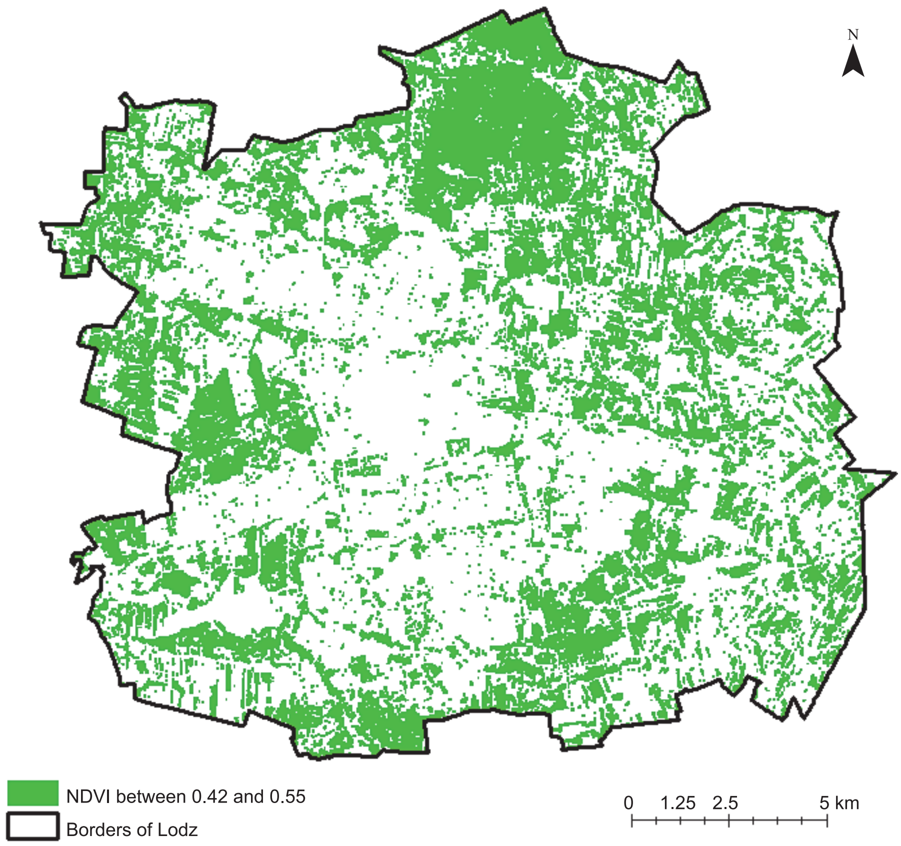

Fig. 14. Areas with an NDVI value within the limits typical for areas officially recognised as greenery in Lodz (0.42<NDVI≤0.55)
Source: own preparation based on own research.

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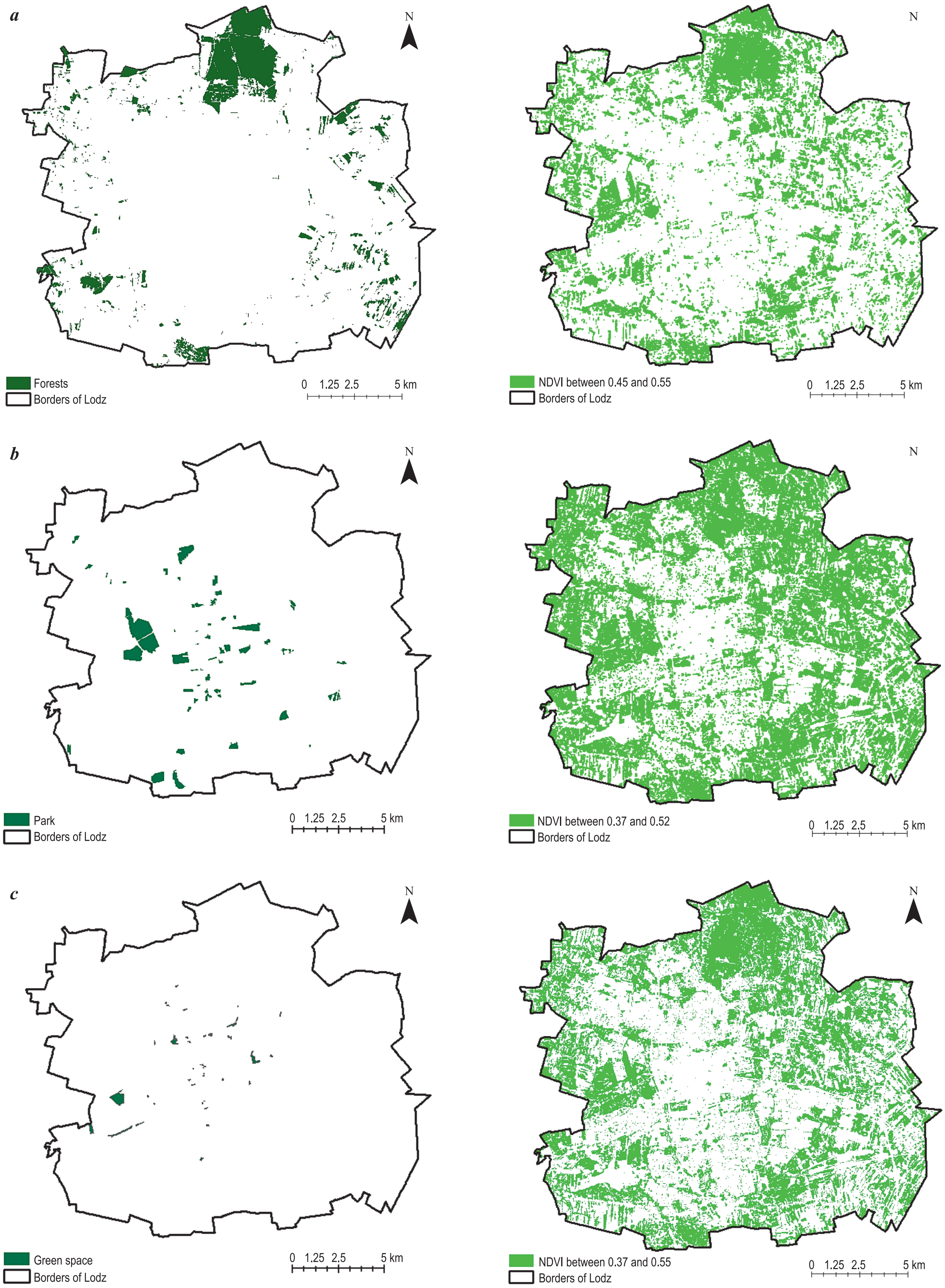

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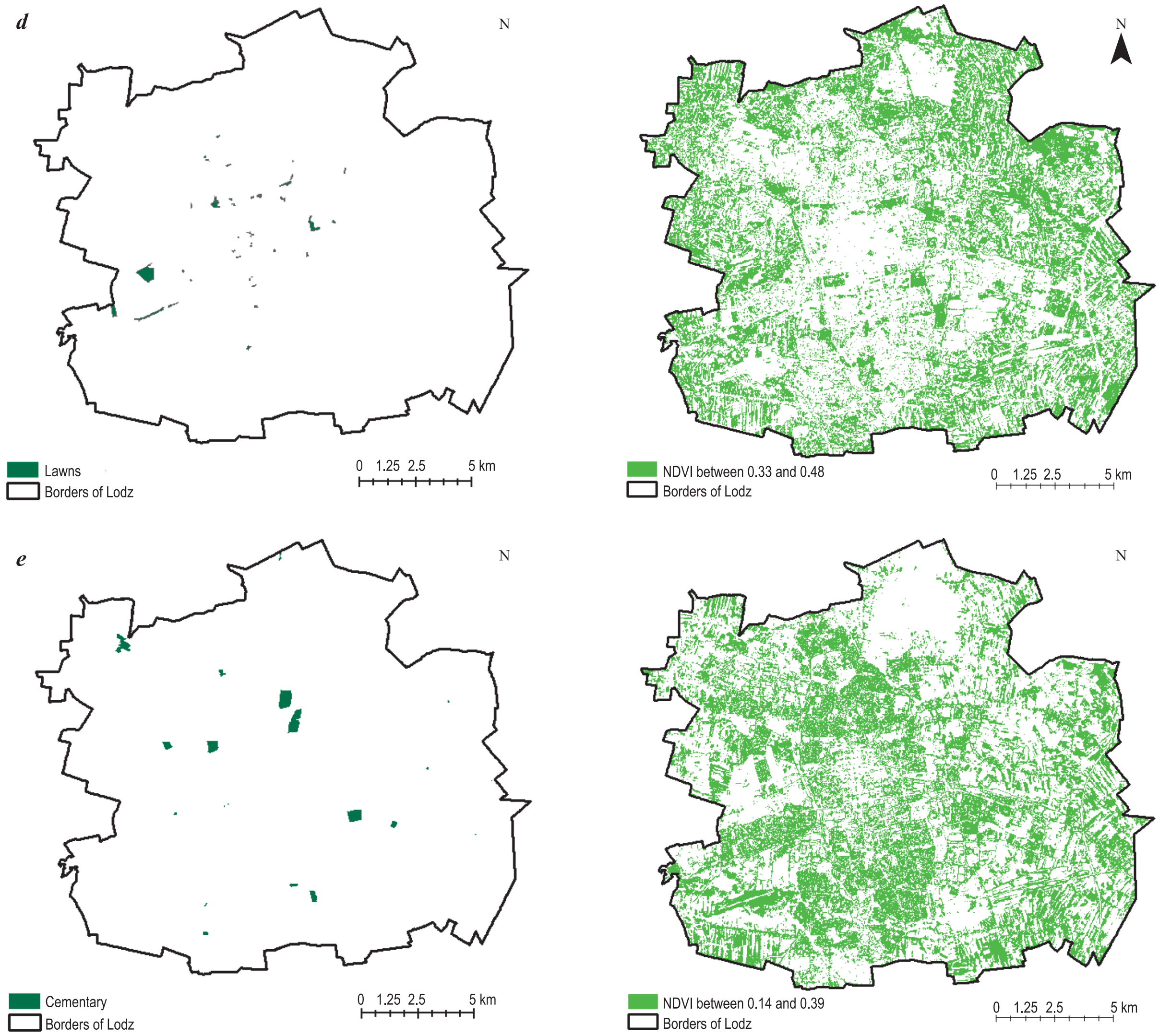

Fig. 15. Location in the Lodz city of (on the left): a) forests, b) parks, c) lawns , d) green squares, e) cemeteries and (on the right) areas where the NDVI value corresponds to their typical ranges (compare with Fig. 10 and Table 3)
Source: own preparation based on Landsat data.

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CONCLUSIONS

The presented overview maps (Figures 14–15) very visibly illustrate the fact that there are many areas in Lodz with vegetation at a level not inferior to that in areas officially classified as green areas. The area within the administrative boundaries of Lodz characterised by a similar level of vegetation development as in the areas included in public reports is over 2.5 times larger (30.77 km^2 to 77.78 km^2). This demonstrates that more than ¼ of the city area (26.56%) does not differ in terms of greenery from the areas officially classified as green. However, it should be noted that the range of NDVI values (0.42–0.55), on the basis of which green areas were determined, was underestimated by the index value for cemeteries (0.14-0.39) and also by squares (0.33-0.48). These areas, due to the fact that they are equipped with various elements of impervious surface, have less greenery, as it mixes with surfaces covered with concrete and asphalt with very low NDVI values (Siciński, 1986). It should be noted that cemetery is defined as a green area in the Act on Nature Conservation, but in the Polish Classification of Buildings it is included in the category of buildings (intended for worship and religious activities), similarly in the Construction Law Act (Długozima, 2020).

On the opposite side, there are urban forests, which are obviously less intensively developed than the other areas of urban greenery (Łonkiewicz, 1997). In the case of Lodz, the limit NDVI values that characterise these areas to the greatest extent, are set at 0.45–0.55. Despite quite characteristic physiognomy, similar NDVI values were detected in an area of over 56 km^2, which is almost three times the area of the forests themselves (Fig. 15a).

In general, the results show that there are much more green spaces, comparable in terms of vegetation abundance with the official green spaces. That means the city is underestimated when talking about the greenery.

Another issue is the presence of these areas in the place where the inhabitants of Lodz live and their immediate surroundings. Despite the fact that almost 1/5 of the area of Lodz has greenery comparable to that of the forest, only one inhabitant in 200 has direct access to it without having to leave their place of residence. In the case of the NDVI zone corresponding to parks and lawns, only 4% of the inhabitants (or 27 thousand in absolute numbers) have similar quality greenery in their place of residence. In the case of cemeteries, the situation is the opposite, as the majority of inhabitants (77%) have similar greenery in their place of residence. This shows that most cemeteries do not have the same environmental functions as forests, parks or lawns (Długozima, 2014).

It is also noteworthy that, despite the often very uneven distribution, the range determined by taking a next value of NDVI in increments of 0.05 starting from the modal values ranged between 67.32% and 68.44% of the analysed areas, while for normal distribution it is 68.3%. The above results therefore indicate that the method used to determine the characteristic values, as regards the NDVI for individual forms of land use, is correct.

It is also worth considering the possibility of linking the NDVI or other vegetation indices with features that describe other qualities of the vegetation, such as its height and volume. Proposals in this area were presented by Worm and others (2019), based on the example of the city of Lodz.

In addition to these research, it might be a good idea to take into consideration an open access spatial datasets, e.g. OpenStreetMap where users who know a specific area classify the space based on its physiognomy.

A similar approach to the assessment of the greenness of the city was adopted by Gupta et al. (2012). They made an attempt to take into account, in addition to vegetation, also the characteristics of buildings (density and height), which were to indirectly indicate the density of the population. The data they used for this purpose came from the interpretation / processing of remote sensing data, while we used information from official databases. Additionally, what distinguishes our approach is the reference of NDVI intervals to easy-to-imagine objects and related forms of covering (and filling) the space

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with greenery (parks, trees, lawns, squares, cemeteries), while the above-mentioned authors adopted the artificial boundaries of the intervals values for NDVI and other products. What is common, however, is the endeavor to identify, finally, areas requiring, as a priority, greater development of green areas.

Table 4. Translated and original names and their abbreviations concerning institutions and databases used in this work

Translated name	Original name in Polish
TOD, Topographic Objects DataBase	BDOT10k, Baza Danych Obiektów Topograficznych
GGOD, General Geographic Objects DataBase	BDOO, Baza Danych Obiektów Ogólnogeograficznych
LPR, Land and Property Register	EGiB, Ewidencja Gruntów i Budynków
LCG, Lodz Centre of Geodesy	ŁOG, Łódzki Ośrodek Geodezji

Source: own preparation.

Author contributions: authors have given approval to the final version of the article. Authors contributed to this work as follows: A.B. and K.B. developed the concept and designed the study, A.B. collected the data, A.B. and K.B. analysed and interpreted the data, A.B. prepared draft of article, K.B. revised the article critically for important intellectual content.

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