DOI: 10.5586/aa.1736

Publication history
Received: 2018-02-25
Accepted: 2018-05-06
Published: 2018-06-29

Handling editor
Bożena Denisow, Faculty of Horticulture and Landscape Architecture, University of Life Sciences in Lublin, Poland

Authors' contributions
AR, BC: idea of the study, writing the manuscript; AR: field and laboratory work, statistical analyses

Funding
This research was supported financially by the Ministry of Science and Higher Education of Poland as a part of statutory activities of the Department of Ecology, University of Maria Curie-Skłodowska in Lublin.

Competing interests
No competing interests have been declared.

Citation
Rysiak A, Czarnecka B. The urban heat island and the features of the flora in the Lublin City area, SE Poland. Acta Agrobot. 2018;71(2):1736. https://doi.org/10.5586/aa.1736

ORIGINAL RESEARCH PAPER

The urban heat island and the features of the flora in the Lublin City area, SE Poland

Anna Rysiak, Bożena Czarnecka*

Department of Ecology, Institute of Biology and Biotechnology, Maria Curie-Skłodowska University, Akademicka 19, 20-033 Lublin, Poland

* Corresponding author. Email: bozenna.czarnecka@poczta.umcs.lublin.pl

Abstract

Various forms of human activity in large cities contribute to the creation of a specific climate and new environmental conditions for plants. One of the most important results is the so-called atmospheric urban heat island (UHI). The aim of this study was to compare the thermal conditions in the Lublin City center with those of suburban areas, and so confirm the existence of the UHI and then analyze the influence of thermal conditions on features of the flora. The analysis of the air temperatures was based on data from 2000 to 2014 provided by meteorological stations in the Lublin City center and its nearest surroundings. Floristic data were collected during field studies between 2012–2014 and included species richness and frequency, life forms, and synecological groups of the flora and its elements. The thermal requirements of species were defined on the basis of ecological indicator values (EIVs). Our research confirmed the presence of the UHI in the Lublin City center. Over the study period, the mean temperature in the city center was by 0.87°C higher than that in the suburban areas. The largest differences in mean annual air temperature between the city center and the suburbs were recorded in 2007 and 2011–2013. In total, 552 species were recorded, including six life-form and synecological groups, 246 thermophilous and 436 heliophilous species. The species richness, proportion of therophytes, alien, thermo- and heliophilous species decreased with distance from the city center. The thermal conditions expressed by the EIV L and T ranged from L = 4.5, T = 3.8 in the city center, to L = 3.1, T = 3.4 in the suburbs. An ordination analysis facilitated determination of the relationships between characteristics of the flora, the EIV values, and land use classes. An increasing level of anthropopressure was found to be positively correlated with thermal conditions and the flora traits.

Keywords
urban flora; thermophilous species; climate change; "floristic heat island"

Introduction

Various forms of human activity in large cities are concentrated in relatively small areas and contribute to the creation of a specific local climate [1]. One of the most important effects of the urban climate is an increase in the air temperature in the city by comparison with the surrounding areas. This phenomenon is called the "urban heat island" (UHI). The UHI has been recognized as the "most obvious manifestation of urbanization" [2] and remains the most intensively studied climatic feature of cities [3–5]. The UHI is defined as the presence of any area warmer than its surrounding landscape that can be developed in built-up and rural areas. The intensity of the UHI is usually expressed as the air temperature difference between urban and rural environments, although the meanings of the terms "urban" and "rural" are somewhat blurred [6]. The annual mean air temperature of a city with a population of 1 million people or more can be 1–3°C warmer than its surroundings [7,8]. A great number of factors are involved in the formation of the UHI. These include general climatic features dependent on local factors, e.g., weather and geographic location, relief, urban structure, progressive replacement of natural by built-up surfaces, density and type of settlement, reduction and fragmentation of vegetation areas, and additionally by urban geometry and anthropogenic heat emissions [7,9–11]. There are two types of main heat island, surface and atmospheric, which differ in many aspects. A surface heat island is formed by heat emission absorbed by urban surfaces, e.g., roofs and pavements. It is always present during the day and night, is most intense during the day and in the summer, and shows more variation of temperature. The warmer air in urban areas compared to the cooler air in nearby rural surroundings defines the atmospheric UHI. It varies much less in intensity than the surface heat island. An atmospheric UHI may be small or nonexistent during the day, most intense at night or predawn and in the winter, and shows less variation of temperature [9,12,13].

The process of urbanization, which has been so profoundly established, transformed the European landscape during the last century and has created new environmental conditions for plants [14]. Urban flora and vegetation have specific features and differ significantly from those of the surrounding nonurbanized areas. Biological homogenization increases because the same "urban-adaptable" species become increasingly widespread and locally abundant in cities [15,16]. A relationship has been observed between the quality of urban and suburban floras and the temperature gradient between cities and their surrounding areas [17]. The urban climate contributes to a prolonged growing period due to the warmer conditions and fewer days of frost, and influences the phenology of plant species. Plants in highly urbanized areas often flower earlier than plants of the same species in less urbanized areas due to the UHI effect [18,19]. Furthermore, temperature influences species distribution. Species are therefore expected to mirror temperature conditions in urban areas. Those that prefer or are adapted to rather warm habitats (thermophilous species) are mainly found in the urban center [20–23].

Studies on the xerothermic flora of Lublin were carried out in the 1950s. At that time, patches of xerothermic vegetation occurring in seminatural habitats in the north and northeastern part of the city were described [24–26]. At the beginning of the twenty-first century, authors paid attention to the occurrence of the xerothermic flora within the city limits on habitats with varying degrees of transformation [27–29]. For example, Rysiak [30] evaluated the distribution and contribution of the group of xerothermic species (i.e., thermo- and heliophilous plants together) in the whole contemporary flora in the Lublin territory.

In the present work, we explore questions about the presence of the UHI in Lublin City and the existence of correlations between air thermal conditions, the type of land use and land cover, and the requirements of the flora expressed as selected ecological indicator values (EIVs). Our main hypothesis was that the plant species composition, especially the occurrence of thermophilous species, yields relevant information about the long-term air temperature distribution within an urban agglomeration. We therefore expect that the atmospheric UHI will be significantly correlated with the "floristic heat island" and the occurrence and abundance of alien and native thermophilous plants.

Material and methods

Study area

Lublin is the largest city of southeastern Poland and the capital of the province. In its present administrative boundaries, it covers an area of 148 km^2 between 51°08′–51°18′ N and 22°27′–22°41′ E and has a population of 300,000 permanent residents. The city is located in the central-northern part of the macroregion of the Lublin Upland on the border of four subregions: Nałęczów and Świdnik plateaus, Bełżyce Plain, and Giełczewska Elevation [31]. The city of Lublin is characterized by specific climatic properties. The mean annual air temperature is 7.9°C. The coldest month is January and the warmest July, with mean air temperatures 3.6°C and 18.6°C, respectively. The mean annual precipitation is 556 mm. The highest precipitation is recorded in July (ca.

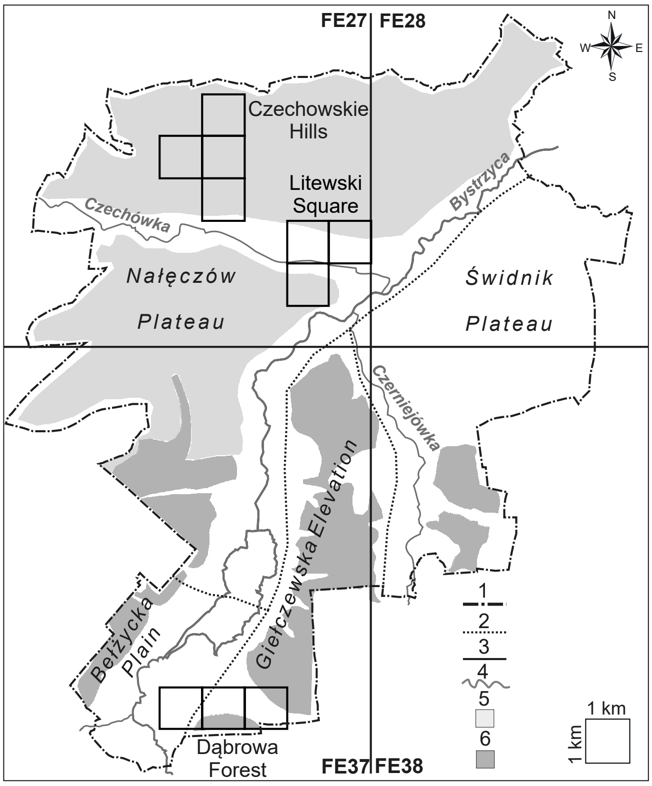

Fig. 1 Location of the study sites on the background of ATPOL grid, physico-geographical subregions of the Lublin Upland by Kondracki [31] and main Quaternary substrates: 1 – city limits; 2 – boundaries of subregions; 3 – squares of ATPOL grid 10 × 10 km; 4 – rivers and water bodies; 5 – loess cover; 6 – loess-like and clay covers.

77.0 mm) and the lowest in January (ca. 30.0 mm). The mean annual insolation is 4.5 hours per day and 1,542 hours per year. The mean annual cloudiness is 68%. Snow cover lies for 60–80 days per year. The average length of the vegetation period in the Lublin area is 209 days [32].

In the territory of Lublin, the essential Quaternary substratum is composed of loess and loess-like soils with clay covers (Fig. 1). The former sediments predominate in the western part and the latter in the southern part of the city. The borderland between these covers is the Bystrzyca River valley [33,34]. Different soil types are found in the Lublin City area. The prevalent types are clay-dusty and sandy-dusty brown soils, and grey-brown soils. In the river network valleys, there are mosaics of alluvial and black soils and, sporadically, marshy and peaty soils. Within densely built-up areas there are usually highly anthropogenically degraded soils in terms of their physical and chemical properties. Most often, these are soils of the urban and industrial type with varying degrees of contamination. Highly productive soils of an anthropogenic type predominate on the arable land widespread around the central part of the city [35].

The present research was carried out at three study locations: Litewski Square (LSq), which has been under urban pressure for 600 years, Czechowskie Hills (CzH) with a long-term use as a military training ground located in the city center, and the Dąbrowa Forest (DF) in the suburbs.

The study sites correspond to the arrangement of squares used in the ATPOL grid system [36]. The distribution of species was recorded for a grid of 1 × 1 km and the study area occupied 10 such squares, i.e., 10 km^2 in total (Fig. 1). The landscape structure determined by the land use and cover variability and the communication network were assessed on the basis of Landsat digital data available from the European Environmental Agency [37]. These urban areas are classified with land cover classes contributing to the urban infrastructure based on their function and location which was <200 m apart. We mapped the distribution of land use and land cover and calculated their proportions using a Geographic Information System ESRI [38] for each plot square and the whole study area. In this study, eight land cover and land use classes were considered (Tab. 1, Fig. 2): forests (F); seminatural areas (Sa), i.e., meadows and xerothermic grasslands; urban greening (Ug); agricultural areas (A), i.e., arable lands and pastures; settlement class (S): loose (LS), compacted (CS), and roadways (Ro).

Tab. 1 Participation of different land use and land cover classes in the study sites: Litewski Square (LSq), Czechowskie Hills (CzH), Dąbrowa Forest (DF).

	Land use and land cover (%)						
					Settlement		
Study plot	Forests (F)	Seminatural areas (S)	Urban greening (Ug)	Agriculture areas (A)	Compact (Cs)	Loose (Ls)	Roads (Ro)
LSq	0	0	25	0	20	25	30
CzH	0	70	8	10	10	0	2
DF	83	10	0	5	0	0	3

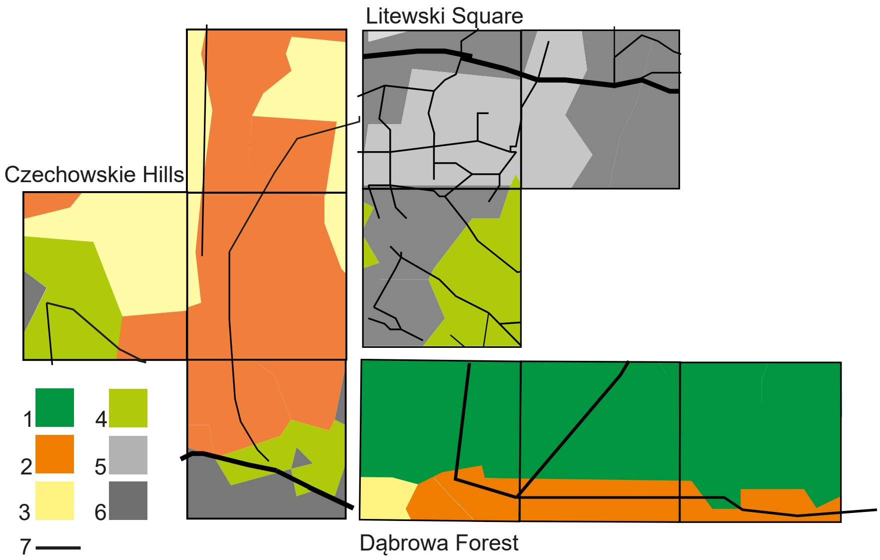

Fig. 2 Participation of the EEA [37] land use and land cover classes in the study sites: 1 – forests; 2 – seminatural areas; 3 – agriculture areas; 4 – urban greening; 5 – loose settlement; 6 – compact settlement; 7 – roads.

Meteorological data

Temperature data were collected from automatic weather stations at two locations: Litewski Square (N 51°14′54′, E 22°33′38″, altitude = 195.3 m a.s.l.) – the weather research station of the Maria Curie-Skłodowska University, and Radawiec (N 51°18′49″, E 22°40′40″, altitude = 240 m a.s.l.) – the airport meteorological station located 13 km southwest of the city center. The temperature data from LSq correspond to CzH and those from Radawiec described the Lublin suburbs, DF. The source meteorological material included the values of the mean daily air temperature from 2000 to 2014. On the basis of the daily values of temperature, annual, monthly, and seasonal averages were calculated for the four calendar seasons: spring (March–May), summer (June–August), fall (September–November), and winter (December–February). A classification of 11 thermal classes of months, seasons, and years was prepared using the method proposed by Lorenc and Suwalska-Bogucka [39]. This method is based on calculating and comparing the average (*M*) and standard deviation (*SD*) of monthly, seasonal, and annual temperature for each year (T_{Av}), with the average temperature for the baseline 15-year-long period (T_{LtAv}) decreased or increased by a suitable *SD*. The next step was to determine the thermal classes and diagrams according to a specific pattern: cool, green, and warm colors indicate periods of lower, normal, and higher air temperature, respectively. The intensity of the colors indicates an increase or decrease in the temperature value in the study period (see Tab. 2).

Tab. 2 Pattern of thermal classification for months, seasons, and years on the basis of the method of Lorenc and Suwalska-Bogucka [39].

Thermal class	Ranges of temperatures
Extremely warm (Ew)	$T_{Av} > T_{LtAv} + 2.5\ SD$
Anomalously warm (Aw)	$T_{LtAv} + 2.0\ SD < T_{Av} \leq T_{LtAv} + 2.5\ SD$
Very warm (Vw)	$T_{LtAv} + 1.5\ SD < T_{Av} \leq T_{LtAv} + 2.0\ SD$
Warm (W)	$T_{LtAv} + 1.0\ SD < T_{Av} \leq T_{LtAv} + 1.5\ SD$
Fairly warm (Fw)	$T_{LtAv} + 0.5\ SD < T_{Av} \leq T_{LtAv} + 1.0\ SD$
Normal (N)	$T_{LtAv} - 0.5\ SD \leq T_{Av} \leq T_{LtAv} + 0.5\ SD$
Fairly cool (Fc)	$T_{LtAv} - 1.0\ SD \leq T_{Av} < T_{LtAv} - 0.5\ SD$
Cool (C)	$T_{LtAv} - 1.5\ SD \leq T_{Av} < T_{LtAv} - 1.0\ SD$
Very cool (Vc)	$T_{LtAv} - 2.0\ SD \leq T_{Av} < T_{LtAv} - 1.5\ SD$
Anomalously cool (Ac)	$T_{LtAv} - 2.5\ SD \leq T_{Av} < T_{LtAv} - 2.0\ SD$
Extremely cool (Ec)	$T_{Av} < T_{LtAv} - 2.5\ SD$

T_{Av} – average temperature for a given period; T_{LtAv} – average temperature for a long-term study period; *SD* – standard deviation.

Floristic data

Floristic data were collected during field studies between 2012 and 2014 at the three sites taking into account land use and cover types within the study squares (Fig. 2). The analysis of the flora was performed at two levels: the general flora of all the study sites and the flora of each specific site [40]. Five main characteristics were taken into account: species richness, life form as described by Zarzycki et al. [41] after Raunkiaer [42], synecological affiliation of species after Matuszkiewicz [43], flora elements (origin and naturalization) on the basis of that used by Pyšek et al. [44] and Tokarska-Guzik [45], and frequency of species using a scale where: 1 – sporadic species, 2 – rare and nonabundant species (covering <10% of the study site), 3 – frequent and abundant species (covering 10–50%), and 4 – common and very abundant species (covering >50%). The nomenclature used for plant species followed that proposed by Mirek et al. [46]. Special attention was paid to thermophilous and heliophilous species. These groups of plants were identified on the basis of the values of selected ecological indicators (EIVs). Species for which the values for temperature (T) and light (L) were equal to or >4 were regarded as thermophilous and heliophilous, respectively [41].

Statistical analysis

The environmental conditions of the study patches were evaluated on the basis of the weighted average of the ecological indicator values T and L [41] and abundance of species. They were calculated using a formula proposed by Łomnicki [47]:

$$W = \frac{\sum_{i=1}^{n} A_i I_i}{\sum A_i}$$

where W is the weighted average, A_i is the abundance of the i-th species in a given site, I_i is the ecological indicator value for the i-th species, and n is the number of species in the study site. Species responses to environmental treatments were evaluated using the multivariate ordination methods in Canoco version 5.0. According to the length of the gradient from a preliminary analysis, principal components analysis (PCA) was used [48,49] with flora features (number of species) as response variables, landscape structure as explanatory variables (predictors), and EIVs as passive variables.

Results

Thermal conditions in the city center compared to the suburbs

From 2000 to 2014, the city center was distinguished by higher (of 0.87°C) average multiannual air temperature than that recorded in the suburbs (Radawiec). This result was confirmed by the values of the mean monthly, seasonal, and annual temperatures, which were higher in the center of Lublin than in the suburbs over the period analyzed. The greatest differences ranging from 1.15°C to 1.44°C were noted for the mean temperatures in June, July ,and August. In May and September, these differences were 0.93°C and 0.95 C, respectively. The smallest differences (approximately 0.5°C) were reported in December, January, and February (Tab. 3). The mean monthly temperature values contributed to those noted in the seasons of the year (Fig. 3). Summers and falls were considerably warmer in the city center than in the suburbs (especially in 2000–2006). The differences in the mean temperature values noted in spring ranged from 0.62°C in March to 0.93°C in May and were higher in the city center. The mean temperature noted in the city center in winter (−1.56°C) was nearly 0.5°C higher than in the suburban areas (−2.03°C). The largest differences in the mean values of the annual air temperature between the city center and the suburbs were recorded in 2007, 2011, 2012, and 2013 (Fig. 4). They were 1.24°C, 1.07°C, 1.03°C, and 1.0°C, respectively.

Analysis of the thermal classification for months, seasons, and years showed the dominance of normal thermal periods, which were not substantially different from the long-term averages, in both the city center and the suburban areas (Tab. 4, Fig. 5). Their number ranged from 101 in the center of Lublin to 118 in the suburbs. A greater number of cool periods (negative *SD* from the mean multiannual temperature) was recorded in the center of Lublin (72) when compared to the suburbs (61). There were more warm periods (positive *SD* from the multiannual average) in the city center (78) than in the suburbs (75). The highest fluctuation of temperature values and, hence, the variability of the thermal periods was shown by the long-term monthly means for both

Tab. 3 Values of average air temperature (T_{LtAv}) and standard deviation (*SD*) for months, seasons, and years between 2000 and 2014.

Period	T_{LtAv} (°C) City center	T_{LtAv} (°C) Suburbs	*SD* of T_{LtAv} (°C) City center	*SD* of T_{LtAv} (°C) Suburbs	Differences of T_{LtAv} (°C)
Months					
January	−2.40	−2.91	2.67	2.95	0.51
February	−1.56	−2.01	2.90	3.06	0.45
March	2.87	2.25	2.62	2.47	0.62
April	9.69	8.93	1.22	1.18	0.76
May	14.86	13.93	1.18	1.22	0.93
June	17.96	16.56	1.01	1.06	1.40
July	20.73	19.29	1.50	1.42	1.44
August	19.52	18.37	0.58	1.02	1.15
September	14.22	13.27	1.36	1.40	0.95
October	9.03	8.35	1.68	1.83	0.68
November	4.58	4.02	1.49	1.71	0.56
December	−0.72	−1.16	3.06	3.01	0.44
Seasons					
Spring	10.62	9.14	10.35	16.48	1.48
Summer	19.48	18.07	20.96	19.46	1.41
Fall	9.31	8.55	11.45	13.17	0.76
Winter	−1.56	−2.03	0.04	−1.16	0.47
Study period					
2000–2014	9.07	8.20	0.54	0.51	0.87

areas analyzed. The seasons of the year in the suburban areas were almost normalized and normal (N), and fairly cool (Fc) summers were dominant when considering the multiannual approach. In the city center, the seasons were mostly classified as N and fairly warm (Fw), likewise the years. Several extreme thermal periods were recorded during our study. February and May 2002 and March 2007 were anomalously warm (Aw) in both areas analyzed. In the suburbs, the winter in 2008 was extremely warm (Ew) and August 2010 was Aw. The city center was characterized by Aw April 2000, February and May 2002, January, March, and June 2007, and March 2014. Extremely cool (Ec) periods, the winters of 2008 and 2010, were noted only in the suburbs. July in 2000 and June in 2001 were anomalously cool (Ac). Only one Ac season, the summer of 2009, was noted in the city center (Tab. 4, Fig. 5). The results of the investigation of air temperatures over the 15-year period confirmed the presence of an atmospheric UHI in the Lublin City center.

Characteristics of the floras of the city center and suburbs

Five hundred and fifty-two vascular plant species represented the total flora of three study sites (Tab. 5). Six life-form and synecological groups were distinguished, which included 246 thermophilous and 436 heliophilous species. Among them, 31 species are common in both the city center and the suburban areas. These include *Amaranthus retroflexus*, *Artemisia campestris*, *Diplotaxis muralis*, *Fumaria officinalis*, *Hyoscyamus niger*, and *Veronica hederifolia*. The analysis of the life-form spectra indicated that hemicryptophytes constituted the greatest share of the total flora (He; 299 species). This is typical for habitats located in a temperate climate. Next in order, we noted therophytes (Th; 127 species); these are annual species specific to dry habitats in urban areas, represented for example by built-up areas (Tab. 5, Fig. 6A). Three ecological groups

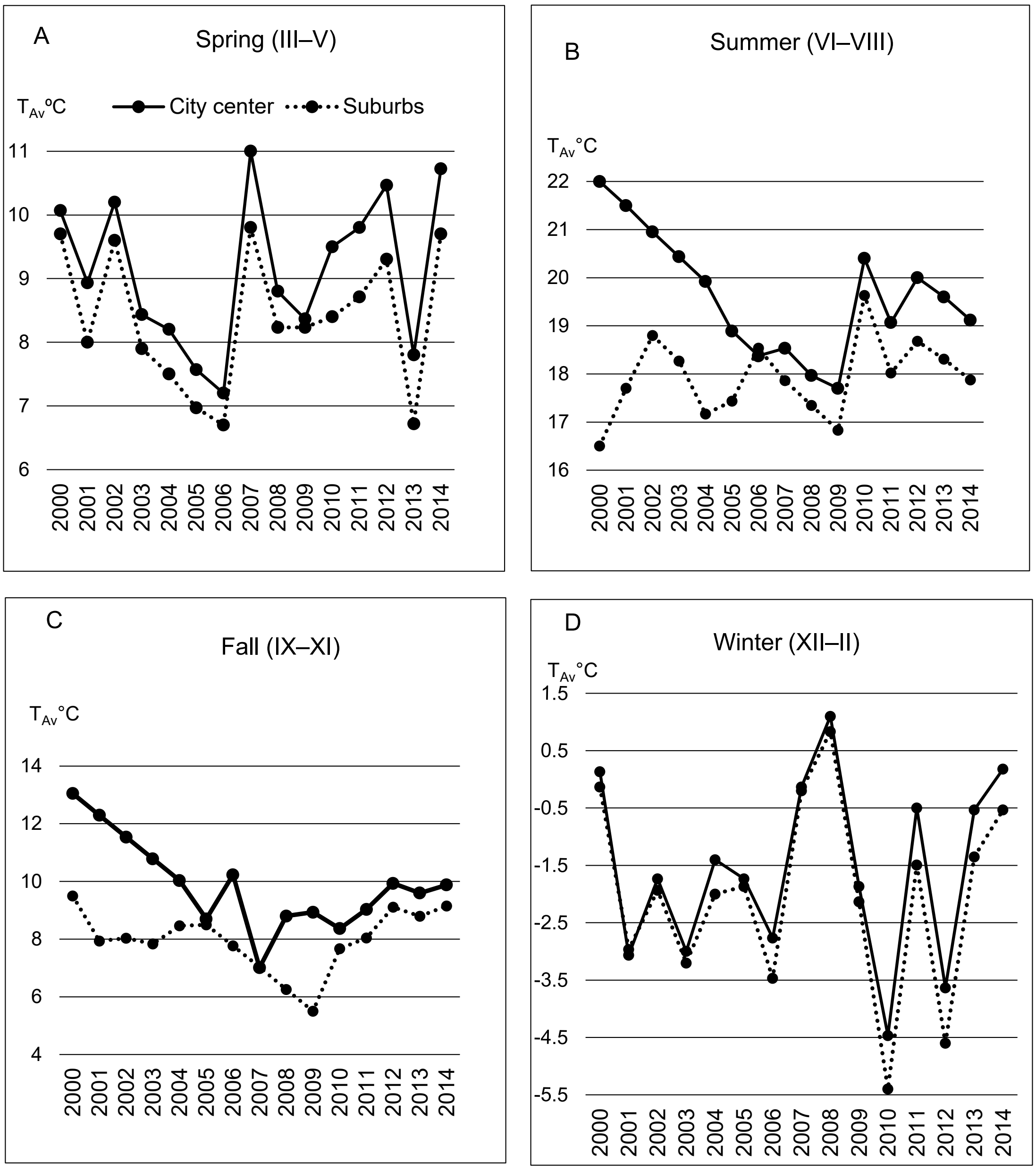

Fig. 3 The variability of average seasonal air temperature (T_{Av}) in the study period.

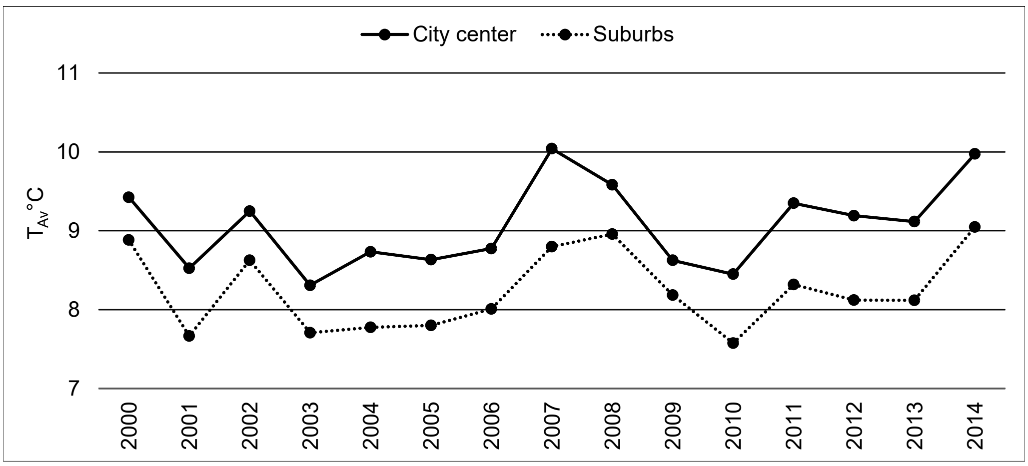

Fig. 4 The variability of average annual air temperature (T_{Av}) in the study period.

Tab. 4 Comparison of the number of thermal classes for the city center (Litewski Square) and suburbs (Radawiec).

Thermal class	Study period 2000–2014					
	Months		Seasons		Years	
	City center	Suburbs	City center	Suburbs	City center	Suburbs
Ew	0	0	0	1	0	0
Aw	7	4	0	2	0	0
Vw	0	7	4	0	2	2
W	19	17	7	1	0	2
Fw	30	34	10	4	3	1
N	74	71	20	42	7	5
Fc	20	23	9	5	2	5
C	12	10	6	2	1	0
Vc	18	13	3	1	0	0
Ac	0	1	1	0	0	0
Ec	0	0	0	2	0	0

For abbreviations, see Tab. 2.

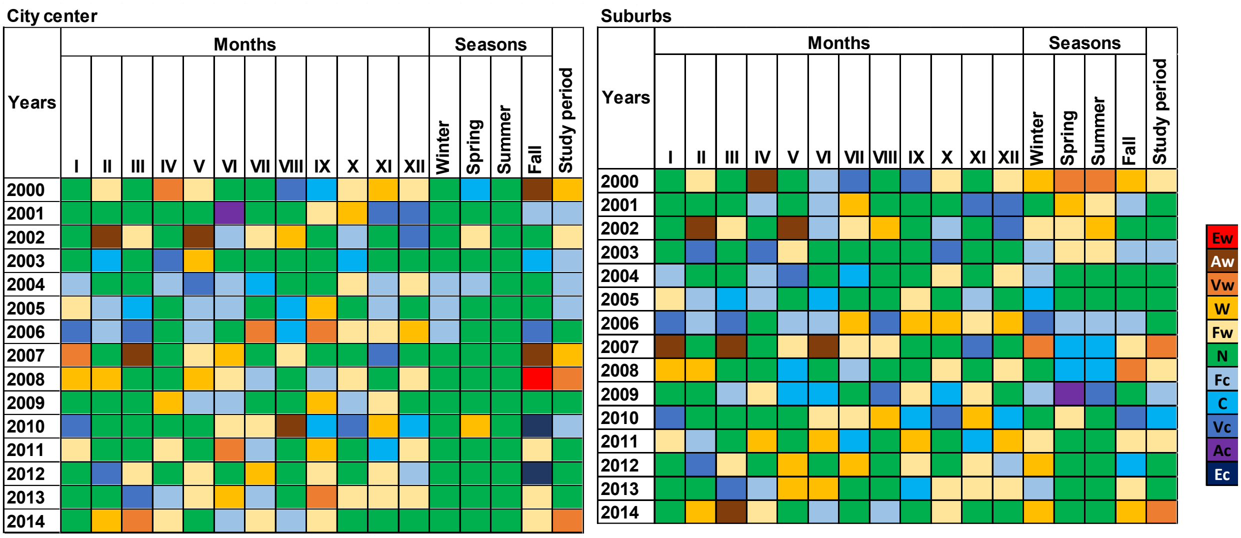

Fig. 5 Thermal classification of months, seasons, and years in the Lublin City center and suburbs based on the method of Lorenc and Suwalska-Bogucka [39]. For abbreviations, see Tab. 2.

of plants dominated (68%) in the whole study area: ruderal, forest, and xerothermic communities. The remaining vegetation (32%) comprised meadow, segetal, aquatic, and riparian species (Fig. 3B). In terms of flora elements, the study area was dominated by native (Na; 414) rather that alien (A; 138) species. The dominance of native species was recognized at all study sites. Among the alien species (Fig. 6C), established aliens (Ea; 110) predominated over casual aliens (Ca; 28).

The detailed analysis of the characteristics of the flora in the study sites revealed certain regularities. The species richness decreased along the distance from the city center. The highest number of species was recorded at LSq, whilst DF was characterized by the lowest species richness. The sites located in the city center (LSq, CzH) exhibited some common features with the suburbs (DF). There was a similar share of phanerophytes and hemicryptophytes among life forms as well as forest, meadow, aquatic, riparian, xerothermic, and segetal species representing the synecological groups. The number of native species was comparable between the city center and suburbs. A higher number of

Tab. 5 Flora features of study sites: Litewski Square (LSq), Czechowskie Hills (CzH), Dąbrowa Forest (DF).

	Study area						
	Total	CzH		LSq		DF	
	No. of species						
Flora features	**10 km²**	**4 km²**	**1 km²**	**3 km²**	**1 km²**	**3 km²**	**1 km²**
Species richness	552	410	102	353	118	214	71
Life forms							
Phanerophytes (Ph)	66	43	11	36	12	29	10
Chamaephytes (Ch)	16	16	4	10	3	11	4
Hemicryptophytes (H)	299	232	58	180	60	119	40
Geophytes (Ge)	39	18	4.5	20	6	25	8
Therophytes (Th)	127	99	25	104	35	30	10
Hydrophytes (Hy)	5	2	0.5	3	1	0	0
Synecological groups of species							
Forest and brushwood (F)	121	71	18	50	17	108	36
Meadow (M)	88	78	19	56	19	42	14
Xerothermic (X)	116	95	24	59	20	14	5
Aquatic and riparian (W)	39	9	2	27	9	3	1
Ruderal (R)	138	110	27	118	39	30	10
Segetal (S)	50	47	12	43	14	17	6
Elements of flora							
Native species (Na)	414	308	77	237	79	189	63
Alien established species (Ea)	110	96	24	108	36	23	8
Alien casual species (Ca)	28	6	1.5	8	3	2	0.7
Participation of							
Thermophilous species (Th), T ≥ 4	246	196	49	166	55	63	21
Heliophilous species (He), L ≥ 4	436	360	90	313	104	119	40

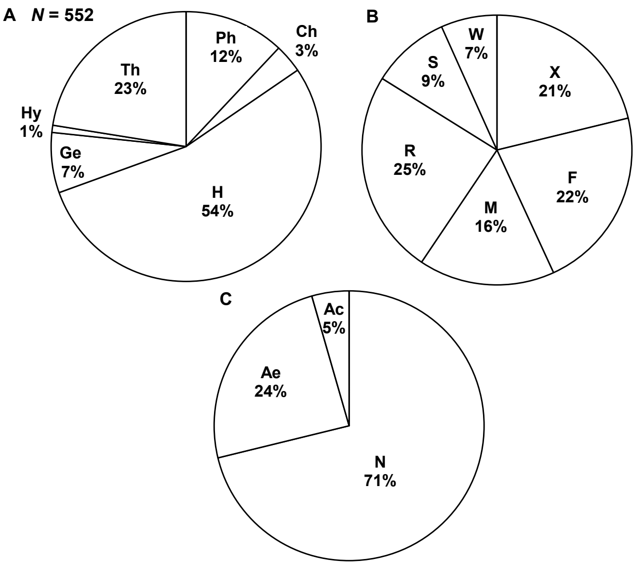

Fig. 6 General features of the flora with participation of: (**A**) life forms, (**B**) synecological groups, and (**C**) elements of the flora. For abbreviations, see Tab. 5.

therophytes, ruderal, and alien species were noted at LSq, related to the species richness. The characteristic features of the suburban flora (DF) included a high proportion of geophytes and forest species and a small number of alien species (Tab. 5, Fig. 7A–C).

The comparative analysis of the EIVs for the flora of the city center sites (CzH, LSq) and the suburban site (DF) revealed slight differences in species abundance and their features. Based upon the quantitative and qualitative composition of the city center flora, it can be stated that LSq and CzH have the characteristics of a "floristic heat island". This was determined primarily by the high proportion of thermo- and heliophytes (Tab. 5). They represented over 67% and 72% in the flora of LSq and as much as 79% and 85% of the flora at CzH, respectively. Among these, taxa simultaneously representing helio- and thermophytes account for 27% and 44% at LSq, respectively and 26% and 44%, respectively, at CzH. The 97 taxa, notably *Agrimonia eupatoria*, *Asparagus officinalis*, *Asperugo procumbens*, *Berberis vulgaris*, *Bromus inermis*, and *Coronilla varia*, were all common in the city center. Nevertheless, the two sites differed in the qualitative characteristics of the flora.

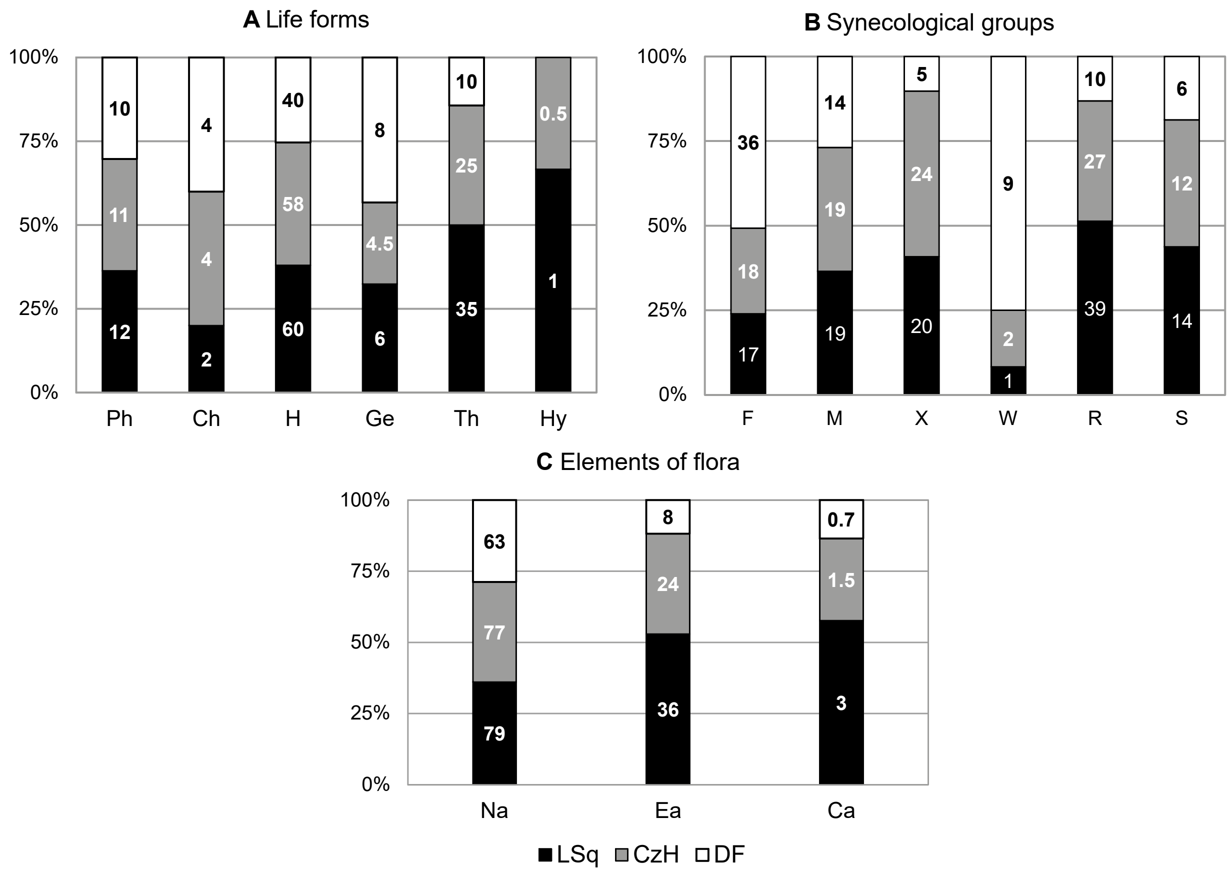

Fig. 7 Flora features of particular study sites (number of species km^2). For abbreviations, see Tab. 5.

CzH supported a specific enclave of xerothermic vegetation in the city center. This was associated with terrain features, loess formations covering the areas, and land use which had limited the succession of trees (Fig. 1, Fig. 2, Tab. 1). Xerothermic grassland species from the classes *Festuco-Brometea* and *Trifolio-Geranietea sanguinei* were abundantly represented in the area. Among the xerothermic grassland species, 14 with T = 5 were noted, e.g., *Lavathera thuringiaca*, *Rosa gallica*, *Thalictrum simplex*, *Veronica austriaca*, and *V. teucrium*, and 61 with T = 4.5, e.g., *Achillea pannonica*, *Anemone sylvestris*, *Trifolium alpestre*, *Sedum maximum*, and *Vincetoxicum hirundinaria*. In contrast to CzH, LSq was a typical anthropogenic heat island. This was evidenced by the land use; built-up areas and roads constituted 75% of surface of LSq (Fig. 2, Tab. 1). This in turn was confirmed by the proportion of thermophilous species; values of T = 5 and T = 4.5 were determined for eight species and 42 taxa, respectively. These two groups were represented by *Atriplex tatarica* and *Astragalus cicer* and by *Acinos arvensis*, *Asperugo procumbens*, *Avena fatua*, *Bromus sterilis*, *B. tectorum*, *Portulaca oleracea*, and *Setaria viridis*, respectively. These species are therophytes forming ruderal communities or species characteristic of thermophilous grasslands or scrubs on alternative ruderal sites. The thermal conditions in the city center expressed by the weighted average of the ecological indicator values L and T were strikingly similar, i.e., L = 4.5, T = 3.8 (for CzH), and L = 4.4, T = 3.7 (for LSq), which confirmed the qualitative traits of the flora presented above. The differences reported were determined by the land use forms.

The characteristics of the third area analyzed, the DF, counterbalance the other two sites. The values of the EIVs expressed by their weighted average for the DF were L = 3.1 and T = 3.4. Thermophilous species represented only 29% of the flora. There were no thermophilous taxa with the highest ecological indicator value (T = 5). Thermophytes were represented by 17 taxa with T = 4.5 and 35 with T = 4. These were early spring plants with a large proportion of geophytes, e.g., *Ajuga genevensis*, *Convallaria majalis*, *Hepatica nobilis*, *Ranunculus bulbosus*, and *Primula veris*. The proportion of photophilous species in this area was approximately 54%.

The PCA ordination analysis facilitated determination of the relationships between the characteristics of the flora and the EIV values and land use classes (Fig. 8). The ordination diagram shows the relationship between the study sites, share of land use and land cover classes, and values of the EIVs for light and temperature (response variables on the case scores). The first axis on the ordination diagram explained ca. 67% of the variance, and the second axis 33%. Both axes indicated the gradient according to which the study squares were ordered in ordination space. CzH and LSq samples were positively correlated with the first axis of the ordination diagram (eigenvalue 9.4), whereas DF was negatively correlated with both axes. Ecological indicators (L, T) and land use and cover classes such as Ug, Ro, and S typical of urban areas were positively correlated with the first axis. This axis represents a gradient of anthropopressure. This was related to the increasing L and T values. The proportions of forests (F) and agricultural (A) areas are negatively correlated with both axes and statistically significant. The second axis was positively correlated with the proportion of agricultural (A) and seminatural areas (S) and it indicated the increasing proportion of agricultural areas in the sites studied. All the response variables of the study squares were statistically significant at a level of $p < 0.05$, except for the seminatural areas and dry grassland on the first axis.

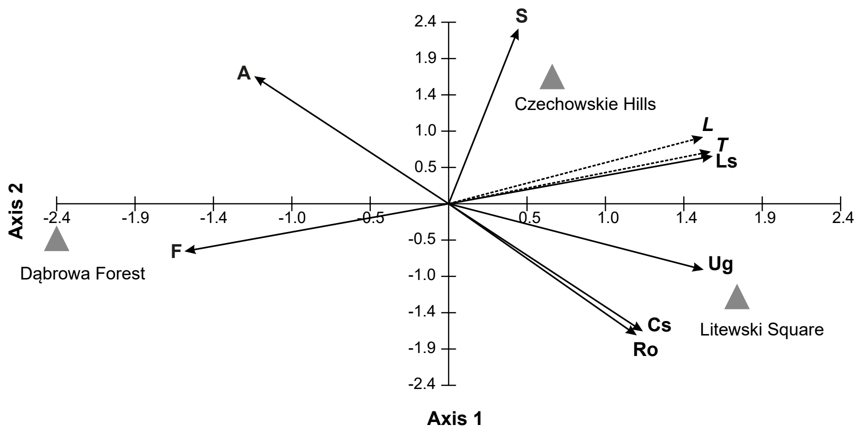

Fig. 8 PCA analysis for land use and land cover classes and values of selected EIV's. Eigenvalues: Axis 1 – 9.41, Axis 2 – 3.08. Cumulative percentage: Axis 1 – 67.42, Axis 2 – 38.58.

Discussion

This study presents an analysis of the differences in the monthly, seasonal, annual, and multiannual air temperature values between the city center and suburban areas in Lublin from 2010 to 2014. The analysis of the meteorological data in the study period revealed a typical UHI in the city. In this period, the mean difference in the temperature recorded in the city center and suburbs was 0.87°C. Similar phenomena have long been observed in Lublin. For example, the mean daily temperature in the city center in 1976–1998 was by approximately 0.9°C higher than in the city outskirts (Felin, north Lublin, 6 km away from the center) [50], and the difference in the temperature between the city center and peripheries (Hajdów, northeast Lublin, 7 km away from the center) in 1996 was as large as 1.5°C [51]. The UHI in Lublin is concentrated in the city center, as demonstrated by the relatively large thermal differences (0.8°C) between the LSq and Felin measurement stations [50]. The greatest differences, 1.2–1.3°C, were noted by the authors mentioned above for the minimum annual temperatures; the differences for the maximum temperatures were distinctly lower, 0.3–0.5°C. A gradual increase in the temperature in the center of Lublin between 1951 and 2010 was noted by Filipiuk [52]. The author compared the values of the mean temperatures in this 60-year period (1951–2010) and showed that the mean annual temperature (8.3°C) in the last 30 years (1981–2010) was higher by 0.8°C than in the previous 30-year period (1951–1980). In the longer period of our study (to 2014), there was a further increase (to 9.04°C) in the mean temperature in the city center and greater differences were noted between the city center and suburban areas. Filipiuk [52] documented a slow, periodic increase in the average temperatures in the city center. The mean monthly temperatures from January to March increased from 1.5°C to 1.6°C, and the seasonal values increased by 1.3°C for the spring and 1.1°C for the winter. Our investigations confirm these trends indicating thermal contrasts between the city center and the suburban areas. Periods of extreme and anomalous temperature values deviating from the mean multiannual temperature are a sensitive indicator of thermal differences between the city center and nonurban areas. The thermal classification developed by Lorens and Suwalska-Bogucka [39] used in this study highlighted these phenomena and has shown that between 2000 and 2014 there were 22 warm, 31 very warm and one anomalously warm months (30 in the city center, 24 in the suburban areas). Simultaneously, there were eight warm, four very warm, and one anomalously warm seasons and one warm year. The same method was used in the study conducted by Filipiuk [52] who documented the concentration of months and years in the period 1999–2000 with standardized temperature values exceeding the mean 60-year temperature by at least one standard deviation. The last year that was classified as cool was 1996 and there were 7 warm and very warm years in the period analyzed. Filipiuk et al. [50] demonstrated the same phenomenon for daily temperatures; during the study period, the number of hot days was over twofold greater in the center of Lublin than at the Radawiec station located 13 km away from Lublin.

The climatic features described above are correlated with the land use forms and qualitative traits of the floras. Given the high proportion of built-up areas and the largest number of alien species, LSq was defined as "an anthropogenic heat island". The UHI is associated with therophytes, alien plants including thermo- and heliophilous species, and areas with dense development. The study has shown a diversity of thermal preferences of the vascular plants of Lublin, which is characteristic for major urban areas [20–22,30,40,53–57]. The average temperature indicator values for the floras of the study areas in the Lublin center (CzH, LSq) and suburban area (DF) are close to the values reported by Wittig and Durwen [56] and Witosławski and Bomanowska [57]. The characteristic urban layout with a densely built-up historical center contributes to homogenization of an urban flora on a European scale. Alien species, often thermo- and photophilous therophytes, concentrate in built-up and industrial areas [1,14,20]. The share of life forms in the flora exhibits similar regularities. In densely built-up centers of cities in Poland, e.g., Warsaw, the proportion of therophytes and thermophilous species is 44% and 45% of the urban flora, respectively [22,54,55]. The number of thermophilous species that increased towards the city center was also observed in Łódź, where the proportion of thermophytes ranged from 0.6% in suburban areas to 17.5% in the center [57]. In total, the contemporary flora of the Lublin City area included 1,052 vascular plant species. Among them, there is the group of thermophilous and heliophilous species including 194 xerothermic and psammophilous grassland species, and 236 therophytes [30,40]. The proportion of squares with presence of the species analyzed varied between the different habitats in the whole Lublin area. The frequency measured as species number in the particular ATPOL squares occupied by thermophilous species varied from one to 44. Habitat conditions, especially the thermal environment, and the history of flora of the area analyzed could account for species distributions [30]. The density of thermophilous species identified as UHI was the highest for the LSq and CzH, and the lowest for the DF. The CzH is a natural area of thermophilous and dry grassland flora (floristic UHI) which was created by the loess ground, location, and history of land use. The city center (LSq) represents a typical atmospheric UHI.

A correlation between the traits of flora analyzed and temperature in the city center and the suburbs was observed. Strong relationships between land use and the terrain features and temperature were demonstrated by Wojkowski [58] for Cracow (south Poland). Dense settlement in the city center is characterized by high spatial variation of temperature values, which is associated with the diversity of the types of land features and forms of land use. The investigations demonstrated two areas in Cracow with a markedly elevated temperatures, i.e., UHI in the compact development of the city and in the area of the metallurgical complex in Nowa Huta. The influence of different landscape features and the size of the city on the thermal conditions on a local scale were confirmed by investigations conducted by Oke [3] and Kunert [59]. It was shown that in cities located in lowland areas, the compact built-up areas were notably characterized by the highest temperatures. Forests were characterized by lower values of temperature than not only those noted in built-up areas but also the standardized multiannual values. Notwithstanding, the temperature values depend on the type and density of plant communities. Midforest settlements exert a significant impact on the forest microclimate, raising the temperature above mean day level.

The size of a city substantially contributes to an increase in the temperature values in areas with intense activity within the UHI. This is particularly evident in areas of compact, high and low settlement, as well as in city parks [59].

Acknowledgments

The authors are grateful to the two anonymous reviewers for their criticism and valuable comments on the manuscript and to Dr Krzysztof Siwek for providing some of the meteorological data.

References

1. Sukopp H, Wurzel A. The effects of climate change on the vegetation of Central European cities. Urban Habitats. 2003;1(1):66–86.
2. Landsberg H. The urban climate. New York, NY: Academic Press; 1981.
3. Oke TR. City size and urban heat island. Atmos Environ. 1973;78:769–779. https://doi.org/10.1016/0004-6981(73)90140-6
4. Oke TR. The urban energy balance. Prog Phys Geogr. 1988;124:471–508. https://doi.org/10.1177/030913338801200401
5. Souch C, Grimmond S. Applied climatology: urban climate. Prog Phys Geogr. 2006;302:270–279. https://doi.org/10.1191/0309133306pp484pr
6. Stewart I, Oke TR. Newly developed "thermal climate zones" for defining and measuring urban heat island magnitude in the canopy layer. In: Timothy R. Oke Symposium; 2009 Jan 11–15; Phoenix, AZ, USA. Boston, MA: American Meteorological Society; 2009. p. J8.2A.
7. Oke TR. The energetic basis of the urban heat island. Q J R Meteorol Soc. 1982;108:1–24. https://doi.org/10.1002/qj.49710845502
8. Aniello C, Morgan K, Busbey A, Newland I. Mapping micro-urban heat island using Landsat TM and a GIS. Comput Geosci. 1995;218:965–969. https://doi.org/10.1016/0098-3004(95)00033-5
9. Oke TR. Urban climates and global environment change. In: Thompson RD, Perry A, editors. Applied climatology: principles & practices. New York, NY: Routledge; 1997. p. 273–287.
10. Voogt JA. Urban heat island. In: Munn T, editor. Encyclopedia of global environmental change. Vol. 3. Chichester: John Wiley and Sons; 2002. p. 660–666.
11. Christen A, Vogt R. Energy and radiation balance of a Central European city. Int J Climatol. 2004;24(11):1395–1421. https://doi.org/10.1002/joc.1074
12. Roth M, Oke TR, Emery WJ. Satellite-derived urban heat island from three coastal cities and the utilization of such data in urban climatology. Int J Remote Sens. 1989;10:1699–1720. https://doi.org/10.1080/01431168908904002
13. Voogt JA, Oke TR. Thermal remote sensing of urban areas. Remote Sens Environ. 2003;86(3):370–384. https://doi.org/10.1016/S0034-4257(03)00079-8
14. Sukopp H, Werner P. Urban environments and vegetation. In: Holzner W, Werger MJA, Ikusima I, editors. Man's impact on vegetation. Dordrecht: Springer; 1983. p. 247–260. https://doi.org/10.1007/978-94-009-7269-8_19
15. Jongman RHG. Homogenization and fragmentation of the European landscape: ecological consequences and solutions. Landsc Urban Plan. 2002;58:211–221. https://doi.org/10.1016/S0169-2046(01)00222-5
16. McKinney ML. Urbanization as a major cause of biotic homogenization. Biol Conserv. 2006;127:247–260. https://doi.org/10.1016/j.biocon.2005.09.005
17. Jochner S. Menzel A. Urban phenological studies – past, present, future. Environ Pollut. 2015;203:250–261. https://doi.org/10.1016/j.envpol.2015.01.003

18. Roetzer T, Wittenzeller M, Haeckel H, Nekovar J. Phenology in Central Europe – differences and trends of spring phenophases in urban and rural areas. Int J Biometeorol. 2000;442:60–66. https://doi.org/10.1007/s004840000062

19. Mimet A, Pellissier V, Quenol H, Aguejdad R, Dubreuil V, Roze F. Urbanisation induces early flowering: evidence from *Platanus acerifolia* and *Prunus cerasus*. Int J Biometeorol. 2009;533:287–298. https://doi.org/10.1007/s00484-009-0214-7

20. Sudnik-Wójcikowska B. The effect of temperature on the spatial diversity of urban flora. Phytocoenosis. Supplementum Cartographiae Geobotanicae. 1998;9:97–105.

21. Celesti-Grapow L, Blasi C. A comparison of the urban flora of different phytoclimatic regions in Italy. Glob Ecol Biogeogr. 1998;7:367–378.

22. Sudnik-Wójcikowska B, Galera H. Floristic differences in some anthropogenic habitats in Warsaw. Ann Bot Fenn. 2005;42:185–193.

23. Kowarik I, Säumel I. Biological flora of Central Europe: *Ailanthus altissima* (Mill.) Swingle. Perspect Plant Ecol Syst. 2007;8(4):207–237. https://doi.org/10.1016/j.ppees.2007.03.002

24. Fijałkowski D. Szata roślinna wąwozów okolic Lublina na tle niektórych warunków siedliskowych. Annales Universitatis Mariae Curie-Sklodowska, sectio C. 1954;9:125–215.

25. Fijałkowski D, Izdebski K. Zbiorowiska stepowe Wyżyny Lubelskiej. Annales Universitatis Mariae Curie-Sklodowska, sectio B. 1957;11:167–199.

26. Izdebski K. Zbiorowiska z roślinnością kserotermiczną w Rudniku k. Lublina i Dobużku k. Łaszczowa. Acta Soc Bot Pol. 1958;27(4):631–648. https://doi.org/10.5586/asbp.1958.034

27. Balana M, Czaraniawski W, Czepiec K, Gosik R, Ptaszyńska A. Walory przyrodnicze projektowanego rezerwatu Górki Czechowskie w Lublinie – stan aktualny i perspektywy rozwoju. Chrońmy Przyrodę Ojczystą. 2004;60(1):67–77.

28. Balana M, Buczyński P, Czerniawski W, Dembicka A, Grądziel T, Ptaszyńska A, et al. Uroczysko Lipnik – cenny przyrodniczo wąwóz lessowy w Lublinie. Uroczysko Lipnik – a valuable nature site in Lublin town. Chrońmy Przyrodę Ojczystą. 2006;62(1):42–51.

29. Wrzesień M, Święs F. Flora i zbiorowiska roślin naczyniowych terenów kolejowych zachodniej części Wyżyny Lubelskiej. Lublin: UMCS Publishing; 2006.

30. Rysiak A. The share of xerothermic species in vascular flora of the city of Lublin (Poland). Acta Agrobot. 2012;65(2):133–146. https://doi.org/10.5586/aa.2012.067

31. Kondracki J. Geografia fizyczna Polski. Warszawa: Wydawnictwo Naukowe PWN; 2009.

32. Kaszewski BM. Klimat. In: Turski R, Uziak S, editors. Środowisko naturalne Lubelszczyzny. Lublin: Lubelskie Towarzystwo Naukowe; 2008. p. 75–111.

33. Chałubińska A, Wilgat T. Podział fizjograficzny województwa lubelskiego. In: Przewodnik V Ogólnopolskiego Zjazdu PTG. Lublin: Polskie Towarzystwo Botaniczne; 1954. p. 3–44.

34. Harasimiuk M, Henkiel A. Objaśnienia do szczegółowej mapy geologicznej Polski. Arkusz Lublin 749 1: 50,000. Warszawa: Wydawnictwo Geologiczne; 1982.

35. Turski R, Uziak S, Zawadzki S. Gleby. In: Turski R, Uziak S, editors. Środowisko naturalne Lubelszczyzny. Lublin: Lubelskie Towarzystwo Naukowe; 2008. p. 211–317.

36. Zając A. Atlas of distribution of vascular plants in Poland ATPOL. Taxon. 1978;27:481–484. https://doi.org/10.2307/1219899

37. European Environmental Agency. Urban atlas – Lublin [Internet]. 2010 [cited 31 May 2018]. Available from: http://www.eea.europa.eu/data-and-maps/data/urban-atlas

38. Environmental Systems Research Institute. ArcView Spatial Analyst: advanced spatial analysis using raster and vector data. Redlands, CA: Environmental System Research Institute; 2003.

39. Lorenc H, Suwalska-Bogucka M. Thermal tendencies of winters in Poland as the indicator of climate variability. Zeszyty Naukowe UJ, Prace Geograficzne. 1996;102:365–374.

40. Rysiak A. Atlas of distribution of vascular plants in Lublin. Lublin: Kartpol; 2016.

41. Zarzycki K, Trzcińska-Tacik H, Różański W, Szeląg Z, Wołek J, Korzeniak U. Ecological indicator values of vascular plants of Poland. Cracow: W. Szafer Institute of Botany, Polish Academy of Scienes; 2002. (Biodiversity of Poland; vol 2).

42. Raunkiaer C. The life-forms of plants and statistical plant geography. Oxford: Oxford University Press; 1934.
43. Matuszkiewicz W. Przewodnik do oznaczania zbiorowisk roślinnych Polski. Warszawa: Wydawnictwo Naukowe PWN; 2008. (Vademecum Geobotanicum; vol 3).
44. Pyšek P, Richardson DM, Rejmánek M, Webster GL, Williamson M, Kirschner J. Alien plants in checklists and floras: towards better communication between taxonomists and ecologists. Taxon. 2004;53(1):131–143. https://doi.org/10.2307/4135498
45. Tokarska-Guzik B. The establishment and spread of alien plant species kenophytes in the flora of Poland. Katowice: Wydawnictwo Uniwersytetu Śląskiego; 2005. (Prace Naukowe Uniwersytetu Śląskiego; vol 2372).
46. Mirek Z, Piękoś-Mirkowa H, Zając A, Zając M. Flowering plants and pteridophytes of Poland. A checklist. Cracow: W. Szafer Institute of Botany, Polish Academy of Sciences; 2002. (Biodiversity of Poland; vol 1).
47. Łomnicki A. Wprowadzenie do statystyki dla przyrodników. Warszawa: Wydawnictwo Naukowe PWN; 2003.
48. Ter Braak CJF, Šmilauer P. Canoco reference manual and user's guide. Software for ordination version 5.0. Wageningen: Biometrics; 2012.
49. Lepš J, Šmilauer P. Multivariate analysis of ecological data using Canoco. Cambridge: Cambridge University Press; 2012.
50. Filipiuk E, Kaszewski BM, Zub T. Porównanie warunków termicznych w śródmieściu Lublina z obszarami pozamiejskimi. Acta Universitatis Lodziensis, Folia Geographica Physica. 2008;3:71–82.
51. Kaszewski BM, Siwek K. Cechy przebiegu dobowego temperatury w centrum i na peryferiach Lublina. Acta Universitatis Lodziensis, Folia Geographica Physica. 1998;3:2013–220.
52. Filipiuk E. Klasyfikacja termiczna miesięcy, sezonów i lat w Lublinie w latach 1951–2010. Prac Studi Geograf. 2011;47:129–138.
53. Jackowiak B. Struktura przestrzenna flory dużego miasta. Studium metodyczno-problemowe. Poznań: Bogucki Wydawnictwo Naukowe; 1998. (Prace Zakładu Taksonomii Roślin UAM w Poznaniu; vol 8).
54. Galera H, Sudnik-Wójcikowska B. The flora of the highest building in Poland. The Palace of Culture and Science in Warsaw. Acta Soc Bot Pol. 2000;69(1):41–54. https://doi.org/10.5586/asbp.2000.006
55. Sudnik-Wójcikowska B. The role of flora in bioindication of the temperature conditions in urban areas. In: Jackowiak B, Żukowski W, editors. Mechanisms of anthropogenic changes of the plant cover. Poznań: Bogucki Wydawnictwo Naukowe; 2000. p. 271–279. (Prace Zakładu Taksonomii Roślin UAM w Poznaniu; vol 10).
56. Wittig R, Durwen JK. Ecological-value spectra of spontaneous urban floras. In: Bornkamm R, Lee JA, Seaward MRD, editors. Urban ecology: the 2nd European Ecological Symposium; 1980 Sep 8–12; Berlin, Germany. Oxford: Blackwell Scientific Publications; 1982. p. 23–31.
57. Witosławski P, Bomanowska A. Spatial diversity of thermal preferences of vascular plants in Łódź. Biodivers Res Conserv. 2008;11–12:49–56.
58. Wojkowski J. Wpływ pokrycia i użytkowania terenu na kształtowanie się warunków termicznych w Krakowie. In: Kłysik K, Wibig J, Fortuniak K, editors. Klimat i bioklimat miast. Łódź: Wydawnictwo Uniwersytetu Łódzkiego, Katedra Meteorologii i Klimatologii UŁ; 2008. p. 113–122.
59. Kunert A. Zróżnicowanie temperatury powietrza w skali lokalnej w różnych typach krajobrazu Polski. Prz Geogr. 2011;83(1):69–90. https://doi.org/10.7163/PrzG.2011.1.4

Miejska wyspa ciepła a cechy flory miasta Lublina (południowo-wschodnia Polska)

Streszczenie

W dużych miastach, różnorodne formy działalności człowieka wpływają na tworzenie specyficznego klimatu i nowych warunków środowiskowych. Jednym z najbardziej istotnych efektów tego zjawiska jest atmosferyczna wyspa ciepła UHI (ang. *urban heat island*). Celem pracy było porównanie warunków termicznych w centrum Lublina z panującym na jego przedmieściach, aby określić czy występuje UHI oraz analiza wpływu warunków termicznych na cechy flory.

Analizę temperatury powietrza oparto o dane z lat 2000–2014, zarejestrowane w stacjach meteorologicznych w centrum Lublina i na przedmieściach miasta. Dane florystyczne zebrano podczas badań terenowych w latach 2012–2014 w trzech rejonach miasta. Określono bogactwo gatunkowe i frekwencję flory oraz cehy flory (formy życiowe, przynależność gatunków do grup synekologicznych i elementów flory). Wymagania termiczne gatunków zdefiniowano na podstawie ekologicznych liczb wskaźnikowych EIV (ang. *ecological indicator values*). Badania potwierdziły występowanie UHI w centrum Lublina. W badanym okresie średnia temperatura powietrza w centrum miasta była wyższa o 0,87°C w stosunku do warunków termicznych stwierdzanych na obrzeżach miasta. Największe różnice średniej rocznej temperatury pomiędzy centrum i przedmieściami Lublina odnotowano w roku 2007 i latach 2011–2013. W sumie zidentyfikowano 552 gatunków roślin reprezentujących: sześć form życiowych i grup synekologicznych, 246 termofitów i 436 heliofitów. Bogactwo gatunkowe, udział terofitów, gatunków obcych oraz termo- i heliofitów spadały wraz z oddalaniem się od centrum miasta. Warunki termiczne wyrażone za pomocą EIV L i T wynosiły: L = 4,5; T = 3,8 dla centrum miasta i L = 3,1; T = 3,4 dla obszarów przedmieść. Analiza ordynacyjna wskazała związek między cechami flory, wartościami EIV i formami użytkowania terenu. Poziom antropopresji jest dodatnio skorelowany z warunkami termicznymi i cechami flory.

