

Article

Identification of the Potential Thermal Resilience of Poland's Most Populous Cities Using the Local Climate Zone Framework

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Abstract

The increasing severity of heat waves in cities requires the integration of spatial morphology with temperature-resilient design; however, comparisons of multi-city systems are scarce. The aim of this article is to assess the potential thermal resilience of Poland's largest cities, taking into account local climate zones (LCZs), which aligns with the framework of sustainable urban development. The use of LCZs allows for a comparison of the resilience of cities without being influenced by their historical development, providing a diagnostic basis for climate adaptation. The proposed potential thermal resilience index (R_c) integrates exposure, sensitivity, and adaptive capacity, serving as the operational inverse of structural vulnerability to heat (urban heat vulnerability). The results indicate that 62.5% of the cities are characterized by moderate potential thermal resilience; 31.3% of cities have low resilience, and only 6.2% of cities have high resilience. High potential thermal resilience is associated with a large proportion of LCZs A, B, and D, as well as a reduction in both high-density and low-density development, which provides practical guidance for land-use planning. The index shows geographical variation—higher values were found in southern and southwestern Poland. The results suggest the need to correlate physical interventions with social vulnerability and the macroclimate when designing blue-green infrastructure as a key element of sustainable adaptation.

Keywords: local climate zones; potential urban thermal resilience; spatial heterogeneity; urban climate; Poland



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1. Introduction

Progressive climate change is one of the key challenges of contemporary socio-economic development, especially in heavily urbanized areas. The increase in average air temperature, changes in precipitation patterns, and the increased frequency and intensity of extreme events such as heat waves, heavy rainfall, and periods of drought are also becoming increasingly apparent in Poland [1–4]. However, the effects of these phenomena are not evenly distributed across space. Their impact is strongly modified by both local climatic conditions and the features of the urban environment [5–8].

Cities, as areas with high concentrations of population, infrastructure, and economic activity, are particularly sensitive to climate change [9]. The specific nature of the urban environment leads to the formation of local climate zones (LCZs). Meteorological conditions in LCZs differ significantly from those in the surrounding non-urbanized areas [10–13].

The specific nature of a city contributes to heat accumulation and elevated air temperatures, among other things. Phenomena such as urban heat islands, limited rainwater retention, and a shortage of biologically active areas and tall greenery exacerbate the negative effects of extreme weather events [14]. These phenomena thus increase the risk of threats to the entire urban ecosystem, including the health of residents and the functioning of urban infrastructure [15–19]. Rising temperatures in urban areas contribute to increased mortality and a higher risk of various diseases. The consequence of this higher risk of disease is a significant burden on healthcare systems, especially those with limited adaptive capacity [20–22].

The importance of local climate zones (LCZs) in the context of cities' resilience to progressive climate change is increasingly noted in the literature on the subject [23–28]. The concept of LCZs, developed by Stewart and Oke [29], allows for the description of differences in urban structure and land cover, which in turn significantly influence the formation of the biotope climate of cities [30–32]. Recent analyses have shown that the LCZs system also has a high capacity to differentiate urban thermal environments at the metropolitan level, which has key implications for effectively integrating the zoning scheme with the design and planning of urban resilience to high temperatures [33].

During the warm season, the highest land surface temperatures (LST) are recorded in industrial areas (LCZ 10). During the same season, the lowest temperatures occur in green areas dominated by trees (LCZ A) and over water bodies (LCZ G) [34–37]. Other studies indicate that the highest temperatures in European cities are recorded in zones LCZ 1–3 and LCZ 5. It has also been found that in cities with extensive commercial and industrial areas, the highest temperatures are recorded in zones LCZ 8 and LCZ 10 [30,38,39]. Built-up areas are mainly found in central parts of cities. In turn, natural areas (LCZs A–G) dominate in suburban areas. The highest heat risk intensity is found in city centers. Heat risk intensity gradually decreases from the city center towards suburban areas [40]. The average increase in LST in individual LCZs also depends on the climate zone [41,42].

The diversity of climatic conditions among individual cities in Poland [43–45]—resulting from both their geographical location and urban structure—affects their vulnerability to climate hazards and their adaptation potential. Cities located in different regions of Poland experience different combinations of climate stresses. For this reason, among others, each city requires an individualized approach to planning adaptation measures [46–48]. In this context, the climate resilience of cities concept is becoming increasingly important. Climate resilience of cities is understood as the ability of urban systems to absorb the effects of climate events, adapt to changing conditions, and recover quickly after disruptions [49–51]. This resilience is determined not only by environmental factors, but also by spatial, social, and institutional conditions. All of these conditions shape the preparedness of cities for the effects of climate change to varying degrees [52–54]. From a structural and financial perspective, it is also noted that, in the process of building resilience, the central and local government sectors should play a leading role in spearheading and financing capital-intensive infrastructure that is resilient to heat waves [55].

Due to the scale of potential losses and the number of people exposed to adverse climate phenomena, Poland's most populous cities are particularly important subjects of research in this area [56–59]. At the same time, these cities are characterized by significant diversity in terms of local climate zones, spatial structure, and adaptation measures implemented [60–63]. Despite the growing number of studies on climate change adaptation, there is still a lack of comprehensive comparative analyses that would consistently take into account local climatic conditions in assessing the potential resilience of Poland's largest cities [64–66]. The contemporary rapid increase in the frequency and intensity of heat waves in Central Europe creates an urgent need for advanced research on the thermal resilience

of cities. Conventional assessment frameworks often overlook microscale variations in the geometry and physics of urban spaces, relying instead on overly general station-based indicators. In this context, the Local Climate Zones (LCZs) system serves as a key research tool that allows for an objective correlation between the morphological characteristics of the urban fabric and its actual thermodynamic potential, bridging the gap between theoretical vulnerability models and practical adaptation planning.

Previous studies have mainly linked heat stress to urban heat islands; however, there is a lack of consistent comparative analyses for Polish cities. Existing heat risk indicators focus on sociodemographic or remote-sensing data [67–69], neglecting physical and structural parameters. To address this gap, this study developed a proprietary index of potential thermal resilience. Unlike traditional approaches, it integrates the physical-morphological and biophysical characteristics of LCZ zones within the IPCC framework (adaptive capacity, exposure, and vulnerability) [49]. Consequently, this study avoids replicating existing frameworks, and the proposed index of potential thermal resilience serves as a new operational tool that allows for an objective comparison of the structural resilience of urban spaces and supports spatial planning.

The aim of this article is to identify and compare the potential thermal resilience of the most populous cities in Poland, taking into account their local climate zones. Analyzing cities based on local climate zones allows for a comparable assessment of their vulnerability and adaptive potential, regardless of the scale and specificity of the historical urban development of a given city. In this context, LCZs are a useful tool to support the adaptation planning process, enabling the identification of areas requiring intervention and those that show relatively high potential thermal resilience.

2. Materials and Methods

2.1. Selection of Cities

The study was conducted in 48 Polish cities located in all 16 provinces (NUTS-2) of the country (Figure 1). The total population of the analyzed cities accounted for approximately 30.2% of the population of Poland (Table 1). The selection of cities for analysis was based on the criterion of population size—cities with at least 70,000 inhabitants were included [70]. The largest cities are of particular importance in climate research, especially in the context of the impact of urbanization on meteorological conditions.

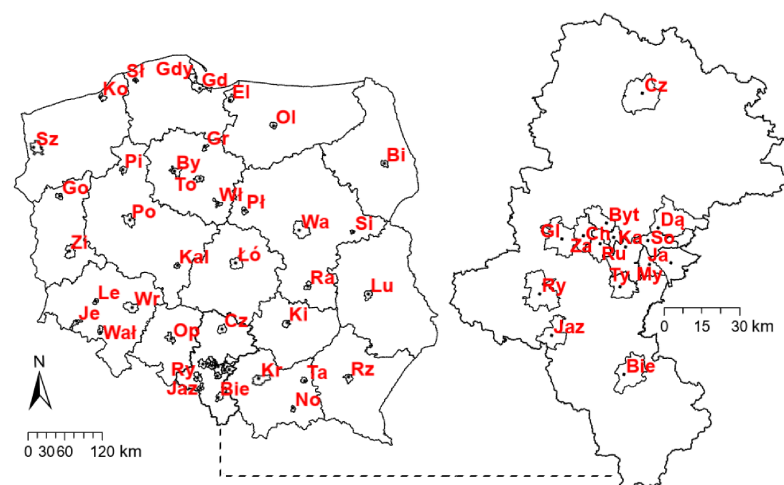


Figure 1. Location of the cities included in the study by province (NUTS-2) in Poland. Explanation of city abbreviations in Table 1.

Table 1. Area and population of the cities analyzed [70].

Abbr.	City	Area (km ²)	Pop. (thous.)	Abbr.	City	Area (km ²)	Pop. (thous.)
Bi	Białystok	102.1	291.7	My	Mysłowice	65.7	71.3
Bie	Bielsko-Biała	124.5	165.8	No	Nowy Sącz	57.6	80.4
By	Bydgoszcz	176.0	326.4	Ol	Olsztyn	88.3	167.3
Byt	Bytom	69.5	147.8	Op	Opole	149.0	126.1
Ch	Chorzów	33.3	100.6	Pi	Piła	102.7	70.1
Cz	Częstochowa	159.7	206.0	Pł	Płock	88.0	111.2
Dą	Dąbrowa Górnicza	188.7	113.5	Po	Poznań	261.9	538.4
El	Elbląg	79.8	112.9	Ra	Radom	111.8	196.0
Gd	Gdańsk	265.9 *	487.4	Ru	Ruda Śląska	77.6	130.3
Gdy	Gdynia	135.2 *	241.2	Ry	Rybnik	148.3	130.9
Gl	Gliwice	133.9	169.9	Rz	Rzeszów	129.0	197.3
Go	Gorzów Wielkopolski	85.7	115.2	Si	Siedlce	31.9	75.3
Gr	Grudziądz	57.8	88.7	Sł	Słupsk	52.7	85.5
Ja	Jastrzębie-Zdrój	85.3	82.3	So	Sosnowiec	91.2	187.1
Ja	Jaworzno	152.4	86.8	Sz	Szczecin	300.6	389.1
Je	Jelenia Góra	109.3	75.1	Ta	Tarnów	72.4	103.1
Kal	Kalisz	69.4	93.1	To	Toruń	115.7	194.8
Ka	Katowice	164.7	279.2	Ty	Tychy	81.8	122.0
Ki	Kielce	109.7	182.3	Wał	Wałbrzych	84.7	100.3
Ko	Koszalin	105.6	105.5	Wa	Warszawa	517.2	1861.6
Kr	Kraków	326.9	806.2	Wł	Włocławek	85.1	100.8
Le	Legnica	56.3	91.9	Wr	Wrocław	292.8	673.7
Lu	Lublin	147.5	329.6	Za	Zabrze	80.4	153.8
Łó	Łódź	293.3	652.0	Zi	Zielona Góra	275.4	138.9

* as of 2022. For Gdańsk and Gdynia, data from 2022 were used to ensure the comparability of land areas and to exclude the internal maritime waters incorporated into the boundaries of these cities in 2024.

The selected cities vary in size (Table 1), level of urbanization, and climatic conditions [71–73]. According to the Köppen-Geiger classification [74], most Polish cities have a continental climate without a dry season and with a warm summer (*Dfb*, cold). Only in the western and northwestern parts of Poland does a temperate climate without a dry season and with a warm summer (*Cfb*, temperate) prevail.

2.2. Demographic and Meteorological Data

The following data were used for the analyses: population density (total population per 1 km²) and population density aged ≥ 65 per 1 km², broken down by gender [70]. In terms of meteorological data, annual precipitation totals and average annual air temperature (1961–2020) were taken into account, as provided by the Institute of Meteorology and Water Management—National Research Institute in Warsaw. Spatial data included latitude (Φ , °N) and longitude (λ , °E). The inclusion of geographic coordinates (Φ , λ) in the multiple regression model was intended to account for macroscale spatial gradients, such as the eastward increase in climatic continentality and changes in radiation balance along the north–south axis.

2.3. Local Climate Zones

The Global Map of Local Climate Zones (LCZs) was used to characterize the structure and morphology of the terrain of 48 Polish cities in the context of the local climate. This map (version 3), developed by Demuzere et al. [75,76], was made available through the website <https://lcz-generator.rub.de/global-lcz-map> (accessed on 15 January 2026). The overall accuracy of the v3 map was 75–80% (for Central Europe, >80%), and the data were from 2022. To reduce uncertainty, a manual visual verification of the designated LCZs was conducted using orthophoto maps [77] and the BDOT10k database [77], which confirmed the accuracy of classification. A slight time discrepancy between the years in which the satellite data for the LCZ classification were collected and the 2024 demographic data from the Central Statistical Office introduced a marginal degree of uncertainty. The population density and macroscale spatial patterns in Poland's largest cities exhibit high structural stability over short multi-year periods, which ensures the validity of the macroscale statistical correlations presented. The Global LCZs Map has been described and used in numerous studies, including Akbulut and Sertel [78], Anjos et al. [79], Hu et al. [42], Pappaccogli et al. [80], and Jiang et al. [81]. The Global LCZs Map with a spatial resolution of 100 m was developed on the basis of satellite images and machine learning methods. The 100-m spatial resolution of the Global LCZ Map v3, while highly effective in national comparative analyses, has some limitations when analyzing smaller urban areas (under 100 km², such as Siedlce or Chorzów).

The Global LCZs Map is based on the universal LCZs classification proposed by Stewart and Oke [29]. This classification distinguishes a total of 17 land cover classes that are relevant to the local climate and modeling of atmospheric responses to urbanization processes. Land cover classes include both built-up areas (LCZs 1–10) and natural areas (LCZs A–G). Since then, the classification has been supplemented only to a limited extent. For example, Zhang et al. [82] introduced an additional 18th LCZ class—LCZM (mixed), which includes grid cells in which the maximum share of a single LCZ class is less than 50%.

ArcGIS Pro 3.6.0 software was used to calculate the area of individual LCZs in the analyzed cities, supported by Python 3.13 scripts that enabled the automation of the spatial data analysis process and the aggregation of areas by LCZ classes. The LCZ raster was cropped to the administrative boundaries of the National Boundary Register [77] using the pixel centroid method. Any local errors in cell classification have a marginal impact on R_c , because, as an aggregate indicator for the entire city, it compensates for local statistical noise.

For Gdańsk and Gdynia, data from 2022 were used to ensure the comparability of land areas and to exclude the internal maritime waters incorporated into the boundaries of these cities in 2024.

2.4. Determination of Potential Thermal Resilience R_c

The potential thermal resilience (R_c , -) of the cities c was determined based on the area shares P_i of individual local climate zones (LCZs 1–10 and LCZs A–G), developed by Stewart and Oke [29].

The R_c index, embedded in the general principles of vulnerability and risk assessment according to the IPCC [49], was calculated as the weighted sum of the difference between adaptive capacity and the sum of exposure and sensitivity:

$$R_c = \sum_{i=1}^n \left(\frac{P_i}{100} \cdot [CA_i - (E_i + V_i)] \right) \quad (1)$$

The R_c index directly operationalizes the IPCC [49] vulnerability framework, where the component CA_i represents adaptive capacity, E_i accounts for exposure, and V_i reflects the system's sensitivity, with all physical parameters assigned to these dimensions according to the classification by Stewart and Oke [29].

Adaptive capacity (CA_i) of class i of LCZ (features enabling compensation and adaptation) was defined as the arithmetic mean of the pervious surface fraction (PSF), height of roughness elements (HRE), and surface albedo (SAL):

$$CA_i = \frac{PSF_i + HRE_i + SAL_i}{3} \quad (2)$$

and applied to classes LCZs 5–6, LCZ 9, LCZs A–D, and LCZ G.

Exposure to risk (E_i) (features of space determining the possibility of stress) was expressed as the average value of the sky view factor (SVF), aspect ratio (AR), and building surface fraction (BSF):

$$E_i = \frac{SVF_i + AR_i + BSF_i}{3} \quad (3)$$

and referred to classes LCZs 1–4, LCZ E.

System sensitivity (V_i) (characteristics increasing susceptibility to stress effects) was calculated as the average of the impervious surface fraction (ISF), terrain roughness class (TRC), and anthropogenic heat output (AHO):

$$V_i = \frac{ISF_i + TRC_i + AHO_i}{3} \quad (4)$$

and applied to classes LCZs 7–8, LCZ 10, and LCZ F.

The analysis assumes that all components of the CA_i , E_i , and V_i indicators have equal weights. The equations for the R_c index included average values (or, in the case of 0, a value of 0.01) for the characteristics controlling the key components of the energy balance of local climate zones, as proposed by Stewart and Oke [29]. These features were used because of their functional role in shaping climate stress and its effects, while avoiding double counting of the same processes.

Before substituting into the R_c equations, each feature was transformed using the min–max method according to the formula:

$$x_n = \frac{x - x_{min}}{x_{max} - x_{min}} \quad (5)$$

For the features HRE , AR , BSF , ISF , TRC , and AHO , an additional transformation was applied:

$$x'_n = 1 - x_n \quad (6)$$

Due to these transformations, all characteristics were reduced to a scale of 0–1, where 0 meant minimal resilience to adverse thermal conditions (heat waves, urban heat islands), and 1 meant maximum resilience.

Next, the R_c values calculated for each of the cities studied were scaled using the min–max method to the range (0, 100), taking the minimum (0.269) and maximum (0.639) values obtained in the analyzed set of cities, according to the formula:

$$R'_c = 100 \cdot \frac{R_c - 0.269}{0.37} \quad (7)$$

This procedure enabled direct comparison of the level of potential resilience between the analyzed cities, revealing even slight differences in the original values of the R_c index (Figure 2). Rescaling was also helpful in determining the potential thermal resilience

categories of the cities studied and in analyzing correlations with independent variables (Table 2).

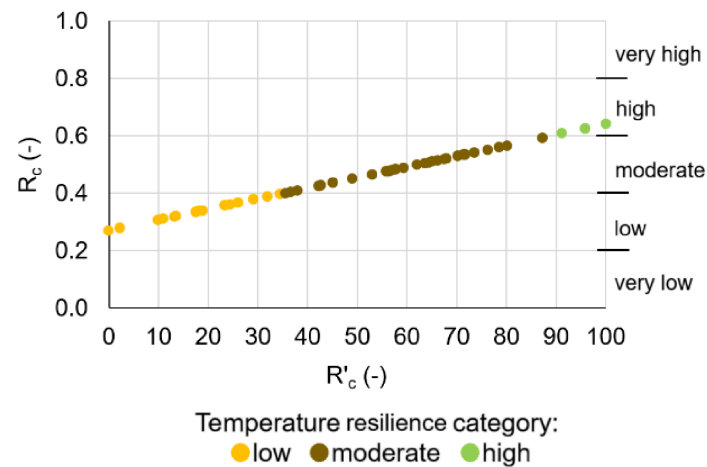


Figure 2. Thermal resilience index (R_c , -) for the cities studied. R'_c —the R_c index rescaled using the min–max method to the range $\langle 0, 100 \rangle$.

Table 2. Classification of the thermal resilience index for the cities studied.

Resilience Category	Range of the Indicator R_c (-)	Range of the Indicator R'_c (-)
very low	$0.0 \leq R_c < 0.2$	—
low	$0.2 \leq R_c < 0.4$	$0.0 \leq R'_c < 34.5$
moderate	$0.4 \leq R_c < 0.6$	$34.5 \leq R'_c < 87.2$
high	$0.6 \leq R_c < 0.8$	$87.2 \leq R'_c \leq 99.9$
very high	$0.8 \leq R_c \leq 1.0$	—

2.5. Statistical Analysis

Spearman's rank correlation analysis was used to assess the relationship between the previously calculated structural index R'_c and selected demographic, climatic, and spatial factors. Data for the 48 cities were included in the analysis. The statistical significance of the correlation coefficients was assessed at a level of at least $p < 0.1$. The assessment of statistical significance allowed for the identification of both strong and moderate relationships, potentially significant from the point of view of the analyses of the independent variables under consideration.

The obtained coefficient values were interpreted in accordance with the adopted classification of the strength of dependence (weak, moderate, strong), with particular attention paid to the direction of correlation. The analysis covered the following independent variables: population density (Pd , persons/km²), population density of men aged ≥ 65 (Nm , persons/km²), population density of women aged ≥ 65 (Nf , persons/km²), annual precipitation (Pr , mm), annual average air temperature characterizing the general macroclimatic background of the studied cities (Ta , °C), as well as latitude (Φ , °N) and longitude (λ , °E). Additionally, the relationship between R'_c and Ta was assessed using curvilinear regression (second-degree polynomial). The aim of this assessment was to identify potential non-linear dependencies that cannot be detected using linear correlation measures. The use of a curvilinear model for the annual mean temperature allows for the accurate capture of nonlinear thresholds and transition zones in urban structures, which are specific to a temperate climate.

In the next stage, a multiple linear regression analysis was performed, in which the indicator of the city's potential thermal resilience (R'_c) was the dependent variable.

Independent variables, identified on the basis of correlation analysis and substantive assumptions, were included in the model. Regression analysis was used to assess the combined and independent impact of a set of factors on the potential thermal resilience of cities, while controlling for other variables. The validity of the regression model was assessed based on residual analysis and standard goodness-of-fit measures.

3. Results

3.1. Spatial Structure of the Cities According to LCZs

An analysis of the percentage share of local climate zones (LCZs) revealed significant differences in the spatial structure between the cities analyzed in Poland. No single dominant land development model was identified for the entire study sample (Figure 3).

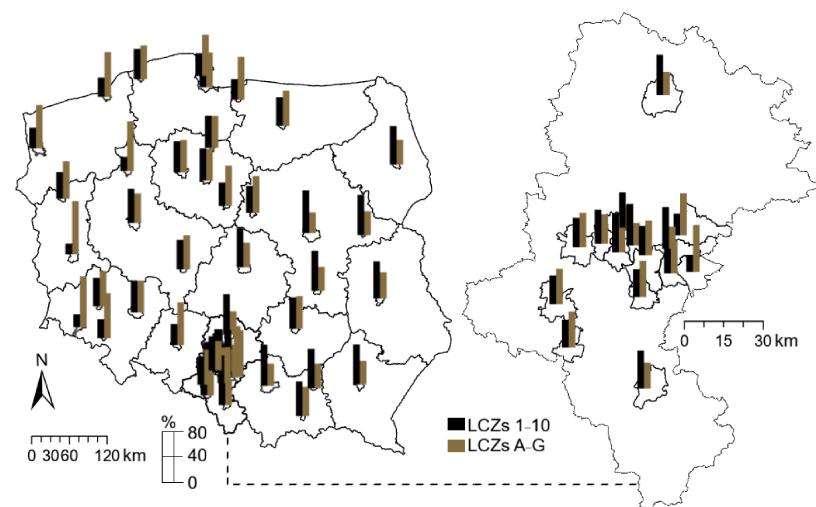


Figure 3. Area share (%) of building zones (LCZs 1–10) and land cover zones (LCZs A–G) in the cities.

The share of building zones (LCZs 1–10) in the analyzed cities ranged from 16.6% to 67.2% of the total city area. In 21 of 48 studied cities, the share of building zones (LCZs 1–10) exceeded 50% of the city's area. In turn, the share of non-built-up zones (LCZs A–G) in the city's area ranged from 32.8% to 83.4%. In this case, in 27 of the 48 cities examined, the share of non-built-up areas exceeded 50% of the total area of the city.

Among the building zones (LCZs 1–10), LCZ 6 (open low-rise) had the largest share of space. The average share of LCZ 6 in the total area of the cities was 29.2%. The share of the LCZ 6 zone area varied among the cities, from 10.4% of the city area in Zielona Góra to 51.9% of the city area in Ruda Śląska (Figure 4). Particularly high values of the LCZ 6 area share in the city area ($\geq 30\%$) were found in 20 cities with a dispersed residential structure. These were mainly the cities that make up the Upper Silesian conurbation (southern part of Poland) and cities with post-industrial origins. This indicates that extensive low-rise development is the dominant element in the spatial structure of these cities. The second largest building zone in terms of the share of the total cities' area was LCZ 5 (open mid-rise), accounting for an average of approximately 8% of the city area. The share of LCZ 5 areas in the city area ranged from 0.9% in Jastrzębie-Zdrój to 27.4% in Warsaw. In many cities, LCZ 5 and LCZ 6 constituted the largest parts of the built-up urban area, and their combined share exceeded 40–60% of the city area in 22 of the 48 cities studied. LCZ 4 (open high-rise) was marginal, occupying only 0.3% of the city area on average. A share of LCZ4 exceeding 0.5% of the city area was recorded in only seven cities, with the highest values ($>1.5\%$ of the city area) found in Gdańsk, Kraków, and Gdynia.

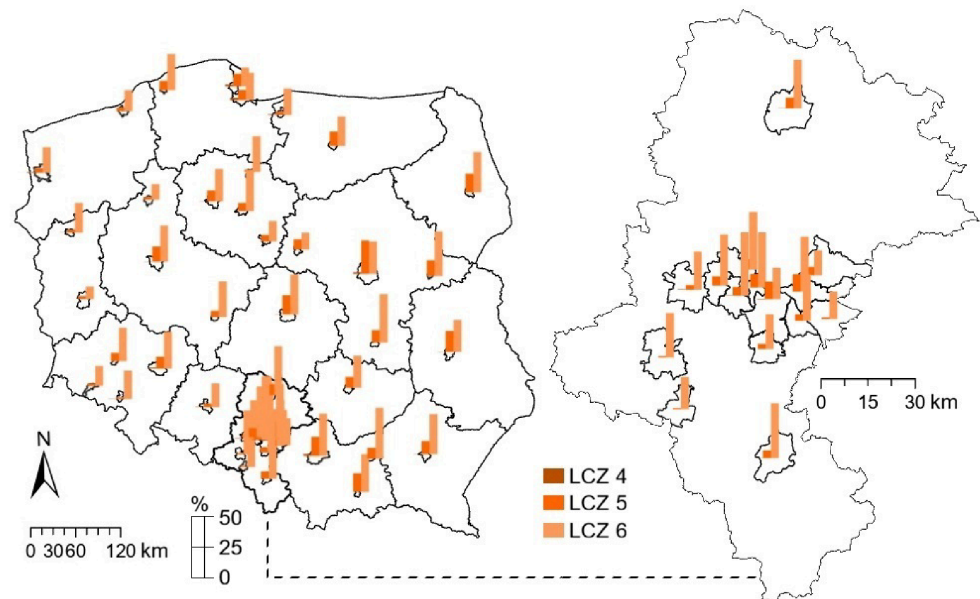


Figure 4. Area share (%) of low-density building zones (LCZs 4–6) in the cities.

The share of the total area of all compact building zones (LCZs 1–3) was low in the analyzed cities and usually did not exceed 0.5% of their total area (Figure 5). The highest values of the share of compact building zones were usually found in the largest urban centers (Warsaw, Poznań, Kraków, Katowice, Wrocław, Opole, Bytom, Łódź, and Szczecin). However, even in these cities, the areas of LCZs 1–3 remained limited. This indicates the relatively small extent of areas with high building density within the administrative boundaries of the cities studied.

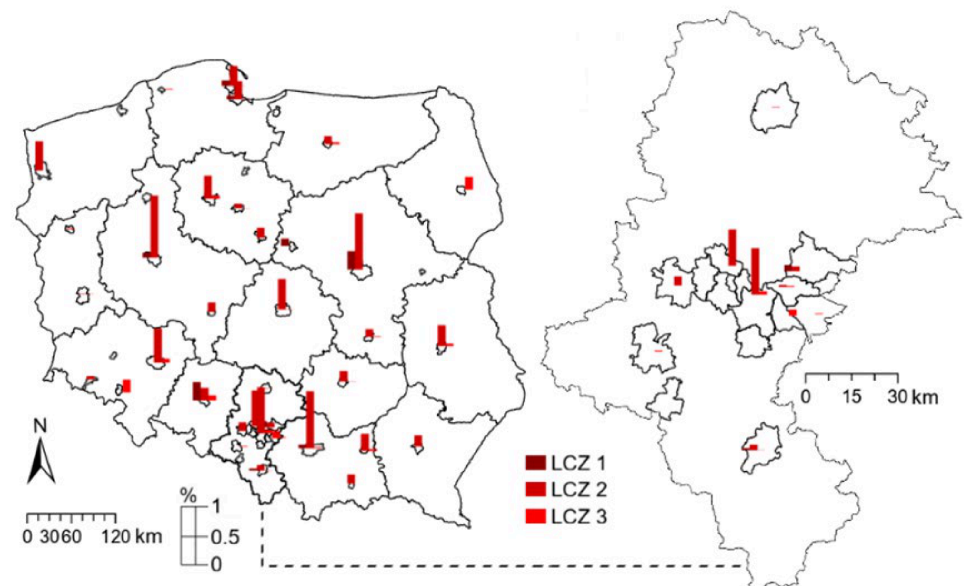


Figure 5. Area share (%) of compact building zones (LCZs 1–3) in the cities.

Industrial and infrastructure building zones (LCZs 8–10) had a moderate and varied share in the area of cities, depending on the economic function of the city (Figure 6). Increased values of the share of the area of these zones, considered collectively, amounting to $\geq 10\%$ of the city area, were found in 24 of the 48 cities studied. These were mainly cities with highly developed industries, logistics, or port functions. The maximum proportion of

LCZs 8–10, approx. 20%, was recorded in Płock. However, in the entire sample, LCZs 8–10 were not the dominant components of the LCZ structure.

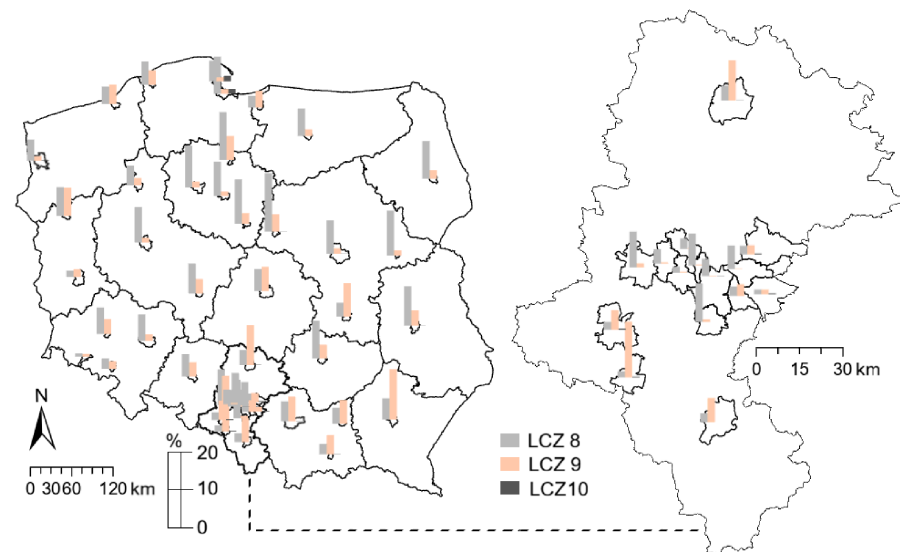


Figure 6. Area share (%) of large-scale, dispersed, and industrial building zones (LCZs 8–10) in the cities.

LCZ A (dense trees) and LCZ D (low plants) had the largest surface areas among the non-built-up zones (Figure 7). The share of LCZ A varied considerably, ranging from a few percent to values exceeding 50% of the city's area. Particularly high shares of this zone were found in cities with a large share of forest complexes within their administrative boundaries, such as Zielona Góra (56.2%), Piła (54.7%), and Gdynia (54.4%). In the remaining 16 cities, LCZ A constituted a significant (>25% of the city area) but not dominant element of spatial structure.

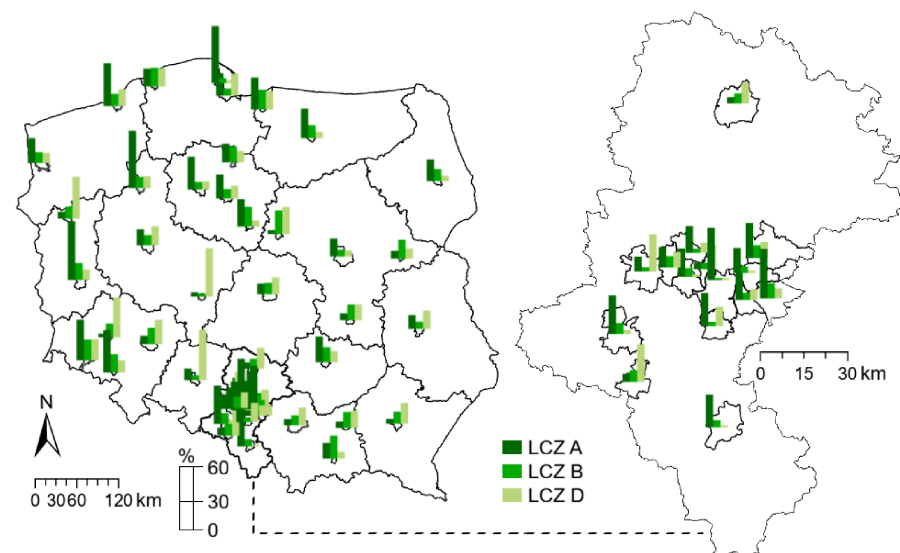


Figure 7. Area share (%) of plant zones (LCZs A–B and D) in the cities.

The second key non-built-up area was LCZ D, which comprised mainly agricultural land and other open areas. The share of LCZ D exceeded 20% of the city area in 12 cities. In this group of cities, the share of LCZ D reached values close to 50% of the city area in two centers (Kalisz: 46.5%; Opole: 48.3%). The high proportion of LCZ D areas within cities was primarily due to the inclusion of extensive agricultural land within the admin-

istrative boundaries of cities, and mainly concerned areas located outside the compact urban structure.

LCZ B (scattered trees) was generally characterized by a smaller, usually not exceeding 15%, and more stable share of area in cities than LCZ A and LCZ D. LCZ B was present in all the analyzed cities, serving as a transitional area between built-up and open areas.

LCZ E (bare rock or paved) and LCZ F (bare soil or sand) occupied very small areas. These zones occurred only locally, most often in connection with industrial activity, technical infrastructure, or specific geological conditions (Figure 8). Their share in the spatial structure of cities was generally less than 0.1% of the total city area.

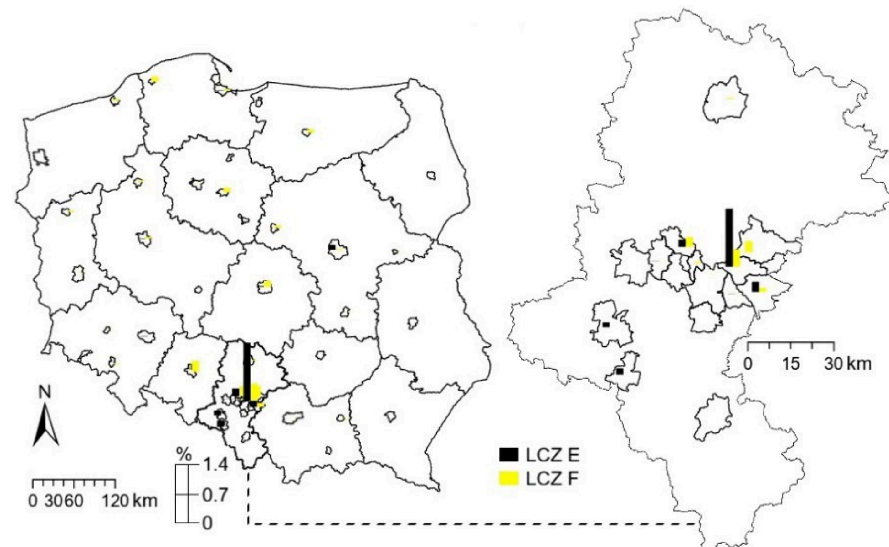


Figure 8. Area share (%) of vegetation-free zones (LCZs E and F) in the cities.

Water zones (LCZ G) varied in terms of their share of the total area of the cities (Figure 9). In cities located on large rivers or near water reservoirs, the spatial significance of LCZ G was clearly greater than that in other cities. The larger shares of LCZ G included 8.6% in Olsztyn, 12.3% in Włocławek, and a maximum of 24.3% in Szczecin. In the case of a larger share of LCZ G in the city area, the presence of this zone can significantly modify local climatic conditions, particularly in summer.

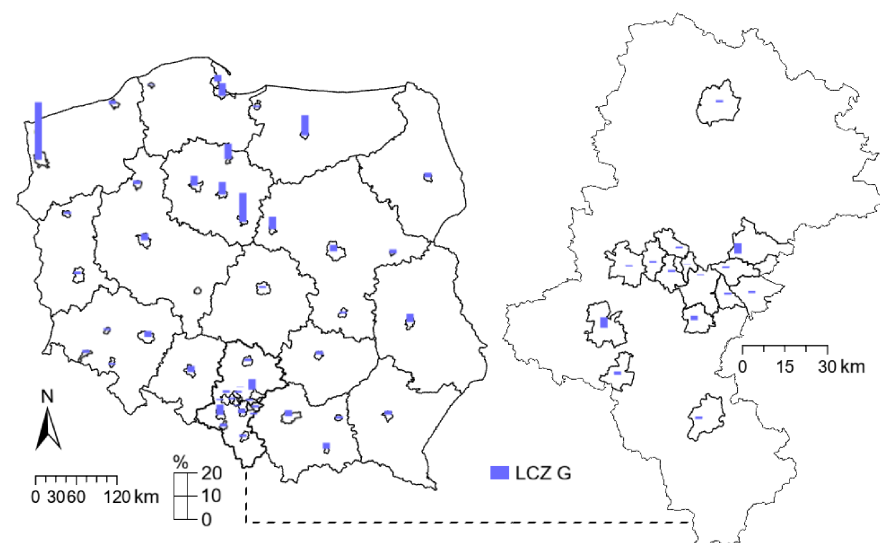


Figure 9. Area share (%) of surface water (LCZ G) in the cities.

3.2. The Potential Thermal Resilience of Cities

Based on the potential thermal resilience index (R_c , -), five resilience categories were distinguished. The analyzed cities were classified into three of the five categories of potential resilience: low ($0.2 \leq R_c < 0.4$), moderate ($0.4 \leq R_c < 0.6$), and high ($0.6 \leq R_c < 0.8$) (Figure 2, Table 2).

Fifteen cities were classified as having low potential thermal resilience, with R_c values ranging from 0.269 (Płock) to 0.397 (Gdynia) (Figure 10). Thirty cities were characterized by moderate potential thermal resilience, whereas only three cities were classified as having high potential thermal resilience. These were Zielona Góra ($R_c = 0.607$), Jastrzębie-Zdrój ($R_c = 0.624$), and Jelenia Góra ($R_c = 0.639$). Unlike Płock (the city with the lowest R_c index value), Jelenia Góra was characterized by a significantly higher proportion of areas with high thermal resilience, primarily forests and dense greenery (LCZ A: 38.9% compared to 3.8%) (Figure 11).

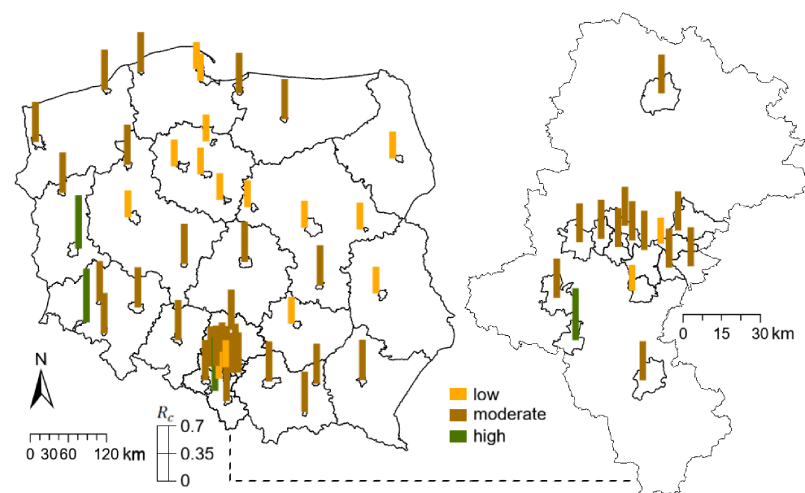


Figure 10. Categories of potential thermal resilience of cities determined on the basis of the index (R_c , -).

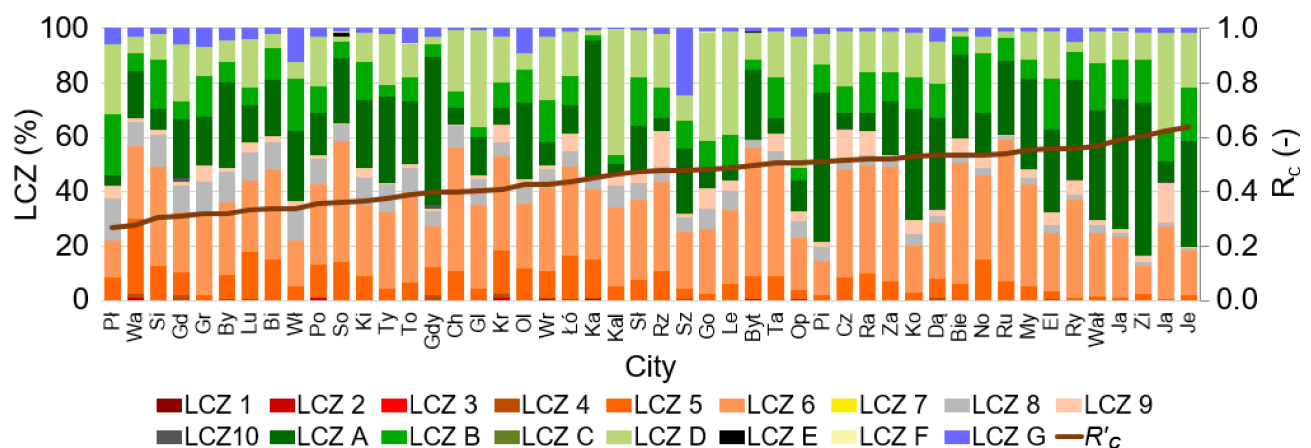


Figure 11. Area share (%) of building zones (LCZs 1–10) and land cover zones (LCZs A–G) by city and corresponding R_c values (-).

An analysis of the LCZ structure revealed significant differences in the share of individual types of land development in the total area of the city (Figures 12 and 13). This variation concerned both the share of building zones (LCZs 1–10) and the share of areas not related to buildings (LCZs A–G), which play a key role in shaping the local thermal conditions.

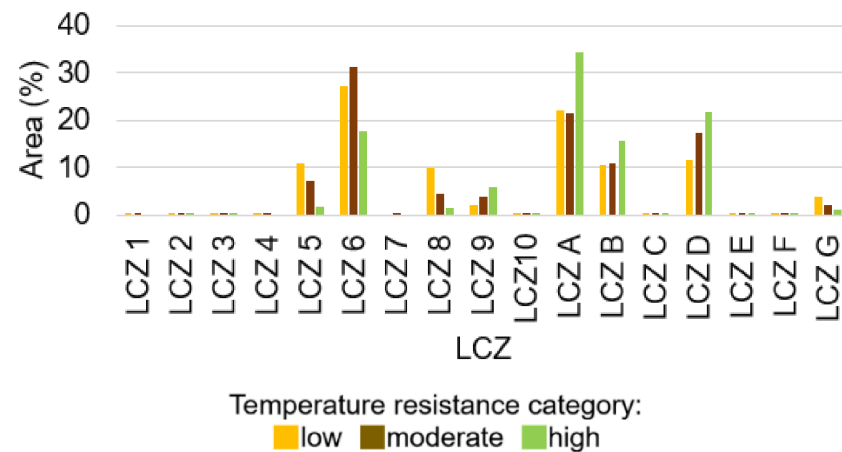


Figure 12. Average area share (%) of building zones (LCZs 1–10) and land cover zones (LCZs A–G) by category of potential thermal resilience of cities.

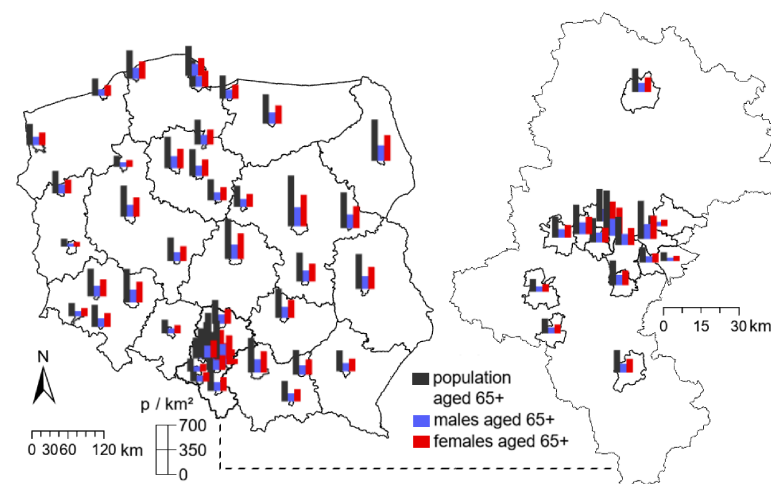


Figure 13. Population density of persons aged ≥ 65 (persons/km²), including male and female density, in the cities.

In cities with low potential thermal resilience, the dominant spatial zone was the open low-rise building zone (LCZ 6). The share of LCZ 6 in the areas of these cities averaged 27.3% (Figure 12). The shares of the open mid-rise building zone (LCZ 5—10.8%) and large low-rise buildings characteristic of warehouses and commercial zones (LCZ 8—10.1%) were also significant. Forest areas (LCZ A) accounted for an average of 22.2% of the area of cities with low thermal resilience, whereas areas with low vegetation (LCZ D) accounted for half as much, i.e., 11.6% of the area of these cities. The share of compact urban building zones (LCZs 1–3) in the areas of cities with low potential thermal resilience was marginal and did not exceed an average of 0.26% in any of the zones.

Cities with moderate potential thermal resilience were characterized by an increase in the importance of LCZ 6 compared to cities with low resilience. Compared to the shares of LCZ 6 in the three analyzed categories of cities, the share of LCZ 6 was highest in cities with moderate resilience (31.2%) (Figure 12). Simultaneously, compared to cities with low resilience, there was an increase in the share of green areas, in particular areas covered with low vegetation (LCZ D—17.5%), and a high share of forests (LCZ A—21.6%). Compared to cities with low potential thermal resilience, cities with moderate potential thermal resilience had a lower share of industrial and large-scale building zones (LCZ 8—4.7%), which indicates a more balanced land use structure.

In cities with high potential thermal resilience, a predominance of non-built-up areas was observed (Figure 12). The largest share of the area of cities with high resilience was occupied by forest areas (LCZ A—34.2%), as well as areas with low vegetation (LCZ D—21.9%) and areas with scattered tree cover (LCZ B—15.8%). Simultaneously, a small share of areas with open low-rise buildings (LCZ 6—17.7%) and a small share of areas with open mid-rise buildings (LCZ 5—1.8%) were observed in cities with high resilience. In this category of cities, a relatively large share of the city area was occupied by areas with scattered buildings (LCZ 9—5.8%), characterized by a lower degree of surface sealing.

3.3. The Dependence of the R'_c Index on Demographic, Climatic, and Spatial Characteristics

Spearman's rank correlation analysis (ρ) revealed statistically significant relationships between the R'_c index, which characterizes the potential thermal resilience category of a city, and selected demographic, climatic, and spatial characteristics (Table 3).

Table 3. Relationship between the R'_c index and the analyzed variables.

Statistical Variable	Abbrev.	Spearman's Rank Correlation Coefficient	Significance Level
Population density over per km ²	Pd (pers. km ⁻²)	−0.499	0.01
Number of males aged 65 and over per km ²	Nm (pers. km ⁻²)	−0.6602	0.01
Number of females aged 65 and over per km ²	Nf (pers. km ⁻²)	−0.548	0.01
Annual precipitation	Pr (mm)	0.593	0.01
Mean annual air temperature	Ta (°C)	0.232	NS
Latitude	Φ (N)	−0.407	0.01
Longitude	λ (E)	−0.294	0.05

NS—not significant.

A moderate negative correlation was found between R'_c and population density ($\rho = -0.499$; $p < 0.01$), indicating that cities with higher potential resilience tend to have lower population concentrations. A similar trend was observed for the population age structure. The potential thermal resilience of a city was negatively correlated with the population density of men aged ≥ 65 per km² ($\rho = -0.6602$; $p < 0.01$) and with the density of women aged ≥ 65 per km² ($\rho = -0.548$; $p < 0.01$). These results suggest that areas with higher potential thermal resilience are often characterized by lower concentrations of older people.

The number of people aged ≥ 65 per km² ranged from 112 in Zielona Góra to 724 in Warsaw, which means a more than sixfold difference between the extreme values (Figure 13). In all the cities studied, women outnumbered men in this age group by an average of 82 persons/km². The number of women aged ≥ 65 ranged from 68 to 451 persons/km², while the number of men aged ≥ 65 per km² ranged from 24 to 178 persons/km². In 12 cities, the difference between the density of women aged ≥ 65 and the density of men aged ≥ 65 exceeded 100 persons/km², which was consistent with the national demographic structure and the longer average life expectancy of women.

A moderate positive correlation was also demonstrated between the potential thermal resilience of a city and the annual precipitation total ($\rho = 0.593$; $p < 0.01$), indicating an increase in thermal resilience with increasing precipitation (Table 3). Although Spearman's rank correlation analysis did not reveal a statistically significant relationship between

the potential thermal resilience of a city (R'_c) and the annual average air temperature ($\rho = 0.232$; $p < 0.109$), further exploration of the data revealed the existence of a significant nonlinear relationship between these variables. This relationship was described using a second-degree polynomial regression model, which took the form of a parabolic function (Figure 14). The negative sign in the quadratic term indicates that the relationship is concave, which means that the potential thermal resilience of cities increases with an increase in the annual average temperature (Ta , °C) up to a certain threshold level, after which it begins to decrease. This model explained approximately 14.6% of the variability in potential thermal resilience and was statistically significant ($R^2 = 0.146$, $p < 0.1$), confirming that the relationship between R'_c and Ta , despite not being linear, was statistically significant. Given the relatively low level of explained variance, the nonlinear relationship obtained should be interpreted with caution, treating it as a clear statistical trend of climatic and spatial nature rather than as a definitive and strong determinism.

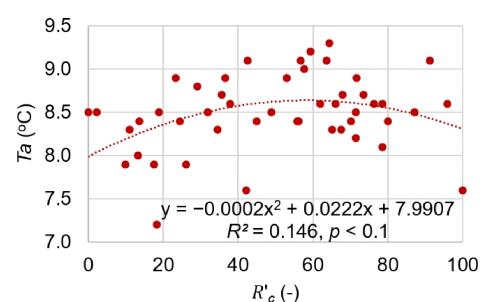


Figure 14. Curvilinear relationship between the R'_c index and the average annual air temperature (Ta , °C).

Spatial relationships also proved to be significant. The potential thermal resilience of cities showed a negative correlation with latitude ($\rho = -0.407$; $p < 0.01$) and longitude ($r = -0.294$; $p < 0.05$), indicating a clear regional variation in the phenomenon under study (Table 3). Higher potential thermal resilience was characteristic of cities located further south and west in Poland, whereas lower potential thermal resilience values were observed in cities in the north and east of the country.

Multiple linear regression analysis was also performed for the dependent variable R'_c on a sample of $N = 48$ (Table 4). The model was statistically significant, $F(4,43) = 17.06$, $p < 0.01$, explaining 61% of the variance of the dependent variable ($R^2 = 0.61$; $R^2_{adj} = 0.58$). All predictors proved to be statistically significant. The annual precipitation (Pr , mm) positively predicted the level of R'_c ($\beta = 0.37$, $p < 0.01$), while the other variables had a significant negative effect on the dependent variable: latitude (Φ ; $\beta = -0.24$, $p < 0.05$), longitude (λ ; $\beta = -0.32$, $p < 0.01$), and number of women ≥ 65 years per km^2 (Nf ; $\beta = -0.37$, $p < 0.01$).

Table 4. Multiple linear regression equation for variable R'_c .

Predictor	Regression Parameter			
	Standardized (β)	Unstandardized (B)	t	p
Intercept		310.425	2.54	0.01
Nf (pers. km^{-2})	−0.37	−0.11	−3.46	0.01
Pr (mm)	0.37	0.104	3.24	0.01
Φ (N)	−0.24	−4.27	−2.14	0.05
λ (E)	−0.32	−4.34	−2.95	0.01

Note: $R^2 = 0.61$; $R^2_{adj} = 0.58$; $F(4,43) = 17.06$, $p < 0.01$; explanations of predictors as in Table 3.

4. Discussion

The results obtained confirmed the widely held view in the literature that the spatial structure of cities, in particular the diversity of local climate zones, is one of the key factors determining their response to thermal stress [83–87].

The high spatial heterogeneity of Polish cities demonstrated in these studies is consistent with the research of Stewart and Oke [29] and Bechtel et al. [88], who emphasize that the LCZ typology reflects not only the current state of development, but also long-term urbanization processes, conditioned by the history of development and regional specificity. The lack of a single dominant spatial development pattern in Polish cities is consistent with the model of post-socialist cities, characterized by a mosaic of functional and spatial structures and a large share of extensive areas within administrative boundaries [89–93]. The dominant share of LCZ 6 (open low-rise), often combined with a share of LCZ 5 (open mid-rise), is consistent with the results of studies conducted in Central and Eastern Europe, which indicate relatively low building intensity and greater dispersion of urban structures compared to Western European cities [11,34,94,95]. The literature emphasizes that although sparsely built-up areas generate a weaker urban heat island effect than compact building zones, their large share—especially with significant surface sealing—can lead to significant heat accumulation and reduced nighttime cooling, particularly during heat waves [96–99]. Such a spatial-analytical assessment of urban heterogeneity also serves as a key starting point for the potential design of heat-resilient structures [33].

A significant role in shaping the thermal resilience of Polish cities is played by the large proportion of non-built-up areas, especially LCZs A and D. Empirical studies clearly show that forest areas and areas with low vegetation are characterized by lower surface and air temperatures than their surroundings, mainly due to intense evapotranspiration and favorable radiation properties [100–104]. According to the literature on the cooling role of urban greenery, the presence of extensive biologically active areas within city administrative boundaries can significantly reduce average temperatures, although this effect is spatially uneven and depends on the degree to which these areas are connected to buildings [105–109].

The importance of the scale and structure of vegetation cover for the effectiveness of urban cooling has been clearly confirmed in quantitative studies. For example, Ziter et al. [110] showed that the local cooling effects of greenery do not add up linearly and that only when a threshold of approximately 40% tree canopy cover is reached can a statistically significant reduction in air temperature be achieved on the scale of a typical city block, mainly through increased evapotranspiration and a reduction in sensible heat flux at the expense of latent heat. In turn, Zaerpour et al. [111] showed that increasing tree canopy cover by 10% can lower air temperature by approx. 0.8 °C, and further increasing cover to 30% can lower air temperature by up to ~1.5 °C. These results directly confirm the cooling effect of increased green space in built-up urban areas and the potential of green spaces for adaptation to climate change.

The proposed potential thermal resilience index R_c is an extension of research approaches integrating exposure, vulnerability, and adaptive capacity, remaining consistent with the conceptual framework of urban climate resilience proposed by, among others, Tyler and Moench [112] and the approach to climate risk and resilience presented in the IPCC report [49]. Unlike indicators based solely on temperature observations, the R_c construct refers to the morphological and biophysical characteristics of the urban environment that directly shape the local energy balance. This approach is consistent with Santamouris's proposal [113] that the assessment of cities' vulnerability to heat stress should take into account not only current thermal conditions, but also the potential of the urban environment to modify them. The R_c index is closely related to the assessment of the spatial, morphological,

and biophysical capacities of urban systems for mitigating heat stress. It serves as a physical starting point and a baseline structural potential upon which comprehensive resilience strategies, considering social, infrastructural, and management factors, can be built.

The resulting distribution of potential thermal resilience categories, with a predominance of cities with moderate potential resilience and a marginal share of cities with high potential thermal resilience, confirmed the results of studies conducted in other countries in the temperate zone [114–116]. The literature [117–119] indicates that high thermal resilience is usually achieved in cities with a high proportion of tall greenery, a low degree of sealing, and limited building intensity—a combination that is relatively rare in Poland’s climate. These results reinforce the arguments in favor of active adaptation policy, in which spatial planning plays a key role in shaping bioclimatic conditions [120–122]. However, any restructuring of urban areas to limit development in favor of biologically active zones involves financial barriers and therefore requires systemic commitment and capital support from the public sector [55].

An analysis of cities with high potential thermal resilience confirmed the findings of studies on the cooling role of woody vegetation and semi-natural areas. A high proportion of LCZs A, B, and D, combined with a reduction in open mid-rise building zones, not only promotes increased evapotranspiration but also improves air circulation. This phenomenon is widely described in the literature as one of the key mechanisms for reducing heat stress [123–126]. The relationships between the value of the R'_c index, i.e., R_c after rescaling, and demographic and climatic factors are consistent with the findings of the literature on social vulnerability to heat. The statistical correlations observed between R'_c and the population density of older adults should be interpreted as a phenomenon of spatial co-location rather than a direct cause-and-effect relationship. Higher concentrations of vulnerable demographic groups coincide with core urban areas characterized by high building density, highlighting the spatial overlap between social vulnerability and structural exposure to heat rather than a strict morphological relationship. Numerous studies indicate that older people are one of the groups most vulnerable to the effects of extreme temperatures. In view of the above, it can be assumed that the large number and spatial concentration of older people increases the overall vulnerability of cities to heat stress [127–129]. At the same time, the positive relationship between potential thermal resilience and annual precipitation suggests that water availability may be important for the functioning of urban greenery and the maintenance of its cooling potential [130–132], although this association may also reflect broader spatial co-variation.

The clear geographical variation in potential thermal resilience, manifested in higher values of the R'_c index in southern and southwestern cities, and lower values of R'_c in northern and eastern cities, appears to align with the known climatic gradients in Poland and regional differences in land use patterns [44,45]. The results of multiple regression, explaining 62% of the variability of the R'_c index, point toward the multifactorial nature of the potential thermal resilience of cities, emphasized in the literature as a potential result of the interaction of spatial, demographic, and climatic factors [133–135]. However, because these external socioeconomic and climatic variables were not used to construct the R'_c index itself, these observed links should be interpreted with caution, as they may primarily reflect their co-variation with the baseline urban spatial structure. In addition, the interpretation of the model must consider the phenological seasonality of vegetation in LCZs A and D, which modifies their actual radiative and aerodynamic properties throughout the year.

In light of the literature, the proposed R_c index can be treated as a useful tool to support the assessment of the potential thermal resilience of cities and the identification of areas requiring priority adaptation measures. Although direct operational validation based on empirical micrometeorological networks in all 48 cities is beyond the scope of

this conceptual study, the biophysical parameters underlying R_c are well established in the empirical literature [47,104,106]. Previous field and remote sensing studies conducted in Polish urban areas (e.g., in Warsaw, Kraków, and Wrocław) consistently confirmed that the spatial distribution of surface temperature extremes closely reflects the morphological characteristics integrated into the structure of the developed index. Its advantage is that it can be used in comparative analyses and strategic planning, especially in the context of the increasing frequency and intensity of heat waves in Central Europe.

In practice, this requires the implementation of strict limits on impervious surfaces and a systemic increase in the share of green infrastructure in land use plans. According to the literature, the R_c index allows the formulation of practical urban planning guidelines as part of adaptation strategies. In LCZ 5 and LCZ 6, it is crucial to create blue-green infrastructure that connects tall vegetation with micro-retention [136] and ensure 30–40% tree canopy cover along pedestrian routes, which reduces local temperatures by 0.8–1.5 °C [111,137]. Furthermore, it is essential to implement cool pavements and roofs to limit heat accumulation [136], while simultaneously protecting LCZs A and D from development to maintain the patency of the ventilation corridors [137]. These measures, implemented through integrated urban heat management plans, are key to the effective climate adaptation of Polish cities and support sustainable development.

A recognized limitation of this analysis is the impact of administrative boundaries on the aggregated results. Cities with extensive forest areas (e.g., Zielona Góra and Gdynia) show higher values of the R_c index for their entire territory. This index reflects the potential of a municipality within its legal boundaries, which is important for local management; however, when comparing urban cores, this specific characteristic must be considered. The main limitation of the R_c index remains the use of fixed weights for geometric and radiative characteristics, which simplifies nonlinear thermal interactions at the urban microscale. Another limitation is the 100 m spatial resolution of the Global LCZ Map v3. Although highly effective in national comparative analyses, it introduces inherent scale limitations when analyzing smaller urban areas (under 100 km², such as Siedlce or Chorzów). At this grid resolution, local micromorphological changes and edge effects may not be fully reflected, which underscores the need to supplement local analyses with higher-resolution spatial data.

5. Conclusions

Polish cities are characterized by high spatial heterogeneity. The urban structure is dominated by LCZ 6 (open low-rise) and LCZ 5 (open mid-rise) development zones. Unbuilt areas, primarily forested (LCZ A) and agricultural (LCZ D), also account for a very large share. The proposed R_c index integrates adaptive capacity, exposure, and vulnerability. It allows for a comprehensive and comparable assessment of cities' potential thermal resilience.

Most of the cities studied (62.5%) are characterized by moderate potential thermal resilience. 31.3% of the cities exhibit low potential thermal resilience, while only 6.2% exhibit high potential thermal resilience. High index values result from the predominance of green spaces and the limited presence of dense and low-density development. Potential thermal resilience shows marked geographical variation. Higher index values are found in southern and southwestern Poland. A multiple regression model explains 61% of this variation. Significant predictors include geographic coordinates, population density of women aged ≥ 65 , and annual precipitation. Location-based variables reflect the influence of the country's macroclimatic spatial gradients.

The key significance of assessing potential heat resilience lies in its diagnostic role in contemporary urban ecology. The R_c index allows for a precise determination of the

impact of the morphological characteristics of built-up areas (built types) and biophysical properties of land cover types. This tool assesses the potential thermal resilience of Poland's largest cities. This analysis is independent of the historical conditions of development and urban layout. Under Poland's climatic conditions, high potential thermal resilience is uncommon. Therefore, systematic monitoring and identification of spatial and analytical factors are priorities. This provides an objective foundation and information base for further analyses of cities' vulnerability to climate change.

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