NATURE-BASED PRESCHOOL GARDENS FOR THERMAL CONDITION REGULATION: IMPLICATIONS FOR CLIMATE-SENSITIVE POLICY AND PLANNING

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Abstract: Cities are places with concentrations of people and the effects of their activities, which are particularly exposed to the impacts of climate change. In this respect, one of the challenges for planners and decision-makers is urban heat mitigation regarding the higher intensity of heat islands and heat waves. Shaping urban tissue is fundamental in ensuring thermal comfort for city dwellers. Particular attention should be paid to children as they are more vulnerable to thermal stress. Hence, the study aims to enhance climate-sensitive urban planning and policy by providing evidence on the impact of green infrastructure (GI) and small-scale nature-based solutions (NBSs) such as preschool gardens (PGs) in urban heat mitigation in Poznań, Poland. In addition to recognising the thermal conditions of PGs, we investigated their thermal impact on the surrounding areas. We also analysed preschoolers' exposure to urban heat during their stay in PGs. The study employed Geographic Information System (GIS) and remote sensing data from Landsat 8 to generate the normalised difference vegetation index (NDVI) and surface temperature rasters. The results reveal that the thermal impact of PGs depends on their size, NDVI and the tree canopy cover (TCC) of both PGs and their surroundings. PGs are valuable areas that regulate thermal conditions in the city. We recommend optimising PGs into more nature-oriented spaces (NDVI > 0.3) that might play the additional role of site-scale cooling shelters. The universal methodology developed and adopted in the study allows for scaling the research to other cities in the temperate climate zone.

Keywords: climate-sensitive planning and policy, preschool gardens, cooling effect, land surface temperature, NDVI

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Introduction

Cities are increasingly exposed to the impacts of climate change through temperature increases (Norton et al. 2015) and frequent extreme events such as heatwaves and tropical nights (Tomczyk, Bednorz 2016, Solecki et al. 2018). Additionally, dynamic urban development exacerbates temperature conditions, contributing to the heat island phenomenon (Roth et al. 1989, Lee 1993, Majkowska et al. 2017, Saaroni et al. 2018).

One of the solutions to tackle climate change effects is green infrastructure (GI), which is a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services (ESs) (EU 2013), which has potential to moderate the above-identified

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climate change impacts in towns and cities (Gill et al. 2007). GI that contributes through regulating ESs to reducing risk factors resulting from urban heat (Kabisch et al. 2017) can be developed and understood as large-scale nature-based solutions (NBSs) (EU 2015). It can be intentionally planned, designed and managed to foster climate change adaptation as "solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience" (EU 2015). In addition to these regulating ESs, GI composed of diverse elements also provides valuable cultural benefits, offering spaces for rest and recreation to diverse social groups, whose needs and perceptions of GI may vary (Jones et al. 2022, Bąkowska-Waldmann, Piniarski 2023). To enhance such multiple benefits, interventions may involve enlarging the GI surface through establishing new GI elements, physical changes of existing GI elements that increase multifunctionality and/or quality and various uses of GI and soft actions promoting GI (Zwierzchowska et al. 2019).

GI and generally vegetation play important roles in mitigating thermal conditions in urban areas (Gill et al. 2007, Bowler et al. 2010, Norton et al. 2015, Saaroni et al. 2018). This crucial function results mainly from the evapotranspiration, tree shading and modification of surface roughness, impacting wind flow and heat exchange (Qiu et al. 2013, Saaroni et al. 2018). Mature trees with large, dense crowns have been found to be the most effective for cooling (Gromke et al. 2015, Zhou et al. 2021, Kim et al. 2024).

Many studies show the vital role of urban parks and forests in mitigating urban heat (Cao et al. 2010, Oliveira et al. 2011, Grilo et al. 2020, Jang et al. 2024). While all green spaces, despite their size, provide vital ESs (Gill et al. 2007), most of the urban green areas investigated in climate studies were relatively large-scale, and fewer studies focus on the cooling potential of small-scale green spaces (Lin et al. 2017).

Despite current evidence on the thermal benefits of vegetation and water bodies, further research is needed to investigate how cooling capacities are influenced by different types, quantities and spatial arrangements of GI (Bartesaghi-Koc et al. 2019). Recognition of the cooling abilities of small green spaces is especially important for supporting the transition of a dense urban environment, where it is not possible to introduce large parks or forests. In this regard, Bowler et al. (2010) indicated that a cooling effect beyond the boundary of the green area is particularly important for public health. Therefore, a key line of future research on green space cooling effects is to investigate the influences of distance and size on the cooling effects of green areas, allowing spatial arrangements of greening. In this context, understanding the effect of land cover changes on surface and air temperatures in urban micro-scale environments is crucial for supporting sustainable planning and policy in densely built-up areas (Kim et al. 2016).

Currently, about 50% of the global population lives in urban settings, and it is projected that the number will grow by up to 70% by 2050 (UN 2019). Given this, the importance of urban thermal conditions in shaping the quality of life increases. Within urban populations exposed to unfavourable thermal conditions, children are recognised as particularly vulnerable to the effects of urban heat (WHO 2008). According to a review conducted by Antoniadis et al. (2020), their higher vulnerability results from physiological factors such as: 1) higher surface area to body-mass ratio, which causes higher heat absorption; 2) higher metabolic rate that leads to higher heat production; 3) lower height of children, which exposes them more to the thermal impacts of long-wave heat fluxes of high surface temperatures; 4) undeveloped thermoregulation; 5) different process of heat loss (dry convective); and 6) rapid heat exchange. Since excessive heat can negatively affect children's health and wellbeing (Bäcklin et al. 2021, Malmquist et al. 2021), they should be given special protection, including measures, such as providing shaded play areas and green spaces (UNICEF 2024). Despite this fact, thermal conditions are still rarely considered in planning and designing spaces devoted to children (Vanos 2015). Urban schoolyards are often covered with artificial materials with high heat capacities and/or heat conductivities, insufficient shading and location in densely built-up areas, which creates unfavourable thermal conditions. Moogk-Soulis (2002, 2010) showed that schoolyards can even be a heat island due to their higher surface temperature than their surroundings. Only recently the issue of thermal conditions in spaces predestined for children such as playgrounds (Qi et al. 2022), schoolyards or preschool outdoor space (Sun et al. 2023, van den Bogerd et al. 2023, Wallenberg et al. 2023, Zhao et al. 2024) is getting an increasing interest. The studies cover a wide range of aspects, from the conceptual framework highlighting the potential of green schoolyards (van den Bogerd et al. 2023), through the development of models showing the impact of shade on heat stress in preschool yards (Wallenberg et al. 2023), to simulation of selected built-up and atmospheric parameters at the design stage, showing that optimisation in this regards can reduce the overall thermal stress (Sun et al. 2023). In addition, research tests the performance of grey technical solutions for heat mitigation, such as sun sails and mist-sprays systems (Zhao et al. 2024).

Considering that outdoor activities are recommended for children as they are beneficial for their health and development (Rose et al. 2008, Wu et al. 2013, Xiong et al. 2017, Wallenberg et al. 2023), providing safe and comfortable thermal conditions in schoolyards and preschool gardens (PGs) becomes a new paradigm in the planning and design of multifunctional urban green spaces.

Taking the above into consideration, the main aim of this study is to enhance urban planning and policy in times of changing climate through providing evidence of the impact of GI and small-scale NBSs in urban heat mitigation. The objectives of this study are as follows:
1. to recognise the potential of small-scale NBSs such as PGs to lower the temperature at the site scale [identification of PG cooling effect (PGCE)];
2. to recognise the thermal conditions of PGs;
3. to estimate preschoolers' exposure to urban heat during their stay in PGs.

This study in PGs provides baseline data on the impact of such small-scale green spaces on shaping thermal conditions for preschoolers and the nearest neighbourhood. Such evidence is fundamental to formulate recommendations for an integrated approach for planning and design that includes, among others, climate change adaptation. The proposed research methodology and the findings obtained may contribute to climate-sensitive planning and design initiatives in other cities within the temperate climate zone.

Materials and methods

Study area

Poznań has a population of approximately 545,000 inhabitants and an area of 262 km^2, and is one of the largest cities in Poland (Statistics Poland 2022). The city is located in the temperate climate zone and is characterised by average temperature over multiple years (1991–2020) of 9.4°C and average precipitation over multiple years (1991–2020) of 538 mm. However, recent data show an increase in the average annual temperature coupled with a decline in annual precipitation levels (IMWM 2023).

As with many other cities, Poznań faces the problem of climate change, which is expressed through rising temperature, more frequently occurring heat waves and tropical nights (Półrolniczak et al. 2018), among other factors, and those phenomena are predicted to increase by 2050 (UCAP 2019).

In Poznań, there are 263 preschools attended by 20,297 children (Department of Education of Poznań City Hall 2019), of which 87% (230) have their own outdoor space that plays the role of a PG (Fig. 1). However, they vary in terms of the share and composition of green spaces. According to the national regulations, preschools operate year-round; however, during summer holidays, they may operate on a limited basis. Still each child is guaranteed care at their home preschool during the summer duty period.

We analysed thermal conditions of all PGs (N = 230) against the background of the city's land surface temperature (LST). To provide a local-scale perspective, we further examined three detailed case studies: preschools No. 42, No. 87 and No. 115, located in one of the most densely built-up areas of Poznań.

Materials and methods

The first step was to identify and map preschools with their own outdoor area – a PG (Fig. 2). Next, maps of average LST (ALST), tree canopy cover (TCC) and a distribution of the normalised difference vegetation index (NDVI) were prepared to recognise thermal conditions of PGs and their relationship to the existing vegetation.

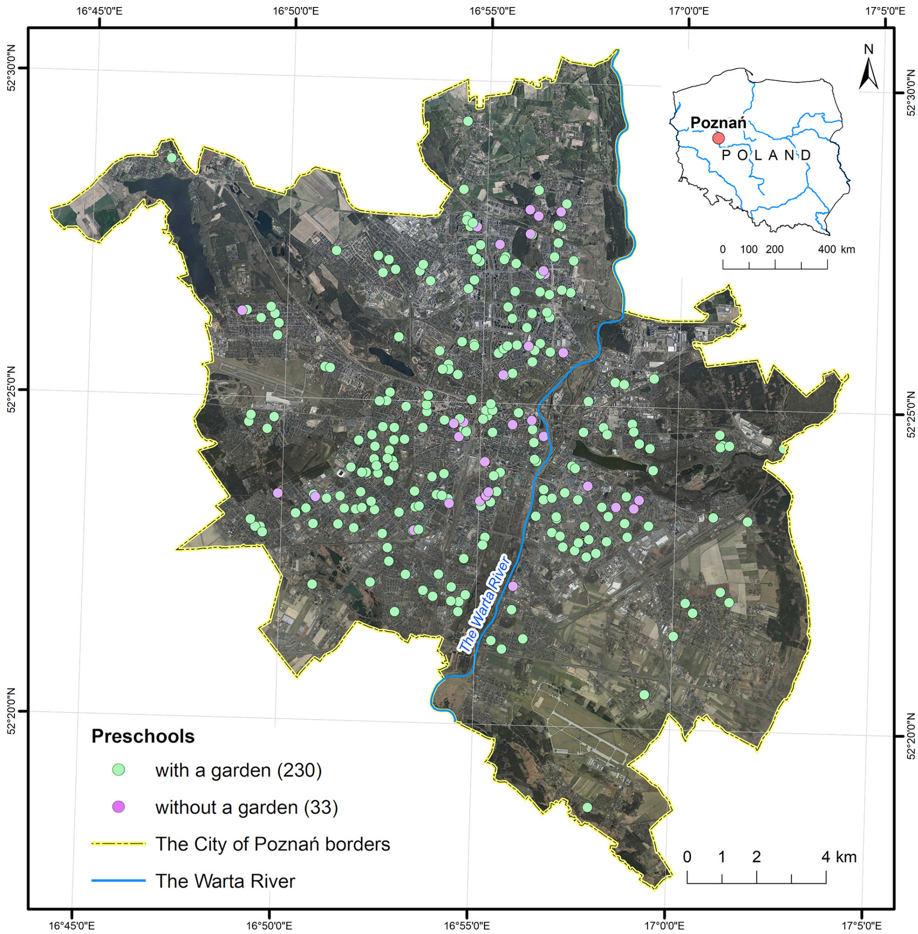

Fig. 1. Location of PGs in Poznań based on data from the Department of Education of Poznań City Hall (2019) and the orthophoto of Poznań (SISP 2021).
PGs – preschool gardens

Then, based on the ALST map, the air temperatures (T_{air}) were modelled, showing the thermal condition of PGs for children. Finally, PGCE was assessed, taking into account differences in ALST between each PG and its closest neighbourhood within a 45 m ring buffer, and the thermal profiles were analysed. We calculated average building heights in ring buffers of PGs using the BDOT10k (2022) topographic database as a secondary factor for analysing PGCE. The methods applied in the following steps are presented in the next sections.

Land surface temperature (LST), vegetation index and tree canopy cover (TCC)

The thermal conditions of PGs were recognised by analysing the distribution of LST obtained from satellite imaging, which is a common approach in urban climate studies (Voogt, Oke 2003, Tomlinson et al. 2011, Zhan et al. 2013, Zhou et al. 2019), as well as in studies assessing the thermal impact of green spaces (Cao et al. 2010, Estoque et al. 2017, Jang et al. 2024).

We utilised the Landsat Surface Temperature product and selected bands of Landsat 8 Operational Land Imager (OLI)/Thermal Infrared Sensor (TIRS) scenes from Collection 2 Level 2 Science Products (EROS 2024). The data were processed according to Cook et al. (2014) and the thematic guide (LSDS 2020). Using Earth Explorer, we searched for images that captured the city's warmest weather conditions, ensuring that cloud cover was < 3%. Our selection focused solely on images free of cloud interference within the study area, allowing for accurate and clear observations. As a result, we included the thermal infrared bands ST_B10 from five multispectral satellite images that met the mentioned criteria. They were captured on the following dates: 7 June 2018, 3 June 2019, 26 June 2019, 23 September 2019 and 8 August 2020. The images were acquired during clear weather conditions,

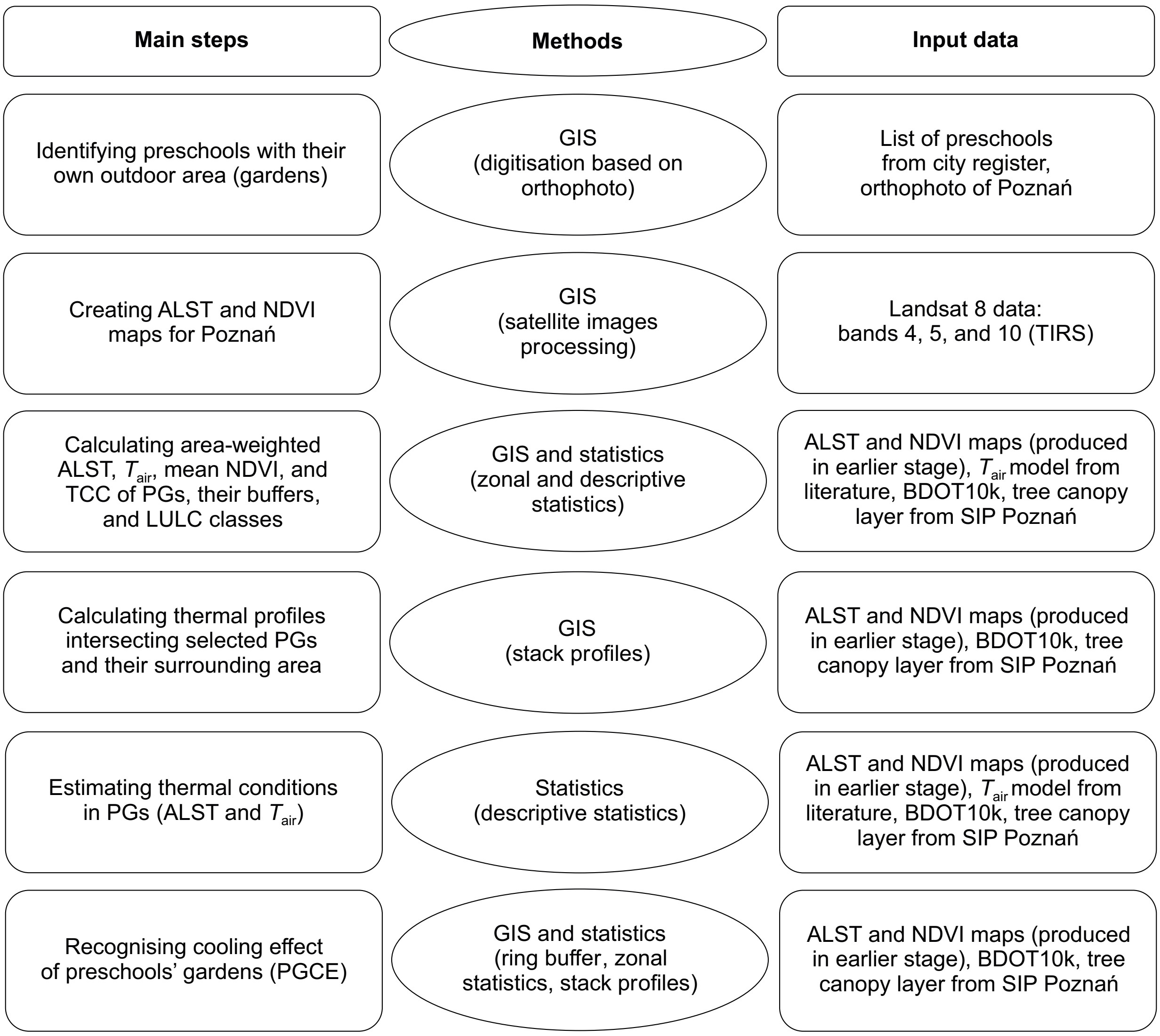

Fig. 2. Study framework.
ALST – average land surface temperature; NDVI – normalised difference vegetation index; TIRS – thermal infrared sensor; T_{air} – air temperature; TCC – tree canopy cover; PG – preschool garden; LULC – land use and land cover; SIP – spatial information system; PGCE – preschool garden cooling effect; GIS – geographic information system

characterised by a cloud-free sky and full sun exposure over the entire city, at the time of 9:44–9:51 GMT (11:44–11:51 CET). These images depict sunny weather typical of late spring, summer and early autumn – referred to as the warm season – when high temperatures may negatively impact the thermal comfort of Poznań residents.

To calculate LST, raw values of each pixel of the surface temperature bands were first multiplied using a scale factor and then enlarged by including additive scale factor (ASF) [Eq. (1), see LSDS (2020)]. In the next step we converted the LST values from Kelvins to Celsius degrees [Eq. (2)].

$$LST_K = (DN \times MSF) + ASF \quad (1)$$

$$LST_C = LST_K - 273.15 \quad (2)$$

where:
- LST_K – LST in Kelvins (K),
- DN – digital number (value of each pixel of surface temperature band),
- MSF – multiplicative scale factor equal to 0.00341802,
- ASF – additive scale factor equal to 149,
- LST_C – LST in Celsius degrees (°C).

As proposed by Majkowska et al. (2017), we created a raster map of the $ALST_C$ from five images using the raster calculator in ArcMap [Eq. (3)].

$$\text{ALST} = \frac{\sum_{i=1}^{n} \text{LST}_\text{C}}{n} \quad (3)$$

where:
- ALST – average LST (°C),
- LST_C – LST in Celsius degrees (°C) for a given pixel,
- n – number of scenes (pixels).

In this study, we included the greenness level by employing the NDVI, which is commonly used in studies related to surface temperature (Walawender 2009). With NDVI, we were able to group PGs according to the greenness levels of vegetation (Lo, Quattrochi 2003, Feyisa et al. 2014). We calculated NDVI as proposed by Lillesand et al. (2004) based on Landsat bands 4 [red band (RED)] and 5 [near infrared band (NIR)] [see Eq. (4)]. For each of the PGs, the mean NDVI was calculated using the zonal statistics tool [Eq. (5)].

$$\text{NDVI} = \frac{(\text{NIR} - \text{RED})}{(\text{NIR} + \text{RED})} \quad (4)$$

$$\text{ANDVI} = \frac{\sum_{i=1}^{n} \text{NDVI}}{n} \quad (5)$$

where:
- NDVI – normalised difference vegetation index,
- NIR – near infrared band, Landsat 8 band 5,
- RED – red band, Landsat 8 band 4,
- ANDVI – average NDVI of a given polygon,
- n – number of NDVI pixel values intersected by a given polygon.

For PGs and their buffers, we calculated TCC as the percentage share of canopy cover (%). It was based on the tree canopy layer (SISP 2018), which provides information on the canopy coverage at a 0.5 m spatial resolution in the year 2018. We also analysed how building height in PG buffers (measured by the number of floors) affects thermal conditions in PGs. We identified a number of floors using the vector Topographic Objects Database (BDOT10k 2022).

The relationships between selected variables and ALST and PGCE were assessed using the Pearson correlation coefficient.

While analysing the thermal conditions in PGs, we also considered the air temperature distribution, estimated using the LST data and the non-linear regression model developed for Poznań by Majkowska et al. (2017) [see Eq. (6)]. The authors of the model used thermal data from TM Landsat 5 satellite images, along with meteorological data that represent air temperature at 2 m above the ground in various areas of the city of Poznań, obtained from *in situ* measurements with HOBO sensors. The model is notable for its high coefficient of determination (r^2 = 0.84).

$$T_\text{air} = b_0 \times (\text{ALST}_\text{c})^{b_1} \quad (6)$$

where:
- T_air – estimated air temperature at a height of 2 m above ground level (°C),
- b_0, b_1 – model coefficients: b_0 = 0.633 and b_1 = 1.035,
- ALST_C – average LST (°C).

We compared the estimated air temperature values in PGs to the number of preschoolers from the city register, taking into account thresholds from the Atlas of Poland Climate (Tomczyk, Bednorz 2022), in which warm days (25.1–30.0°C) and hot days (> 30.0°C) are distinguished.

Preschool garden cooling effect (PGCE)

The PGCE was defined as the mean LST difference between the PG and its buffer as proposed by Cao et al. (2010) and Chibuike et al. (2018), who measured a park's cooling island intensity. A similar approach is commonly used in studies on the intensity of surface urban heat islands measured as LST differences between urban and surrounding reference areas (Zhou et al. 2019). We calculated PGCE using Eq. (7) based on Chibuike et al. (2018). Negative values of PGCE indicate a cooling effect ($\text{ALST}_\text{pg} < \text{ALST}_\text{b}$) and positive ones a warming effect of given PGs ($\text{ALST}_\text{pg} > \text{ALST}_\text{b}$).

$$\text{PGCE} = \text{ALST}_\text{pg} - \text{ALST}_\text{b} \quad (7)$$

where:
- ALST_b – average LST (°C) calculated for a given buffer of PG,
- ALST_pg – average LST (°C) calculated for a given PG.

We analysed PGCE within a 45 m distance, which results from the spatial resolution and geometric parameters of Landsat 8 TIRS that collects data with a 100 m spatial resolution resampled to 30 m (USGS 2019). Storey et al. (2014) have shown that the geometric accuracy varies from 7.4 m in the case of TIRS Band-to-Band Registration Accuracy (requirement value < 18 m) to 32.7 m in the case of TIRS Absolute Geodetic Accuracy (requirement value < 76 m). Taking the above into account, we applied buffers, the size of which exceeded the spatial resolution (pixel size) and geometric performance values of the input data (Zhan et al. 2013). A similar justification was presented by Chibuike et al. (2018).

However, it is necessary to stress that there is no standard approach in delimitation buffer zones thus far. Other studies that quantified greenspace cooling effects applied various buffer parametrisations, e.g., from 30 m intervals from the edges of parks to a maximum distance of 420 m (Feyisa et al. 2014), 100 m intervals to a maximum distance of 200 m (Łowicki, Taklińska 2025) and 100 m around each case study greenspace (Shih 2017).

For the three selected case study preschools, we investigated the PGCE using the thermal profiles (stack profiles) showing the temperature change within a distance interval (e.g. Walawender 2009, Majkowska et al. 2017). We used an ALST raster and a sampling interval of 30 m according to the map resolution.

Results

Thermal conditions of preschool gardens

Average land surface temperature (ALST)

We identified 230 preschools with PGs (87% of all preschools in the city). The mean surface area of gardens was 1585 m^2, with a minimum of 26 m^2 and a maximum of 6893 m^2. As much as 59% (135 objects) had surface areas lower than the mean value. This study has found no significant correlation between surface area and $ALST_{pg}$ ($r = -0.0287$, $p = 0.665$).

The distribution of NDVI was also quite diverse and ranged from nearly 0.1 to 0.4, with an area-weighted mean of 0.24 being equal to the median. Hence, half of the mapped PGs had NDVI values > 0.24, and the second half had lower values. The average NDVI (ANDVI) of PGs proved to be significantly negatively correlated with $ALST_{pg}$ ($r = -0.4608$, $p = 0.000$), same as ANDVI of garden buffers with $ALST_{pg}$ ($r = -0.7547$, $p = 0.000$).

PGs had a wide range of TCC, from 0% to 97.5%, with an area-weighted mean of 41.3%. In the case of 132 PGs, TCC was lower than the mean. TCC of PGs was found to be significantly negatively correlated with the $ALST_{pg}$ ($r = -0.1481$, $p = 0.025$). Similar relationship was found also for the $ALST_{pg}$ and the TCC of their buffers ($r = -0.5805$, $p = 0.000$).

The ALST values of PGs ranged between a maximum of > 42°C, a minimum of > 29°C and a mean near 37°C. The mean value was > 2°C higher than the mean ALST calculated for the whole city. Land use/land cover (LU/LC) patterns in Poznań could partially explain this condition since 88% of PGs are located in land use classes of the highest mean ALST levels, and this could have a warming impact on the thermal conditions in the gardens. The analysis of preschool distribution has shown that 64% of gardens are located (have their centroids) in densely built-up areas (continuous and discontinuous dense urban fabric), 24% in industrial and commercial units, near 5% in the discontinuous medium-density urban fabric, about 3% in green urban areas and > 4% in other LU/LC classes.

The mean $ALST_{pg}$ was lower in the groups of gardens with a higher mean NDVI value (Fig. 3). In the case of Poznań, the difference in ALST between extreme groups of PGs (grouped by NDVI) was > 1.8°C, which emphasises the role of greenery in mitigating urban heat.

However, the effect of NDVI does not always explain the temperature difference. For this reason, we have incorporated additional

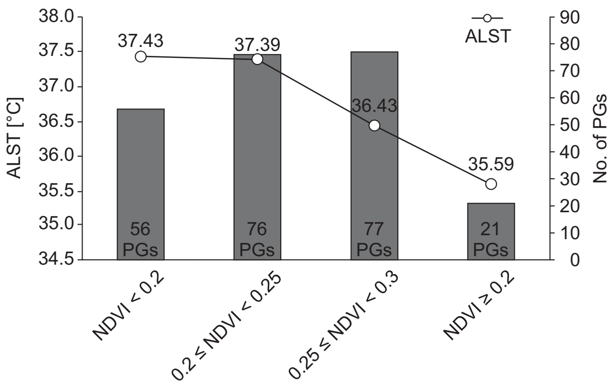

Fig. 3. Differences in preschool garden ALST depending on NDVI levels based on Landsat 8 data (EROS 2024).
ALST – average LST; LST – land surface temperature; NDVI – normalised difference vegetation index; PGs – preschool gardens

parameters, such as TCC (%), and building height (the mean number of floors) into our analysis. Table 1 shows that four groups of PGs can be distinguished.

The relationship between NDVI and ALST was visible for 160 PGs. However, there were 29 PGs where despite their relatively high vegetation cover (ANDVI > 0.25, mean TCC = 38.4%), the ALST was above average. There were also 41 PGs where, despite relatively low ANDVI and TCC, ALST was below average. In the cases of groups 2 and 4, the impact of the intensity of development in the vicinity of PGs could have been significant. In group 2 of PGs, the mean height of buildings within PG buffers was the highest, suggesting a higher warming influence from buildings. In group 4, the mean height of buildings was the lowest (Table 1), indicating less warming influence. It is consistent with the correlation found in this study between the height of buildings in PG buffers and the $ALST_{pg}$ (r = 0.1508, p = 0.022, N = 230) – as the mean height of buildings in PG buffers increases, the $ALST_{pg}$ also increases.

Average air temperature

Air temperature in PGs at about noon in the summertime and during radiation weather conditions estimated based on ALST ranged from almost 21°C to > 30°C. This indicates that most preschoolers (94.5%) spend time in gardens characterised by estimated air temperatures ranging from > 25°C to nearly 30°C (warm days). Additionally, 0.2% of preschoolers who spend time in PGs might be exposed to air temperatures > 30°C that characterise hot days (Fig. 4).

Table 1. Greenness and building characteristics of PGs and their buffers based on Landsat 8 data (EROS 2024) and TCC (SISP 2018).

Statistics	Group 1 PGs with high ANDVI (≥0.25) and below average ALST (<36.83; N = 76)	Group 2 PGs with high ANDVI (≥0.25) and above average ALST (>36.83; N = 29)	Group 3 PGs with low ANDVI (<0.25) and above average ALST (>36.83; N = 84)	Group 4 PGs with low ANDVI (<0.25) and below average ALST (<36.83; N = 41)
TCC (%) in PGs				
Mean	42.74	38.38	32.41	30.31
Median	42.73	37.84	32.38	32.96
Min	0.00	4.91	0.00	0.00
Max	97.50	68.90	81.80	85.79
TCC (%) in PG buffers				
Mean	30.71	22.42	17.44	23.17
Median	31.15	21.76	16.44	22.86
Min	4.01	7.54	3.54	7.61
Max	90.06	40.34	39.20	38.85
Greenness level (ANDVI) of PGs				
Mean	0.28	0.28	0.20	0.20
Median	0.28	0.27	0.20	0.21
Min	0.25	0.25	0.08	0.12
Max	0.40	0.33	0.24	0.24
Greenness level (ANDVI) of PG buffers				
Mean	0.26	0.22	0.18	0.22
Median	0.25	0.22	0.18	0.21
Min	0.17	0.16	0.08	0.15
Max	0.40	0.27	0.25	0.27
Number of floors in buildings located within buffer zones of preschools				
Mean	2.31	2.80	2.47	2.15
Median	2.00	2.00	2.00	2.00
Min	0	0	0	1
Max	18	18	18	12

ALST – average LST; ANDVI – average NDVI; LST – land surface temperature; NDVI – normalised difference vegetation index; PGs – preschool gardens; TCC – tree canopy cover

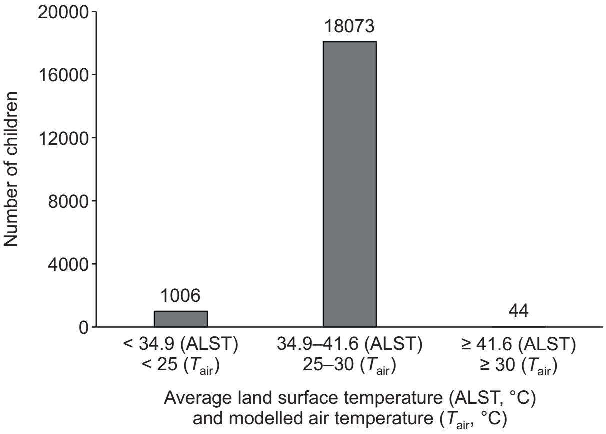

Fig. 4. Preschoolers and thermal conditions in PGs based on Landsat 8 data (EROS 2024) and the Poznań City Hall register.
PGs – preschool gardens

Preschool garden cooling effect on neighbourhoods

Results of buffer analysis

Based on the buffer analysis, we identified 137 PGs that cool down the nearest surroundings within a distance of 45 m. Notably, 29 results were excluded due to their level of uncertainty. Thus, we confirmed the cooling impact of 117 PGs and the warming effect of 84 gardens. The mean cooling effect was about −0.16°C with a minimum of −0.03°C and a maximum of −0.51°C. In contrast, the mean warming impact was about 0.18°C with a minimum of 0.03°C and a maximum of 0.62°C.

PGs varied based on area, NDVI and ALST, among other parameters as presented in Table 2. The cooling PGs are characterised by nearly 0.5°C lower temperature on average than the ones with warming effect (area-weighted mean ALST in Table 2).

Those generating a cooling effect were usually more extensive. Their mean surface area was approximately 19% larger than that of gardens with a warming impact. However, there was no significant correlation between surface area and PGCE size in PGs (r = −0.0292, p = 0.660, N = 201).

Values of the vegetation index were also slightly higher for cooling gardens. This is well observed in groups of gardens according to the NDVI levels. The mean cooling effect (PGCE) increased from −0.11°C with NDVI < 0.2 to −0.20°C with NDVI ≥0.3 (Fig. 5). We have found a significant negative correlation between PGCE and ANDVI in both PGs (r = −0.2805, p = 0.000, N = 230) and their buffers (r = −0.2315, p = 0.000, N = 201).

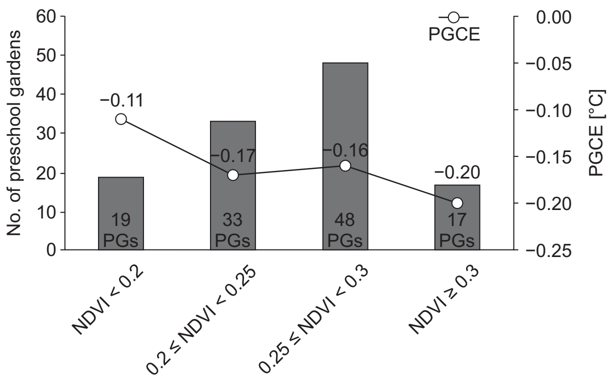

Fig. 5. The intensity of PGCE according to the NDVI levels based on Landsat 8 data (EROS 2024) and the Poznań City Hall register.
NDVI – normalised difference vegetation index; PGCE – PG cooling effect; PG – preschool garden

Table 2. Characteristics of PGs in Poznań due to the PGCE status based on the orthophoto of Poznań (SISP 2021) and Landsat 8 data (EROS 2024).

Characteristics	ALST (°C)	Area (m²)	NDVI	TCC (%)	Average building height (No. of floors)
Preschools with cooling effect, N = 117					
Minimum	29.35	48	0.09	0.00	1.07
Maximum	40.09	5300	0.40	97.50	9.25
Area-weighted mean	36.66	1767	0.26	44.97	3.02
Mean	36.47	1767	0.25	40.79	2.93
Standard deviation	1.55	1425	0.05	21.20	1.54
Preschools with warming effect, N = 84					
Minimum	34.18	26	0.08	0.00	1.00
Maximum	42.39	6893	0.33	85.79	7.33
Area-weighted mean	37.14	1481	0.24	34.05	2.46
Mean	37.28	1481	0.22	31.20	2.43
Standard deviation	1.46	1435	0.05	21.61	1.25

ALST – average LST; LST – land surface temperature; NDVI – normalised difference vegetation index; PGCE – PG cooling effect; PGs – preschool gardens; TCC – tree canopy cover

The impact of TCC is also evident in PGs. The gardens with cooling potential had a TCC area-weighted mean > 10 percentage points higher than the ones with warming potential. The TCC in PGs ($r = -0.2095$, $p = 0.001$, $N = 201$) as well as in their buffers ($r = -0.2265$, $p = 0.001$, $N = 230$) and PGCE proved to be significantly negatively correlated.

Both groups of PGs differ in terms of the level of development in their surroundings, which is measured by the average height of the buildings nearby. The data presented in Table 2 shows that PGs with a cooling effect are surrounded by higher buildings. This suggests that these gardens are situated in a potentially warmer environment, as taller buildings tend to generate more heat due to their larger heat exchange surface. Hence, the difference in surface temperature between PGs and their buffers (PGCE) may be greater. This study has found a significant negative correlation between PGCE and average building height in buffers ($r = -0.1813$, $p = 0.006$, $N = 201$).

PGs are located in various LU/LC settings. The cooling gardens were situated mainly in the discontinuous dense urban fabric (50%) and continuous urban fabric (21%). PGs with a warming effect were predominantly located in the classes mentioned above (53%) and in industrial, commercial, public, military and private units (32%). PGs that cool down their vicinity are more often located in residential areas (75%) than those with warming impacts (59%). Hence, their positive cooling effect in the summer may benefit a larger group of inhabitants.

Thermal profiles of selected case studies

We investigated the cooling effects of three case study gardens, for preschools No. 42, No. 87 and No. 115 (Table 3), by analysing thermal profiles to evaluate their impact on local thermal conditions.

The thermal profile of the garden in Preschool No. 42 and its vicinity (Fig. 6) showed a 2.45°C (PGCE) difference in ALST between a local hotspot (40.40°C), situated in the surrounding dense built-up area and the coolest part of the garden (37.95°C). This was observed at a distance of 100 m if we measure it from the local hotspot to the garden's border. The profile also indicates the change of thermal conditions within the garden. The difference of ALST between two spots on the garden's edges intersecting the profile was about 1°C. The first one was located within a high tree stand (in the coolest part of the garden), and the second was near the tall buildings characterised by higher ALST. The share of grey infrastructure in the garden's 100 m buffer zone was almost 75%.

The second profile (B) describes the thermal condition of the garden in Preschool No. 87 and its vicinity (Fig. 6). The analysed garden is smaller than the previous one and is surrounded by tight buildings. The share of GI in its 100 m buffer zone is > 87%. The PGCE was about 1°C if we consider the difference between the local hotspot (40.72°C) and the coldest site inside the garden (39.73°C). The estimated temperature difference was lower than in the first case study, as more buildings isolate this green space. However, the distance of the thermal impact is similar.

Different thermal conditions relate to the case of the garden in Preschool No. 115 (Fig. 6, profile C). The share of grey infrastructure in its 100 m buffer zone was about 65%, the lowest in the analysed cases. The cooling effect of the garden could not be extracted from the overlapping impact

Table 3. Characteristics of selected case studies based on Landsat 8 data (EROS 2024) and the Urban Atlas (EEA 2020).

Parameter	Preschool No. 42		Preschool No. 87		Preschool No. 115	
	PG	Buffer (45 m)	PG	Buffer (45 m)	PG	Buffer (45 m)
Area (m^2)	3446	18,616	2853	17,432	1029	12,595
NDVI	0.27	0.16	0.24	0.15	0.22	0.20
ALST (°C)	38.26	38.55	39.80	39.96	37.74	37.59
TCC (%)	57.09	17.97	60.47	17.13	36.63	15.23
Mean number of building floors	0	3.43	0	3.67	0	4.00
LU/LC	Continuous urban fabric (S.L.: > 80%)		Continuous urban fabric (S.L.: > 80%)		Industrial, commercial, public, military and private units	

ALST – average LST; LST – land surface temperature; LU/LC – land use/land cover; NDVI – normalised difference vegetation index; PG – preschool garden; TCC – tree canopy cover

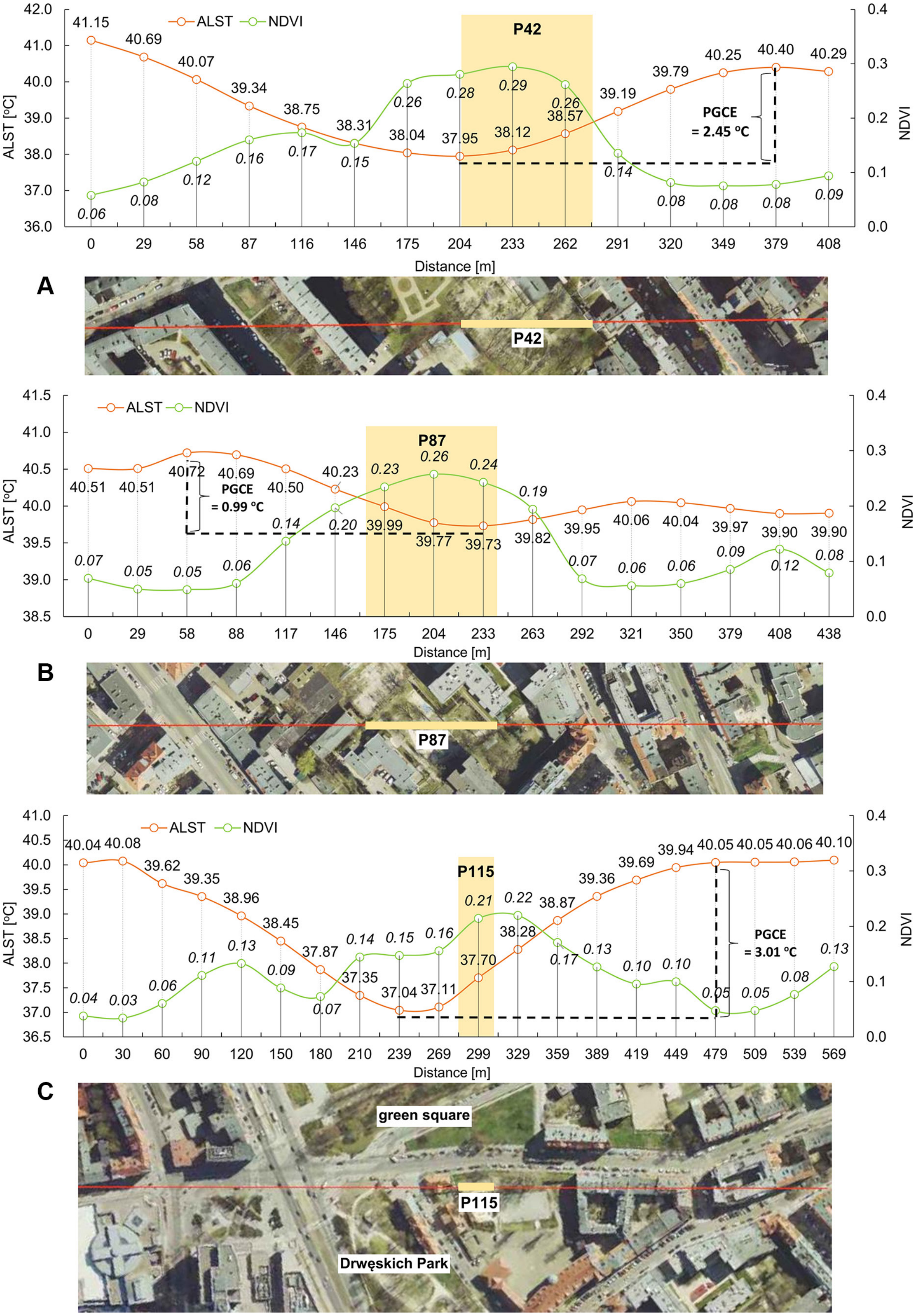

Fig. 6. Thermal profiles of the case studies, gardens and its vicinity based on Landsat 8 data (EROS 2024) and the orthophoto of Poznań (SISP 2021).

of larger green areas in the vicinity (Drwęskich Urban Park). In addition, the local cold spot was not inside the PG, suggesting more significant factors affecting the thermal conditions. The cumulative cooling intensity of all green spaces was about 3°C.

The results show that the greenery of preschools has a cooling effect on the environment, which is clearly visible when using the thermal profile method.

Discussion

Importance of thermal conditions of preschool gardens for children and neighbourhood

Climate change results in the increased number of hot days and heatwaves, making it harder to maintain comfort in cities. This affects also preschools, where young children (ages 3–6 years) play outside in warm season. Yet, climate policies or space design often overlook children's needs (Pegram, Colon 2020).

This study has shown that PGs located in a diverse urban context vary in terms of size, NDVI and TCC, which translates into different thermal conditions illustrated by ALSTs ranging from ≈33°C to > 39°C.

The air temperature estimated based on ALST shows that 94.5% (18,073) of preschoolers can experience temperatures > 25°C to 30°C, while 0.2% (44) might be exposed to air temperatures > 30°C that characterise hot days. According to Półrolniczak et al. (2018), hot days occurred in Poznań on average 18 times per year (within the period of 1966–2015), with a maximum of 37 days in 2006. The frequency of this phenomenon is increasing (Wibig 2021).

The need to deal with high temperatures affects preschools and school yards in various geographical contexts. The review conducted by Antoniadis et al. (2020) revealed three factors contributing to heat issues, namely land cover materials with high heat capacities and/or heat conductivities, like asphalt or concrete, a lack of shade and proximity to other hot areas.

Bäcklin et al. (2021) have revealed that an important factor that shapes local climate conditions is shade provided mainly by trees. Their results indicate that PGs with fewer trees are more exposed to heat stress than those with many trees. Zhang et al. (2017) have also shown that planting trees is the most effective solution for improving school outdoor thermal comfort. Shading recreational areas for children can also lower the risk of heat stress during hot weather (Vanos et al. 2017) and reduce the risk of sunburn and skin cancer through reducing ultraviolet radiation exposure (Gage et al. 2019). Lanza et al. (2021) have confirmed that more children interact with trees during periods of high heat index than during periods of moderate heat index, which highlights the crucial role of trees in cooling the play space during the hottest periods.

The green spaces in PGs can provide not only a better thermal environment for pupils using those spaces but also thermal impacts beyond the preschool's borders that can contribute to living conditions of local communities. However, ameliorating the impact of climate heat on children's health is not common practice in designing play spaces in an urban context (Vanos 2015). Not surprisingly, schoolyards are often 'heat islands' with higher temperatures than the surrounding streets (Moogk-Soulis 2002, 2010).

The results of this study have shown that PGs could be cooler or warmer than the surroundings. Similarly, there was strong variation in thermal conditions of PGs (Bäcklin et al. 2021). Although the average cooling potential of PGs in the neighbourhood was rather low, the thermal profiles of the selected case studies illustrated that such an impact can be much higher, up to 2.5°C. When placed within the broader range of 1–7°C reported for urban green spaces, this demonstrates a meaningful cooling potential (Soltanifard, Amani-Beni 2025).

The potential of GI for cooling the neighbourhood is related to vegetation type. As our results have shown, the PGs with higher TCC were characterised by cooler thermal conditions. A more specific study conducted by Lehnert et al. (2021) showed that the cooling impact of trees on the heat stress index was detected up to 10.5°C in Universal Thermal Climate Index (UTCI), while low vegetation was able to reduce the UTCI by not more than 2.3°C.

The thermal conditions of preschools are also impacted by the surrounding urban context. As simulations conducted by Zhang et al. (2017)

indicated, the temperature of the playground area might increase by approximately 2.0°C at 2 p.m. under a high-rise neighbourhood scenario.

The ability to regulate local climate conditions by small-scale solutions such as PGs in densely built-up areas can contribute to (thermal) comfort within PGs and in neighbouring public spaces. However, the strength of thermal regulation is highly related to local complex conditions and land-use management. The results of this study are consistent with a review showing that cooling intensity is shaped by vegetation type, spatial configuration and urban morphology (Soltanifard, Amani-Beni 2025).

Implications for climate-sensitive urban planning and policy

Shaping comfortable thermal conditions in urban settings is among the various challenges that face Poznań and many other cities where climate change effects along with urban development can lead to unfavourable heat (UCAP 2019).

This study provides evidence of usefulness in identifying thermal 'hotspots' as the priority areas for interventions towards better thermal conditions. The hotspot areas are characterised by a high density of built-up structures and a high share of artificial surfaces. Such spaces have limited opportunities for implementing new large-scale green elements. Still, there is room for greening existing open spaces and introducing new small-scale NBSs. As Oke et al. (2017) emphasised, increasing vegetation cover and incorporating natural landscape features into already built-up areas are the best means of managing urban climate effects at all scales. This approach has recently been applied in the context of educational facilities, where transformation initiatives are being implemented (coolschools.eu).

This study has shown that NDVI can be an accessible measure for monitoring green areas and a supporting measure for indicating places for interventions towards better thermal conditions. NDVI of ≥0.3 showed lower ALST and can be used as a threshold for planning for better thermal conditions and delimiting the areas that have the potential to mitigate urban heat. The given NDVI threshold has been used in other studies to identify GI and its effect on temperature (Arellano, Roca 2022). In Barcelona, Spain and its metropolitan area, NDVI > 0.4 and a minimum size threshold of 0.5 ha (Barcelona Regional 2019) have been used for delimiting green areas that play the role of outdoor climate shelters ('*refugis climàtics*') (Baró et al. 2021). According to Barcelona Regional (2019), a climate shelter is considered an indoor or outdoor accessible space that during extreme weather episodes provides the population with thermal comfort, rest and safety. With this definition in mind, Polish cities can enhance their adaptation strategies by adopting the successful practices applied in Barcelona. This can be achieved as part of urban climate adaptation plans by identifying potential climate shelters, particularly through an assessment of institutional greenery based on our research findings.

This study has shown that PGs that are present in various city locations, including dense urban areas, are valuable reservoirs of open spaces. However, PGs, similar to schoolyards, are often designed in a traditional way with large asphalt surfaces and limited green spaces (Danks 2010). Planning, designing and retrofitting PGs and/or schoolyards can transform their space into local cooling spots. Such an approach was applied in Barcelona, where selected schoolyards are used as climate shelters (Baró et al. 2021). By introducing blue, green and grey technical solutions, schoolyards support the city's adaptation to climate change and ameliorate the exposure of the school population to urban heat. The transformed schoolyards play the role of climate shelters for pupils and local residents as they stay publicly open (Cartalis 2020). Similarly, the project OASIS developed in Paris (Baró et al. 2021) focuses on transforming pilot school playgrounds into cool islands using NBSs and a co-design approach (Sitzoglou 2020).

Incorporating bioclimatic urban design principles into reshaping public spaces could contribute to more comfortable environments for urban communities; in particular, increasing focus on bioclimatic design can be translated across urban spaces (Cortesão et al. 2016).

Limitations

The use of NDVI and LST enabled the assessment of vegetation and thermal conditions across 230 PGs in Poznań without the need for labour-intensive *in situ* measurements. Increasingly accurate satellite imagery, such as Landsat 8/9, provides standardised, spatially explicit and fully open data that are useful for urban climate research. Despite some criticisms regarding its coarse resolution, NDVI remains a widely applied green space metric (Huang et al. 2021), including also in studies involving children (Kabisch et al. 2017). However, the spatial resolution of the Landsat bands utilised (30 m) can be a limitation, particularly for smaller research areas. In this study, the larger size of PGs relative to pixel size helped mitigate uncertainty. While direct field-based measurements (i.e. using microclimate sensors) and remote sensing based on unmanned aerial vehicles (UAVs) offer higher precision for site-scale studies, they are costly and face challenges related to spatial range (e.g. as using a UAV to conduct measurements simultaneously across many distant locations is limited). Bridging the gap between fine-scale assessments and broadly available data remains crucial for effective climate-sensitive urban planning.

Conclusion

Thermal conditions in cities are becoming globally an increasingly important feature of healthy living. At the same time, compact development limits the space for new large-scale green interventions, emphasising the need for using existing spaces for re-greening or implementing small-scale NBSs. This study revealed the potential of small-scale PG impact on thermal conditions within PG boundaries and in the neighbourhood against the background of thermal conditions at the city scale.

The mean ALST differences of > 1.8°C were detected between PGs with higher NDVI (≥0.3) and those with lower NDVI (< 0.2). Assessment of thermal conditions using NDVI at the site scale is helpful, especially when more detailed data or site scale measurements are not available. Similarly, the information about the share of TCC shows the role of vegetation in cooling PGs and supports the identification of PGs where greening interventions could be applied to improve thermal conditions. As we show, during warm season the estimated air temperature in PGs ranges from 21°C to > 30°C, when providing thermal comfort during outdoor activities is important for human well-being and health.

The measurements of PG impacts on thermal conditions in the neighbourhood show twofold results. The average impact of PGs on thermal conditions within 45 m was detected at a low level (−0.16°C, +0.18°C). However, thermal profiles of selected case-studied PGs were more useful to capture PGCE from about −1°C to −2.45°C, illustrating a site-specific context.

The study's findings emphasise the critical importance of climate-sensitive urban planning, advocating for transforming PGs into NBSs in Poznań and other cities, not only in Poland. The proposed strategy enhances urban resilience to the thermal effects of climate change, in conditions of escalating competition for urban land. Our approach shows PGs that were previously perceived only or predominantly as attractive places for children are also tools for shaping thermal conditions in the city (especially cooling ones, which can be considered climate shelters/refuges). It emphasises the multifunctional role of green spaces in the city and their conscious design and management towards adaptation to climate change.

We add to the discussion that could support climate-sensitive planning and decision-making in cities. Further work should focus on providing ready-to-apply indicators that can serve to measure the baseline state as well as monitor changes in green spaces and their impact on urban thermal conditions.

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Authors' contributions

PL: conceptualisation, methodology, data curation and processing, investigation, visualisation, writing and editing and correspondence with editors. IZ: conceptualisation, methodology, investigation, writing and editing.

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