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SPATIAL ASSESSMENT OF GREEN SPACES AT EDUCATIONAL FACILITIES IN OLSZTYN (POLAND): THEIR POTENTIAL TO SUPPORT STUDENT WELL-BEING

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Abstract

School grounds are among the most intensively used everyday environments of children and adolescents, yet their vegetation is rarely evaluated in terms of its capacity to support users' well-being. This study assesses the structure, quality and functionality of green spaces at ten primary and secondary schools in Olsztyn (north-eastern Poland) using exclusively open geospatial data: Sentinel-2 NDVI summer composites, high-resolution canopy height models, Landsat-derived land surface temperature, OpenStreetMap, the national BDOT10k topographic database and orthophotomaps. Four indicator groups: green area share, tree canopy cover, vegetation structure and neighbourhood greenness, complemented by a checklist of nature-contact elements, were aggregated into a novel School Green Well-Being Potential Index (SGWPI), while land surface temperature served as an independent validation criterion. The results reveal substantial differentiation of school green spaces across the city (SGWPI 32.5–76.8): no school reaches 30% tree canopy cover on its grounds, summer surface temperatures of school grounds span 5.6°C and are governed by the canopy of the 100 m surroundings rather than of the parcels themselves, and primary schools score systematically lower than secondary schools. The proposed remote-sensing workflow is fully reproducible and transferable to other medium-sized cities.

Keywords: green schoolyards, student well-being, NDVI, tree canopy cover, urban green infrastructure, Olsztyn

1. INTRODUCTION

Contemporary cities face the necessity of shaping environments that support the health and well-being of their inhabitants, particularly children and adolescents, for whom the quality of everyday surroundings is essential for physical, cognitive and emotional development [10, 18, 44]. The school is

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one of the most important places of everyday life of young people, and its surroundings constitute an integral element of the educational environment. In recent years, increasing attention has been paid to the role of green areas at educational facilities as spaces supporting regeneration, concentration, physical activity and building a positive relationship with nature [6, 9, 22].

Research indicates that access to high-quality green areas may benefit human functioning through stress reduction, improved capacity to concentrate and increased opportunities for psychological rest [18, 29]. The importance of greenery in this context is explained, among others, by Attention Restoration Theory [19, 20] and Stress Reduction Theory [38, 39], according to which the natural environment supports regenerative processes by providing stimuli distinct from the intense urban environment. Experimental studies confirm these mechanisms in the school context: classroom window views of green landscapes accelerated recovery from stress and mental fatigue among high-school students [27], while breaks spent in parks improved adolescents' concentration and perceived well-being [43]. Particular importance is attributed to tall greenery, biological diversity and spaces enabling direct contact with elements of nature [11, 23]. Recent syntheses indicate that nature exposure and school-led greenspace interventions may support children's and adolescents' mental, physical and social well-being, although the certainty and consistency of effects vary across outcomes and study designs [63, 64]. The BREATHE project also linked exposure to green and blue spaces with behavioural development in schoolchildren [3].

A growing body of empirical evidence links the greenness of schools and their surroundings with cognitive and academic outcomes. In a landmark prospective study of 2,593 primary-school children in Barcelona, greenness at and around schools enhanced the 12-month progress in working memory and attention [14], and lifelong residential exposure to green space was associated with better attentional function in early school age [15]. Analyses of large school samples in the USA showed that tree cover, but not lawns or shrubs, predicted better academic achievement [23, 24, 36, 45], and the strength of the relationship depended on the remote-sensing measure and the spatial scale adopted [8, 9]. Recent European evidence indicates that green school grounds may compensate for the deficit of nature in otherwise green-poor urban surroundings [1]. Systematic reviews confirm positive effects of schoolyard greening interventions on physical activity, socioemotional health and cognitive functioning of pupils [6, 42]. School-level analyses also indicate that these relationships are highly sensitive to how exposure is delimited: a study of 3,421 elementary schools in Ontario, using actual property boundaries alongside 1.6 km and 5 km neighbourhood buffers, found no association between greenness and standardised test scores at the school boundary or at 1.6 km, and a negative association at 5 km [65], whereas other school-level analyses have reported positive associations between surrounding green landscapes and academic performance [47]. Such divergent results suggest that part of the reported heterogeneity stems from the spatial unit of analysis rather than from greenness itself, which argues for exposure zones matched to the space pupils actually use.

Green areas at schools simultaneously perform numerous environmental functions. Appropriately designed green spaces may limit local overheating, improve thermal comfort during periods of high temperatures, increase biological diversity and create conditions for nature education in the place of everyday use [5, 7, 12]. Unshaded artificial surfaces of schoolyards reach hazardous temperatures during heat episodes [41], whereas tree canopies may reduce mean radiant temperature in schoolyards by up to several dozen degrees and sustain children's physical activity during recess [4, 26]. In the face of intensifying climate change impacts, the importance of green educational spaces thus extends beyond aesthetic and recreational functions, becoming an element of urban climate-resilient infrastructure [13, 33].

Despite the growing interest in the green schools' concept and in the design of educational spaces based on Nature-Based Solutions [7], many existing school grounds are still not fully used as potential spaces supporting user well-being. They are often characterised by a simplified vegetation structure, the dominance of grassed surfaces, limited species diversity and an insufficient number of places enabling contact with nature [17, 32, 40]. At the same time, there is a need to develop assessment methods for these spaces based on objective environmental indicators, which allow their potential to be determined without the necessity of conducting user perception studies. Open Earth-observation data and derived products: vegetation indices [31], high-resolution canopy height models [25, 37] and land surface temperature, make such an assessment fully reproducible. Recent research further emphasises that the design and diversity of school grounds matter, not only their total green cover. A review of primary-school grounds identified a shortage of evidence-based guidance linking specific design features with educational and health outcomes [62], while direct observations showed that play-zone diversity, tree shade and nature-based features can support more active and prosocial recess behaviours [66]. A conceptual framework for green schoolyards likewise highlights multiple pathways through play, learning, restoration, biodiversity and climate resilience [68], and a recent systematic review suggests that biodiversity itself may be relevant to children's mental health and well-being, although the evidence base remains heterogeneous [61].

In Poland, research on greenery at educational facilities has concentrated mainly on functional, aesthetic or didactic aspects, and on accessibility and visibility of greenery on children's school routes [17, 28, 35], while a comprehensive assessment of the quality of these spaces in the context of the well-being of young users and urban climate adaptation is still lacking. Medium-sized cities are a particularly interesting research area, as school grounds there often constitute significant local resources of green infrastructure [33]. Benchmarks such as the 3-30-300 rule, at least 3 trees visible from every building, 30% tree canopy cover in every neighbourhood and access to green space within 300 m, explicitly include schools among the facilities to which they apply [21, 34]. Recent methodological guidance also shows that estimates of compliance with the 3-30-300 rule depend on how its components and spatial units are operationalised [59], which is relevant when adapting the benchmark to school settings.

The aim of this study is to assess the structure, quality and functionality of green areas at selected primary and secondary schools in Olsztyn and to determine their potential to support student well-being on the basis of objective spatial and environmental indicators derived exclusively from open remote-sensing and geospatial data. The study focuses on the analysis of physical features of school greenery, such as its area, vegetation structure, share of tall greenery, tree canopy cover, summer thermal conditions and the presence of elements conducive to everyday contact with nature.

The following research hypotheses were formulated:

H1. Schools differ substantially in terms of the area, structure and diversity of their green spaces.

H2. Schools with a larger share of tall greenery and greater tree canopy cover exhibit lower median summer land surface temperature of their grounds, indicating a higher potential for thermal comfort.

H3. Schools with a more diversified vegetation structure (trees, shrubs, herbaceous vegetation) are characterised by a higher regenerative potential than schools dominated by lawns.

H4. The presence of elements conducive to contact with nature (educational gardens, shaded rest areas, multi-layer plantings) increases the potential of school grounds to support everyday student well-being.

The specific objectives comprised: (1) determination of the area of green spaces at the schools, (2) analysis of vegetation structure, (3) assessment of tree canopy cover and shading of spaces used by pupils, (4) assessment of the spatial diversity of greenery, (5) identification of elements supporting contact with nature, and (6) development of a synthetic indicator of the potential of school greenery to support student well-being.

2. MATERIALS AND METHODS

2.1. Study area

Olsztyn (53°46′N, 20°29′E) is the capital of the warmińsko-mazurskie voivodeship in north-eastern Poland, located within the Olsztyn Lake District on the Łyna River. The city covers 88.3 km² and had 166,697 inhabitants at the end of 2024 (Statistics Poland, Local Data Bank). Olsztyn is considered one of the greenest Polish cities: 11 lakes lie within its administrative boundaries, occupying approximately 10% of the city area, forests cover about 21% of the area (including the City Forest of approx. 1,050 ha, one of the largest municipal forests in Europe), and maintained municipal greenery occupies a further ca. 560 ha [16, 33]. The climate is humid continental (Dfb according to the Köppen classification), with a mean annual air temperature of about 8°C. In response to intensifying heat waves and droughts, the city adopted the Climate Change Adaptation Plan of the City of Olsztyn until 2030 (Resolution No. XXII/398/20 of 26 June 2020), which identifies the educational sector and unsealed green areas among its fields of intervention.

2.2. Selection of schools

Ten public schools were selected for analysis: five primary schools and five secondary schools (Table 1). The facilities were chosen purposively so as to represent different districts, different periods of urban development, from the pre-war compact quarters of the city centre and Zatorze, through large-panel housing estates of the 1960s–1980s (Pojezierze, Kormoran, Nagórki), to the estates of the 1980s and 1990s (Jaroty), as well as different sizes of school grounds. Such a selection makes it possible to capture the typological diversity of school green spaces in a medium-sized Polish city.

Table 1. Educational facilities selected for the analysis

No.	School	Type	District	Address
1	Primary School No. 1 (SP 1 im. R. Knosały)	primary	Zatorze	ul. Moniuszki 10
2	Primary School No. 2 (SP 2)	primary	Kościuszki	ul. Kościuszki 70
3	Primary School No. 3 (SP 3)	primary	Pojezierze	ul. Kołobrzeska 13M
4	Primary School No. 6 (SP 6)	primary	Osiedle Mazurskie	ul. Gdyńska 17
5	Primary School No. 33 (SP 33)	primary	Pieczewo	ul. Jeziołowicza 2
6	I High School (I LO im. A. Mickiewicza)	secondary	Śródmieście	ul. Mickiewicza 6
7	II High School (II LO im. K.I. Gałczyńskiego)	secondary	Śródmieście	ul. Małłków 3
8	III High School (III LO im. M. Kopernika)	secondary	Podleśne	al. Sybiraków 3
9	School Complex of Economics and Commerce (ZSEH)	secondary (vocational)	Podleśna	ul. Paderewskiego 10/12
10	School Complex of Chemistry and General Education (ZSChiO)	secondary (vocational)	Pojezierze	ul. Kołobrzeska 29

2.3. Data sources and processing

The assessment was based exclusively on open geospatial data, without field inventory. The boundaries of the school grounds were obtained from OpenStreetMap using the Overpass API and verified, where necessary, against the plots of the national BDOT10k topographic database (educational services complexes, KUOS class) and the current orthophotomap of the national Geoportal (ground sample distance of 5–10 cm for Olsztyn). All analyses were performed in the PL-1992 coordinate system (EPSG:2180) for four analysis units per school: the school grounds and buffers of 100 m, 300 m and 500 m from the boundary of the grounds. Buffer sizes follow the conventions of school-greenness studies [9, 14, 29] and the 3-30-300 accessibility benchmark [21].

Vegetation cover was characterised using a cloud-free median composite of Sentinel-2 Level-2A imagery (COPERNICUS/S2_SR_HARMONIZED collection) for the summer months (June–August) of the analysed year, masked with the Cloud Score+ product (cs_cdf $\geq$ 0.6). The Normalized Difference Vegetation Index (NDVI) was calculated from the near-infrared (B8) and red (B4) bands at 10 m resolution. Following the literature [31], pixels with NDVI $\geq$ 0.3 were classified as vegetated and pixels with NDVI $\geq$ 0.5 as dense (predominantly woody) vegetation; a sensitivity analysis was performed for thresholds of 0.2 and 0.4. Water surfaces were masked using the ESA WorldCover v200 land cover map (class 80).

Tree canopy cover was determined from the global c.a. 1 m canopy height model derived from very-high-resolution imagery by a self-supervised vision transformer [37], adopting a canopy height threshold of 2 m (with sensitivity tests at 2.5 m and 3 m), and controlled against the ETH 10 m global canopy height model [25] and the tree class of ESA WorldCover. Because the source imagery of the 1 m model predates the NDVI analysis, canopy layers were treated as quasi-static structural layers and visually verified on the current orthophotomap. The mean and standard deviation of canopy height within each analysis unit were used as proxies of the vertical structure diversity of vegetation.

Summer thermal conditions were characterised by land surface temperature (LST) derived from the Collection-2 Level-2 products of Landsat 8 and Landsat 9 (band ST_B10, rescaled to °C) as the median of all scenes with cloud cover below 20% acquired between June and August. Owing to the 30 m resolution of the thermal product, LST was interpreted only for the school grounds and buffers of at least 100 m [26].

Elements conducive to direct contact with nature: educational gardens, shaded rest areas, flower meadows, multi-layer plantings, nature trails and sensory beds, were identified by visual interpretation of the high-resolution orthophotomap supported by OpenStreetMap attributes, using a binary checklist for each school. The selected elements are conceptually consistent with selected domains of the Green Schoolyard Evaluation Tool (GSET), particularly greenery, design, and play and learning [69], and with the broader conceptual framework for healthy green schoolyards [68]. Because the present assessment relied exclusively on remote geospatial data, the checklist was restricted to features that could be identified reliably from high-resolution orthophotographs and OpenStreetMap data. All satellite processing was implemented in Google Earth Engine; the processing scripts and Overpass queries are available from the authors.

2.4. Indicators

For each school, indicators were grouped into five domains corresponding to the conceptual framework of the study: (i) green area share, (ii) tree canopy cover, (iii) vegetation structure diversity, (iv) availability of greenery in the immediate neighbourhood, and (v) summer thermal comfort, complemented by the checklist of nature-contact elements. Table 2 summarises the definitions and data sources of the indicators.

Table 2. Indicators of school green space quality and their data sources

Indicator	**Definition**	**Data source / resolution**
Green area share	share of pixels with NDVI ≥ 0.3 (vegetated) and ≥ 0.5 (dense vegetation) in the analysis unit	Sentinel-2 L2A, summer median composite, 10 m
Mean NDVI	mean NDVI of the analysis unit (water masked)	Sentinel-2 L2A, 10 m; ESA WorldCover v200 water mask
Tree canopy cover	share of pixels with canopy height > 2 m	global canopy height model, ~1 m [37]; control: ETH 10 m [25], ESA WorldCover
Vegetation structure diversity	mean and standard deviation of canopy height; shares of tree / grass classes	canopy height models; ESA WorldCover v200, 10 m
Neighbourhood greenness	mean NDVI in the 100 / 300 / 500 m buffers; reference to the 3-30-300 rule	Sentinel-2 L2A, 10 m
Summer thermal conditions	median summer land surface temperature (LST)	Landsat 8/9 C2 L2, ST_B10, 30 m
Nature-contact elements	checklist: educational garden, shaded rest areas, flower meadow, multi-layer plantings, sensory beds	orthophotomap (Geoportal, 5–10 cm), OpenStreetMap, visual interpretation

2.5. School Green Well-Being Potential Index (SGWPI)

To synthesise the multidimensional assessment, the School Green Well-Being Potential Index (SGWPI) was developed. Each component indicator was normalised to the range 0–1 using min–max normalisation across the analysed schools. Land surface temperature is deliberately not included in the index: it serves as an independent, external validation criterion, so that the explanatory composite and the thermal outcome used to test H2 remain statistically separated. The index was calculated as:

$$SGWPI = 100 \cdot \Sigma\, w_i \cdot z_i \tag{2.1}$$

where z_i is the normalised value of the i-th component and w_i is its weight: green area share of the school grounds – 0.20, tree canopy cover – 0.25, vegetation structure diversity – 0.20, neighbourhood greenness (300 m) – 0.20, nature-contact elements – 0.15. The weighting reflects the prominence given to tree canopy in the literature on restorative school environments [23, 24, 36] and in the 3-30-300 benchmark [21]. SGWPI values range from 0 to 100; on this basis, the schools were ranked according to their potential to support student well-being. The robustness of the ranking is assessed through sensitivity analyses, an equal-weights variant and leave-one-component-out variants, compared with the baseline ranking using Spearman's rank correlation, and the external validity of the index is evaluated by correlating SGWPI and its tree-canopy component with the median summer LST of the school grounds (expected negative association, H2). Given the small sample ($n = 10$), relationships are assessed with rank-based statistics and interpreted descriptively rather than inferentially.

Table 3. Components and weights of the School Green Well-Being Potential Index

SGWPI component	Indicator basis	Weight
Green area share of school grounds	share of NDVI ≥ 0.3	0.20
Tree canopy cover	share of canopy height > 2 m	0.25
Vegetation structure diversity	SD of canopy height; class shares	0.20
Neighbourhood greenness	mean NDVI, 300 m buffer	0.20
Nature-contact elements	checklist score (0–5)	0.15

3. RESULTS

Results are based on the school-ground boundaries derived from OpenStreetMap (Section 2.3); the checklist of nature-contact elements is pending orthophoto interpretation, and the SGWPI is therefore reported in a provisional four-component variant with proportionally rescaled weights.

The area of the analysed school grounds ranged from 0.26 ha (SP 3) to 2.38 ha (III LO, grounds shared with Primary School No. 5) (Table 4). The mean share of vegetated surfaces (NDVI ≥ 0.3) within school grounds was 60.3%, ranging from 26.3% at SP 2 to 81.4% at SP 33; dense, predominantly woody vegetation (NDVI ≥ 0.5) covered between 3.3% (SP 3) and 57.8% (SP 33). Tree canopy (canopy height > 2 m) covered on average 13.7% of school grounds, with the highest values at I LO (27.5%) and ZSEH (25.1%) and the lowest at SP 3 (0.2%), where lawns and paved surfaces dominate. Mean canopy height of the tree stands ranged from 3.4 m (SP 3) to 8.5 m (II LO), and its standard deviation, used as a proxy of vertical structure diversity, from 0.5 m to 4.5 m. Median summer land surface temperature of school grounds ranged from 33.3 °C (III LO) to 38.9 °C (ZSChiO), a span of 5.6 °C. LST was not correlated with canopy cover of the grounds themselves ($\rho = -0.02$, $p = 0.95$), an expected consequence of the small parcel size relative to the 30 m thermal pixels, but was strongly and negatively correlated with canopy cover of the 100 m surroundings ($\rho = -0.86$, $p = 0.002$ for ground-level LST; $\rho = -0.92$, $p < 0.001$ for the 100 m buffer), indicating that the thermal environment of schools is governed by tree canopy at the neighbourhood scale (H2).

Neighbourhood greenness (mean NDVI in the 300 m buffer) ranged from 0.31 (I LO) to 0.55 (SP 33). None of the ten schools met the 30% canopy component of the 3-30-300 benchmark within their grounds (maximum 27.5%), and only two (SP 33 and III LO) did so within the 300 m buffer. Threshold sensitivity tests confirmed the robustness of the indicators: school rankings were virtually identical for canopy height thresholds of 2, 2.5 and 3 m (Spearman $\rho \geq 0.98$) and moderately stable for NDVI thresholds of 0.2–0.4 ($\rho = 0.76$–0.88).

The provisional SGWPI values ranged from 32.5 to 76.8 points (Table 4). The highest potential to support student well-being was found for III LO (76.8), SP 33 (74.5) and I LO (67.4), which combine large vegetated shares with relatively green surroundings; the lowest for SP 2 (32.5), SP 6 (34.1) and SP 3 (40.1), where sealed surfaces dominate and dense vegetation is nearly absent. Secondary schools scored on average markedly higher than primary schools (mean 62.2 vs 45.0 points), a pattern worth emphasising, since younger children are the group for which everyday contact with nature carries the greatest developmental benefits. The ranking proved robust in sensitivity analyses: the equal-weights variant reproduced it almost exactly ($\rho = 0.99$), and leave-one-component-out variants correlated with the baseline at $\rho = 0.79$–0.84.

Table 4. Values of the indicators and the provisional (four-component) SGWPI for the analysed schools (school grounds)

School	**Area [ha]**	**NDVI**	**Veg. [%]**	**TCC [%]**	**CH mean [m]**	**LST [°C]**	**NDVI 300 m**	**SGWPI**
SP 1	0.54	0.39	58.2	10.5	6.2	35.5	0.38	43.7
SP 2	0.55	0.21	26.3	18.9	5.8	37.3	0.33	32.5
SP 3	0.26	0.35	66.7	0.2	3.4	35.2	0.55	40.1
SP 6	0.87	0.31	39.8	6.6	5.2	37.5	0.44	34.1
SP 33	1.97	0.51	81.4	11.5	6.7	35.3	0.55	74.5
I LO	1.04	0.52	78.6	27.5	7.4	35.3	0.31	67.4
II LO	1.28	0.46	65.4	6.2	8.5	36.4	0.42	57.3
III LO	2.38	0.45	69.2	18.4	7.4	33.3	0.53	76.8
ZSEH	0.56	0.29	38.2	25.1	7.7	36.1	0.38	55.3
ZSChiO	2.17	0.50	79.2	12.1	6.8	38.9	0.34	54.4

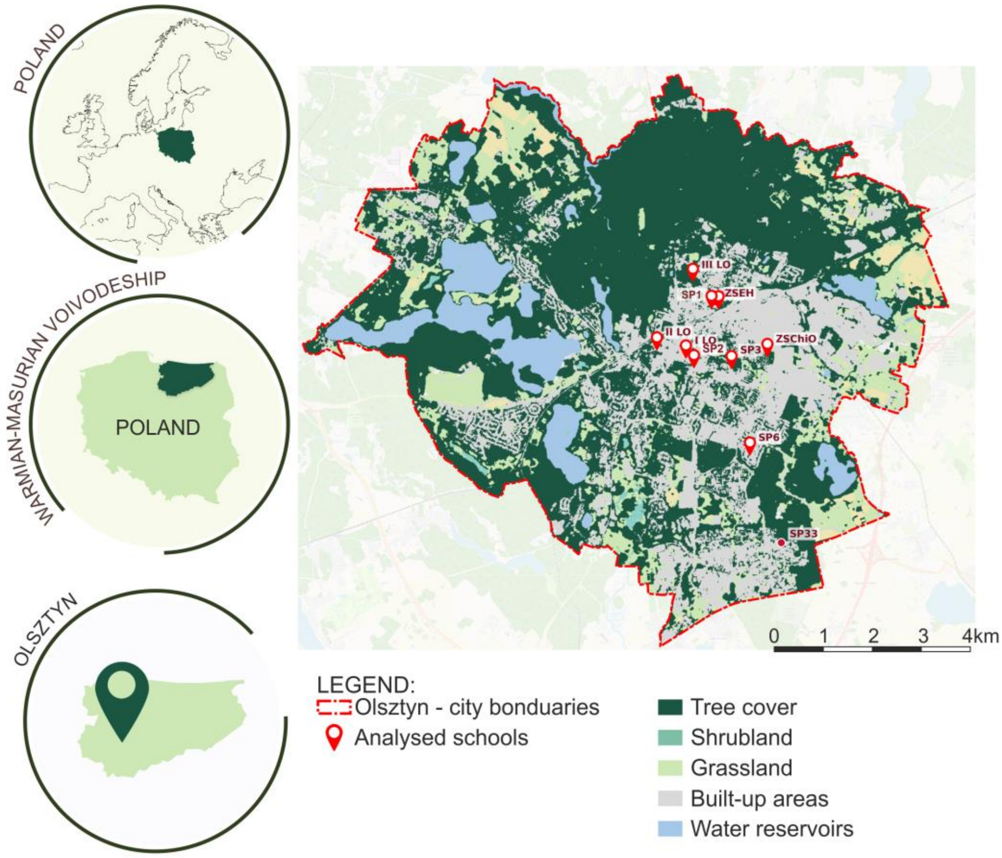

Fig. 1. Location of the analysed schools against the land cover of Olsztyn (ESA WorldCover 2021)

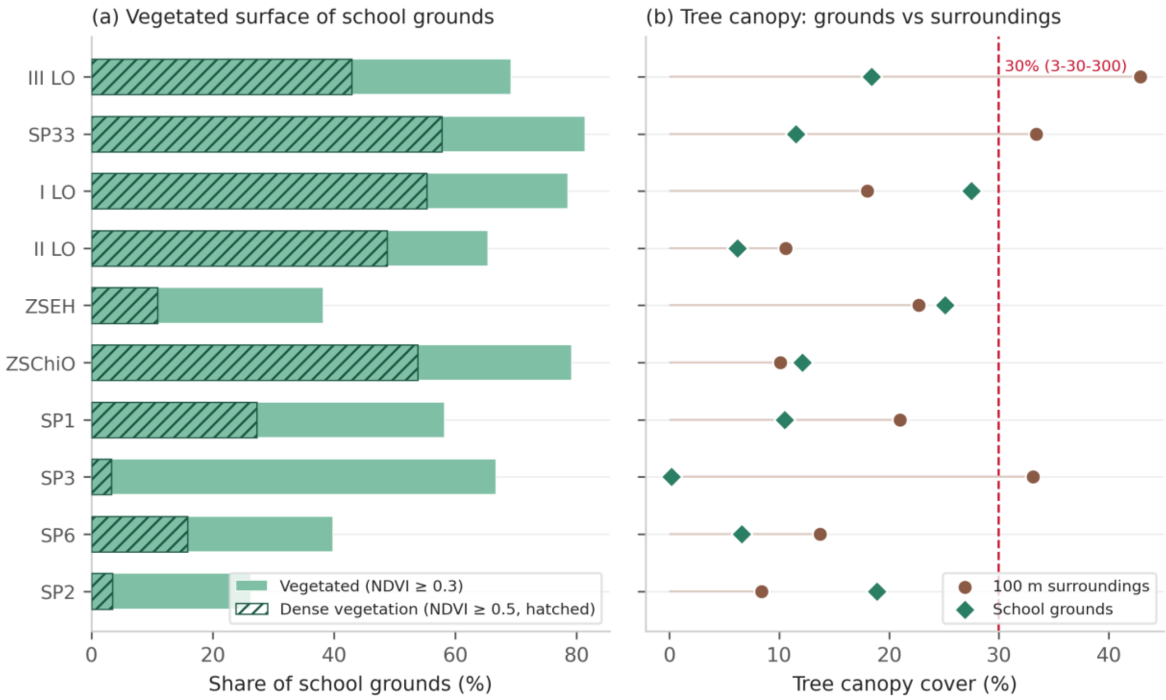

Fig. 2. (a) Vegetated surface (NDVI ≥ 0.3; hatched: NDVI ≥ 0.5) and (b) tree canopy cover of school grounds and their 100 m surroundings, with the 30% canopy benchmark of the 3-30-300 rule

4. DISCUSSION

The results confirm the substantial differentiation of school green spaces in a medium-sized Polish city (H1) and are consistent with European and North American evidence that the quality and structure of school greenery, rather than its mere presence, determine its potential to support users. The observed dominance of lawns with limited canopy cover corresponds to the pattern described for schools in the USA, where large featureless expanses of grass were negatively related to student outcomes, whereas tree cover showed positive associations [23, 24, 32, 36]. Recent schoolyard studies similarly suggest that spatial configuration and design diversity are consequential: play-zone diversity, tree shade and nature-based features were associated with more active and prosocial recess behaviours [66], whereas primary-school pupils in "greener" schoolyards showed more exploratory and manipulative play, fewer non-engaged behaviours and more positive social interactions [70]. This supports hypotheses H2 and H3 and indicates that the conversion of monofunctional lawns into multi-layer plantings should be the primary direction of modernisation of Olsztyn's school grounds. The observed canopy levels can also be placed in an international context: the Olsztyn mean of 13.7% is almost identical to the 13.6% recorded across 387 Toronto elementary schools [36], and clearly above the median of 6.4% found in student-use zones of more than 10,000 California schools, for which a 30% canopy goal has been formally adopted [46]. A comparison of 1,259 primary schools in four European cities likewise found no substantial gains in school-related green infrastructure between 2006 and 2018 [48]. Olsztyn schools are thus internationally mid-range, and still universally below the 30% benchmark.

The thermal dimension of the assessment gains importance in the context of climate change adaptation. Schools with the lowest canopy cover exhibited the highest summer land surface temperatures, in line with measurements and simulations showing that unshaded schoolyard surfaces reach hazardous temperatures [41] while tree canopies radically improve thermal comfort and sustain children's outdoor activity [4, 5, 26]. Since the heating season in north-eastern Poland increasingly overlaps with heat episodes in June and September, shading of playgrounds and sports fields should be treated as health-protective infrastructure rather than as a landscaping supplement, which corresponds to the objectives of the Olsztyn climate change adaptation plan and to the blue-green infrastructure solutions postulated for the city [13]. The magnitude of such contrasts is consequential: unshaded playground surfacing can reach 87 °C against 42 °C under tree shade [41], simulated tree additions reduce mean radiant temperature in schoolyards by up to 31 °C [4], and in Austin schoolyards spanning 8.5–22.5% canopy, a range almost identical to ours, children at the greenest site accumulated six percentage points more moderate-to-vigorous activity during hot recesses [26]. Central European playground measurements identify tree shade as more effective than engineered shade sails [49], and a national LST screening of 54,780 US schools documented systematic between-school temperature differences of the same order as the 5.6 °C span observed here [50].

The strong dependence of school-ground LST on the canopy of the 100 m surroundings, contrasted with the absence of an on-parcel association, is mechanistically expected rather than artefactual. Daytime canopy cooling operates non-linearly at the city-block scale of 60–90 m, with the strongest effects above roughly 40% cover [52]; tree canopy within 250 m of schools predicts pupil outcomes better than canopy within 1000 m [51]; and the operative exposure zone in the landmark Barcelona cognition study comprised the school grounds together with their immediate surroundings [14]. For planning practice, this implies that greening the streets and quarters around schools is at least as consequential for the school thermal environment as planting within the fence line.

Reference to the 3-30-300 benchmark [21, 34] situates the results in an international normative context: none of the ten schools meets the 30% canopy criterion within its grounds, and only two do so within the 300 m neighbourhood. These deficits are consistent with large-scale assessments of the benchmark: across 862 European cities, only 28% of the population lived in neighbourhoods with at least 30% tree cover and only 13.5% fulfilled all three criteria [58], while an assessment of more than 2.5 million buildings in eight global cities identified inadequate tree canopy as the principal reason for non-compliance [60]. The latter study further indicated that existing trees were frequently too small to provide sufficient canopy cover [60]. At the same time, the strong association between neighbourhood-scale canopy and school-ground LST observed here suggests that the benchmark is best interpreted at the scale of school surroundings rather than parcels: even a well-treed schoolyard cannot compensate thermally for a bare neighbourhood. It should be stressed, however, that benchmark values developed for residential environments require caution when transferred to school grounds, where the intensity of use and the daily time-activity patterns of pupils differ from those of residents.

The systematically lower scores of primary schools deserve particular attention in the light of environmental justice research. School greenery deficits have been shown to track social disadvantage among US schools [23, 53] and around Dutch primary schools [54], and school-level heat exposure is likewise unequally distributed [50]. For older students, the evidence base is less conclusive: a systematic review of secondary and tertiary education settings reported heterogeneous exposure and outcome measures and insufficient evidence for firm conclusions [67], and a German longitudinal study of two birth cohorts found no consistent association between residential or school greenspace and school grades in adolescents [30]. Such null findings indicate that the mere quantity of greenness around schools need not translate into measurable outcomes, which reinforces the rationale for assessing vegetation structure and canopy rather than aggregate greenness alone. Because younger children benefit most from everyday contact with nature and are physiologically most vulnerable to heat, the primary schools at the bottom of the SGWPI ranking constitute natural priorities for municipal intervention.

The strength of the proposed approach lies in its full reproducibility: all input data (Sentinel-2, Landsat, canopy height models, OpenStreetMap, BDOT10k, orthophotomaps) are open, and the workflow implemented in Google Earth Engine can be directly transferred to other cities. Nevertheless, several limitations must be acknowledged. First, the assessment is based on physical characteristics of space and does not include perception or actual use by pupils; the SGWPI should therefore be interpreted as potential rather than realised well-being support [2, 40]. Second, the canopy height models predate the vegetation-index analysis, which may lead to local misestimation of canopy cover where recent removals or plantings occurred; visual verification on the orthophotomap mitigates but does not eliminate this error. Third, school grounds mapped in OpenStreetMap may deviate from cadastral boundaries; hence their verification against BDOT10k. Fourth, LST at 30 m resolution characterises the thermal environment of the grounds as a whole and not of individual play areas. Finally, organisational barriers documented for Polish schools may prevent the actual use of even high-potential green spaces in everyday teaching [17]; linking the spatial assessment with surveys of school communities is therefore an important direction for further research. Multi-indicator assessments of school greenery have recently begun to emerge, a nine-indicator distributive-justice framework for 408 Brussels schools [57] and a composite greenness score for 5,773 Dutch primary schools [54], but, to our knowledge, none integrates canopy structure, an independent thermal outcome and 3-30-300 benchmarking in a single open-data index.

The practical implications of the study concern both school management and urban policy. The SGWPI ranking identifies facilities where interventions will bring the greatest gains in well-being potential, and the component structure of the index indicates the type of intervention required (e.g. increasing canopy cover versus enriching ground-level vegetation structure). The results may support the programming of municipal greening schemes analogous to the Polish programmes of de-paving and greening school grounds implemented in Wrocław, Gdańsk and Poznań, and to the European "cool schoolyards" model [7, 12]. Evaluated international programmes demonstrate that such interventions deliver measurable benefits: Barcelona's climate-shelter schoolyards, which added 74 trees, 26 water points and 2,213 m² of shade while removing about 1,000 m² of concrete across eleven schools, significantly improved pupils' reported well-being [55]; the Paris OASIS programme had converted 75 schoolyards by 2022, with some 73 ha of asphalt identified for de-sealing [56]; and a Dutch prospective study documented gains in schoolyard appreciation, physical activity and post-recess attention after greening [40]. Recent evidence also supports interventions designed to increase ecological and structural diversity rather than green area alone. In a two-year non-randomised controlled study of four primary schools, schoolyard greening explicitly designed to enhance vegetation structure and native species was associated with improved prosocial behaviour and with gains in selective attention, although the degree of biodiversity enrichment achieved was not quantified [71]. These findings complement systematic evidence that school-led nature interventions can benefit several dimensions of pupils' well-being, although effects remain heterogeneous across outcomes [64]. Peer-reviewed evaluations of the analogous Polish schemes are still lacking; the present assessment thus provides the first quantitative baseline for a Polish city against which future interventions can be measured.

5. CONCLUSIONS

The study proposed and tested a fully remote, reproducible method of assessing green spaces at educational facilities, aggregated into the School Green Well-Being Potential Index (SGWPI). The schools with the highest potential to support student well-being were III LO, SP 33 and I LO, owing to large vegetated shares, comparatively diverse vegetation structure and greener surroundings. The most important deficits identified across the sample were the scarcity of tree canopy within school grounds (mean 13.7%; no school reaches the 30% benchmark), the dominance of sealed surfaces at the city-centre schools, and the systematically lower scores of primary schools relative to secondary schools. Median summer surface temperatures of school grounds spanned 5.6 °C and were governed by the canopy of the 100 m surroundings rather than of the parcels themselves.

The main directions of modernisation of school grounds in Olsztyn should include increasing tree canopy cover over playgrounds and rest areas, converting parts of monofunctional lawns into multi-layer plantings and flower meadows, and introducing educational gardens and other elements enabling everyday contact with nature. The proposed workflow, based exclusively on open data, can be applied by local governments to monitor school green spaces and to prioritise greening investments in the context of climate change adaptation.

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