Landscape Architecture

ARTICLE

Building-Scale Deficit and Thermal Concordance in Bratislava Urban Green Infrastructure

Nigel Dunnett* and **James William**

The University of Sheffield

* Correspondence: n.dunnett@sheffield.ac.uk

Abstract

Green infrastructure assessment in an urban context should make clear whether the problem in the vicinity of buildings concerns vegetation quality, accessibility to any relevant public green space or urban parks that foster daily activity. Such distinct problems imply separate meanings for green infrastructure planning when the distribution of extensive green areas in the periphery, neighbourhood vegetation, and amenity-rich parks in the urban fabric is unbalanced. The present article looks at Bratislava in Slovakia using five classes of values for close-neighbourhood green quality, wider-neighbourhood green quality, public green-space accessibility, urban-park accessibility, and vegetation-temperature association. The study investigates which of these green-service qualities constitutes the constraint in the vicinity of buildings, and whether Forest Index–land surface temperature connection influences interpretation of neighbourhood vegetation. The shares of ordinal classes are transformed to the service means, residual deficit, lower tail, share of high services, grid-building displacement measure, public green space/park separation measure, and heat-induced vegetation pressure. Public green-space accessibility scores the highest mean value of 0.473 in relation to buildings while urban-park accessibility receives the lowest mean value of 0.226. In turn, the share of low and very-low-value categories of urban-park accessibility constitutes the largest lower-tail proportion with 81.5%. Close-neighbourhood green quality and wider-neighbourhood green quality reveal service means of 0.358 and 0.380, respectively, together with corresponding proportions of lower tails of 64.8% and 62.6%, respectively. Forest Index possesses the mean Spearman absolute association coefficient with land surface temperature of 0.762, indicating strong association between vegetation deficit and thermal environment. In conclusion, Bratislava faces major problems concerning lack of urban park access and poor vegetation quality in the close vicinity of buildings.

Keywords: urban green infrastructure; building exposure; urban parks; green-space accessibility; land surface temperature; Forest Index; Bratislava

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1. Introduction

The urban greenness of a healthy and climate-adaptive urban fabric is a critical factor in its formation. Vegetated areas, tree canopy and accessible green public spaces contribute to cooling, shading, evaporation, improving air quality, ensuring ecological connectivity, psychological recovery, physical activity and social interaction [18, 23, 25, 26]. Not all forms of greenery produce the above effects to the same extent. A forest-covered hill, a lawn field, an overshadowed residential courtyard, a river bank and a park equipped with seats and paths each create a unique combination of ecological function, thermal regulation and usability in the course of everyday life. A single assessment of greenness within a city may therefore conceal the condition of greatest importance to building scale.

The health literature has found a strong relationship between green exposure, mortality rates, mental health, cognitive function and physical well-being. Greenness, its reach to dwellings and walkability have been associated with better health outcomes, and the results vary greatly according to definitions of greenness exposure, accessibility, vegetation type, age group and mobility range [2, 6, 8]. However, the quality of the park itself counts. Just being close to parks does not guarantee access, especially if a park does not offer the necessary infrastructure for recreation, rest and activities in the outdoors [13, 24, 27]. The same applies in the European context of compact cities.

Compact development may save green land at the urban fringe, but it will increase pressure on inner-city areas. Local parks, courtyards, open parcels and vegetated streets become more scarce due to densification. City-wide availability of green spaces does not provide an accurate description of urban exposure. A building might be located in an urban environment with a lot of green space at the metropolitan scale, without having high quality vegetation in its immediate vicinity or good access to a recreational park. Scale is thus an issue not merely technical in nature, but rather an issue of semantic change. A grid cell describes a larger land cover, but a building represents the starting point of individual exposure and daily movement better [11, 15, 16, 21].

This difference extends to the thermal characteristics of the urban environment. Vegetation helps to moderate temperatures through shading, evaporation and reduced impervious surfaces. Nevertheless, thermal regulation depends on canopy structure, vegetation density, surrounding materials and assessment scale [4, 17, 28]. NDVI is a commonly used metric of greenness, yet it does not always make a clear distinction between tree-vegetated and grass-dominated areas. Tree-specific measurements are therefore vital in assessing shade and canopy density. If the vegetation index shows a significant negative correlation with LST, its low values are indicative not only visually but also in terms of the thermal environment and climate mitigation [5, 20].

These considerations are relevant in studying the urban environment of Bratislava, as there are a variety of urban landscapes, including compact central districts, housing estate areas, parks, riparian vegetation, vineyards, suburban development and forested areas. Therefore, broad public green reach may not necessarily be an indicator of local vegetation quality or urban park service. The functional values of green space categories, the ordinal distribution of services and the relationships between vegetation indices and temperatures are provided by Bobálová et al. [3]. Based on the values reported, this paper evaluates whether the critical condition for the built environment is public green reach, park access, nearby green quality, distant green quality or heat-related vegetation pressure.

The approach is limited in its scope. Rather than aggregating the four service measures in one composite index, the values of each individual variable have to be kept as numerical. An index that combines all the services would merge the indicators of AGSI and AUPI, making no differentiation possible between their conditions. One building may benefit from having access to a public green space without having a park with necessary amenities in its immediate vicinity. A building may be near a park, yet have poor tree-specific vegetation quality in its immediate environment. Hence, a building-level interpretation has to keep track of the numbers assigned to the variables and measure them on a uniform scale. It is also useful for monitoring purposes, as such an approach would allow distinguishing between poor access, poor local vegetation and poor park facilities.

The paper does not seek to map any new data on Bratislava. The main contribution of this work consists in the service interpretation of the available vegetation values. The originality of the paper derives from the building-scale service evaluation with the following result: 81.5% of buildings have poor scores in the category of AUPI, over 60% of buildings have poor scores for the NGQI variables, and only 38.4% have poor scores in AGSI. This makes a great difference to the urban green planning agenda, as the priorities in addressing a shortage of green service are now clearly stated.

2. Materials and analytical procedure

2.1. Bratislava green-service setting

Bratislava has a rich and varied green space environment, yet not all of it is equally beneficial in relation to the urban population. Large parks may dominate the urban environment visually, yet the quality of local vegetation may vary. In addition, not all parks in Bratislava provide recreational services at the building scale. For this reason, two different spatial units are considered: grid cells and individual buildings. While the former assesses the greenness condition of the urban environment in general, the latter provides information about the condition of green spaces attached to residential areas, where exposure takes place on a daily basis.

Comparison of the two spatial representations is important for interpreting Bratislava's green services. A high value in a grid cell may reflect greenery outside the boundaries of the urban building stock, while a low value in a building may indicate poor service for a place where the urban population has its residence and work locations, and where outdoor temperature exposure occurs. A high correspondence would imply a similarity in values of grid cells and buildings, while a divergence would show whether the grid-scale representation underestimates or overestimates building-level service.

2.2. Functional distance and area classes

A service is a combination of a functional distance measure and area requirement. Seven functional distance classes are distinguished depending on the size of the area and travel distance to it. Residential green space is the smallest class: its size is 0.1 ha and travel distance 150 m. The largest green space class is metropolitan green space: its size is 450 ha, and travel distance 5900 m. Intermediate classes are named after their functions: play, neighbourhood, quarter, district and city green spaces.

Table 1. Functional green-space classes.

Functional class	Minimum area (ha)	Rounded area (ha)	Rounded distance (m)	Transport interpretation
Residential green	0.06	0.1	150	Walking and cycling
Play green	0.52	0.5	350	Walking and cycling
Neighbourhood green	1.8	2	600	Walking, cycling, and driving
Quarter green	5.9	6	1000	Walking, cycling, and driving
District green	13	15	1400	Walking, cycling, and driving
City green	69	70	2700	Cycling and driving
Metropolitan green	450	450	5900	Cycling and driving

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Class hierarchy in Table 1 explains why access to a public green space and access to an urban park cannot be conflated into one access service condition. Indeed, a city could have a large public green area within a travel range which does not provide residents with proximity to any urban parks within their walking range on a daily basis. Thus, class thresholds give us the first reason to separate ecological reach from park access services.

Classes 150 m and 350 m in Table 1 are most significant in terms of access to urban park, while 2700 m and 5900 m are most significant in terms of access to metropolitan or city green spaces suitable only for occasional recreation. Such a distinction makes it clear that the strength of AGSI cannot be interpreted as strong evidence for a high value of AUPI. Subsequent analysis will reflect the above differentiation.

Distance rings in Figure 1 illustrates increasing service fields starting from residential green up to metropolitan green areas. However, the former ring does not compensate for lack of proximity to green areas in cities and metropolises. Therefore, subsequent calculations will rely on separating AGSI and AUPI into distinct access variables.

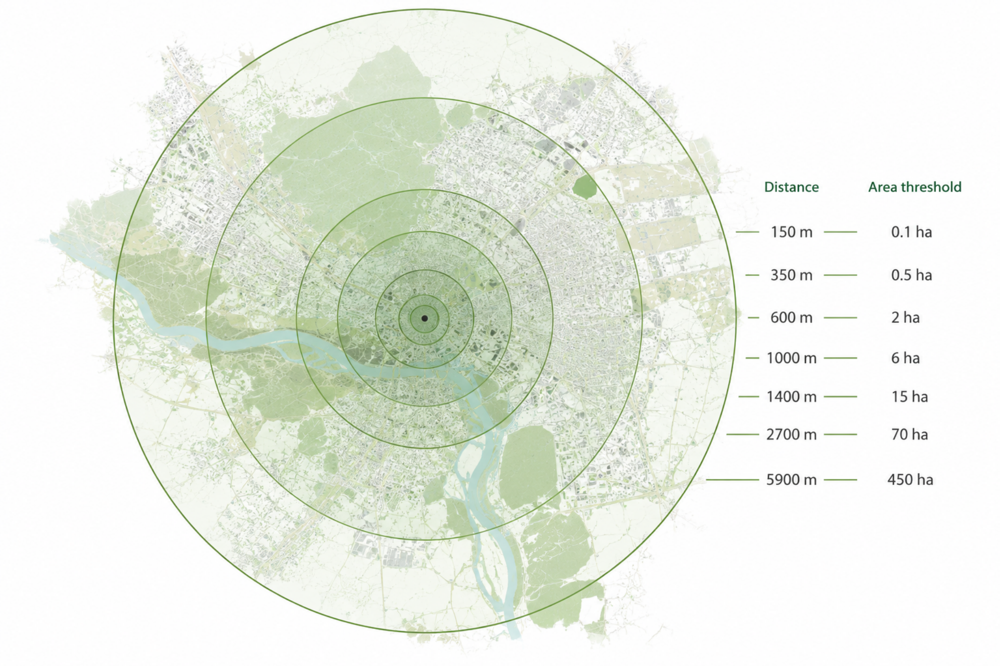

Figure 1. Functional green-space reach.

2.3. Green-quality and access variables

There are four variables to be considered here. $NGQI_{0/30}$ is close-neighbourhood green quality. When referring to grid cells, it means the condition of the cell. If talking about buildings, it means the 30 m neighbourhood. $NGQI_{350}$ is wide neighbourhood green quality. AGSI is the accessibility of public green spaces in the four functional classes. AUPI is the accessibility of urban parks. All four variables are kept distinct as each of them stands for the accessibility through different service pathway - from the local vegetation quality, through the green space reach to urban park service.

All four variables are expressed in five ordinal categories: very low, low, medium, high and very high. The percentage distribution per grid cells and buildings is presented in Table 2. Percentages are stored in the table, but transformed to proportions when calculated. This way the category distribution is preserved, while being able to perform calculation on the service scale of 0–1.

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From the percentages presented in Table 2, three distinctive tendencies can be observed without any calculation. First, AGSI includes a high and very high portion of both grid cells and buildings. Second, AUPI is clearly dominated by very low and low classes - 85.6% and 64.1%, respectively, of all grid cells and buildings are very low. Third, NGQI variables are concentrated in the low class when speaking about buildings.

Table 2. Five-class service distributions.

Variable	Spatial unit	Very low	Low	Medium	High	Very high
$\mathrm{NGQI}_{0/30}$	Grid cells	36.6	16.1	14.7	10.5	22.1
$\mathrm{NGQI}_{0/30}$	Buildings	13.9	50.9	28.6	6.1	0.6
NGQI_{350}	Grid cells	28.9	26.6	17.1	10.8	16.7
NGQI_{350}	Buildings	5.6	57.0	30.2	6.4	0.8
AGSI	Grid cells	28.0	10.0	9.2	10.6	42.1
AGSI	Buildings	17.2	21.2	28.6	24.2	8.9
AUPI	Grid cells	85.6	5.8	3.9	2.0	2.7
AUPI	Buildings	64.1	17.4	11.8	4.6	2.1

The building rows are particularly revealing. $\mathrm{NGQI}_{0/30}$ has 50.9% of buildings in the low class and only 0.6% in the very high class. NGQI_{350} has 57.0% in the low class and 0.8% in the very high class. AUPI has a still more extreme distribution, with only 6.7% of buildings in the high or very high classes. AGSI is the only building-scale variable with a substantial upper tail, reaching 24.2% in the high class and 8.9% in the very high class. The service contrast is therefore visible before any aggregation: broad green-space access is stronger than park access and local green quality.

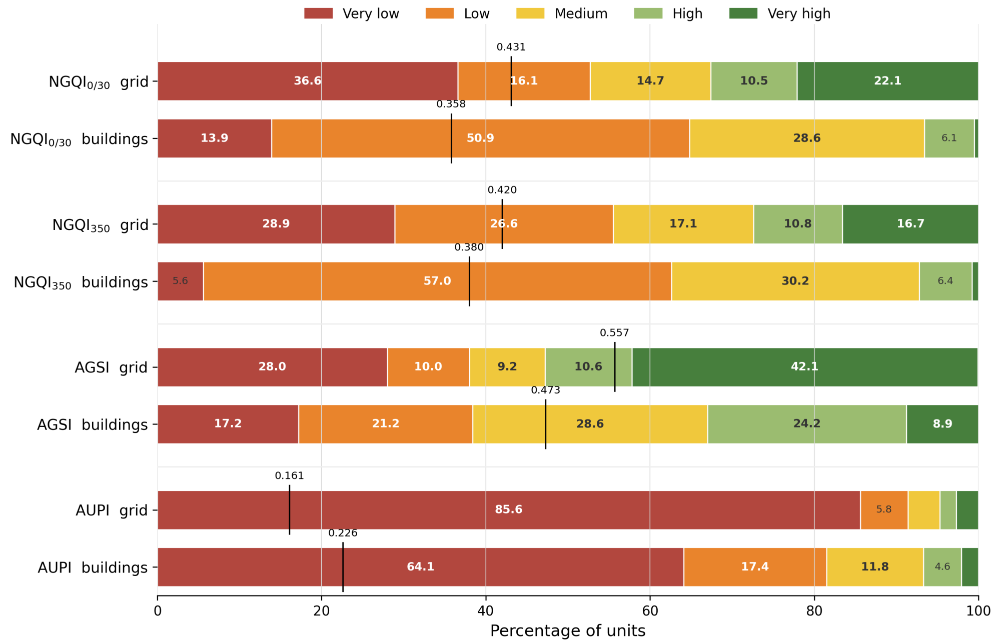

Figure 2. Five-class service shares.

The paired service bars in Figure 2 make the lower-tail structure visible. The building rows for $\mathrm{NGQI}_{0/30}$ and NGQI_{350} are dominated by the low class rather than by high-service classes. AUPI is visually separated from AGSI by its very large very-low segment. This pattern establishes the central accessibility contrast: public green-space reach performs more strongly than urban-park access, but neither local green quality nor park service is strong

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around buildings.

2.4. Ordinal service conversion

The five ordinal classes are converted to normalized midpoint values,

$$c = \{0.1, 0.3, 0.5, 0.7, 0.9\}. \tag{1}$$

For variable m, spatial representation u, and class k, the class share is denoted p_{muk}, with $\sum_{k=1}^{5} p_{muk} = 1$. The service mean is calculated as

$$\mu_{mu} = \sum_{k=1}^{5} p_{muk} c_k. \tag{2}$$

The mean represents an ordinal service expectation. It does not remove the need to read the class shares, but it allows $\mathrm{NGQI}_{0/30}$, NGQI_{350}, AGSI and AUPI to be compared on the same scale.

The residual deficit is

$$D_{mu} = 1 - \mu_{mu}. \tag{3}$$

The lower-tail burden is

$$S_{mu} = p_{mu,1} + p_{mu,2}, \tag{4}$$

where the first two classes are very low and low. The high-service share is

$$H_{mu} = p_{mu,4} + p_{mu,5}. \tag{5}$$

These three quantities have different interpretations. The mean summarises the whole distribution, the deficit describes the unserved portion of the 0–1 scale, and the lower-tail burden identifies the share of grid cells or buildings in the weakest two classes. A high-service share is needed because a variable can have a moderate mean while still lacking strong service conditions for most buildings.

A combined criticality value is calculated as

$$P_{mu} = \frac{1}{2} D_{mu} + \frac{1}{2}\left(S_{mu} + \frac{1}{2} p_{mu,3}\right). \tag{6}$$

The medium class receives half weight in the second term. Medium service is not counted as severe deprivation, but it is also not treated as a strong green-service condition. The calculation therefore gives priority to the lower tail while still recognising that medium values may require improvement in heat-sensitive and park-poor neighbourhoods.

2.5. Grid–building displacement and park separation

Grid–building displacement is calculated as

$$B_m = \mu_{m,\mathrm{grid}} - \mu_{m,\mathrm{building}}. \tag{7}$$

A positive value means that the grid representation is more favourable than the building representation. A negative value means that the building representation has the higher mean. This comparison identifies whether the full urban grid overstates or understates the condition experienced at the building stock.

Public green-space/park separation is calculated as

$$A_u = \mu_{\mathrm{AGSI},u} - \mu_{\mathrm{AUPI},u}. \tag{8}$$

A large positive value indicates that access to qualifying public green spaces is stronger than access to urban parks. This quantity is central to the Bratislava interpretation because park service includes a more specific everyday-use function than broad public green-space reach.

2.6. Vegetation–temperature concordance

Thermal concordance is based on the absolute Spearman association between vegetation variables and land surface temperature. For vegetation variable v, the mean absolute association is calculated as

$$T_v = \frac{1}{n_v} \sum_{d=1}^{n_v} |\rho_{vd}|. \tag{9}$$

The Forest Index coefficient is

$$\Theta_{\mathrm{FI}} = T_{\mathrm{FI}}. \tag{10}$$

Heat-related vegetation pressure is then calculated as

$$C_u = \Theta_{\mathrm{FI}} \frac{D_{\mathrm{NGQI}_{0/30},u} + D_{\mathrm{NGQI}_{350},u}}{2}. \tag{11}$$

This value does not claim causal cooling from the ordinal distributions alone. It states how strongly the local green-quality deficit aligns with a vegetation variable that has a consistent negative relationship with land surface temperature.

The correlations in Table 3 show a consistent negative relationship between vegetation and land surface temperature. FI remains close to 0.76 in absolute magnitude across all dates and both spatial contexts. NDVI is slightly weaker in the whole-city values, while LAI is clearly weaker in the test-area values. The FI values therefore provide a defensible thermal coefficient for interpreting the NGQI deficits.

Table 3. Vegetation–temperature correlations.

Date	Whole-city relationship	ρ	p	Test-area relationship	ρ	p
29 July 2013	FI–LST	-0.767	< 0.0001	FI–LST	-0.758	< 0.0001
29 July 2013	NDVI–LST	-0.734	< 0.0001	LAI–LST	-0.545	< 0.0001
3 July 2015	FI–LST	-0.753	< 0.0001	FI–LST	-0.769	< 0.0001
3 July 2015	NDVI–LST	-0.728	< 0.0001	LAI–LST	-0.572	< 0.0001
19 July 2015	FI–LST	-0.765	< 0.0001	FI–LST	-0.758	< 0.0001
19 July 2015	NDVI–LST	-0.741	< 0.0001	LAI–LST	-0.548	< 0.0001

3. Results

3.1. Levels of service in the building environment

The results on ordinal service means demonstrate that the condition of green infrastructure in Bratislava is far from being an equally deficient situation at each level. At grid scale, the AGSI has the highest mean value, 0.557, while the AUPI variable has the lowest mean value, 0.161. The $\mathrm{NGQI}_{0/30}$ and NGQI_{350} variables have means in-between at 0.431 and 0.420, respectively. The overall value in the grid environment implies high availability of public green space compared to the urban parks availability.

In the case of the building environment, the same hierarchy can be seen although the variables' values depend directly on the level of settlement exposure. In particular, AGSI has the largest mean value, 0.473. Then comes NGQI_{350} with 0.380, $\mathrm{NGQI}_{0/30}$ with 0.358, and finally, AUPI with 0.226. In the building environment, the level of deficiency is relatively low in the case of public green spaces access but relatively high regarding the urban park service and vegetation quality.

The difference between AGSI and AUPI at the building scale is 0.247, while that between $\mathrm{NGQI}_{0/30}$ and NGQI_{350} amounts to 0.022 only. Thus, the difference between these pairs of variables is much larger for the first pair, implying that the accessibility variables refer to quite different environments, whereas the vegetation-quality variables refer to similar ones. This is the key finding of the analysis concerning the service interpretations as accessibility cannot be considered as a single condition here.

Based on the data in Table 4, it can be noted that the AUPI variable characterizes the worst level of service at both scales. In particular, AUPI has the highest level of deficiency, 0.774, and the highest criticality value, 0.824, at the building scale. On the other hand, AGSI has a deficit of 0.527, with the same criticality value. Thus, the vegetation-quality variables $\mathrm{NGQI}_{0/30}$ and NGQI_{350} have the highest levels of deficiency exceeding 0.620.

Table 4. Ordinal service scores.

Variable	Spatial unit	Mean μ	Deficit D	Lower-tail burden (%)	High-service share (%)	Criticality P
$\mathrm{NGQI}_{0/30}$	Grid cells	0.431	0.569	52.7	32.6	0.585
$\mathrm{NGQI}_{0/30}$	Buildings	0.358	0.642	64.8	6.7	0.717
NGQI_{350}	Grid cells	0.420	0.580	55.5	27.5	0.610
NGQI_{350}	Buildings	0.380	0.620	62.6	7.2	0.699
AGSI	Grid cells	0.557	0.443	38.0	52.7	0.434
AGSI	Buildings	0.473	0.527	38.4	33.1	0.527
AUPI	Grid cells	0.161	0.839	91.4	4.7	0.886
AUPI	Buildings	0.226	0.774	81.5	6.7	0.824

The criticality values strengthen this interpretation because they combine the residual deficit with the lower part of the class distribution. AUPI has the highest criticality at grid scale, 0.886, and at building scale, 0.824. $\mathrm{NGQI}_{0/30}$ and NGQI_{350} have building criticality values of 0.717 and 0.699. AGSI has the lowest building criticality, 0.527. The ordering is therefore stable across mean, deficit, lower-tail burden and criticality: urban-park access is weakest, local vegetation quality is second, and broad green-space reach is comparatively stronger.

The building ranking in Figure 3 shows the difference between achieved service and remaining deficit. AGSI has the largest achieved service segment, but more than half of the 0–1 service scale still remains as deficit. AUPI has the smallest achieved service segment and the highest lower-tail burden. The two NGQI values show that vegetation quality is not as weak as park access, yet it is far from a high-service condition around buildings.

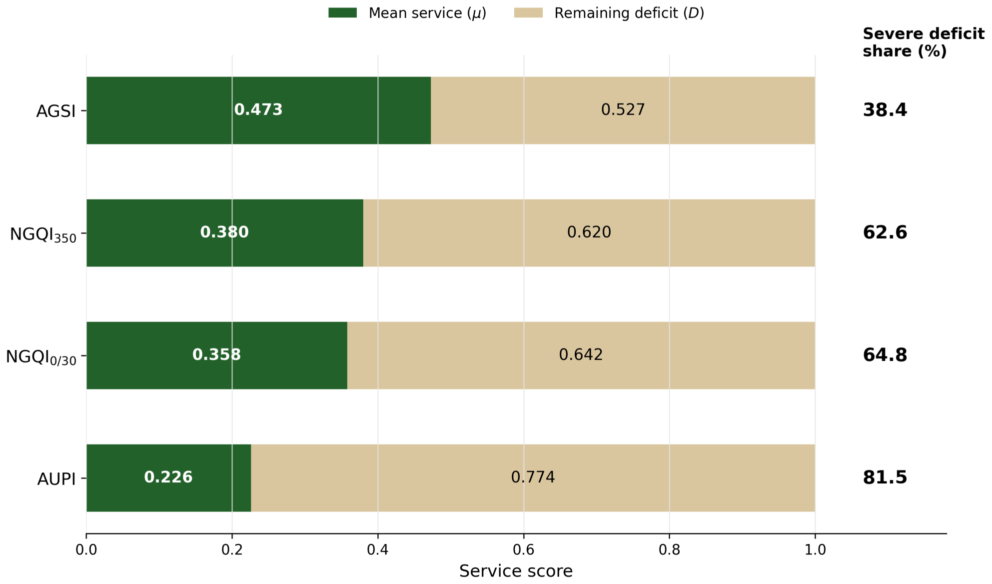

Figure 3. Building service and deficit.

3.2. Lower-tail exposure and high-service scarcity

The lower-tail burden is the clearest measure of service deprivation. At building scale, 81.5% of buildings fall in the very low or low AUPI classes. This value is 16.7 percentage points higher than the close-neighbourhood NGQI burden, 18.9 percentage points higher than the wider-neighbourhood NGQI burden and 43.1 percentage points higher than the AGSI burden. Urban-park accessibility is therefore the dominant lower-tail problem.

High-service scarcity is also pronounced. Only 6.7% of buildings reach the high or very high classes for $\text{NGQI}_{0/30}$, 7.2% for NGQI_{350} and 6.7% for AUPI. AGSI performs better, with 33.1% of buildings in high or very high classes, but two thirds of buildings still remain below high service. The relative advantage of AGSI should therefore be read as comparative strength, not as universal adequacy.

Table 5. Service threshold burdens.

Variable	Spatial unit	Below medium service (%)	Below high service (%)
$\text{NGQI}_{0/30}$	Grid cells	52.7	67.4
$\text{NGQI}_{0/30}$	Buildings	64.8	93.4
NGQI_{350}	Grid cells	55.5	72.6
NGQI_{350}	Buildings	62.6	92.8
AGSI	Grid cells	38.0	47.2
AGSI	Buildings	38.4	67.0
AUPI	Grid cells	91.4	95.3
AUPI	Buildings	81.5	93.3

The threshold values in Table 5 show both the minimum service burden and the high-service burden. Below-medium values isolate the weakest part of the distribution, where AUPI is the clear outlier. Below-high values show that high-service conditions are scarce even for the stronger variables. More than 92% of buildings fall below high service for $NGQI_{0/30}$, $NGQI_{350}$ and AUPI, demonstrating that the building environment has limited high-quality local greenness and park access.

The contrast between the two threshold columns is useful for prioritisation. The below-medium column identifies urgent service weakness, where AUPI dominates. The below-high column identifies the distance from a strong settlement condition, where the problem becomes broader. Even AGSI, the strongest variable, has 67.0% of buildings below high service. Thus, Bratislava should not treat its broad green-space reach as complete. It is simply less deficient than park access and neighbourhood green quality.

3.3. Grid–building displacement

Grid–building displacement identifies whether full-grid assessment is more favourable than the building-level condition. $NGQI_{0/30}$ has a displacement of 0.073, $NGQI_{350}$ has a displacement of 0.041 and AGSI has a displacement of 0.084. These positive values indicate that the grid representation gives a stronger service reading than the building representation for local green quality, wider green quality and public green-space accessibility.

AGSI has the largest positive displacement. Grid cells have an AGSI mean of 0.557 and a high-service share of 52.7%, whereas buildings have a mean of 0.473 and a high-service share of 33.1%. Large green spaces and less densely built parts of the urban grid can therefore elevate the city-wide access reading without providing the same service level at buildings.

The displacement profile in Figure 4 shows one contrasting value. AUPI has a displacement of -0.066, meaning that the building mean exceeds the grid mean. This does not indicate sufficient park access, because AUPI still has the lowest building mean and the highest lower-tail burden. The negative displacement means only that urban parks are more associated with built-up locations than with the full grid, while their absolute service level remains weak.

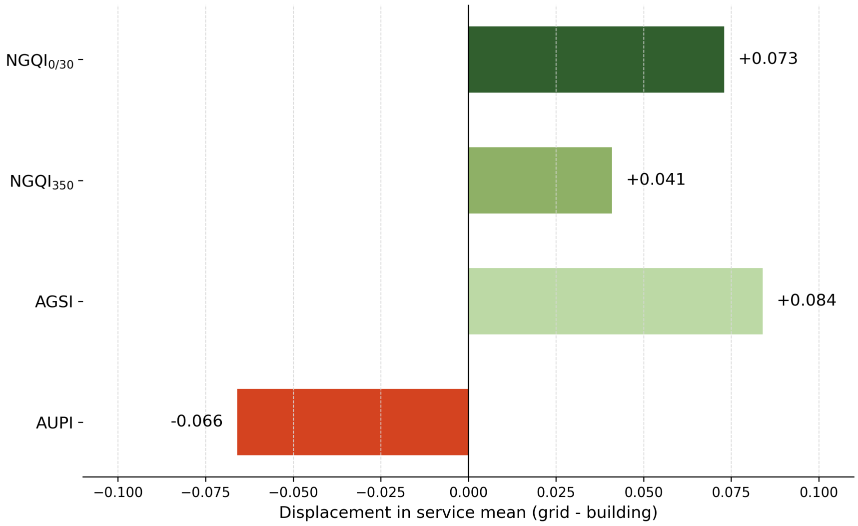

Figure 4. Grid–building displacement.

3.4. Public green-space reach versus urban-park access

The separation between AGSI and AUPI is the strongest accessibility result. At grid scale, the service difference is 0.396. At building scale, it is 0.247. Both values are large on a 0–1 service scale. This difference confirms that qualifying public green-space reach is not equivalent to urban-park access. Large green spaces may be reachable, but everyday park service requires closer, safer and more amenity-bearing spaces.

The paired spans in Figure 5 show that the separation persists under both spatial representations. The grid separation is larger because the full urban grid contains locations where broad green-space reach is substantially better than park service. The building separation is smaller but remains substantial. The AUPI deficit divided by the AGSI deficit is 1.895 for grid cells and 1.469 for buildings, so the park-specific deficit is almost twice the public green-space deficit across the grid and about one and a half times the public green-space deficit at buildings.

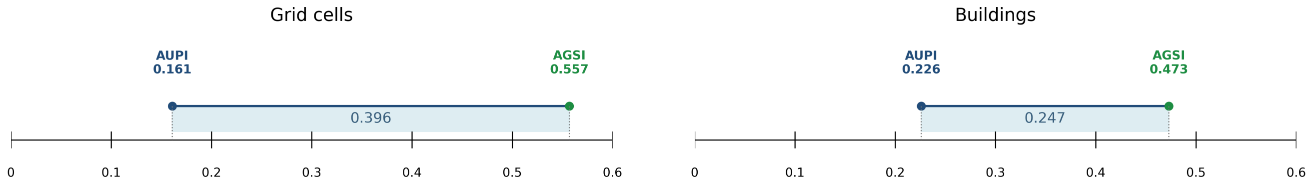

Figure 5. Public green-space and park separation.

3.5. Vegetation–temperature concordance

The thermal values identify FI as the most stable vegetation variable in relation to land surface temperature. Across the whole-city observations, the mean absolute FI–LST association is 0.762, while NDVI–LST is 0.734. Across the test-area observations, FI again averages 0.762, while LAI averages 0.555. The six FI values have a standard deviation of approximately 0.006, indicating very limited variation across the hot-date observations.

The two panels in Figure 6 show the same pattern in different spatial contexts. FI remains close to 0.76 in absolute association on all dates. NDVI is slightly lower in the whole-city values, and LAI is much lower in the test-area values. This result does not exclude other vegetation readings; it supports the use of FI for interpreting local green-quality deficits in heat-sensitive terms.

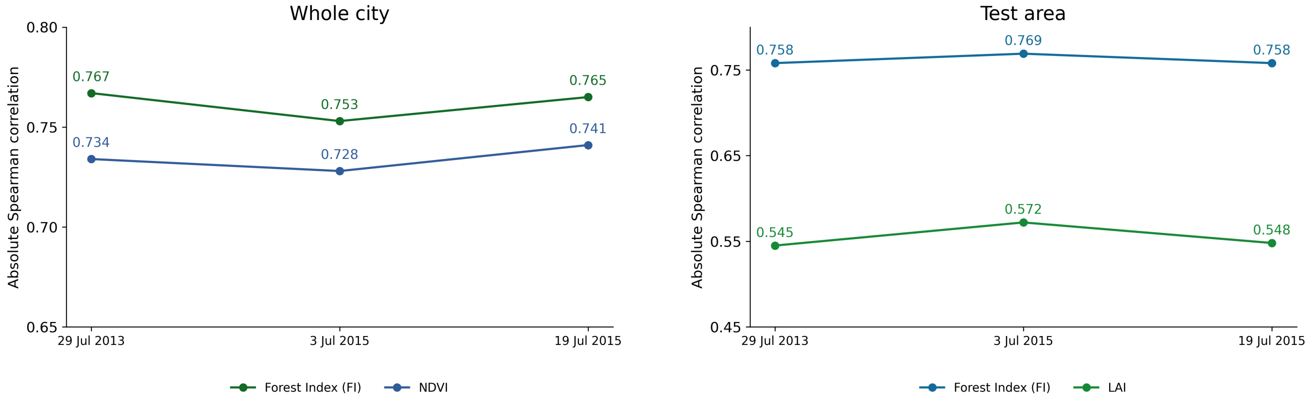

Figure 6. Vegetation–temperature concordance.

3.6. Heat-related vegetation pressure

Heat-related vegetation pressure combines the average deficit in $NGQI_{0/30}$ and $NGQI_{350}$ with the FI thermal coefficient. The grid average green-quality deficit is 0.575, which produces a pressure value of 0.438 after multiplication by 0.762. The building average green-quality deficit is 0.631, producing a pressure value of 0.481. The higher building value shows that local vegetation weakness is greater around the building stock than across the full grid.

The calculation displayed in Figure 7 links the NGQI deficit to temperature association rather than treating green quality as a visual condition only. A building value of 0.481 indicates that weak local vegetation is aligned with a vegetation reading that has a strong negative relationship with land surface temperature. This finding strengthens the planning relevance of tree-rich streets, shaded courtyards, vegetated setbacks and green open spaces near buildings.

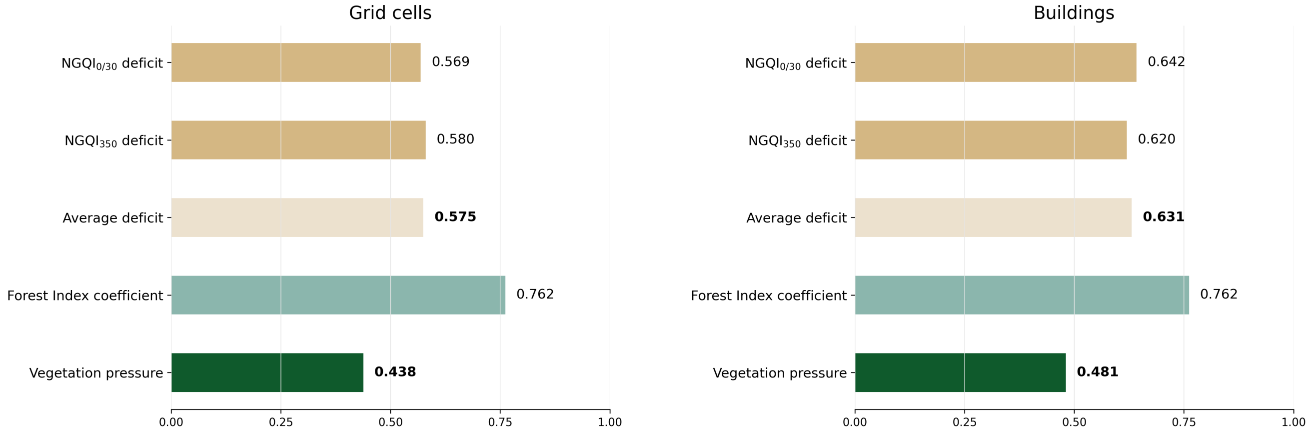

Figure 7. Heat-related vegetation pressure.

3.7. Building-scale ordering of intervention needs

The building-scale order is determined by the share of buildings in the very low or low classes. AUPI has the highest lower-tail burden at 81.5%. $NGQI_{0/30}$ follows at 64.8%, $NGQI_{350}$ at 62.6% and AGSI at 38.4%. This order is not a general greenness ranking. It identifies where building-level service deprivation is most concentrated.

The ranked values in Figure 8 show that urban-park accessibility is the most urgent building-level service limitation. The second and third positions are both vegetation-quality variables, confirming that local greening must accompany park-service improvement. AGSI is the least severe condition, but it still leaves 38.4% of buildings in the lower tail and 67.0% below high service. Broad green-space reach should therefore be preserved and improved, but it should not be treated as a substitute for parks or local vegetation quality.

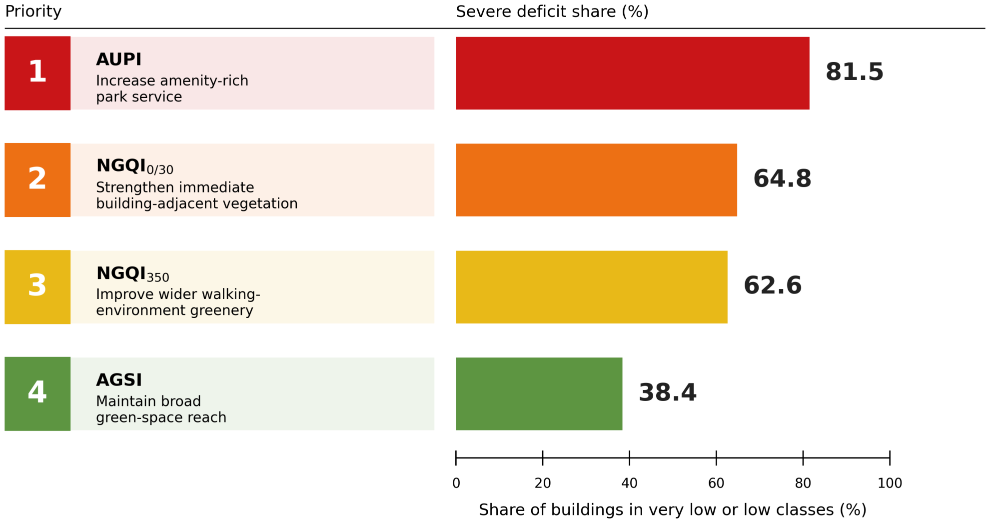

Figure 8. Building-scale service burden.

4. Discussion

4.1. Separation of ecological reach, park access and local vegetation quality

The results concerning Bratislava show that green infrastructure service cannot be considered through an aggregate greenness condition. The four variables considered in this paper capture three distinct service dimensions: AGSI represents ecological reach, AUPI represents park access and $\mathrm{NGQI}_{0/30}$ and NGQI_{350} represent vegetation quality in the immediate and wider neighbourhood, respectively. A broader green area does not automatically imply urban parks or a particular vegetation structure.

Such a separation was also found in research conducted across international settings [11, 15, 18], where the benefits of green spaces were identified as depending on exposure type, accessibility, usability and vegetation structure. The existence of separate conditions precludes a generalisation of Bratislava green-infrastructure service from a single greenness value, such as vegetation quality or area. In Bratislava, the best mean building-scale value is for AGSI and the worst mean is for AUPI. It is, therefore, incorrect to claim that all green infrastructure service components are weak.

4.2. Scale-dependent interpretation of Bratislava's green services

The interpretation depends on the level of aggregation and differs between grid and building representations. The positive displacement of $\mathrm{NGQI}_{0/30}$, NGQI_{350} and AGSI indicates that the aggregate grid level provides a more favourable interpretation than the building-level assessment. For decision-makers, this finding has important policy significance, since grid-based values may include non-residential and peripheral elements that may not reflect local greenness conditions and building environments. Building-level assessment, in turn, offers an alternative that captures better routine exposure.

AUPI behaves differently from other variables, since its mean building value is greater than its mean grid value. In other words, urban parks tend to be concentrated in built-up locations, yet their share among buildings remains extremely low and the percentage of buildings in the lower tail is 81.5%. Consequently, the association with buildings is insufficient for claiming adequate park service, as would be a case with positive displacement.

At the same time, there is a communication implication related to scale in relation to planners and policymakers. Whereas grid cell data provide an appropriate description of the urban landscape, they must not be solely used when evaluating daily environmental conditions. Buildings' values indicate that the interpretation becomes more restrictive when switching from grid cells to the built environment. For example, the mean $\mathrm{NGQI}_{0/30}$ value decreases from 0.431 to 0.358, while the mean AGSI value decreases from 0.557 to 0.473. It is, therefore, more accurate to say that the more settlement-oriented interpretation provides a more critical picture of vegetation and accessibility at the building level.

4.3. Park access as a building-level deficiency

Park service is clearly lacking in the green-infrastructure service configuration of Bratislava. Specifically, the mean AUPI value at the building scale is 0.226, its deficit is 0.774 and the lower tail burden is 81.5%. These figures are more pronounced than in the case of AGSI, whose mean is 0.473 and whose lower tail burden is 75.9%. Public green-space versus park accessibility separation of 0.247 also indicates that the former cannot replace the latter.

In terms of policy, the results offer clear guidance. Large green areas, forested lands and metropolitan green spaces can serve as recreation sites and contribute to the overall ecological reach, but they cannot be counted upon in providing local parks with appropriate accessibility characteristics, amenities and facilities. Older persons, children, caregivers and any individuals with low travel flexibility need urban parks more urgently than distant green space, which calls for focused interventions to enhance access and quality of parks.

4.4. Thermal meaning of local vegetation quality

From a thermal perspective, the findings highlight another aspect of vegetation deficiency around buildings. FI demonstrates stability in association with LST with the mean absolute value of 0.762, and this correlation is higher compared to NDVI's and substantially higher than LAI's. These findings are aligned with previous literature on vegetation influence on urban heat island effects, which highlighted the importance of canopy structure and tree density in cooling cities [4, 20, 28].

The pressure created by vegetation deficit is more pronounced in Bratislava buildings, which can be explained by the weak NGQI values along with the high FI–LST association. While it cannot precisely locate the problem street-by-street, the building-level analysis shows that greenness improvement in close and wider neighbourhoods has important adaptation significance. Specifically, vegetation in close proximity to buildings should be more shading-intensive, continuously covered with trees and include courtyards and setbacks.

4.5. Planning implications

The current analysis has pointed to several directions of action. First, park access should be improved where AUPI values are low, and this applies primarily to residential areas and locations with vulnerable population groups. Second, vegetation quality in close and wider neighbourhoods needs to be improved due to a high lower-tail burden and strong thermal association. Finally, broad green space assets should be preserved, but AGSI values must not be counted as an indicator of adequate park service and vegetation.

When looking at priorities in the context of resource limitations, it is logical to begin with parks since they have the largest lower-tail burden, which includes 81.5% of buildings. If park creation is difficult, the focus should be placed on improvements to existing open spaces and the creation of better accessibility, since even existing parks can be improved before acquisition of additional territory. Vegetation in Bratislava should be enhanced in close and wider neighbourhoods in order to create shade and cooler spots.

4.6. Analytical constraints

The analysis relies on class shares and midpoints obtained from published sources, and no further spatial operations were performed, which means that precise location identification is beyond its scope. While this approach makes each calculation traceable, it leaves certain details unaccounted for. In particular, fine-scale planning needs to rely on population distribution, age composition, locations of schools, hospitals, care facilities, buildings exposed to heat and property ownership status. Midpoint conversion does not capture within-class variance, and the thermal assessment is based on association rather than causal inference.

Nevertheless, despite its limitations, the analysis provides a consistent evaluation of building-scale green-infrastructure service in Bratislava and the thermal role played by local vegetation quality. This information can help planners prioritise interventions and target different service deficiencies in a complementary way rather than trying to improve one of them to the detriment of others.

5. Conclusion

This paper sought to establish which green-service condition most constrains Bratislava's built environment and whether a thermal association with vegetation changes the interpretation of local green-quality deficits. In this regard, the analysis yielded a specific finding: the mean value of AGSI at the building level is 0.473, but it does not compensate for the lack of urban parks and vegetation in Bratislava neighbourhoods. AUPI turns out to be the weakest service condition with a mean value of 0.226 and 81.5% of buildings falling into the lower tail.

Vegetation quality forms the second green-infrastructure limitation, whose values are 0.358 for $\mathrm{NGQI}_{0/30}$ and 0.380 for NGQI_{350}. More than 60% of buildings belong to the lower tails of both variables. At the same time, FI demonstrates stable mean absolute association with land surface temperature of 0.762, and it creates significant heat-related vegetation pressure. Bratislava's interventions should, therefore, follow combined service logic: enhance urban parks and local vegetation quality without sacrificing wide green space reach.

Among other things, it is possible to state the following priorities with certainty: AUPI is more urgent due to the larger share of buildings in the lower tail (more than 80%) and FI-related NGQI is of secondary importance. These findings are derived from grid versus building displacement, AGSI–AUPI separation and vegetation–temperature association.

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