Landscape Architecture

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Resident-Level Sufficiency of Urban Green Infrastructure Services in Moscow Across District, Quarter, and Grid Representations

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Abstract

Large metropolitan green spaces can be described using the total share of land cover types or an ecosystem-services index, but these metrics do not indicate whether vegetation producing the desired services overlaps with people affected by sealing, emissions, heating, surface water runoff, and poor local green space. This paper considers Moscow based on population-oriented ordinally sufficient analysis of the largest urbanized territory. The available data consists of 118 administrative districts, residential quarters, regular grid cells, more than 12 million residents, 841 landscaped objects of green infrastructure, 202.1 km^2 of landscaped green infrastructure, 86 nature reserves covering 149.8 km^2, and six physical services. Calculation is performed with thresholds and score distributions of sanitary-zone vegetation, stormwater regulation, cooling capacity, cultural green access, residential green provision, and roadside green space. Each block is assessed for adequate land share and adequate resident share such that ecological sufficiency and resident coverage will not be confused. It is concluded that there is little correlation between metropolitan green abundance and resident sufficiency. Regulating services appear to be the largest deficit, with adequate land share rising from 12.0% of district area to 19.2% of grid area, whereas adequate resident share goes up merely from 11.3% to 11.7%. Cultural access and residential provision are better accounted for by quarter level with 48.4% of adequate area and 38.3% of adequate population. Roadside green space shows greatest sensitivity to the grid-level analysis with 37.2% of adequate area and 34.2% of adequate population. Moscow therefore has plenty of green space infrastructure but lacks resident sufficiency due to insufficient overlap of ecological services and human exposure to urban environment.

Keywords: urban green infrastructure; ecosystem services; ordinal sufficiency; population exposure; Moscow; spatial scale; green accessibility; roadside greening

1. Introduction

Green infrastructure is an essential feature of the modern metropolis' environment because vegetation and blue-green spaces regulate multiple urban stress factors. Canopy coverage, shrub cover, lawn coverage, wetland areas, parks, boulevards, inner courtyards, riparian margins, and urban forests provide cooling, storm runoff regulation, particulate filtration, noise dampening, visual screen, recreation activities, and restorative nature experience. Research on the

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role of green infrastructures in global environmental policy has demonstrated the potential of such measures for ecosystem service provisioning, climate adaptation, and public health improvement, yet studies have established that the benefits for human well-being depend on exposure, accessibility, and quality of green space, rather than only the amount of vegetation in a city [4, 10, 15, 18, 40, 42, 45]. Therefore, a city can be green in terms of the total number of green infrastructures and yet feature residents surrounded by concrete walls, exposed to traffic pollution, thermal discomfort, and limited accessibility of nearby green spaces.

Prior literature provides some insights into the importance of the problem mentioned above. First, assessments of land cover and fragmentation examine the quantitative and structural dimensions of green land, second, accessibility of green spaces to the population is explored in population-weighted approaches, third, ecosystem-service-based models consider specific functions such as pollutants removal, or trees-based ecosystem services [1, 12, 19, 22, 32]. While each line of research is important and complementary, it focuses on different aspects of green infrastructure management. The current study maintains the physical detail of the green infrastructure assessment performed in Moscow and compares adequate land coverage with sufficient population.

Distribution problems become particularly relevant in large cities with green spaces scattered across central neighborhoods, green parks, transport corridors, derelict lands, residential courtyards, and peripheral forests. Green-space equity and access to cultural ecosystem services have shown that physical green coverage is not equivalent to fair population exposure because benefits of vegetation can be moderated by the distance to green spaces, accessibility of transport connections, residential density, quality of green spaces, opportunities for public visits, and vulnerability of population [6, 13, 24, 39, 47]. The same principle holds for regulating services: cooling, runoff regulation, road-edge greening, and pollutant removal cannot be provided by the same spatial pattern. For example, cooling is determined by canopy coverage, size of patches, surface coverage, air circulation, and proximity of heat-exposed buildings to cooler green areas; runoff regulation relies on imperviousness, soil porosity, vegetation coverage, and drainage network; road greening requires narrow corridors and vegetation continuity; cultural ecosystem services are related to the proximity of squares, boulevards, parks, and urban forests [21, 26, 33, 38, 48]. Thus, one could have a sufficiently large quantity of land meeting one condition and lacking other services.

Spatial support becomes equally important because administrative districts may reflect the governance system and budget allocations, but mix courtyards, transport networks, roads, green parks, industrial facilities, water bodies, and open lands in the same unit. In turn, residential quarters represent closer proxies to everyday use and walking distance, yet they exclude large green patches, transportation networks, and road edges. Regular cells highlight service differences along transportation corridors and vegetated patches, but they may not coincide with neighborhood and administrative units [7, 36]. The problem is not purely technical because differences in spatial supports produce different proportions of land and population meeting service adequacy thresholds.

The case of Moscow is relevant for the study because the city possesses abundant green infrastructure while being subject to environmental stresses. Specifically, the green and blue infrastructure of Moscow has contributed to heat mitigation, runoff regulation, recreational functions, ecological processes, and environmental quality [2, 8, 9, 11, 27, 31, 37, 41, 43, 46]. Moreover, traffic emissions, sealed surfaces, stormwater pressures, and spatial inequalities in heat exposure have been examined in studies specific to Moscow conditions [29, 30, 49]. Hence, Moscow is a proper case for investigating whether a large green infrastructure is capable of providing necessary services to residents and managing associated risks. Furthermore, similar problems arise in many other cities around the world as climate stressors intensify pressure, and population concentrates in dense settlements [25, 44].

In particular, the following questions guide the current study. Does Moscow possess sufficient green infrastructure providing regulating, cultural, and road edge conditions for residents? If yes, what spatial supports are needed to detect green inadequacies? The empirical basis is the Moscow urban green infrastructure index developed by Dvornikov et al. [17], which involves six indicators, threshold scores, area distributions, and population percentages meeting adequacy criteria. Each score represents an ordered service condition, adequate land is differentiated from adequate population, and gains in scales illustrate the mismatch between the two categories.

2. Materials and methods

2.1. Study area and spatial units

The study area is the principal urbanized territory of Moscow City, distinguished from the New Moscow expansion zone. The territory is divided into 118 administrative districts and aggregated into nine administrative okrugs. The population is higher than 12 million inhabitants, while district populations vary between 12,264 and 254,142 residents and average population density is 13,396 inhabitants km^{-2} [17]. There are 841 landscaped urban green infrastructure facilities such as squares, boulevards, parks, and urban forests, occupying an area of 202.1 km^2. Natural protected territories occupy an area of 149.8 km^2. The land-cover composition includes water (3.76%), impervious surface (41.12%), bare soil (9.49%), trees vegetation (22.02%), shrubs (15.06%), and grassland (8.55%).

The analysis of green infrastructure uses data from the Moscow urban green infrastructure index by Dvornikov et al. [17]. The index quantifies selected regulating and cultural ecosystem services based on 118 administrative districts, 1301 residential quarters, and 62538 regular grid cells. Geospatial layers, land cover information, road and sanitary zone boundaries, population estimations, accessibility surfaces, stormwater-runoff, and cooling potential models were used to develop the indicator scores. The analysis utilizes scores, thresholds of adequacy, distributions by area, and percentages of population meeting requirements of services.

Moscow is an appropriate city for green infrastructure analysis because of high overall amounts of green infrastructure and unequal distribution. Overall, more than 470 km^2 is green-infrastructure equipped, which corresponds to 46% of the city territory. Overall green availability is relatively high in international comparison, although access and functionality may differ depending on the territorial context [17, 27]. The problem of green inequality requires a multi-scale analysis rather than aggregate metrics alone.

Spatial supports and primary green infrastructure quantities are displayed on Figure 1. This representation is critical because later percentages will depend on the scale of service representation as administrative district, residential quarter, and grid cell.

2.2. Indicator categories and service thresholds

These six indicators have been chosen because, together, they encompass major regulating and cultural services in the Moscow urban assessment process. DNI indicator describes dust absorption, noise mitigation, and visual screening of technogenic elements within sanitary zones. SRI indicator evaluates stormwater retention performance of urban greenery. CI indicator measures cooling potential during heat waves. GAI indicator estimates access to green recreational amenities of diverse nature and hierarchy by urban population. GPI indicator calculates green area per capita provided within residential quarters. GRI indicator estimates proportion of roadside vegetation within road borders. It is important to note that these indicators cannot be considered as interchangeable – each one represents its own specific mechanism of how vegetation benefits humans or regulates environmental impact. The organization of indicators into two sets has been adopted from CICES ecosystem-service classification for urban contexts [23].

DNI calculates proportion of tree and shrub canopy above 1.1 meters of height within sanitary zones in proximity of building, streets, industrial areas, construction sites, and other types of technical infrastructure. SRI measures percent reduction in the calculated runoff depth between vegetated and unvegetated scenarios, thus directly reflecting green infrastructure stormwater retention capacity. CI determines mean cooling potential ($\mu\Delta T$) in degrees Celsius under conditions of heat waves. GAI indicates the population-weighted average accessibility of green recreational spaces of various sizes and functional levels. GPI reflects number of green space square meters provided for each person in residential neighborhoods. GRI evaluates proportion of vegetated land within road borders.

Physical meaning of six indicators can be seen in Figure 2. The set of pictures below helps understand the nature of urban phenomena that indicators estimate.

The indicator plate prevents an overly broad reading of greenness. A shaded courtyard, a vegetated sanitary zone, a stormwater-retaining verge, and a roadside planting strip all contain vegetation, but they correspond to different

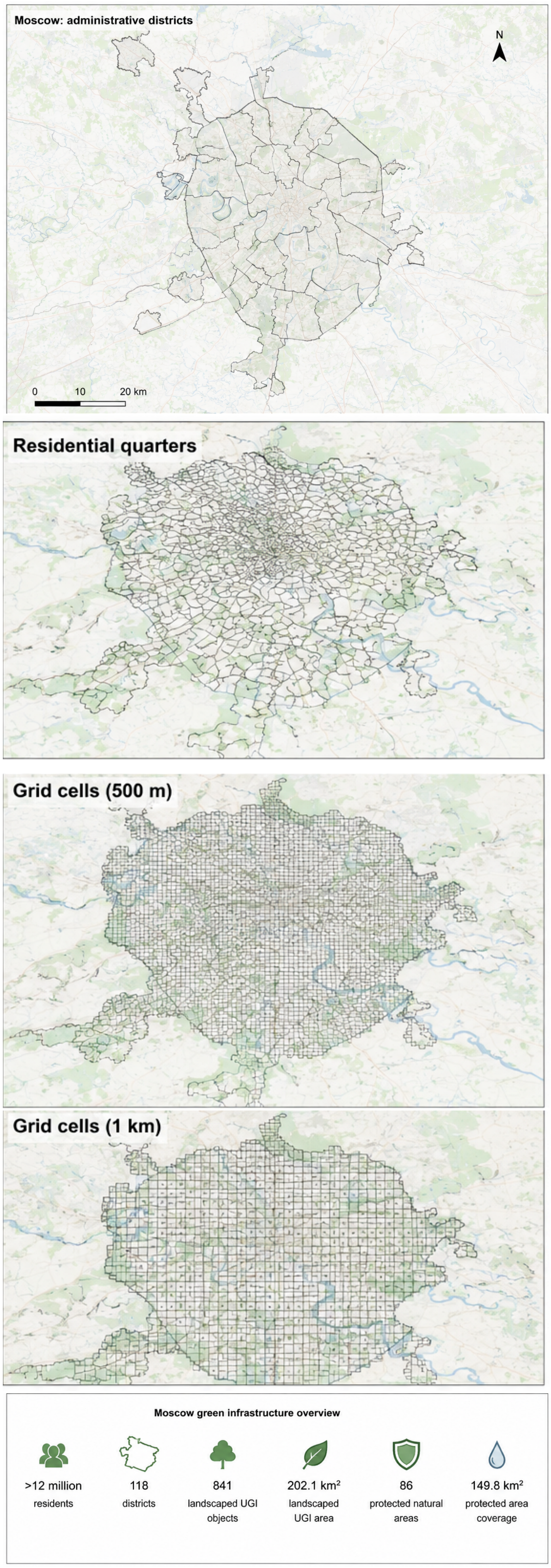

Figure 1. Moscow study area and spatial units.

service mechanisms and must therefore be assessed with distinct thresholds.

The ordinal thresholds follow the Moscow UGI index. DNI, SRI, and GRI are scored from 1 to 4 using 25%

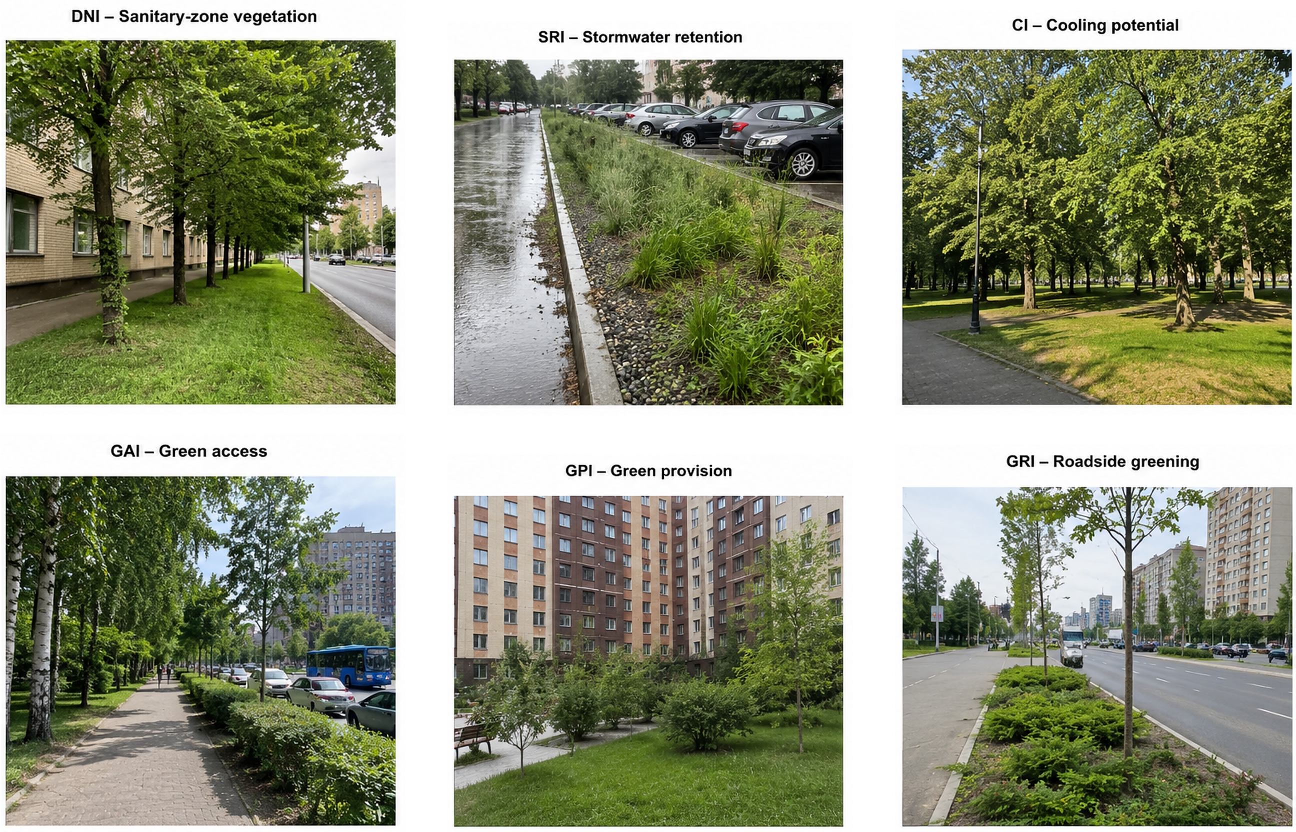

Figure 2. Urban conditions captured by the UGI indicators.

intervals, where 1 corresponds to 0–25%, 2 to 25–50%, 3 to 50–75%, and 4 to values above 75%. CI is scored from 1 to 4 using one-degree cooling intervals, from 0–1°C to 3–4°C. GAI is a unitless accessibility value scored from 1 to 4, where the highest class indicates access to the full set of green-space categories considered. GPI is scored by green space inside residential quarters per capita, with class 1 below 9 m^2, class 2 from 9 to 15 m^2, class 3 from 15 to 25 m^2, and class 4 above 25 m^2. Table 1 summarizes the indicator logic.

Table 1. Indicator definitions and adopted thresholds.

Service block	Symbol	Measured condition	Ordinal thresholds	Spatial units
Regulating	DNI	Canopy share within sanitary zones around roads, buildings, industrial areas, construction areas, and other technogenic land uses	1: 0–25%; 2: 25–50%; 3: 50–75%; 4: >75%	District; grid
Regulating	SRI	Percent reduction in modeled runoff depth between vegetated and non-vegetated conditions	1: 0–25%; 2: 25–50%; 3: 50–75%; 4: >75%	District; grid
Regulating	CI	Mean cooling potential, expressed as $\mu\Delta T$ in °C	1: 0–1; 2: 1–2; 3: 2–3; 4: 3–4	District; grid
Cultural	GAI	Population-weighted access to green spaces of different types and sizes	1: 0–1; 2: 1–2; 3: 2–3; 4: 3–4	District; quarter
Cultural	GPI	Green land-cover area within residential quarters per capita	1: <9 m^2; 2: 9–15 m^2; 3: 15–25 m^2; 4: >25 m^2	District; quarter
Street edge	GRI	Green land-cover share within cadastral road boundaries	1: 0–25%; 2: 25–50%; 3: 50–75%; 4: >75%	District; grid

The ordinal treatment is important because the difference between two adjacent score classes cannot be assumed to have the same ecological or social meaning across all indicators. A movement from 0.8 to 1.2°C cooling, for example, does not carry the same physical meaning as a movement from 24% to 26% roadside vegetation, even though both could shift a unit from score 1 to score 2. For this reason, the scores are used to identify adequacy classes rather than to calculate simple arithmetic averages.

The corresponding panel in Figure 3 shows the score classes and adequacy conditions used in the calculations. The visual threshold structure supports the ordinal treatment: values are assigned to service classes and then interpreted through adequacy rules rather than averaged as equal numerical intervals.

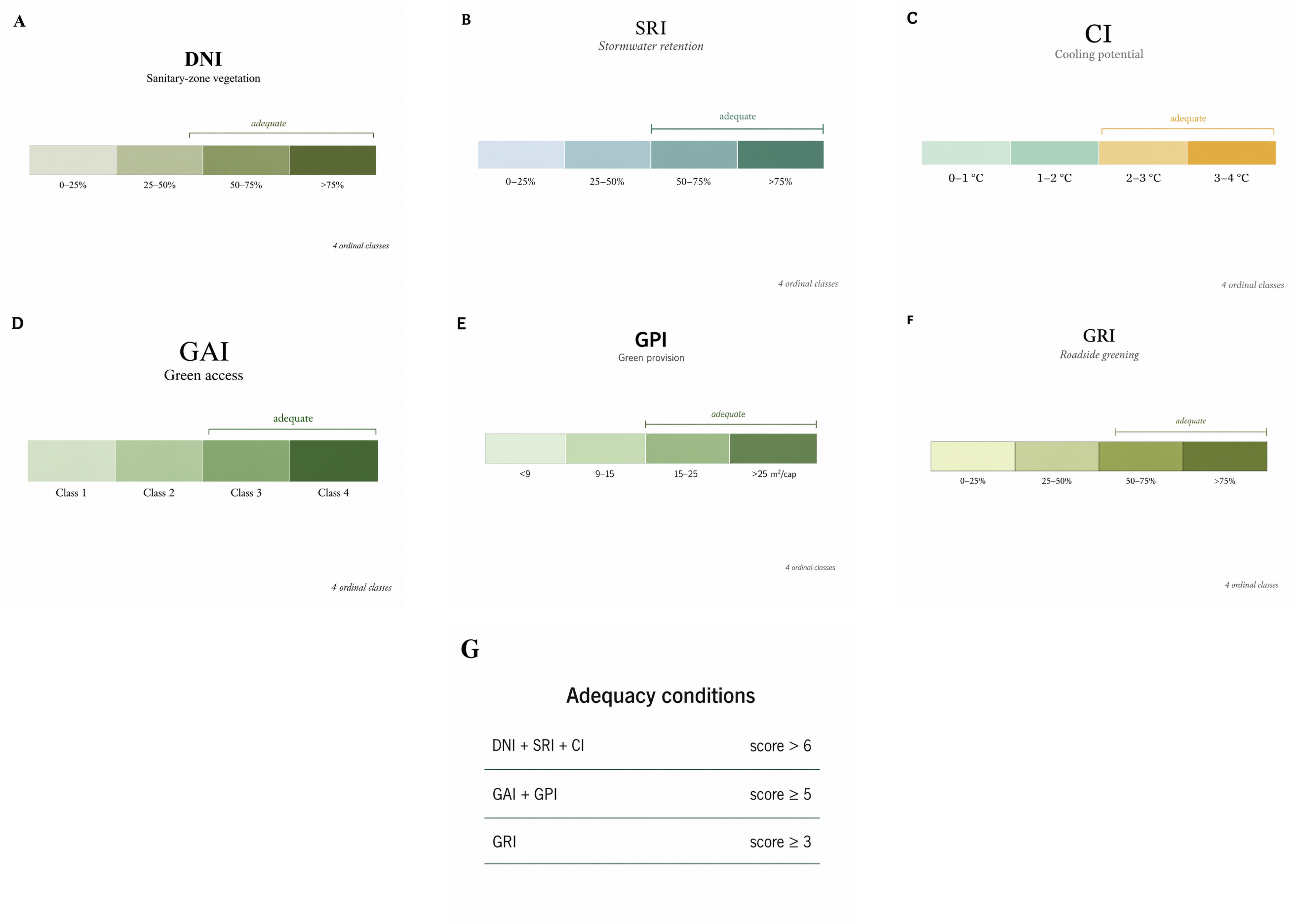

Figure 3. Indicator thresholds and adequacy conditions.

The adequacy gates are deliberately service-specific. A unit can be adequate for roadside greening without being adequate for the combined regulating-service sum, and a quarter can satisfy cultural access and provision without implying strong cooling or runoff regulation. This separation is essential for interpreting later service contrasts.

2.3. Area-population sufficiency calculations

Let s denote a spatial representation, such as districts, quarters, or grid cells. Let A_s be the percentage of area satisfying the adequacy condition and let P_s be the percentage of population satisfying the same condition. Area shortfall is calculated as

$$S_s^A = 100 - A_s, \tag{1}$$

and population shortfall is calculated as

$$S_s^P = 100 - P_s. \tag{2}$$

These values measure how much of the city area and how much of the population remain outside the adequacy condition. They are not deficit magnitudes in the biophysical sense; rather, they indicate the percentage share not meeting the selected ordinal threshold.

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The relation between adequate area and adequate population is expressed through an resident-alignment term:

$$E_s = P_s - A_s. \tag{3}$$

A negative value means that adequate locations contain a smaller share of the population than their area share. A positive value means that adequate locations contain a larger population share than their area share. Values close to zero indicate that adequacy is approximately proportional to population distribution, although they do not imply perfect spatial equity within each unit.

Scale-disaggregation gains are calculated by comparing a coarser representation c with a finer representation f:

$$G^A_{f-c} = A_f - A_c, \tag{4}$$

$$G^P_{f-c} = P_f - P_c. \tag{5}$$

Area gain identifies whether finer units reveal additional adequate land. Population gain identifies whether that additional adequate land corresponds to additional residents. A large area gain with little population gain implies that fine-scale adequacy is weakly aligned with residential exposure. A large gain in both area and population implies that the coarser unit had masked inhabited adequate locations.

Low-score load is used to describe the proportion of area in weak ordinal classes. If $d_{s,k}$ is the percentage of area in class k, low-score load is defined as

$$L_s q = {}_{k\leq q}\, d_{s,k}, \tag{6}$$

where q is selected according to the service block. For regulating services, the minimum summed score class is interpreted as the most severe class because the observed RES sum begins at 3. For GAI+GPI, classes 2–3 represent low cultural sufficiency. For GRI, classes 1–2 represent inadequate road-edge vegetation. The adequacy threshold for RES is a summed score greater than 6, which is more than half of the maximum possible RES score of 12. The adequacy threshold for GAI+GPI is a summed score of at least 5. The adequacy threshold for GRI is a score of at least 3.

2.4. Spatial-unit comparisons

The algorithm starts with deriving quantities based on the indicator distributions: sufficiency, alignment, and scale gain. Comparisons are made for two spatial units per service block. In the case of regulating services, DNI, SRI, and CI are calculated for districts and grids, as they are available at both levels. The choice of comparison for GAI+GPI follows from the fact that residential green access and provisioning are most directly quantified at the quarter level. Roadside greening (GRI), being a function of road boundary vegetation cover, is available at the two spatial units, but is represented most reliably at the district level.

There is no stochastic imputation. Numerical calculations proceed based on the tabulated percentages of indicator categories, without any uncertainty propagation or simulation of the underlying processes. The methodology is conservative because it assumes neither household-level exposure nor monetary valuation of ecosystem services, and makes no assumption regarding linearity of ordinal indicator classes. Class 4 is not necessarily twice class 2 in the indicator system. Rather, sufficiency is determined by the condition passed and the number of people in the spatial unit that passes it.

3. Results

3.1. Regulating services

Evidence on regulating services demonstrates that green infrastructure in Moscow has sufficient localized service capacity, but insufficient sufficiency for the city's residents. In terms of emissions, motor transport is the main source of air pollution in Moscow; its total contribution is 345,000 tons, including mostly carbon monoxide, nitrogen

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oxides, hydrocarbons, and particulates. The sanitary areas taken into consideration for estimating DNI occupy 158.6 km^2, or 15.4% of city territory, with district coverage ranging from 17.1% to 36.2%. The area covered by canopy taller than 1.1 meters in these sanitary zones is estimated at 26.8 km^2. District DNI estimates range from 2.6% to 44.5%, with no district reaching classes 3 and 4; however, at the grid-cell level, scores range from 0 to 100% [17].

Stormwater regulation is characterized by similar spatial inequalities. While the overall stormwater retention capacity of greenery in Moscow reaches 17.6 m km^{-2}, its district estimates vary significantly, from 3.1 to 87.3 m km^{-2}. The indicator's minimum and maximum at the district level are 2.2% and 58.4%, respectively, or 3 in score terms, whereas the grid estimate reaches 80%, or 4 in score terms. It is also found to correlate with the fraction of tree vegetation at the district level, with $R^2 = 0.91$ for linear regression, and with the fraction of impervious surfaces, with $R^2 = 0.67$ for exponential regression. The relationship reflects the fundamental physics of rainwater runoff, namely that impervious surfaces facilitate runoff, while tree vegetation provides retention and infiltration capabilities [16, 34].

Cooling capacity shows yet another pattern. On the basis of heat-wave conditions used in the Moscow assessment, total potential cooling of urban greenery reaches up to 4°C and averages 1.43 ± 0.77°C. District cooling potential in the centre and in some outlying districts falls below 1°C. Other districts exhibit values in the range of $1-2$°C. High scores are observed on the edge of large parks and urban forests. Cooling capacity at grid resolution attains maximums of 3.5°C and exhibits clustering. This result is consistent with earlier findings that urban green cooling depends not only on the quantity of vegetation but also on its patch size, arrangement, background vegetation, and air movement [36, 37].

Summing the regulating indicators produces estimates from 3 to 7 at the district scale and from 3 to 11 at the grid scale. At grid resolution, the range is wider, implying that there are both very poorly supplied cells and fairly well-supplied ones. Nevertheless, the proportion of adequate area is small. Only 12.0% and 19.2% of district and grid areas, respectively, achieve scores above 6, as do 11.3% and 11.7% of the total population. Additional adequacy at grid resolution thus implies poor alignment with the residence density. Hence, while regulating-service sufficiency is not simply an artifact of district averaging, it remains a problem of insufficient exposure of the population to the available high-sufficiency ecosystems. The implication of this observation for heating and air-pollution mitigation is particularly important because people who benefit from cooling, shading, and runoff moderation usually live on highly impermeable and/or highly trafficked surfaces. High-sufficiency forest and park plots contribute to the green infrastructure in the entire city, but not necessarily to nearby residences, roads, and pavement surfaces.

3.2. Residential green access and provision

Cultural services provide a fundamentally different spatial pattern. The GAI indicator measures access to diverse types of urban green recreational areas. People in the central districts of Moscow do not lack access to green spaces in principle. Large parks can be reached by public transportation, while many small squares are walkable. However, accessibility differs locally. About 2.7 million, or 22%, of the population does not have easy access to squares and boulevards, being situated in districts lacking a sufficient number of these spaces within two-minute walking distance. The number of such districts amounts to 28, mainly located in the northern and southern outskirts of Moscow. Almost 7.8 million people lack walking access to district parks within a 15-minute radius, but 99.6% of city dwellers are able to reach large parks within a 20-minute ride via public transport [17].

The significance of the spatial unit for interpreting the results is demonstrated here. GAI maximum value at the district level equals 3, while it can reach 4, with an average value of 1.8 ± 0.68 for quarter estimates. This standard deviation is much greater than the district values (standard deviation = 0.39). The difference reflects the fact that residential proximity to greenery is not determined by the district average but by the immediate surroundings. Daily cultural services depend not only on the presence of green spaces in a district, but also on their proximity to residential houses, the type of transportation, and their safety [3, 5, 20, 21].

Finally, residential green provision in quarters (GPI) illustrates the importance of spatial unit selection once again. The greenery available to residents of districts in terms of trees, shrubs, and lawns is estimated at 36.6 m^2 per capita in the best cases, while the district-level average is 12.8 m^2. Sixteen districts fail to meet the minimum of 9 m^2/capita. In terms of city-wide GPI, the mean becomes 49.5 m^2/capita, while 115 out of 118 districts have GPI > 9 m^2/capita, and 68 out of 118 – GPI > 25 m^2/capita. Such disparity highlights the need to account for the residential quarter rather than to consider city-wide estimates.

Quarter-wise GPI, however, produces an even stronger imbalance. The quarter-level mean GPI estimate is 71.3 m^2/capita, but the median is 11.3 m^2/capita. This shows that quarter-level GPI distribution is positively skewed, with mean GPI values driven by few quarters having large GPI values and/or small residential populations. In addition, 121 out of 2559 quarters exhibit GPI values below 1 m^2/capita because they do not have any greenery in them. There is very weak spatial clustering in the GPI distribution (I = 0.06), although the latter is statistically significant. Thus, residential green provision shows great local variability and cannot be reliably determined based on neighbouring districts or city-level estimates.

Combining the indicators into GAI+GPI produces the following estimates. GAI+GPI varies from 2 to 6 at the district scale and from 2 to 8 at the quarter scale. Adequacy area increases from 37.5% to 48.4%, and adequacy population – from 32.7% to 38.3%. Therefore, at the quarter level, there is more green land and more inhabitants in such land. Still, even at the quarter level, more than 60% of the population fails to receive sufficient green spaces. Such result has two implications. First, large parks and forest parks in Moscow cannot be considered a sufficient provision of local green spaces. Second, the quarter unit must be employed to identify local provision insufficiencies.

3.3. Roadside vegetation

Among the three ecosystem service blocks, roadside greening is the one that shows the greatest scale sensitivity. Moscow has 127.3 km^2 of road surfaces, half of which were chosen to calculate GRI and DNI. At district scale, the average road area equals 1.1 km^2/district. At least 22 out of 118 districts (those with GRI score $\geqslant$3) are characterized by landscaped road-boundary zone exceeding 50%. By contrast, 14 central districts (where impervious-surface shares are above 55%) show very poor roadside greening scores: GRI < 25%, or 1 in score terms. GRI at the district level is negatively and moderately correlated with impervious-surface fraction, with $R^2 = 0.4$ and $p < 0.05$ [17].

District-wise distribution of GRI indicator is characterized by dominance of its lowest classes: 13.7% district area corresponds to class 1, 68.6% – to class 2, 17.3% – to class 3, and 0.4% – to class 4. Combining the classes producing satisfactory GRI, we obtain adequate area share of 17.7%. At grid resolution, the proportion of class 1 decreases to 33.4%, while the proportions of classes 2, 3, and 4 increase to 29.4%, 15.5%, and 21.7%, respectively. Consequently, the proportion of adequate area becomes 37.2%. The population adequacy grows similarly: from 18.7% at the district scale to 34.2% at the grid level.

While the previous results concerned regulating services, wherein increasing adequacy area did not translate into adequacy population, roadside vegetation has the opposite property. District-level averages mask both the poorly greened road corridors in the centre and adequately vegetated road sections at finer resolution. Given that roadside vegetation can help remove pollutants, mitigate noise and heat, and intercept storm water, GRI should be evaluated not solely as a cultural amenity. Rather, it is a street-specific condition with multiple co-benefits [33–35]. Low roadside greening adequacy at the district scale and its marked growth at the grid scale imply that the city-scale greening efforts must target specific streets instead of relying on district averages. The continuity of street greening may be more relevant than its total value within districts since pedestrians, cyclists, public transportation passengers, and residents experience roadside vegetation in linear form. It is possible for a district to feature good road greening but still leave important road edges ungreened.

In summary, the results on sufficiency and alignment are presented in Figure 4. Regulating-services area improves under grid representation, but the population value remains unchanged. By contrast, roadside greening gains both adequate area and adequate population at the grid resolution.

Comparing the two sets of values demonstrates that area adequacy and resident adequacy should not be considered substitutes. On the one hand, the regulating-service grid contributes positively to land adequacy (by 7.2 percentage

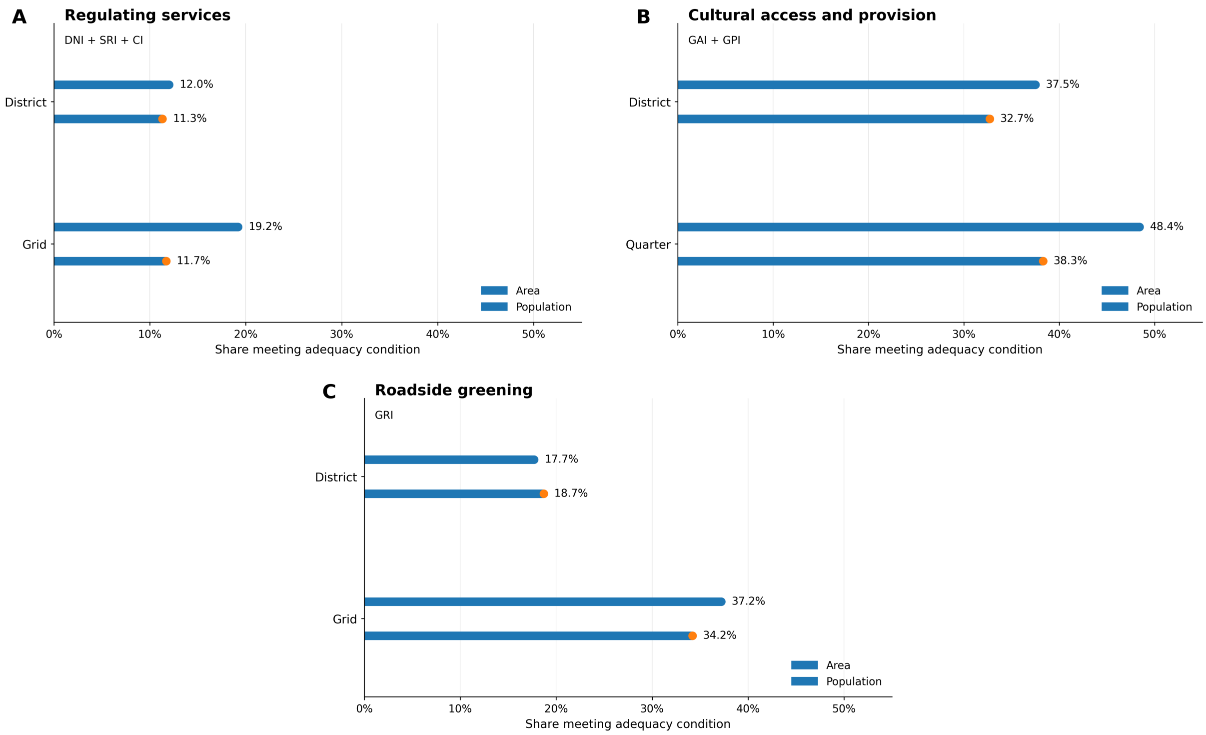

Figure 4. Adequate area and resident shares.

points), but does nothing to raise resident adequacy (contributes 0.4 percentage points). Thus, high-service surfaces are poorly situated with respect to residential exposure. On the other hand, roadside greening tends to exhibit the opposite behavior: many cells that are adequate according to the grid metric are inhabited corridors.

3.4. Area and resident adequacy

Ordinal distributions are summarized in Table 2. As can be seen from these distributions, the regulating-service scores tend to cluster in the low-intermediate classes, although they cover the whole interval. District scores are concentrated in classes 3–5: thus, 21.6%, 45.5%, and 20.9% of the district area belong to these classes; in total, 88.0% of the district area does not have an adequate score. Grid scores range further down into class 8 and up to class 11, while class 3 itself becomes more pronounced. Importantly, presence of pockets having high-service levels does not affect the population sufficiency measure significantly.

In the case of GAI+GPI, the transition from district representation to quarters leads to a significant redistribution of land in score space from the fourth class into the classes 2–8. The latter contain more score 1 land, compared to the former, but at the same time contain higher scores. As mentioned earlier, such property is a hallmark of disaggregation in the sense that both inadequacy and adequacy can become apparent on smaller maps. Finally, for GRI, grid representation increases the score 4 share but also increases the score 1 share.

The distribution table explains why the adequacy values differ by service. Regulating services remain concentrated below the threshold, cultural provision shifts toward a wider quarter-level range, and road greening becomes more polarized as the unit becomes smaller. The result is not a uniform increase with finer spatial support; it is a more exact description of where adequacy and deficiency coexist.

The score distributions in Table 2 are visualized in Figure 5. The panels reveal why the adequacy percentages should not be read as simple greenness totals: each service block has a different distributional shape and a different sensitivity to spatial representation.

The distribution panels make the ordinal nature of the evidence visible. Higher score classes appear under finer supports, but low classes also expand in several cases. This pattern supports a cautious interpretation: disaggregation improves spatial specificity rather than automatically improving the apparent service condition.

Table 2. Score distributions and adequacy shares.

Service block	Spatial unit	Score-class area distribution (%)	Adequate area (%)	Adequate population (%)
Regulating services, summed	District	3: 21.6; 4: 45.5; 5: 20.9; 6: 5.7; 7: 6.3	12.0	11.3
Regulating services, summed	Grid	3: 23.5; 4: 36.0; 5: 21.3; 6: 9.0; 7: 5.1; 8: 1.4; 9: 0.9; 10: 1.8; 11: 1.0	19.2	11.7
GAI+GPI	District	2: 1.6; 3: 7.6; 4: 53.3; 5: 30.1; 6: 7.4	37.5	32.7
GAI+GPI	Quarter	2: 5.4; 3: 17.1; 4: 29.0; 5: 29.8; 6: 14.4; 7: 3.9; 8: 0.3	48.4	38.3
Green-road indicator	District	1: 13.7; 2: 68.6; 3: 17.3; 4: 0.4	17.7	18.7
Green-road indicator	Grid	1: 33.4; 2: 29.4; 3: 15.5; 4: 21.7	37.2	34.2

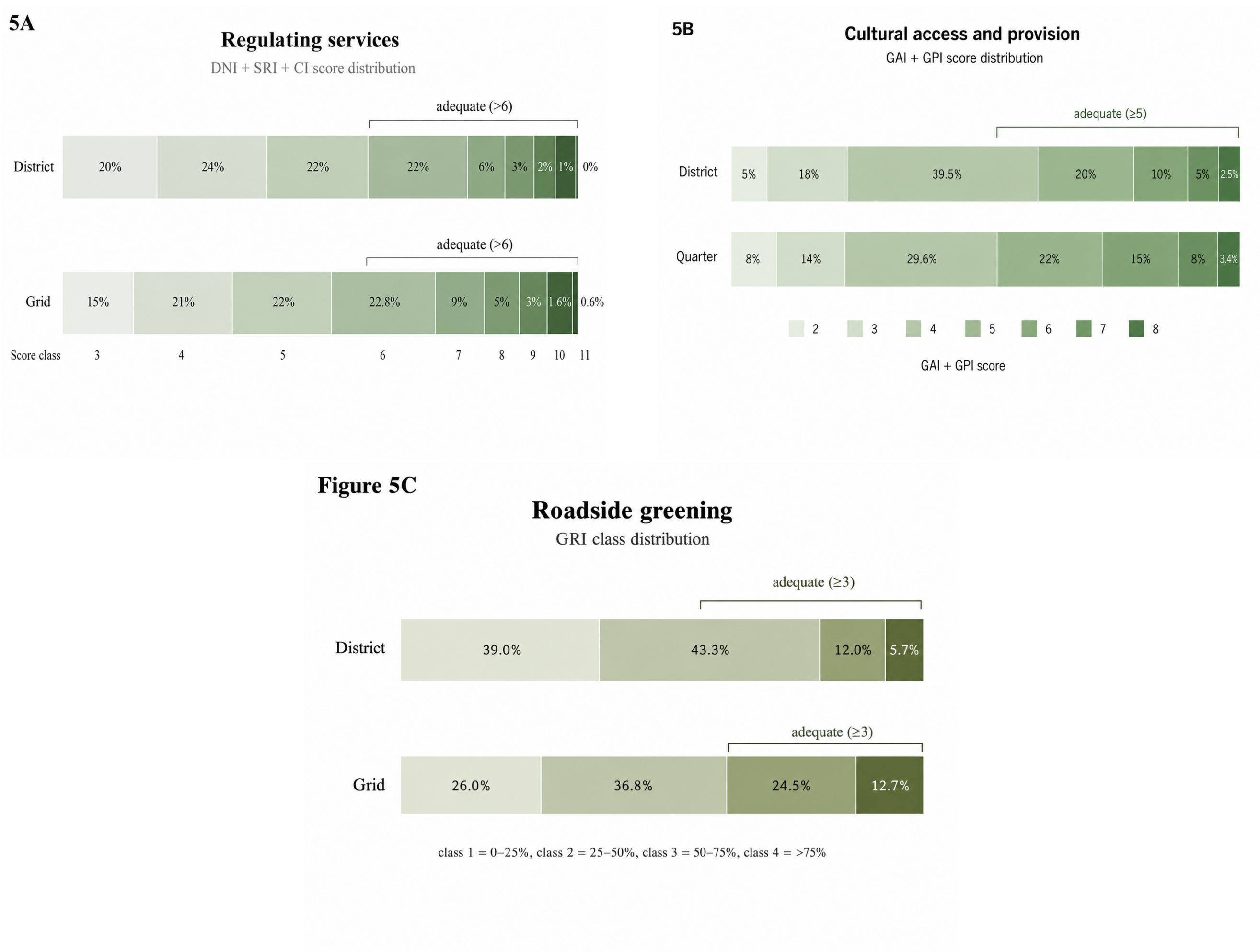

Figure 5. Service score distributions.

3.5. Scale and resident alignment

As shown in the tables above, the limiting services are the regulating services, which face deficits of 88.0% in area and 88.7% in population at the district scale and 80.8% in area and 88.3% in population at the grid scale. The resident alignment shifts from –0.7 to –7.5, which shows that the new adequate area identified through the grid scale is less populated than the mean population. Practically, this means that the increase in the measurement scale allows the recognition of adequate services but not adequately served residents.

In the case of cultural access and residential provision, a somewhat similar trend is observed. Shortfalls of 62.5% in area and 67.3% in population are registered at the district scale while they drop to 51.6% in area and 61.7% in population at the quarter scale. Notably, however, the resident-alignment factor is negative at the latter and drops from –4.8 to –10.1 percentage points, which means that although quarter-scale measurement identifies greater shares of adequate population and areas, the adequate areas are underrepresented in terms of their populations.

An entirely different dynamic is seen for roadside greening. While the shortfall measures are high – 82.3% in area and 81.3% in population at the district scale, they decrease to 62.8% in area and 65.8% in population at the grid scale. Also, the resident alignment shifts from 1.0 to –3.0. Importantly, the extent of the gain achieved when applying the new scale is considerable, which indicates a high sensitivity to the unit used in the measurements.

Table 3. Shortfall and resident alignment.

Service block	Spatial unit	Area shortfall (%)	Population shortfall (%)	Resident alignment (percentage points)
Regulating services	District	88.0	88.7	-0.7
Regulating services	Grid	80.8	88.3	-7.5
GAI+GPI	District	62.5	67.3	-4.8
GAI+GPI	Quarter	51.6	61.7	-10.1
Green-road indicator	District	82.3	81.3	1.0
Green-road indicator	Grid	62.8	65.8	-3.0

The shortage table reveals that resident reach is the strongest deficiency of the regulating-service category. Lowering area shortages at grid scale does not eliminate the population shortages, as the surplus cells are not placed in regions where there are many people. Resident-alignment can thus be considered a succinct metric for determining if the adequate areas also matter socially.

The values in Table 4 represent gains made in terms of areas versus population. The regulating-services category achieves gains of 7.2 and 0.4 percentage points of adequate area and population respectively, transitioning from districts to grid cells. GAI+GPI achieves gains of 10.9 and 5.6 percentage points of adequate area and population respectively, transitioning from districts to quarters. Lastly, GRI attains gains of 19.5 and 15.5 percentage points of adequate area and population respectively, transitioning from districts to grid cells. It should be noted that the most scale-sensitive service is roadside greening while the most population-misaligned service is regulating services.

Table 4. Scale gains between spatial supports.

Service block	Scale comparison	Area gain (percentage points)	Population gain (percentage points)	Interpretation
Regulating services	District to grid	7.2	0.4	Additional adequate grid cells are weakly aligned with resident population.
GAI+GPI	District to quarter	10.9	5.6	Quarter detail reveals meaningful residential variation but adequacy remains limited for most residents.
Green-road indicator	District to grid	19.5	15.5	Roadside greening is strongly affected by spatial aggregation and benefits from fine-scale diagnosis.

The corresponding panel in Figure 6 presents the same disaggregation gains graphically. The figure clarifies the contrast between a physical area gain and a resident gain: regulating services add adequate land but almost no additional adequate population, while GRI gains are large for both quantities.

These gain panels emphasize the numerical contrast between cartographic improvement and resident improvement. The almost-flat population response to regulating services stands out as the most decisive diagnostic feature since it confirms the inadequacy of spatial detail alone in dealing with the service-population problem.

Low-score load reinforces this interpretation. For GRI, classes 1–2 cover 82.3% of the district area but 62.8% of the grid area, indicating the widespread nature of roadside vegetation deficiency despite the grid improvement. For GAI+GPI, classes 2–3 cover 9.2% of the district area but 22.5% of the quarter area, suggesting that quarter-level

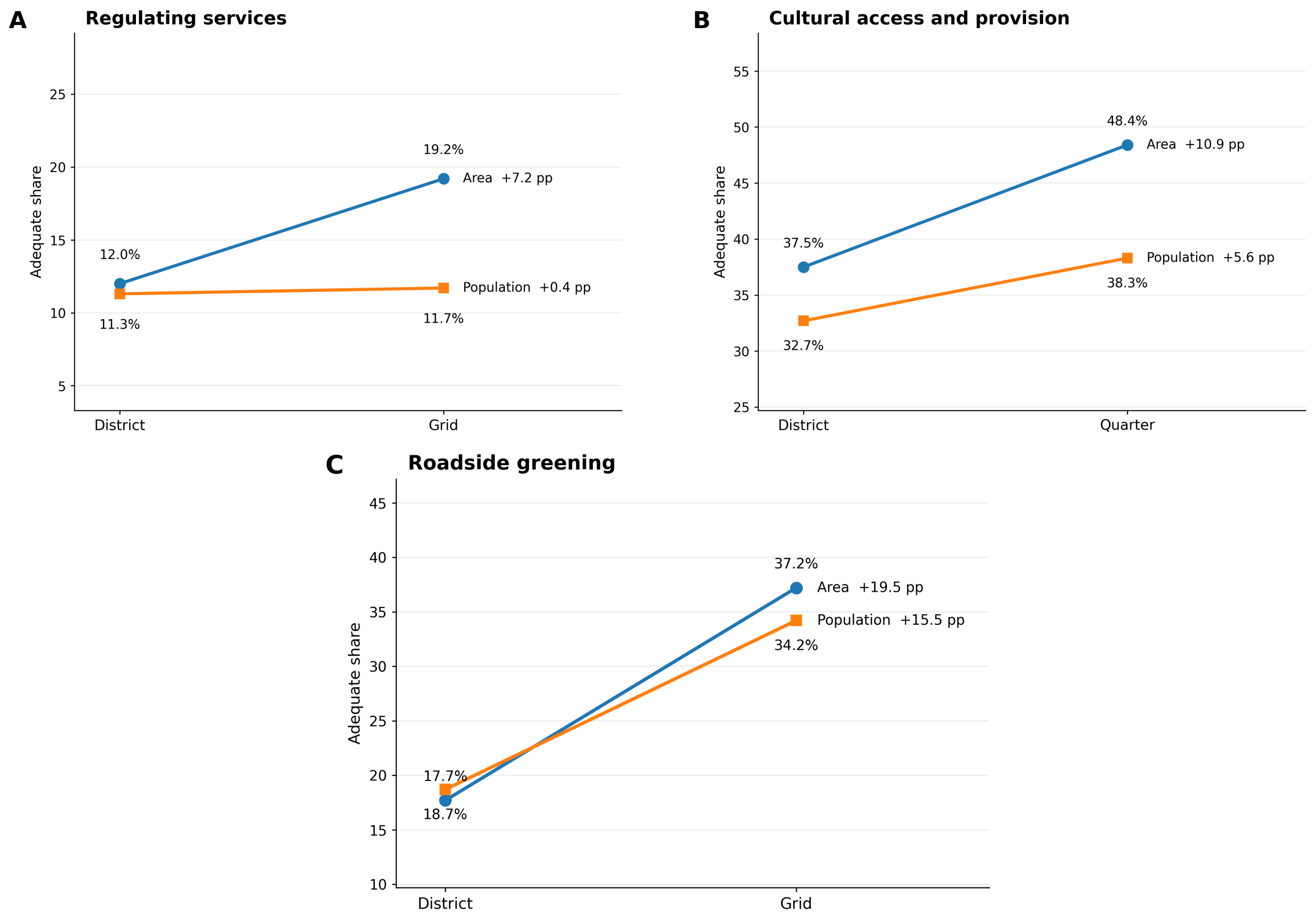

Figure 6. Scale-related adequacy gains.

analysis uncovers pockets of poorly supplied residents. For RES, the minimal-sum class covers 21.6% of the district area and 23.5% of the grid area, with the majority of area falling into intermediate classes that still fail the adequacy condition. Thus, Moscow is not merely divided between green and non-green areas; it features extensive intermediate zones with inadequate service supply.

4. Discussion

4.1. Green stock and resident reach

The key finding is that the presence of extensive green infrastructure in Moscow does not necessarily mean sufficiency of ecosystem services for the population. The city is justified in claiming its abundance of greenery, yet the sufficiency diagnostic procedure reveals poor sufficiency levels for regulating services in particular, with just one ninth of residents enjoying these benefits. In other words, the green-stock approach and the sufficiency approach offer two very different conclusions. While the former focuses on quantity and coverage, the latter highlights whether the condition is reached at the residents' locations and the areas where environmental pressures concentrate.

The contrast is especially clear for regulating services. Grid-scale analysis detects more adequate regulating-service area than district analysis, yet adequate population hardly changes. It means that some highly functional green areas make considerable contributions to the urban ecological system, yet fail to provide services to residents who are most exposed to environmental pressures. Large forest parks, vegetated zones near urban edges, and green cells with few occupants are capable of producing cooling, runoff moderation, and air purification, but they may lack proximity to densely populated sealed neighbourhoods. It does not imply that the aforementioned green areas are inadequate per se; it means that reliance on such areas is a poor indicator of sufficient ecosystem services in the entire city.

Cultural services display another kind of mismatch. Quarter-scale analysis helps in detecting a higher level of adequacy compared to districts thanks to better representation of residential exposure, yet the majority of the population still fails to meet the adequacy condition. This result corresponds to the distinction between availability to green amenities and proximity to small green spaces, residential courtyards, and district parks. Inability of residents to visit large parks regularly is not alleviated by the fact that all of them can travel to such parks through public transportation means [14, 26].

Roadside greening is an intermediate category in terms of spatial scale. As with the preceding categories, the grid reveals more adequate GRI area and population than the district. Yet the difference in population is especially notable, confirming that a finer grid uncovers many areas with local greening benefits. Roadside greening is local and strongly scale-sensitive, as well as associated with multiple environmental pressures. Improving vegetation along roadsides can have multiple positive effects, provided that local species selection, maintenance, sightline issues, traffic concerns, soil volume, and pollution-trapping capacity in street canyons are adequately addressed [33, 35].

4.2. Scale selection and planning interpretation

The current results show that scale has distinct impacts on the interpretations of various services. In the case of regulating services, a finer grid reveals more adequate service area without increasing adequate population. It is a typical population misalignment problem. For cultural service access and residence, a quarter-scale map reveals more adequate service coverage and also discovers many more low-score pockets. This is a residential heterogeneity issue. Finally, roadside greening receives a considerable boost on the grid level with regard to both adequate area and adequate population. In this case, we face a hidden local adequacy problem. Ignoring this heterogeneity could blur the important implications of scale.

It is natural to think of administrative districts as basic urban units since they align with governance, budgetary decisions, public reporting, and strategic comparison. However, the level of aggregation inherent in districts is too coarse to accurately represent various services. A district featuring large parks within it and highly sealed residential blocks may still receive an intermediate score despite its population receiving negligible benefits. While district scores can be useful for strategic comparisons, they are less effective in identifying specific interventions. It is essential to use fine-grained maps whenever designing specific interventions and planting projects.

Still, finer grids are not inherently superior to other options. A grid serves as a technical tool for measurement, not a lived urban entity. The outcomes generated by grid cells depend on their sizes, alignments, and service footprints. A grid cell can capture roadside greening and locally oriented temperature patterns, but it cannot account for park access or residential greenspace use. On the contrary, quarters are more socially significant for assessing green infrastructure availability. Yet quarters may not reflect process-based services like cooling or runoff reduction since they extend beyond residential areas. The proper interpretation is service-specific; one should choose the optimal spatial unit depending on ecological process and exposure pathway.

This approach corresponds to the broader discussions on ecosystem-service mapping. Various tools and indicators are appropriate under different circumstances depending on their purpose and empirical inputs. Green infrastructure indices based on land cover, accessibility, and process-based modeling have complementary functions for urban planning [5, 22, 24]. While the creation of a citywide green infrastructure index is useful for producing a comprehensive planning signal, the diagnosis of insufficiencies and resident reach requires a more disaggregated approach. The current ordinal diagnostic method maintains this differentiation by refusing to translate each ecosystem service into a single continuous metric.

The corresponding panel in Figure 7 translates numerical findings into three planning requirements. Improvements in regulating services will require a closer alignment between high-service vegetation and urban development. Improvements in cultural service access will necessitate a focus on local residential heterogeneity. Improvements in roadside greening will call for patchwork greening of discontinuous streetscapes.

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Figure 7. Planning limitations indicated by resident adequacy.

These insights are reflected in the planning priorities. The improvement of regulating services should be focused on populated sealed environments, quarter-level actions should be focused on residential everyday provision, and road-edge actions should focus on discontinuities in corridor greenspaces rather than only the overall greening.

4.3. Priorities for Moscow green-infrastructure management

The first priority that emerges is the need to emphasize regulating-service improvement at the level of populated sealed environments, rather than simply focusing on green-area preservation. In central and eastern parts of the city, there is limited potential for regulating service improvement, due to a combination of high imperviousness levels and lack of roadside vegetation in densely built-up areas. In these environments, new or improved green infrastructures should be assessed based on their ability to modify local environmental conditions, rather than just contribute to the total amount of green spaces in a district.

For stormwater management, this implies the need to prioritize soil de-sealing, tree pit enlargement, rain gardens, vegetated swales, and other types of permeable surfaces that will help to reduce runoff production in populated sealed areas. The analysis confirms that SRI is strongly related to the share of tree-vegetation and impervious surface in each grid cell. Thus, stormwater interventions in Moscow should not be spread randomly; they should take place precisely where high marginal runoff risk is generated in conjunction with opportunities for improving permeability [16, 30, 34].

The second priority concerns urban cooling. Though large parks are important, they are insufficient. Large green areas are indeed associated with positive cooling effects in Moscow, but central districts with insufficient local cooling cannot rely on cooling produced by remote large green areas. Local cooling is needed, through green pockets, street trees, courtyards, green roofs, and shaded walkways that will help to decrease heat exposure of local residents. The cooling threshold, used in this study, is partly model-dependent and refers to heat wave conditions; however, the idea of insufficiency remains robust from a practical perspective [11, 37].

For cultural access and residential provision of green space, quarter-level targeting is essential. The presence of 121 quarters with less than 1 m^2 of identified green infrastructure per capita implies severe local deficiency despite the availability of apparently sufficient district-level resources. Targeted interventions can involve the redesigning of courtyards, pocket parks, school yards and institutional green spaces, as well as creation of safe pedestrian access routes to green areas. The goal is not just achieving a certain per capita value for the green area, but creating sufficient green access that meets the needs of various age categories and is considered acceptable for use in terms of quality and safety [3, 21, 28].

Finally, regarding the greening of road networks, a great deal of gain is possible for Moscow via a street-by-street improvement strategy. In those districts with a particularly low average GRI, substantial increase in the amount of road-side vegetation is needed, while in districts with moderate GRI values, the coverage should be increased. Boulevards and green corridors can help achieve this, but their usefulness depends on location relative to the pedestrians' routes, residential neighborhoods, and emission-producing traffic flows. The cross-service benefits of greenery, such as reduction of dust and noise and moderation of heat in addition to interception of runoff, justify the treatment of GRI as a cross-service indicator, not just as an indicator of aesthetics [34, 35].

4.4. Analytical limits

Population-weighted ordinal diagnosis is easy to interpret as all calculations can be mapped back to score distributions and adequacy shares. Also, the method is conservative as it does not rely on any assumption about equality of interval between the ordinal classes and the assumption about the existence of households' exposure. The added value of the method is in allowing the separation of physical adequacy and population adequacy. These advantages are especially helpful when no spatial layers are available, only service-class tables can be found for a particular indicator.

In turn, the limits of the method are fairly obvious. First of all, the method does not identify the exact district, quarter, grid cell, street, or cadastral parcel where investments are needed, except for the situation where an available spatial layer provides information at a sufficiently fine resolution. Also, the ordinal diagnosis does not imply any assessment of the costs of intervention, land ownership issues, underground utilities, soil volumes, feasibility of plantings, plant species, maintenance capability, public reaction, etc. Finally, the method adopts an adequacy threshold taken from the original Moscow assessment, while different national standards, health-based adequacy thresholds, or local norms can lead to a shift of the threshold values, but without affecting the logic of separating area and population components of adequacy.

However, there is an additional limitation concerning the indicator assumptions made in the study. The cooling and stormwater indicators are based on extreme-case models that include the removal of green infrastructure and simulations of heat waves and precipitation events. While these assumptions allow stress-testing the performance of the indicator, they overstate green infrastructure supply under ordinary weather conditions. The CI indicator score relies on cooling increment, measured at one-degree increments. This assumption, while quite transparent, is also somewhat judgemental. The same applies to the GAI indicator, which includes assumptions about accessibility: the idea that people accept a certain green-space size as sufficiently accessible at a certain distance [7, 17, 36]. The population-weighted sufficiency diagnosis does not resolve these problems, but it helps to understand their implications for the interpretation of area and population components.

Finally, the population part is also an approximation. Adequacy shares show what part of the population lives in adequately provided spatial units; however, they say nothing about individual behavior, about travel patterns, or about workplace proximity and quality of green space near homes. It is particularly important for Moscow, where heat risk and vulnerability to the effects of climate change have proven to be heterogeneous. Future research should build links between the presented population-based analysis and existing information about household vulnerability and exposure to heat, local air pollution measurements, as well as survey data on pedestrians' mobility patterns. At the same time, the approach should continue relying on the same caution in interpreting service classes.

The summary of the service-based interpretation is shown in Figure 8. These are the most succinct numerical results showing the answer to the question posed: there is sufficient green capacity in the city; however, none of the three service blocks achieve resident adequacy.

Figure 8. Population-weighted UGI sufficiency summary.

5. Conclusions

The main research objective was whether Moscow's vast quantity of urban greens produces adequate regulating, cultural, and roadside conditions among resident populations across the districts, quarters, and grids. It turns out that while green capacity in Moscow is indeed great, resident sufficiency is lacking. The clearest evidence of this is the regulating-service block. While disaggregation from district to grid increases adequate area from 12.0% to 19.2%, adequate population remains unchanged at 11.3% to 11.7%. Additional adequately greened space discovered when using the grid representation is apparently not found where it adds significantly to resident coverage. In terms of heat regulation, runoff management, dust reduction, noise buffering, and visual screening, the fundamental problem is one of spatial mismatch between service-production vegetation and urban population.

The cultural access and residential green provision case differs. The quarter-level representation is superior to the district average since access to urban green and residential green area are experienced in the immediate surroundings of the home. Adequate GAI + GPI area rises from 37.5% to 48.4%, while adequate population rises from 32.7% to 38.3%. Thus, while the quarter-level diagnosis does reveal differences among districts regarding the real-life situation of residents, the fact is that the majority of them fall outside the adequate condition. Major parkland contributions help the city maintain its green capacity, but not overcome resident green deficits.

The roadside greening service block turns out to be the most sensitive one to the finer scale representation used. Grid-representation analysis reveals increases in adequately GRI-covered area from 17.7% to 37.2% and adequate population from 18.7% to 34.2%. This indicates that green roadsides are poorly served by a district-average approach and should be diagnosed at a finer scale, such as corridors or grids. Consequently, the adequate solution to green road edge vegetation is not to set one goal for the entire city but three – improving regulating vegetation in populated sealed traffic areas, residential quarter greens, and greening along roads.

Urban greens infrastructure assessment can benefit from measuring adequate area, adequate population, and scale sensitivity. One measure cannot convey what level of services are available and which of them can be considered adequate to the urban populations. For Moscow, the population-scaled ordinal assessment makes clear that greenness and greenness sufficiency are related but not identical concepts. Thus, in the decision-making process, the specific service provision must be identified in specific environments where particular resident populations are underrepresented.

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