IRSTI 47.49.27 https://doi.org/10.26577/JGEM81220265

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SPATIAL HETEROGENEITY OF GREENNESS IN ALMATY ACROSS DISTRICTS: COMPARING TOTAL AND ROAD-PROXIMATE URBAN GREENNESS (M²/PERSON) USING A SUMMER 2025 NDVI COMPOSITE

The aim of this study is to quantify the spatial heterogeneity of greenness in Almaty across eight administrative districts and to compare total greenness (within administrative boundaries) with road-proximate urban greenness constrained to the road-buffer-defined urban proxy, using area- and per-capita indicators (m²/person). The methodology is based on Sentinel-2 L2A data (Copernicus Browser) and a summer NDVI composite for June–August 2025 constructed as the pixel-wise median of eight low-cloud scenes. Greenness was mapped using NDVI thresholding (primary threshold NDVI > 0.30; sensitivity analysis for NDVI > 0.25 and NDVI > 0.35). Road-proximate urban greenness was operationalized as green pixels located within a 500-m buffer around the street network (QuickOSM), followed by district-level zonal statistics in QGIS; per-capita values (m²/person) were computed using official population statistics as of 1 July 2025 (Bureau of National Statistics). The originality and value of the study lie in a reproducible separation of "territorial" versus "urban-fabric" greenness for a city whose administrative extent includes large natural landscapes, improving interpretability and reducing upward bias in district comparisons. Results show that for NDVI > 0.30, Almaty's total green area equals 591.45 km² (254.94 m²/person), whereas road-proximate urban greenness equals 442.05 km² (190.54 m²/person), representing 74.7% of total greenness by area. At the district level, road-proximate urban greenness ranges from 49.24 m²/person (Almaly) to 476.39 m²/person (Medeu), a 9.67-fold disparity; the top three districts are Medeu, Nauryzbay, and Turksib, while the lowest values occur in Almaly, Auezov, and Zhetysu. District rankings are robust to the NDVI threshold choice (0.25/0.30/0.35).

Keywords: NDVI, Sentinel-2, road-proximate urban greenness, green space, Almaty, m²/person.

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Алматы қаласының аудандары бойынша көгалданудың кеңістіктік әртектілігі: 2025 жылғы жазғы NDVI-композит негізінде жалпы және жол желісіне жақын көгалдануды (м²/адам) салыстыру

Бұл зерттеудің мақсаты – Алматы қаласының сегіз әкімшілік ауданы бойынша жасыл жамылғының кеңістіктік әркелкілігін сандық тұрғыдан бағалау және аудандық шекаралар ішіндегі жалпы жасыл жамылғыны жол буфері арқылы анықталған қалалық прокси-аймақпен шектелген жол желісіне жақын қалалық жасыл жамылғымен салыстыру. Бағалау үшін аумақтық және жан басына шаққандағы көрсеткіштер (м²/адам) қолданылды. Зерттеу әдістемесі Sentinel-2 L2A деректеріне (Copernicus Browser) және 2025 жылғы маусым–тамыз айлары үшін бұлттылығы төмен сегіз спутниктік көріністің пиксельдік медианасы негізінде құрастырылған жазғы NDVI композитіне негізделді. Жасыл жамылғы NDVI шекті мәндері арқылы карталанды: негізгі шек ретінде NDVI > 0.30 алынды, ал сезімталдықты талдау үшін NDVI > 0.25 және NDVI > 0.35 мәндері қолданылды. Жол желісіне жақын қалалық жасыл жамылғы QuickOSM арқылы алынған көше желісінің айналасындағы 500 м буфер шегінде орналасқан жасыл пиксельдер ретінде анықталды. Одан кейін QGIS бағдарламасында аудандық деңгейде зоналық статистика есептелді, ал жан басына шаққандағы мәндер (м²/адам) 2025 жылғы 1 шілдедегі ресми халық саны деректері негізінде есептелді (Ұлттық статистика бюросы). Зерттеудің өзіндік ерекшелігі мен құндылығы әкімшілік аумағына ірі табиғи ландшафттар кіретін қала үшін «аумақтық» жақын» жасыл жамылғыны қайталанатын әдіс арқылы ажыратуында. Бұл нәтижелерді түсіндіруді жақсартып, аудандар арасындағы салыстыруларда көрсеткіштердің шамадан тыс жоғары бағалануын азайтады. Нәтижелер көрсеткендей, NDVI > 0.30 кезінде Алматы қаласының жалпы жасыл аумағы 591.45 км² құрайды (254.94 м²/адам), ал жол желісіне жақын қалалық жасыл жамылғы 442.05 км² құрайды (190.54 м²/адам), бұл жалпы жасыл аумақтың 74.7%-ына тең. Аудандық деңгейде жол желісіне жақын қалалық жасыл жамылғы 49.24 м²/адамнан (Алмалы) 476.39 м²/адамға дейін (Медеу) өзгеріп, айырмашылық 9.67 есені құрайды. Ең жоғары көрсеткіштер Медеу, Наурызбай және Түрксіб аудандарында байқалса, ең төмен мәндер Алмалы, Әуезов және Жетісу аудандарында тіркелді. Аудандардың рейтингі NDVI шекті мәндерінің таңдалуына қатысты тұрақты болып қалды (0.25/0.30/0.35).

Түйін сөздер: NDVI, Sentinel-2, жол желісіне жақын қалалық жасыл жамылғы, жасыл кеңістік, Алматы, м²/адам.

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Пространственная неоднородность озеленения Алматы в разрезе районов: сравнение общей и городской озелененности, прилегающей к дорожной сети (м²/чел.) по летнему NDVI-композиту 2025 года

Целью данного исследования является количественная оценка пространственной неоднородности озелененности Алматы по восьми административным районам, а также сравнение общей озелененности в пределах административных границ с городской озелененностью, прилегающей к дорожной сети и ограниченной городским прокси-пространством, определенным на основе дорожного буфера. Для оценки использовались площадные показатели и показатели на душу населения (м²/чел.). Методология исследования основана на данных Sentinel-2 L2A (Copernicus Browser) и летнем NDVI-композите за июнь–август 2025 года, построенном как пиксельная медиана восьми спутниковых сцен с низкой облачностью. Картирование озелененности выполнено методом пороговой классификации NDVI: в качестве основного порога использовано значение NDVI > 0.30, а для анализа чувствительности применены пороги NDVI > 0.25 и NDVI > 0.35. Городская озелененность, прилегающая к дорожной сети, была операционализирована как зеленые пиксели, расположенные в пределах 500-метрового буфера вокруг улично-дорожной сети, полученной с помощью QuickOSM. Далее в QGIS была рассчитана зональная статистика на уровне районов, а значения на душу населения (м²/чел.) определены с использованием официальных данных о численности населения по состоянию на 1 июля 2025 года (Бюро национальной статистики). Оригинальность и ценность исследования заключаются в воспроизводимом разделении «территориальной» и «городской» озелененности для города, административная территория которого включает крупные природные ландшафты. Такой подход повышает интерпретируемость результатов и снижает риск завышения показателей при сравнении районов. Результаты показали, что при NDVI > 0.30 общая площадь зеленых территорий Алматы составляет 591.45 км² (254.94 м²/чел.), тогда как городская озелененность, прилегающая к дорожной сети, составляет 442.05 км² (190.54 м²/чел.), что соответствует 74.7% от общей площади озелененности. На районном уровне значения городской озелененности, прилегающей к дорожной сети, варьируются от 49.24 м²/чел. в Алмалинском районе до 476.39 м²/чел. в Медеуском районе, что соответствует 9.67-кратному различию. Тремя районами с наибольшими показателями являются Медеуский, Наурызбайский и Турксибский районы, тогда как самые низкие значения наблюдаются в Алмалинском, Ауэзовском и Жетысуском районах. Ранжирование районов остается устойчивым при выборе различных пороговых значений NDVI (0.25/0.30/0.35).

Ключевые слова: NDVI, Sentinel-2, городская озелененность, прилегающая к дорожной сети, зеленые пространства, Алматы, м²/чел.

Introduction

Urban green spaces are increasingly recognized as critical infrastructure for public health and climate resilience in rapidly growing cities. A growing evidence base links exposure to urban greenery with improved mental well-being, reduced all-cause mortality risk, and health benefits mediated through physical activity, stress reduction, and improved environmental quality (Gascon et al., 2016; Twohig-Bennett & Jones, 2018; WHO, 2016; WHO, 2017). In parallel, vegetation contributes to urban climate adaptation by mitigating heat exposure through shading and evapotranspiration; empirical syntheses generally find cooler conditions in greener urban sites, particularly parks and tree-covered areas (Bowler et al., 2010). These benefits make greenness a policy-relevant indicator, especially in cities experiencing intensifying heat and environmental pressures.

However, the benefits of urban greenery are not even distributed. A substantial body of environmental justice and planning research documents "green inequality" – systematic spatial disparities in the quantity and quality of green space across neighborhoods and administrative units, often aligning with differences in development intensity and socio-economic conditions (European Environment Agency, 2022; Rigolon, 2016; Wolch et al., 2014). This motivates district-level assessments that can reveal which parts of the city experience relative deficits, providing an evidence base for targeted greening interventions and equitable planning.

Remote sensing offers a practical, scalable approach for quantifying greenness consistently across large urban territories. The Normalized Difference Vegetation Index (NDVI) is one of the most widely used satellite-derived indicators of vegetation presence and vigor and is typically computed as (NIR−Red)/(NIR+Red) (Tucker, 1979; USGS, 2020). NDVI has been widely adopted to monitor vegetation patterns and dynamics, including within urban environments, due to its interpretability and compatibility with multi-temporal analyses (Huete et al., 2002; Pettorelli et al, 2005). Nevertheless, NDVI-based road-proximate urban greenness measurement requires methodological decisions – seasonal timing, compositing strategy, and classification thresholds – that can influence absolute estimates and should therefore be reported transparently and tested for robustness (Huete et al., 2002; Pettorelli et al, 2005).

A further challenge arises when administrative boundaries include extensive natural or semi-natural landscapes that are weakly connected to the inhabited urban fabric. This is particularly relevant for Almaty, a city located in the foothills of the Trans-Ili Alatau, where the official city territory and district extents encompass areas with strong elevation and land-cover contrasts (Akimat of the city of Almaty, 2025, December 17; Encyclopaedia Britannica, 2026, February 3). Under such conditions, greenness measured over the full administrative extent ("total greenness") may overstate greenness that is plausibly experienced or relevant for day-to-day urban life. Complementary "built-up" or "urban-fabric" proxies can therefore improve interpretability by focusing measurement on spaces closer to the street network or residential areas. This framing is consistent with the broader literature emphasizing not only the amount of green space, but also its spatial availability and proximity to everyday activity spaces (WHO, 2016; European Environment Agency, 2022; Przewoźna, 2024).

Against this background, the present study quantifies spatial heterogeneity of greenness in Almaty across its eight districts and explicitly compares (i) total greenness within administrative boundaries versus (ii) road-proximate urban greenness defined using a road-proximity proxy. Using Sentinel-2 Level-2A imagery accessed through the Copernicus Data Space Ecosystem Browser (Copernicus Data Space Ecosystem, 2025, November 26-28) and district population statistics as of 1 July 2025 (Bureau of National Statistics of Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2025, November 19), we compute district-level greenness supply indicators (green area and m^2/person) from a summer 2025 NDVI median composite and evaluate classification sensitivity across commonly used NDVI thresholds. The study's contributions are: (1) an explicit demonstration of how total versus urban-fabric greenness definitions affect per-capita estimates in a city with large natural areas inside administrative limits; (2) a district-level ranking of greenness supply for identifying relative deficits; and (3) a transparent, reproducible workflow using open satellite data and GIS methods suitable for replication and future extensions.

Methodology

This study focuses on Almaty (Kazakhstan) and its eight administrative districts: Alatau, Almaly, Auezov, Bostandyk, Zhetysu, Medeu, Nauryzbay, and Turksib. District boundaries were used as the primary spatial units for aggregation and comparison of greenness indicators.

Vegetation greenness was assessed using the Normalized Difference Vegetation Index (NDVI) derived from Sentinel-2 Level-2A (surface reflectance, BOA) data accessed via the Copernicus Data Space Ecosystem Browser (2025, November 26-28). Sentinel-2 provides multispectral imagery suitable for land monitoring applications, including vegetation (Copernicus Data Space Ecosystem, 2025, November 27). NDVI is defined as:

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (1)$$

where NIR and Red denote reflectance in the near-infrared and red bands, respectively (USGS, 2020). City and district boundaries were obtained in QGIS using OpenStreetMap administrative relations downloaded through the QuickOSM plugin (Overpass API), queried within Almaty and returned as multipolygon geometry for the city and districts. District and city population totals were taken from the Bureau of National Statistics of Kazakhstan: Population of the Republic of Kazakhstan by gender and type of locality (as of July 1, 2025), Table 2 (population by regions/cities/districts), published 14 Aug 2025 (2025). The road network was retrieved from OpenStreetMap using QuickOSM within the Almaty boundary. Pedestrian trails/paths were excluded; all remaining road classes were retained for buffering.

All GIS processing was performed in QGIS 3.34.15. Spatial analyses were carried out in a projected coordinate system to enable area-consistent calculations: WGS 84 / UTM Zone 43N (EPSG:32643). Raster outputs used a final pixel size of 16.503 m, corresponding to a cell area of:

$$S_{pix} = 16.503^2 = 272.35\ m^2 \quad (2)$$

All intermediate and final datasets were saved in non-proprietary formats (GeoTIFF for rasters; GeoPackage for vectors) to support reproducibility.

To represent peak vegetation conditions and reduce snow/seasonality effects, a summer period (June-August 2025) was used. Eight Sentinel-2 L2A scenes were manually selected based on visual clarity after applying an initial filter of maximum cloud coverage ≤ 20% in the Copernicus Browser: 18.06.2025, 28.06.2025, 03.07.2025, 13.07.2025, 23.07.2025, 12.08.2025, 22.08.2025, 27.08.2025 (2025, November 25-26). A summer NDVI composite was generated using the pixel-wise median across the selected dates. The median composite was chosen to reduce sensitivity to outliers (residual clouds/haze and transient artifacts) while preserving stable seasonal greenness patterns.

Continuous NDVI values were converted into binary greenness masks using three thresholds – NDVI > 0.25, NDVI > 0.30, and NDVI > 0.35. The threshold 0.30 was treated as the primary specification, while 0.25 and 0.35 were used for sensitivity analysis to evaluate robustness of district comparisons to plausible urban vegetation cutoffs. Each threshold produced a raster mask with values 1 (green) and 0 (non-green).

Because Almaty's administrative area includes large natural landscapes, including foothill and forested zones, full administrative-boundary aggregation can inflate greenness-per-capita indicators and reduce their relevance for the inhabited urban fabric. To address this issue, we operationalized a road-proximate urban greenness proxy based on the street network. Specifically, the road network was retrieved from OpenStreetMap using QuickOSM; pedestrian trails and paths were excluded, while all remaining road classes were retained. A 500 m buffer was then generated around the road network, dissolved into a single polygon, and clipped to the official boundary of Almaty city. The resulting city-clipped 500 m road-buffer polygon was used as a spatial mask to extract NDVI-defined green pixels located within the road-proximate urban zone. Thus, "urban greenness" in this study refers to the part of the total NDVI-derived green area that intersects with the 500 m road-buffer mask.

The 500 m buffer distance was selected as a compromise between a strict accessibility threshold and the need to delineate the everyday urban fabric of Almaty. A narrower 300 m buffer corresponds more closely to minimum walking-distance recommendations, but in this study, it could underrepresent courtyard greenery, street-tree corridors, and green parcels located within larger urban blocks. In contrast, a wider 1000 m buffer would risk extending the proxy zone into peripheral foothill, semi-natural, and non-residential landscapes, especially in the southern districts, thereby reintroducing the upward bias associated with Almaty's large administrative territory. Therefore, the 500 m threshold was used not as a full network-based accessibility model, but as an operational proxy for greenness located within the road-proximate urban fabric. This choice is consistent with the 300-500 m distance range commonly used in urban green-space accessibility studies and allows a balanced comparison between total administrative-boundary greenness and road-proximate urban greenness.

For each district d and NDVI threshold t, two sets of indicators were computed:

(1) The number of green pixels within each district was obtained via zonal aggregation of the binary mask:

$$N_{d,t}^{total} = \sum_{i \in d} M_t(i) \quad (3)$$

where $M_t(i) \in \{0,1\}$ is the greenness mask at threshold t. Total green area was computed as:

$$A_{d,t}^{total} = N_{d,t}^{total} \times S_{pix} \quad (4)$$

(2) Using the masked road-proximate urban greenness raster:

$$N_{d,t}^{urban} = \sum_{i \in d} (M_t(i) \times U(i)) \quad (5)$$

where $U(i) \in \{0,1\}$ indicates whether pixel i lies within the dissolved 500 m road buffer. Urban green area was computed as:

$$A_{d,t}^{urban} = N_{d,t}^{urban} \times S_{pix} \quad (6)$$

Using population Pop_d for each district (as of 1 July 2025), per-capita indicators were computed as:

$$GPC_{d,t}^{total} = \frac{A_{d,t}^{total}}{Pop_d} \quad (7)$$

$$GPC_{d,t}^{urban} = \frac{A_{d,t}^{urban}}{Pop_d} \quad (8)$$

Citywide indicators were derived analogously by treating the city polygon as the aggregation unit.

For quality control three checks were applied: (1) spot checks confirmed that threshold rasters contained only values 0/1 (required for interpreting sums as pixel counts); (2) for each district and threshold, road-proximate urban greenness did not exceed total greenness (minor boundary effects at district edges were treated as negligible and attributable to rasterization/edge assignment); and (3) district rankings and disparities were evaluated across NDVI > 0.25/0.30/0.35 to assess how strongly results depend on threshold choice.

We explicitly acknowledge that: (1) NDVI captures vegetative greenness but does not distinguish publicly accessible green space from private greenery; (2) the 500 m road-buffer provides a transparent proxy for the road-proximate urban fabric rather than a full network-based accessibility model; and (3) the resulting urban proxy depends on the completeness and classification quality of OpenStreetMap road data, the selected buffer distance, and raster boundary effects, which may introduce uncertainty in some peripheral areas.

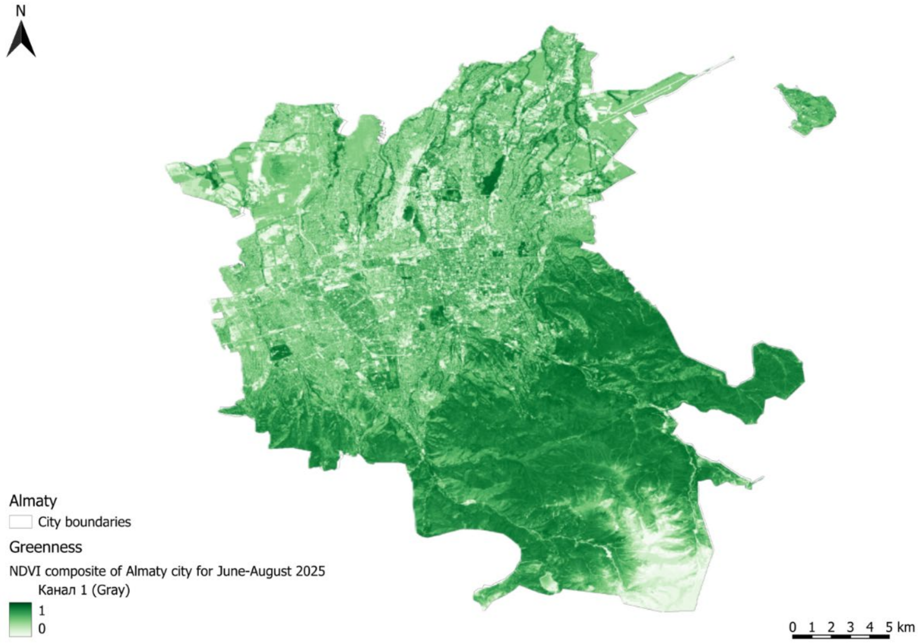
In addition, the final raster grid, with a pixel size of 16.503 m and a cell area of 272.35 m², implies that area estimates are subject to mixed-pixel and edge effects, especially along narrow green corridors and district boundaries. Future work can reduce these uncertainties by using higher-resolution built-up layers or automated urban extent products, and by enforcing a target grid closer to Sentinel-2's native 10 m sampling for NDVI-derived masks.

All figures and maps presented in this study were compiled by the authors based on the data and methods described above.

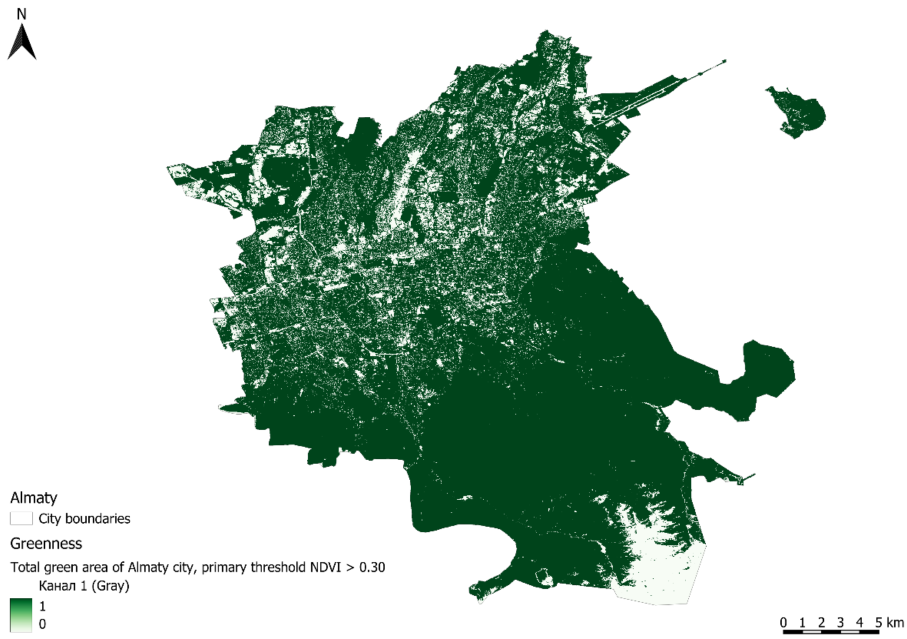
Results and discussion

Using the summer 2025 NDVI composite (Figure 1A) and the primary threshold NDVI > 0.30 (Figure 1B), the estimated total green area within Almaty's administrative boundary equals 591,452,690.4 m² (≈ 591.45 km²), corresponding to 254.94 m²/person (population 2,319,893 as of 1 July 2025). When greenness is constrained to the road-proximate urban zone defined by the 500 m road-network buffer, the urban green area equals 442,046,382.7 m² (≈ 442.05 km²) and 190.54 m²/person (Figure 1D) (Table 1).

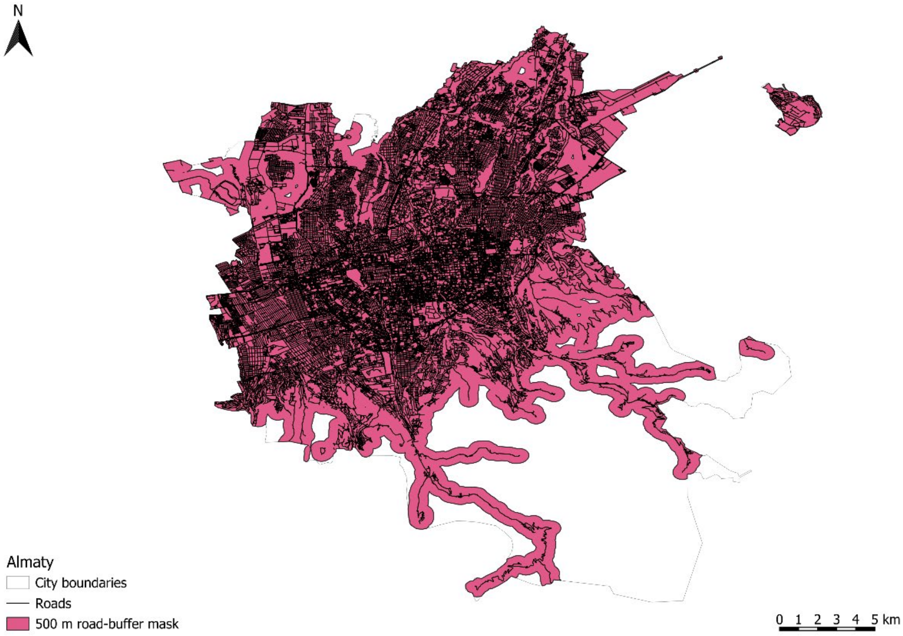
Figure 1
Spatial distribution of NDVI-derived greenness in Almaty, summer 2025



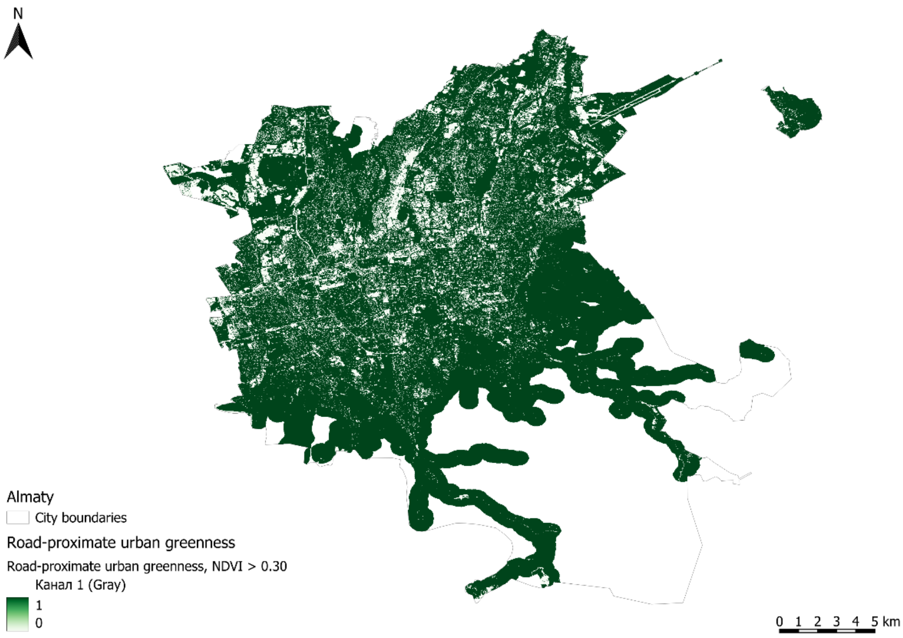
1A. NDVI composite of Almaty city for June-August 2025



1B. Total green area of Almaty city, primary threshold NDVI > 0.30



1C. 500 m road-buffer mask



1D. Extracted road-proximate urban greenness, NDVI > 0.30

Table 1

The area of total greenery and road-proximate urban greenery in Almaty city for the summer of 2025

Region	Number of population, person	The number of pixels of total greenery	The total area of greenery, m^2	The total area of greenery per person, m^2/person	The number of pixels of road-proximate urban greenery	The total area of road-proximate urban greenery, m^2	The area of road-proximate urban greenery per person, m^2/person
Almaty city	2 319 893	2 171 664	591 452 690,4	254,94	1 623 082	442 046 382,7	190,54

Thus, road-proximate urban greenness accounts for 74.7% of total greenness by area, and the citywide per-capita estimate decreases by 64.40 m²/person (from 254.94 to 190.54 m²/person), i.e., by approximately 25%. This indicates that a non-trivial share of NDVI-defined greenness lies outside the road-proximate urban fabric and inflates administrative-boundary greenness metrics.

District-level results show pronounced spatial heterogeneity in both total and road-proximate urban greenness (Table 2). The spatial distribution of greenness in the NDVI composite (Figure 1A) and derived green area maps (Figures 1B and 1D) reflects Almaty's pronounced topographic and land-use gradient. The highest NDVI values are concentrated in the southern districts – Medeu and Bostandyk – where natural forest belts, riparian vegetation along the Malaya and Bolshaya Almatinka rivers, and the Ile-Alatau National Park buffer form continuous high-NDVI patches. Moving northward toward the flat, densely built-up core (Almaly, Auezov, Zhetysu), NDVI values drop sharply and greenness becomes fragmented into narrow linear elements (street trees) and small isolated parcels (courtyards, schoolyards). Turksib district, despite its northern location, retains relatively higher road-proximate urban greenness (220.87 m²/person), likely reflecting lower residential density and the presence of peri-urban parcels with maintained vegetation. These spatial patterns align with Almaty's current urban development priorities: municipal greening programs have targeted street-tree planting and courtyard greening (mahalle greening) as primary measures – interventions most needed in the low-greenness northern districts identified here.

Table 2

The area of total greenery and road-proximate urban greenery in Almaty districts for the summer of 2025

District	Number of population, person	The number of pixels of total greenery	The total area of greenery, m^2	The total area of greenery per person, m^2/person	The number of pixels of road-proximate urban greenery	The total area of road-proximate urban greenery, m^2	The area of road-proximate urban greenery per person, m^2/person
Alatau	393 247	285 761	77 827 008,35	197,9	272 421	74 193 859,35	188,66
Almaly	271 429	49 044	13 357 133,4	49,21	49 074	13 365 303,9	49,24
Auezov	358 611	67 039	18 258 071,65	50,91	67 136	18 284 489,6	50,98
Bostandyk	343 586	329 415	89 716 175,25	261,11	256 977	69 987 685,95	203,69
Zhetysu	199 417	100 901	27 480 387,35	137,8	100 900	27 480 115	137,8
Medeu	253 550	888 443	241 967 451,1	954,31	443 514	120 791 037,9	476,39
Nauryzbay	231 449	229 737	62 568 871,95	270,33	212 454	57 861 846,9	249,99
Turksib	268 604	218 578	59 529 718,3	221,62	217 840	59 328 724	220,87

Under road-proximate urban greenness (NDVI > 0.30), values range from 49.24 m²/person in Almaly district to 476.39 m²/person in Medeu district, i.e., a 9.67-fold difference – absolute gap 427.15 m²/person. The top three districts by road-proximate urban greenness are Medeu – 476.39 m²/person, Nauryzbay – 249.99 m²/person, and Turksib – 220.87 m²/person. The bottom three are Almaly – 49.24 m²/person, Auezov – 50.98 m²/person, and Zhetysu – 137.80 m²/person.

Comparing total versus road-proximate urban greenness clarifies where administrative metrics are most affected by non-road-proximate green areas (Table 2). The strongest reduction occurs in Medeu, where greenness decreases from 954.31 m²/person (total) to 476.39 m²/person (urban) –

approximately a 50% decrease – consistent with large natural areas not captured by the road-buffer proxy. A moderate reduction is also observed in Bostandyk (from 261.11 to 203.69 m²/person, a 22% decrease). In contrast, several districts show minimal differences between total and road-proximate urban greenness, indicating that most NDVI-defined greenness lies within the road-proximate zone in these areas (e.g., Zhetysu and Turksib; differences near zero).

Table 3

The area of total greenery and road-proximate urban greenery in Almaty districts for the summer of 2025 (NDVI > 0.25)

District	Number of population, person	The number of pixels of total greenery	The total area of greenery, m^2	The total area of greenery per person, m^2/person	The number of pixels of road-proximate urban greenery	The total area of road-proximate urban greenery, m^2	The area of road-proximate urban greenery per person, m^2/person
Almaty city	2 319 893	2 239 566	609 945 800,1	262,91	1 682 732	458 292 060,2	197,54
Alatau	393 247	305 020	83 072 197	211,24	290 863	79 216 538,05	201,44
Almaly	271 429	51 746	14 093 023,1	51,92	51 762	14 097 380,7	51,93
Auezov	358 611	70 534	19 209 934,9	53,56	70 628	19 235 535,8	53,63
Bostandyk	343 586	335 702	91 428 439,7	266,1	263 146	71 667 813,1	208,58
Zhetysu	199 417	106 793	29 085 073,55	145,85	106 803	29 087 797,05	145,86
Medeu	253 550	901 990	245 656 976,5	968,86	449 769	122 494 587,15	483,11
Nauryzbay	231 449	236 175	64 322 261,25	277,91	218 876	59 610 878,6	257,55
Turksib	268 604	228 693	62 284 538,55	231,88	227 947	62 081 365,45	231,12

Table 4

The area of total greenery and road-proximate urban greenery in Almaty districts for the summer of 2025 (NDVI > 0.35)

District	Number of population, person	The number of pixels of total greenery	The total area of greenery, m^2	The total area of greenery per person, m^2/person	The number of pixels of road-proximate urban greenery	The total area of road-proximate urban greenery, m^2	The area of road-proximate urban greenery per person, m^2/person
Almaty city	2 319 893	2 112 969	575 467 107,2	248,05	1 570 555	427 740 654,3	184,37
Alatau	393 247	268 016	72 994 157,6	185,61	255 535	69 594 957,25	176,97
Almaly	271 429	46 869	12 764 772,15	47,02	46 899	12 772 942,65	47,05
Auezov	358 611	63 845	17 388 185,75	48,48	63 943	17 414 876,05	48,56
Bostandyk	343 586	324 005	88 242 761,75	256,82	251 703	68 551 312,05	199,51
Zhetysu	199 417	96 144	26 184 818,4	131,3	96 139	26 183 456,65	131,3
Medeu	253 550	877 989	239 120 304,2	943,08	438 185	119 339 684,8	470,67
Nauryzbay	231 449	223 802	60 952 474,7	263,35	206 528	56 247 900,8	243,02
Turksib	268 604	209 680	57 106 348	212,6	208 988	56 917 881,8	211,9

Sensitivity analysis confirms that district comparisons are robust to plausible NDVI thresholds (Tables 3,4). For road-proximate urban greenness, switching from NDVI > 0.25 to NDVI > 0.35 changes per-capita values by roughly ~3-13% relative to the NDVI > 0.30 baseline across districts (smallest relative change in Medeu; larger relative changes in several low-greenness districts and in Alatau). Importantly, the top-3 (Medeu, Nauryzbay, Turksib) and bottom-3 (Almaly, Auezov, Zhetysu) district rankings remain unchanged across thresholds, supporting the stability of the identified spatial pattern.

Internal checks confirmed the expected inequality road-proximate urban greenness ≤ total greenness for most districts and thresholds. Two districts exhibited very small inversions attributable to raster edge assignment along district boundaries: for NDVI > 0.30, urban pixel counts exceeded total pixel counts by 30 pixels in Almaly and 97 pixels in Auezov. Given the raster cell area (≈272.35 m²), these differences correspond to approximately 0.03 m²/person and 0.07 m²/person, respectively – negligible relative to district-level magnitudes and not affecting conclusions. Similar minor differences were observed for thresholds 0.25 and 0.35.

The results demonstrate strong intra-urban heterogeneity of greenness across Almaty's districts. Under the primary specification (NDVI > 0.30), road-proximate urban greenness ranges from ~49 m²/person in the most deficit districts (Almaly, Auezov) to ~476 m²/person in Medeu, producing nearly a tenfold disparity. Such gaps are consistent with the expectation that administrative districts differ substantially in their land-use structure, development intensity, and proximity to large vegetated landscapes. In dense, highly built-up areas (e.g., central districts), greenness tends to be spatially fragmented and dominated by narrow corridors (street trees) and small parcels, which are harder to capture as "large-area" greenness at the district scale. Conversely, districts adjacent to extensive natural landscapes or large park/forest systems can maintain very high greenness-per-capita even when restricting analysis to the road-proximate zone.

A key methodological and substantive finding is that citywide and district-level greenness estimates depend strongly on whether the measurement is taken over the full administrative extent ("total") or constrained to the road-proximate urban proxy. Citywide, the road-proximate urban proxy retains ~74.7% of total greenness area, while per-capita greenness declines from 254.94 to 190.54 m²/person. This indicates that a meaningful portion of NDVI-defined greenness falls outside the road-proximate urban fabric and can inflate administrative-boundary indicators.

At the district level, the contrast is most evident in Medeu, where road-proximate urban greenness is roughly half of total greenness (954.31 – 476.39 m²/person). This pattern is consistent with Medeu's inclusion of large vegetated areas that are not necessarily representative of everyday greenness exposure for the majority of residents. In contrast, several districts show minimal differences between total and road-proximate urban greenness, implying that most vegetated pixels are concentrated within the road-proximate zone. Therefore, reporting only "total greenness" risks overstating the greenness available within the inhabited fabric and may obscure the districts where greenness deficits are most relevant for urban planning.

The spatial pattern is robust to plausible classification choices. The top- and bottom-ranked districts remain unchanged across NDVI thresholds 0.25/0.30/0.35, suggesting that the observed heterogeneity is not an artifact of a single cutoff. Although absolute per-capita values shift with the threshold (as expected when moving from a more inclusive to a more conservative vegetation definition), the stability of rankings strengthens confidence in the qualitative conclusions regarding relative district deficits. Practically, this implies that greenness disparities in Almaty are sufficiently pronounced to be detectable under a range of reasonable NDVI definitions, which is important for comparability and policy interpretation.

From a planning perspective, the results identify districts with consistently low road-proximate urban greenness-per-capita (notably Almaly and Auezov, and to a lesser extent Zhetysu) as priority areas for interventions that increase vegetated cover within the urban fabric. Because district-scale deficits can be driven by both limited available land and high population exposure, the most feasible strategies in low-greenness districts are typically those that do not require large contiguous parcels – e.g., strengthening street-tree networks and green corridors, pocket parks, greening of schoolyards and courtyards, and targeted redevelopment of underutilized land. Conversely, districts with high greenness-per-capita (especially Medeu and Nauryzbay) may benefit less from "more greenness" in aggregate and more from ensuring connectivity, maintenance, and equitable distribution within the built-up zone.

Importantly, the distinction between total and road-proximate urban greenness helps avoid misprioritization: a district can appear "green" under total metrics due to peripheral natural landscapes while still having localized greenness deficits within its built-up neighborhoods. Therefore, operational planning should consider urban-fabric greenness indicators as more actionable inputs than administrative-boundary totals in a city with large natural areas inside its official limits.

Several limitations should be considered when interpreting the findings. First, NDVI captures surface "greenness" and does not directly distinguish vegetation type, height, or public accessibility; consequently, NDVI-based greenness-per-capita should be interpreted as a biophysical indicator rather than a measure of park access. Second, the “urban” proxy zone is derived from a road-buffer approach, which may exclude some relevant urban green areas beyond the buffer or include vegetated areas along roads that are not necessarily publicly accessible or usable. The proxy also depends on the completeness and classification quality of OpenStreetMap road data and on the selected buffer distance. Third, the final grid resolution (16.503 m) implies mixed-pixel effects and boundary assignment uncertainty, which can produce negligible edge discrepancies between total and urban pixel counts in a small number of cases, without affecting district-level conclusions.

Future work can address these limitations by (1) validating the road-buffer urban proxy with independent built-up products (e.g., global built-up layers) and comparing multiple definitions of “urban extent”; (2) incorporating higher-resolution land cover or tree canopy data to better differentiate vegetation types; and (3) evaluating accessibility with network-based methods using entry points to parks and pedestrian connectivity to complement NDVI-based greenness supply metrics.

Conclusion

This study quantified the spatial heterogeneity of greenness in Almaty across eight districts using a summer 2025 Sentinel-2 NDVI median composite and compared total greenness (within administrative boundaries) with road-proximate urban greenness, operationalized as greenness located within a dissolved 500 m buffer of the road network. Three NDVI thresholds (0.25/0.30/0.35) were used to test robustness, with NDVI > 0.30 as the primary specification.

At the city scale (NDVI > 0.30), total green area reached 591.45 km² (254.94 m²/person), while road-proximate urban greenness amounted to 442.05 km² (190.54 m²/person), i.e., 74.7% of total greenness by area. This confirms that administrative-boundary greenness indicators can be meaningfully inflated by vegetated land outside the road-proximate urban fabric in a city with extensive natural landscapes inside its formal boundary.

At the district scale, greenness proved highly uneven. For road-proximate urban greenness (NDVI > 0.30), per-capita values ranged from 49.24 m²/person (Almaly) to 476.39 m²/person (Medeu) – a 9.67-fold disparity. The top three districts by road-proximate urban greenness were Medeu, Nauryzbay, and Turksib, while the lowest values were consistently observed in Almaly and Auezov (followed by Zhetysu). The contrast between total and urban metrics was most pronounced in Medeu, where restricting greenness to the road-buffer zone reduced the per-capita indicator by approximately half, highlighting the importance of reporting “urban-fabric” metrics for planning interpretation.

Sensitivity analysis showed that the district ranking is robust to plausible NDVI thresholds (0.25/0.30/0.35): the top-3 and bottom-3 districts remained unchanged, indicating that the identified spatial pattern is not driven by a single classification cutoff. Minor boundary effects (small pixel-count inversions in two districts) were negligible and did not affect conclusions.

From a practical perspective, the results suggest that greening priorities should focus on districts with persistently low road-proximate urban greenness-per-capita (notably Almaly and Auezov, and to a lesser extent Zhetysu) through interventions that are feasible in dense urban fabrics – e.g., strengthening street-tree networks, park pockets, and green corridors. Methodologically, the proposed workflow provides a transparent and reproducible way to distinguish territorial greenness from road-proximate urban greenness, improving the interpretability of per-capita indicators in cities with large non-residential natural areas.

Future work should reduce remaining uncertainties by validating the road-buffer proxy against independent built-up extent products, incorporating higher-resolution land-cover/tree-canopy data, and extending from proximity proxies to network-based accessibility measures where detailed inputs are available.

Acknowledgements

This research was funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan under project AP26103653 Recreational capacity

modeling using UAV, GIS and AI tools to prevent overtourism in Ile-Alatau National Park.

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Received: January 29, 2026
Accepted: May 15, 2026