Shade Equity for a Desert City

A Free-Data Framework for Prioritizing Urban Tree Planting across the Districts of Buraydah, Saudi Arabia

Shade Platform (منصة ظِلّ) — shade.ziadabdullah.com

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خارطة الظِلّ في مدينة صحراوية: إطار مبني على البيانات المفتوحة لترتيب أولويات التشجير الحضري في أحياء مدينة بريدة

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Abstract

Saudi Arabia's national greening effort is unprecedented in scale: the Saudi Green Initiative targets 10 billion trees over the long term and more than 600 million trees and shrubs by 2030, with 159 million trees reported planted by March 2026 [1][2][3]. City programs such as Green Riyadh (7.5 million trees; green cover from 1.5% to a 9% target) show that large-scale arid-city greening is now established national policy [5]. What is not yet published for any Saudi city is a transparent, reproducible method for deciding **which neighborhoods should be planted first**. This study presents such a method for Buraydah, the capital of Al-Qassim Region, and applies it to all 69 of the city's districts using entirely free and open data: Sentinel-2 vegetation imagery (10 m), Landsat surface-temperature data (30 m), district populations from an ensemble of three gridded sources (WorldPop, Kontur and Meta/CIESIN HRSL) rescaled to the 2022 census total of 571,169, and open district boundaries derived from the National Address platform.

We adapt the Tree Equity Score of American Forests — used across the United States, the United Kingdom, and Toronto — to a hot-desert (Köppen BWh) city for, to our knowledge, the first time [18][19][22]. The adaptation replaces the US goal framework with a 9% green-cover goal aligned with Green Riyadh, and replaces socioeconomic indicators that are unavailable or inapplicable in the Saudi context (race, income, health burden) with two directly measurable pressures: summer land-surface temperature and population density. The resulting **Shade Equity Score** is a single formula: districts far below the 9% goal, and hotter and denser than the city norm, score lowest and rank first for planting.

The September–October 2025 analysis finds citywide vegetated cover of **6.71%** of district area — below the 9% goal — with 50 of 69 districts under the goal and about 75% of the city's population living in those districts. Eighteen districts have less than 3% green cover; they house roughly 158,000 people (28% of the city). Mean summer land-surface temperature ranges from **51.1°C to 58.0°C** across districts. Citywide vegetation averages 52.2 m² per resident, but this figure counts private palm groves and farms and must not be read as accessible public green space, which UN-Habitat's urban review of Buraydah describes as scarce and fragmented [12, p. 98]. A seven-experiment validation battery (goal and weight sensitivity, index and threshold checks against park ground truth, seasonal-window comparison, interannual and within-season stability, and soil-brightness drift) — extended by a dedicated equation-validation study that tested the scoring formula itself against seven alternative constructions (Spearman agreement 0.87–0.996), ran a 3,000-draw Monte Carlo uncertainty analysis, adopted a fixed-goalpost gap normalization (dividing each district's gap by the 9% goal itself) verified to change no rank, and demonstrated the full pipeline end-to-end on a second city (Unayzah, 90 districts, zero algorithmic changes) — confirms that the ranking is robust while any exact top-10 list is not; results are therefore read as a **ranked list to be worked from the top downward**, with each district's probability of top-10 membership published alongside its rank (three districts — Ar Rawdah, Al Manar, Ad Dahi — are top-10-certain at $P > 0.92$), and the six lowest-scoring districts — Ar Rawdah, Al Manar, Ash Shafaq, Ash Shiqah, Ad Dahi, and At Tashlih — clearly the most urgent under all tested weightings — are profiled, with recommendations for a first planting phase aligned with UN-Habitat's Action 3.3 for Buraydah, irrigated with treated wastewater following the Buraydah Oasis precedent of one million trees [9]. The platform accompanying this study updates monthly and is offered as a complement — never a replacement — to the official programs of the Amanah, the Emirate, and the national greening institutions.

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1. Introduction

1.1 A national moment for greening

In March 2021, the Crown Prince announced the Saudi Green Initiative (SGI), with a long-term ambition of planting 10 billion trees across the Kingdom [1]. The near-term milestone was later raised to **more than 600 million trees and shrubs by 2030** (upgraded from an initial 450 million), alongside targets to protect 30% of land and sea and cut emissions by 278 million tonnes per annum [2]. Progress is real and accelerating: by March 2026 the Environment Minister announced **159 million trees planted and the first one million hectares of degraded land restored**, with a 40-million-hectare national landrehabilitation goal (the SGI site states over 74 million hectares as the full 10-billion-tree ambition), more than 2.2 million tonnes of CO_2 sequestered, and over 68,000 jobs created [3] [4]. The National Greening Program — SGI's executive arm — runs 155 initiatives across 11 operational zones and, importantly for this study, monitors its own progress with **remote sensing, satellite imagery, drones, and GIS** [4]. The measurement approach used in this paper is therefore not an outside import: it is the same family of tools the state itself has chosen for tracking vegetation.

At city scale, **Green Riyadh** is the flagship precedent. Launched in 2019 under the Royal Commission for Riyadh City, it aims to plant 7.5 million trees across 120 residential districts by 2030, raise per-capita green space from 1.7 to 28 m², and lift the city's green cover from 1.5% to **9%** of its area — with projected ambient cooling of 1.5–2°C citywide and surface cooling of 8–15°C in intensively planted areas [5]. Its irrigation model is decisive for any desert city: a shift from 11% to 100% treated sewage effluent (TSE), through a 1,350 km irrigation network with capacity up to 1.7 million m³ per day [5]. Green Riyadh proves that greening an arid Saudi city at scale is national policy, that a 9% green-cover goal is considered achievable, and that recycled water is the intended supply.

1.2 Qassim is already planting

Al-Qassim Region is among the most active greening regions in the Kingdom. The **"Qassim Green Land" (أرض القصيم خضراء)** initiative, launched in 2016 with the Emir's support and run in two phases per year (March and October), has reached a reported cumulative total of **7,521,316 trees** across the region's cities, governorates and villages through its fifteenth phase, with a sixteenth phase underway [6][7]. In November 2024 the Emir of Qassim, Prince Dr. Faisal bin Mishaal bin Saud bin Abdulaziz, launched a campaign to plant **one million trees** at Qassim National Park in Buraydah, within a wider regional ambition of five million seedlings by 2030 [8]. In Buraydah itself, the Emir has also inaugurated the completion of planting **one million trees in Buraydah Oasis (واحة بريدة)**, executed by the National Water Company and irrigated with **treated (renewable) water** through a reported three-million-meter irrigation network fed by the city's sewage treatment plant — the largest environmental project in the region and a direct local proof that TSE-irrigated greening works at scale in Buraydah [9]. The Amanah's **"Bahjah" (بهجة)** program delivered, in its 2024 Buraydah edition, 10 new parks, 41 walking tracks totalling more than 44,000 m, 14,777 trees and some 695,000 flowers [10]; and Al-Iskan Park in north Buraydah (186,111 m², 27,179 trees and shrubs) has been described by the Saudi Press Agency as an "environmental and recreational oasis" [11].

1.3 The gap this study fills

Every layer of this effort — national, regional, municipal — publishes **targets and outputs**: trees planted, hectares rehabilitated, parks opened. What no Saudi program or study has yet published, to our knowledge, is a **district-level prioritization method**: a transparent, data-driven answer to the question *"Given limited water, budget, and planting seasons, which neighborhoods should be planted first, and why?"* Green Riyadh's public materials show asset-class quantities (parks, streets, mosques, schools) and phased neighborhood rollouts, while the prioritization rubric itself is not part of the published materials [5]. Two independent literature searches conducted for this study (August 2026) found no peer-reviewed district-level greening prioritization study for Buraydah, and — more broadly — **no published adaptation of the Tree Equity Score family of methods for any hot-desert (BWh), Gulf, or Arab country** [18][19]. The Saudi academic literature measures green-space equity through per-capita and accessibility metrics only (Section 3.4); none applies a composite "gap × priority" score of the kind used across thousands of US, UK, and Canadian neighborhoods.

This paper fills that gap for one city. We adapt the Tree Equity Score to Buraydah's climate, data environment, and policy context; compute it for all 69 districts from entirely free data; and present the results as a practical decision aid for the Emirate of Al-Qassim and the Amanah. Everything in the method is open: open imagery, open boundaries, open population grids, and an open formula that a municipal engineer can verify line by line.

2. Study Area: Buraydah

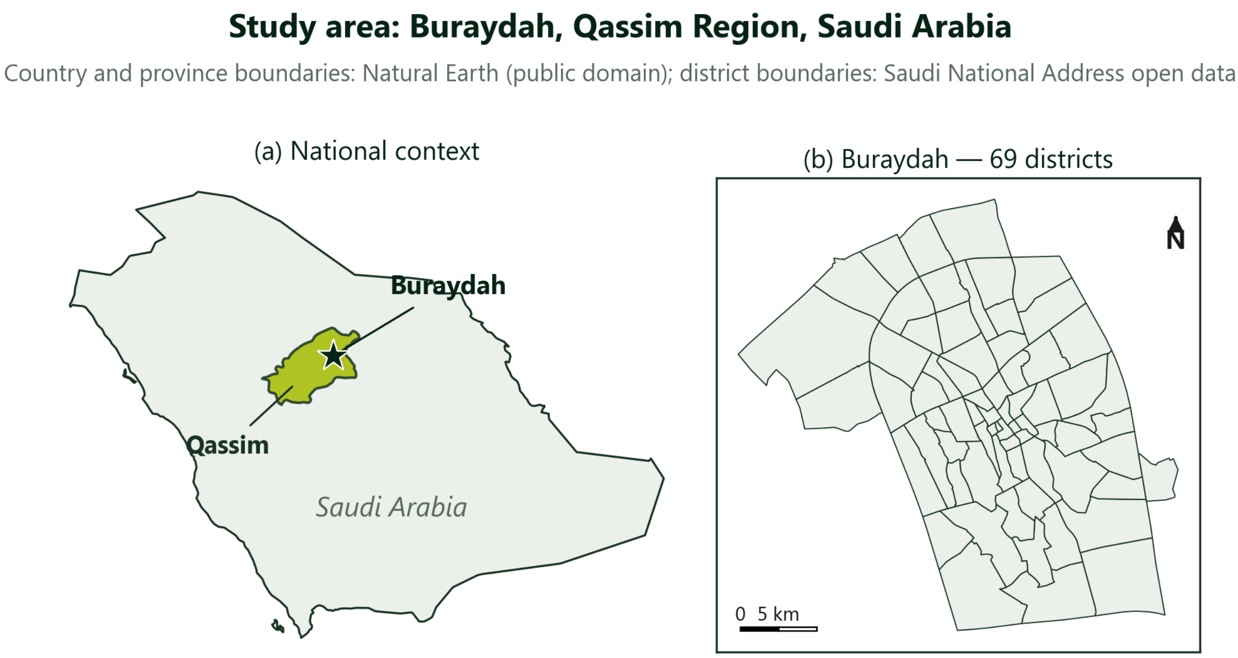

Figure 1: Location of Buraydah within the Kingdom of Saudi Arabia and Al-Qassim Region.

2.1 The city

Buraydah (26.33°N, 43.97°E; elevation 600–650 m) is the capital of Al-Qassim Region and its administrative, commercial and agricultural center. The 2022 national census records **571,169 residents** in Buraydah city, and 677,647 for the city together with its dependent centers and villages — just over half the region's population [16][13]. The city sits on the northern bank of Wadi Al-Rummah, which UN-Habitat's urban review calls "the city's main environmental feature" [12, p. 74], within one of the Kingdom's most productive agricultural areas: Qassim is the country's "food basket," and date palms account for over a third of the city's registered agricultural land [12, p. 60].

This study uses the 69 districts (أحياء) of Buraydah city as recorded on the National Address platform (Section 4.1) as its analysis units.

Figure 2: The 69 districts of Buraydah used in this study.

2.2 Climate and heat

Buraydah's climate is hot desert (Köppen BWh). Annual rainfall is low and reported inconsistently across sources — roughly **90–150 mm per year** depending on source and period (93 mm per climate-data.org, ~102 mm per Wikipedia, 146 mm per Saudipedia; UN-Habitat's report itself gives both 134.4 and 146 mm) [14][15][13][12, pp. 18, 73] — with a declining projection to about 103 mm/yr over the coming decades [12, p. 73]. Summers are extreme: mean August temperatures around 43°C [13]. The UN-Habitat review reports that recorded heat-wave cases in Qassim rose from 2 in 1978–1995 to 62 in 1996–2013, and that evaporation rates have risen sharply [12, p. 72].

Two heat-related facts matter directly for this study. First, **an urban heat island effect is documented in Buraydah**: both Saudipedia [13] and the UN-Habitat review [12, pp. 28, 72] note that the urban area is increasingly warmer than its rural surroundings, attributed to land-use and energy patterns rather than climate change alone. UN-Habitat's Figure 39 maps the city's heat-island risk zones and its cool northwest breeze corridors, and frames heat mitigation as a walkability and public-space opportunity [12, pp. 72–73].

4.4 Environmental & Climate Change Risk Implications

4.4.1 Urban heat islands and desertification

Buraidah is located in the North Central area of the Al Qassim Region, in a relatively flat area, at 600-650 metres above sea level. It has a semiarid to a hyper-arid climate with extreme conditions that are being exacerbated by climate change. Changes in air temperature have been registered at the national level in the past decade. Due to climate change, in most areas temperatures have been increasing by about 0.2°C to 0.3°C per decade. In the Al Qassim Region, a substantial increase ranging from 0.052°C between 1978 and 2003 to 0.12°C between 2004 and 2013. Projections indicate an expected temperature of 27.1°C from 2030 to 2079, compared to the current minimum annual temperature of 25.1°C. These patterns intensify the occurrence of heat wave events, which have increased in the Al Qassim area from two events between 1978 and 1995 to 62 incidents from 1996 to 2013. They also impact the soil aridity, whose index is very low in the region, at less than 0.05.

On the contrary, it is essential to acknowledge that sandstorm events have been decreasing by about 31% over the last 20 years. Sandstorms are caused by Southwest winds which carry the sand from the dunes into the city. The agricultural land, located around those dunes supports the stabilisation of the soil and reduces the intensity and number of these storms.

Another prevailing wind direction comes from the Northwest bringing in cooling breezes to the city, which positively affects the local climate.

The urban climatic conditions are an important element to be considered in relation to energy consumption, citizen health, and urban form. Urban form, emerging from both streets layout, public space, and buildings typologies, has, therefore, a considerable impact in the way cities in Saudi Arabia cope considering its hyper-arid climate. All these conditions are increasing the Urban Heat Island Effect, which means that the urban area is increasingly warmer than its rural surroundings. This is not only due to climate change but is also caused by human activities, such as the modification of land uses and usage of energy. Often, vernacular and historic urban patterns perform better from an urban microclimate point of view.

Sustainable urban planning plays a pivotal role in reducing such effects by framing the urban patterns and living models that a city provides. In this sense, for the future of Buraidah, it is similarly vital to integrate climate conditions in a way that the development protects and prevents sandstorms and hannels the breeze to create a pleasant urban environment.

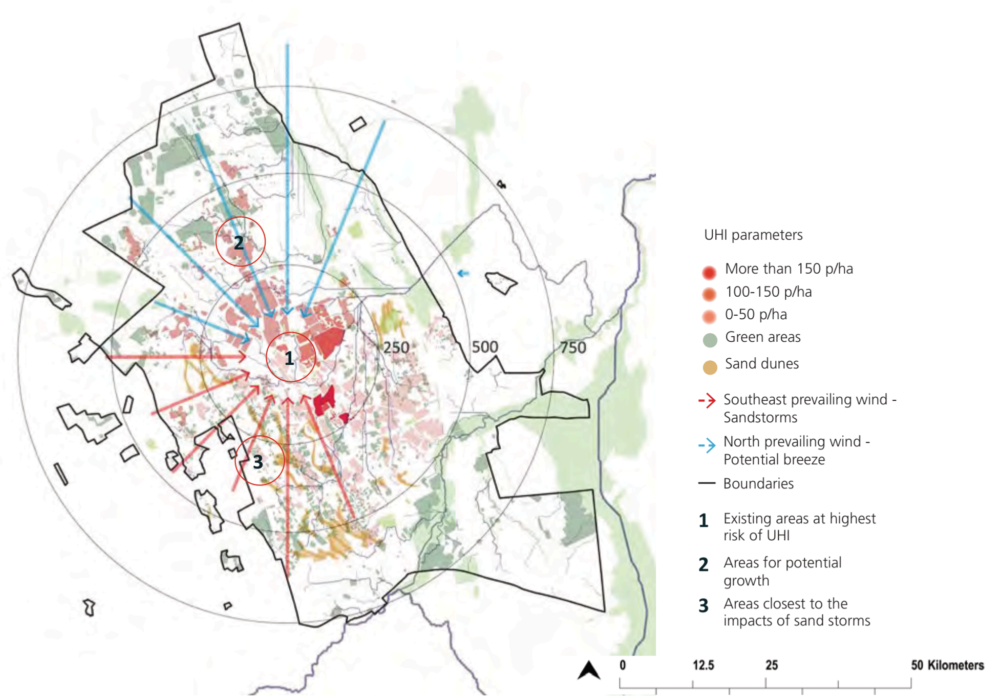

Fig. 39. Urban heat islands analysis

Figure: Urban heat island analysis of Buraydah (UN-Habitat Figure 39). Source: Ministry of Municipal and Rural Affairs & UN-Habitat, Buraidah Comprehensive Urban Vision, Future Saudi Cities Programme, 2019, English edition, p. 70.

Second, vegetation demonstrably cools Buraydah. A 2025 study of Saudi agricultural areas using Landsat time series found that vegetation reduced land-surface temperature by **4.53°C** at Buraydah sites, and that the city's surrounding vegetated area expanded between 2010 and 2023 (304.34 km² in 2023) [39]. UN-Habitat likewise notes that the farmland around the dunes stabilizes soil and damps sandstorms [12, p. 72]. Trees in Buraydah are not ornamental; they are functional climate infrastructure.

2.3 Urban form: a low-density, horizontally extended city

The UN-Habitat / Ministry of Municipal and Rural Affairs *Buraidah Comprehensive Urban Vision* (2019) provides the definitive urban diagnosis. Its headline findings [12]:

- Population at the time of the report: about 620,000 (its GIS analysis uses 621,212), growing at 3.67% per year — above regional and national averages — and projected to reach 780,000 by 2030 (pp. 52, 55, 70–71).
- Built-up area: **27,469 ha**, at an average density of only **22.5 persons/ha**. Since 1975 the city's area grew about **58-fold** while its population grew less than fivefold (pp. 55–57).
- Per-capita urbanized land is **440 m² per person against a UN-Habitat benchmark of 66.67 m²** (p. 56) — the physical signature of the city's rapid horizontal expansion.
- **37% of the built-up area — 10,163 ha — is vacant "white land"** (pp. 41, 64), of which 67% is earmarked for future residential use (p. 80). Some 10,000 ha of vacant land inside the built area makes outward growth unnecessary (pp. 70–71).
- Only 29% of residents have access to public services including parks; less than 6% live within a 10-minute walk of a mixed-use area (pp. 65, 84).

2.4 Green space: what the urban review found

On green space specifically, the UN-Habitat review is explicit: green public areas in Buraydah are **"scarce, fragmented, and isolated from the blue network of the wadis,"** and the shortage of green space in the central districts "must be addressed" [12, p. 98]. Standard neighborhood plans require a central open space, but "in many cases these have never been developed" (p. 122). The open-space deficit is compounded because much of the greenery inside the city is **private farmland, inaccessible to the public** (p. 82) — a point that becomes central when we interpret satellite-derived per-capita figures in Section 5.3. The report's structural remedy is to rebuild a green network: preserve farmland, reconnect the green and blue systems, restore the wadis as the city's public green-space spine, and reserve white land for green public space (pp. 74, 91, 122–123). Notably, the report contains **no**

parks inventory and no per-capita green-space figure — the city has simply not yet had the kind of measured baseline this study provides.

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3. How Greening Is Measured: A Short Review

3.1 Official Saudi metrics

Saudi programs report greening chiefly through **output counts and coverage ratios**: trees and shrubs planted (SGI: 159 million by March 2026 [3]; Qassim Green Land: a reported 7.5 million [6]), hectares of land rehabilitated (1 million ha by March 2026 [3]), percent green cover (Green Riyadh: 1.5% → 9% [5]), and square meters of green space per capita (Green Riyadh: 1.7 → 28 m^2 [5]). These are the right metrics for tracking delivery. What they do not answer is *allocation*: where, within a city, the next tree does the most good. That question needs a score computed per neighborhood.

3.2 The Tree Equity Score

The most widely deployed neighborhood-level answer is the **Tree Equity Score (TES)** of American Forests [17]. TES is a 0–100 metric computed for each US census block group and now covering every urban area in the United States — over 260 million people can look up their neighborhood's score [21]. A score of 100 means the neighborhood's canopy goal is met; **the lower the score, the higher the planting priority** [18].

The logic is a single formula in four steps [18][19]:

1. **A canopy goal** per neighborhood. TES v1 set baseline goals by biome — 40% canopy for forest biomes, 20% grassland, **15% desert** — adjusted by population density (factors 0.5–1.2), so a desert city's practical goal ranges from about 7.5% to 18%. The 2023 version 2.0 shifted the adjustment to building density as a proxy for plantable space [19].
2. **A canopy gap**: GAP = GOAL − existing canopy (negative gaps set to zero), normalized citywide as GAPscore = GAP / GAPmax, a 0–1 fraction.
3. **A priority index E**: the mean of several min–max-normalized indicators of need. TES v1 used five (income, employment, race, age dependency, urban-heat severity); v2 uses seven, adding health burden and linguistic isolation, and applies a floor so every neighborhood retains non-zero priority: E = 0.1 + 0.9 × mean(indicators) [19].
4. **The score**: **TES = 100 × (1 − GAPscore × E)**.

Because normalization is computed within each city, TES is a *relative* instrument: it ranks neighborhoods against each other, not against other cities [18]. That property suits a municipal decision tool, and we retain it for the exposure index — while anchoring the gap term to the fixed 9% goal rather than the city's largest gap (Section 4.5), a distance-to-target normalization in standard composite-indicator practice [55] that keeps gap scores comparable across years and cities.

TES has crossed borders twice. The **United Kingdom** adaptation (December 2023, with the Woodland Trust and the Centre for Sustainable Healthcare) covers more than 34,000 urban neighborhoods; it lowered the baseline goal to 30%, added an air-quality indicator (NO_2 and PM2.5), and **dropped race** as an indicator [22][23]. **Toronto** (April 2024) applied the v2 formula at census-tract level with seven Canadian indicators and building-density goals [19]. Both adaptations demonstrate the method's central virtue: the formula travels, while the goal and the indicators are recalibrated to local ecology and local data. An independent Calgary replication reportedly went further, substituting a locally adopted 16% canopy target for the biome baseline [25].

Two cautions from the literature carry into our design. First, American Forests itself has **abandoned universal canopy targets**, writing that 40–60% is attainable only in forested regions and that 20% (grassland) and 15% (desert) are realistic baselines — universal targets ignore local ecological and climatic context [20]. Second, a 2025 comparison of five prioritization tools in Austin found that while all converge on the same disadvantaged side of the city, the *top-ranked* neighborhoods differ across tools; the authors advise understanding a tool's construction before using it and endorse no tool as universally superior [24]. We therefore present our score's construction in full (Section 4.5) and recommend triangulating its top ranks against local knowledge before committing funds.

Crucially for this study: as of August 2026, official TES adaptations exist for the US, UK, and Toronto only. The closest desert deployments are Phoenix and Tucson, both under the US 15% desert baseline [26]. **We found no published TES-style adaptation for any hot-desert (BWh) country** — the research gap this paper addresses.

3.3 Benchmarks: what "enough green space" means

Several international benchmarks recur in this field, and it is worth stating precisely which are sound:

- **3-30-300 rule** (Konijnendijk, 2021–2022): every home should see 3 trees, sit in a neighborhood with ≥30% canopy, and be within 300 m of green space [27]. In a

Barcelona test only 4.7% of the sampled population met all three components [28]; in a semiarid Mexican city, only **0.2% of neighborhoods** reached the 30% component, with the authors questioning whether standardized thresholds should apply across climates [35]. The 30% component is a forest-biome number; for Buraydah we treat 3-30-300 as an aspiration for the access component (300 m), not the canopy component.

- **WHO guidance**: green space of at least 0.5–1 ha within 300 m linear distance of every home [29].
- **The "WHO 9 m² per capita" figure**: this widely repeated number is a **citation myth — it is not traceable to any WHO document** [30]. Its origin is uncertain (variously attributed to 1968 Italian planning standards and to later report chains); the false attribution to WHO is the verified fact. We use 9 m²/capita in charts only as a "widely used convention," never as a WHO standard, and we benchmark instead against Green Riyadh's official 28 m²/capita target [5].
- **SDG indicator 11.7.1** measures the share of built-up area that is open public space, with access measured within 400 m; UN-Habitat's ideal allocation is 45–50% of urban land to streets and open public space [31].
- **Green cover as % of city area**: Green Riyadh's 1.5% → 9% [5] is the operative national benchmark, and the one we adopt as the goal in our score.

3.4 Green equity in Saudi cities

A young but consistent Saudi literature documents that green space in the Kingdom's cities is still limited by international benchmarks and unevenly distributed within cities. In Riyadh, a 2026 GIS-and-survey assessment found green space growing since 2018 but unevenly distributed, with the least-served district below 1 m² per capita [32]. In Jeddah, per-capita public green space was measured at just 0.5 m² (versus 1.18 m² in Riyadh and 5.4 m² in Dammam) [33]; a 2025 study documents a classic "luxury effect," with extensive green space in wealthy northern districts and limited access in southern ones, and green-rich areas up to 4.8°C cooler [34]. In Al-Khobar, a 2025 spatial-justice analysis of community parks reported more than twenty neighborhoods without park access [52]. All of these studies use per-capita and accessibility metrics; **none constructs a composite gap-times-priority score**, and none addresses Buraydah.

Saudi remote-sensing studies add two technical warnings taken up in Section 4. First, vegetation indices in arid cities operate in a compressed range — citywide maximum NDVI in Riyadh was only 0.43–0.51 [36]. Second, the familiar assumption that greener areas are cooler does not transfer simply to deserts: NDVI–LST correlations in arid settings are weak, seasonal, and can reverse sign [40], with Jeddah showing an essentially zero citywide NDVI–

LST correlation (r = 0.049) while built-up density correlated strongly with heat [37], and Al-Khobar showing a consistently *positive* NDVI–LST correlation [38]. Arid cities also frequently exhibit a **daytime surface "cool island"**: the irrigated, built city can be cooler at midday than the bare desert around it, while the nighttime heat island remains positive [41]. The practical consequences: compare districts to each other, never to open desert; use summer daytime LST as an exposure measure in its own right rather than assuming it is a linear function of greenness; and prefer soil-adjusted indices for sparse vegetation (Section 4.3).

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4. Data and Methods

The analysis pipeline is deliberately simple, fully automated, and built from free, openly documented sources. Figure 10 summarizes the flow; every parameter is stated below and recorded in the project's machine-readable metadata.

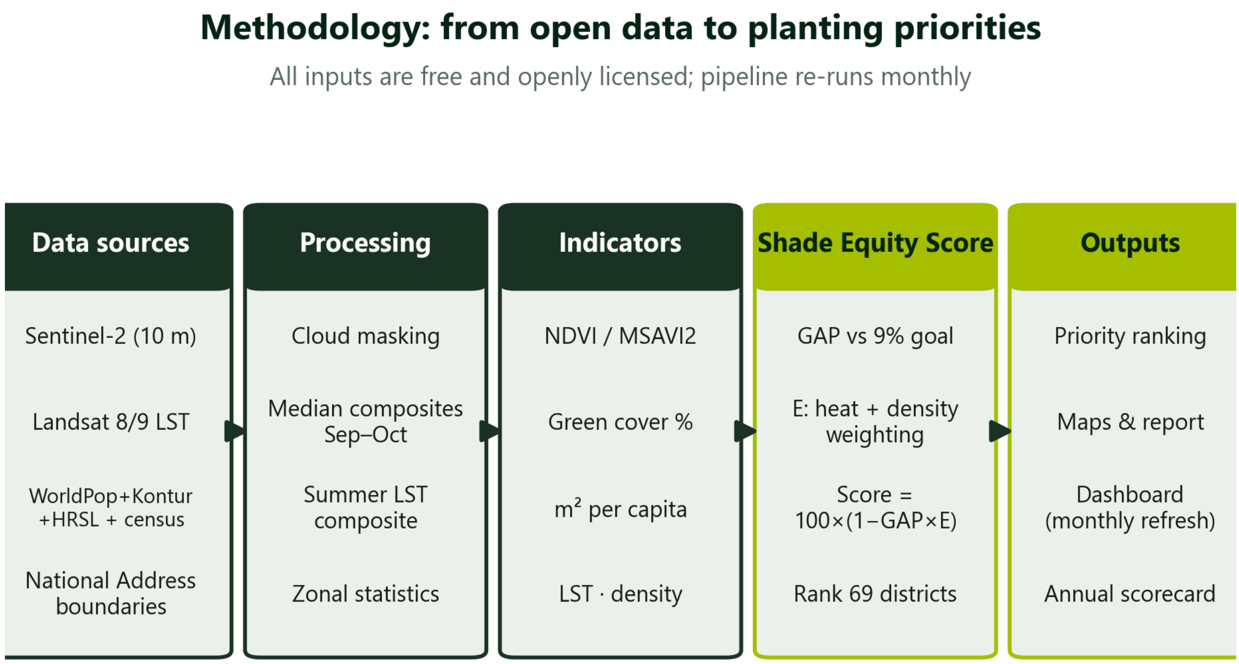

Figure 10: Methodology flow — open data sources, processing, indices, and score.

4.1 District boundaries

District polygons come from the open **Saudi-Arabia-Regions-Cities-and-Districts** repository (GPL-2.0), whose data were collected from the National Address platform (maps.address.gov.sa) [46]. Filtering to Buraydah (city_id 11) yields exactly **69 district polygons** with Arabic and English names. The snapshot dates from January 2022 and therefore predates any later district renaming or boundary changes; this vintage is accepted as matching the 2022 census period. Processing used UTM zone 38N (EPSG:32638). All 69 polygons passed through a geometry-validation step as part of the pipeline's quality-assurance workflow: one polygon (Khub Ath Thanyan, 10400011034) carried an invalid self-intersecting ring in the source data, which the audit detected and repaired (standard `make_valid`/zero-buffer correction, restoring its true 1.73 km^2 area) before zonal statistics were computed. No estimated or filled values remain in the published table.

4.2 Population

No district-level census population is publicly released in Saudi Arabia — the finest public level is the city [47]. District populations were therefore estimated from gridded-population models — and, because any single model can carry local artifacts, from an **ensemble of three independent sources** rather than one: the **WorldPop constrained 2020 grid (100 m, Built-Settlement Growth Model / BSGM constrained variant)** [48], which allocates people only to detected settlement pixels — essential in a desert, where unconstrained grids smear population into uninhabited land; the **Kontur Population dataset (November 2023 release, 400 m H3 hexagons)** [53], area-weighted onto the district polygons; and the **Meta/CIESIN High Resolution Settlement Layer (HRSL, 2020, ~30 m)** [54]. Each source's district shares were rescaled so its city total equals the official **2022 census figure of 571,169** [16] — mirroring WorldPop's own national adjustment method — and the ensemble takes the mean of the three rescaled shares, renormalized to exactly 571,169. A fourth candidate, GHS-POP, was evaluated and excluded as a clear outlier against every other source ($r \le 0.75$; mean absolute share deviation ≈ 62%, with implausible extremes in the palm-grove districts). The three retained sources agree well at district level (pairwise $r \approx 0.89$–0.91 for the independent pairs), and the ranking computed from the ensemble is nearly identical to a WorldPop-only ranking (Spearman $\rho = 0.995$); the full triangulation is documented in the study's internal annex and summarized in Figure 19. The residual uncertainty this introduces at district level is discussed honestly in Section 6.6.

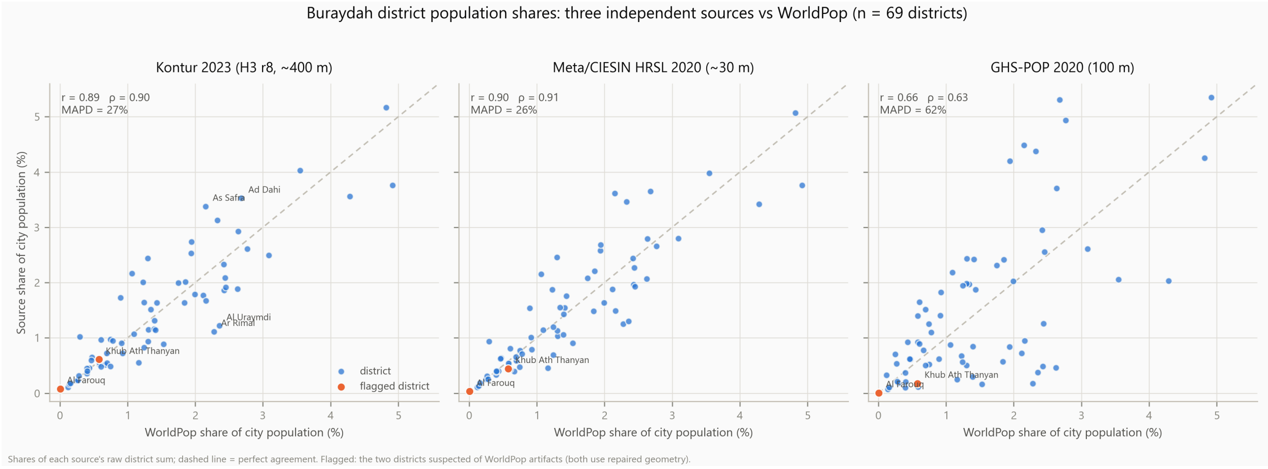

Figure 19: District population triangulation — each source's district share of the city population plotted against WorldPop's (n = 69; dashed line = perfect agreement). The two independent building-based sources track WorldPop closely (r ≈ 0.9), while GHS-POP (right) is the discordant outlier excluded from the ensemble (validation annex figure).

4.3 Vegetation mapping (Sentinel-2, 10 m)

Vegetation was mapped from **Sentinel-2 Level-2A surface reflectance** at 10 m resolution, accessed through the free Earth Search STAC API on AWS Open Data [44]. Following the arid-zone seasonal logic established in the remote-sensing literature for central Saudi Arabia, the **primary window is September 1 – October 31**: by early autumn the ephemeral spring vegetation has senesced and dust activity is at its seasonal low, so **only irrigated urban greenery remains green** — making this the cleanest possible window for measuring exactly the thing a municipal planting program creates, and the natural anniversary window for year-on-year comparison [43]. (Spring composites are useful for total greenness but overlap the February–June dust season, which peaks nationally in April [43], and so require aggressive compositing; they are used in this project's dashboard as secondary layers only.)

For 2025, 30 scenes across 8 cloud-screened dates (6 September – 29 October) were mosaicked and median-composited; for the 2019 baseline, 29 scenes across 8 dates (11 September – 31 October). The year 2019 was chosen as the baseline because it is the first year for which fully corrected Sentinel-2 Level-2A imagery is available at full quality — giving the longest possible comparison span under the identical methodology. Clouds, shadows, and defective pixels were masked using the Scene Classification Layer, and the post-2022 Sentinel-2 radiometric offset was handled explicitly so that 2019 and 2025 reflectances are comparable. In addition, a **water mask** excludes pixels with negative median NDVI — open water, including a newly formed lake in Al Khuzama district — from all district statistics, so that water bodies distort neither the vegetation fractions nor the surface-temperature means (Section 4.4).

Two indices were computed per 10 m pixel:

- **NDVI** — the standard normalized difference vegetation index, retained for comparability with the Saudi literature. A pixel is counted as *green* when **NDVI > 0.25**, a deliberately conservative cutoff within the conventional 0.2–0.3 range for arid urban areas, chosen to exclude bright-soil noise [42]. Each district's **green fraction** is the percentage of its pixels above this threshold.
- **MSAVI2** — a soil-adjusted index that self-calibrates for the bright desert soil background that inflates and destabilizes NDVI at sparse cover [45]. MSAVI2 means are reported per district as the more robust intensity measure.

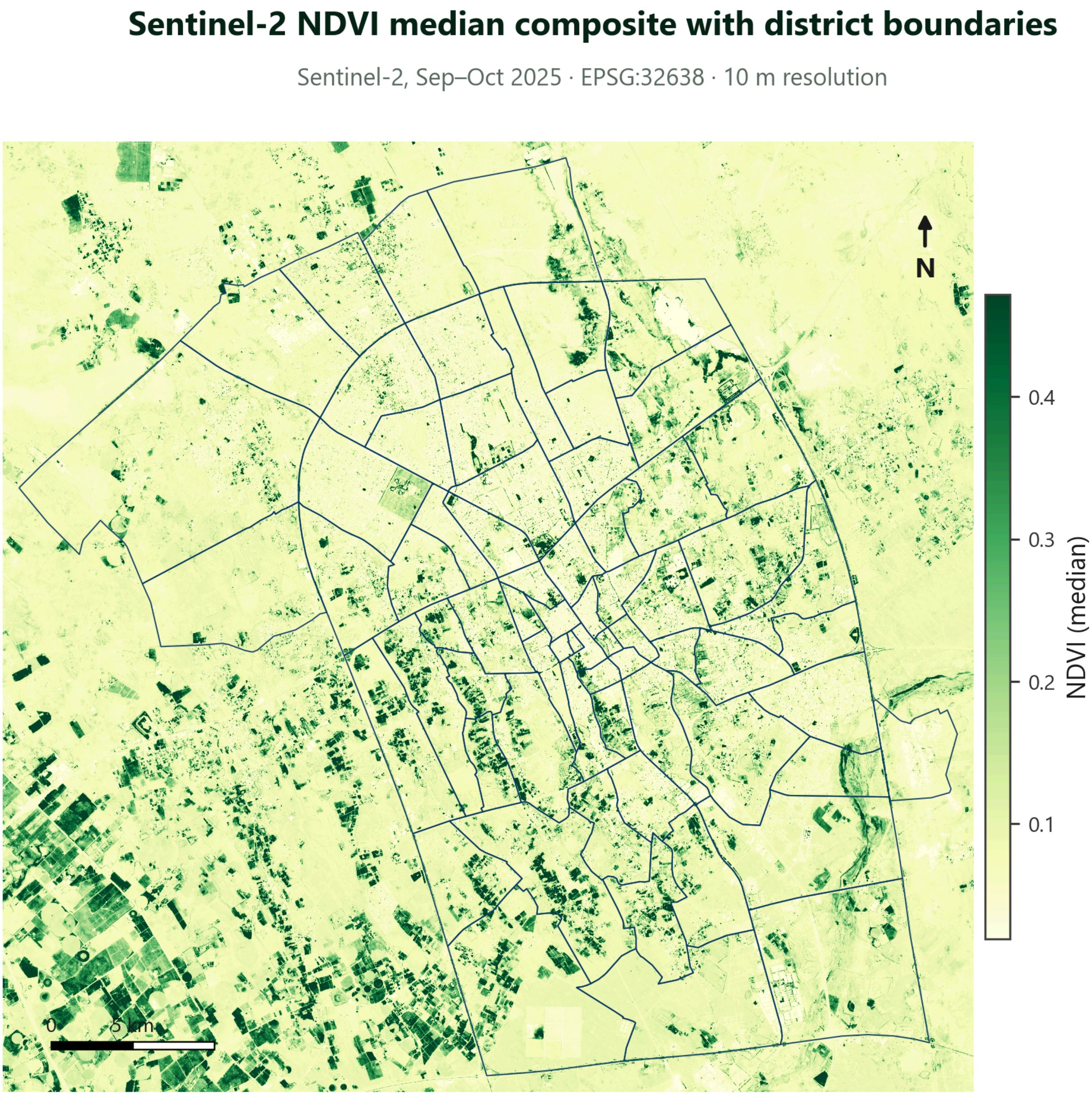

Figure 12: September–October 2025 NDVI composite over Buraydah (Sentinel-2, 10 m).

4.4 Summer heat mapping (Landsat, 30 m)

District heat exposure was measured from the **Landsat 8/9 Collection 2 Level-2 Surface Temperature product** (band ST_B10, delivered at 30 m), accessed through the Microsoft Planetary Computer STAC API [44]. All 34 low-cloud scenes from **1 June – 31 August 2025** were composited (overpass ≈ 10:30 local time); digital numbers were converted to temperature using the standard USGS scale factors and quality-masked before averaging [44]. Open-water pixels identified by the vegetation water mask (Section 4.3) are excluded from the district LST means, since water surfaces read far cooler than the streets around them and would bias any district containing a lake. Each district receives its mean summer land-surface temperature (LST) and its deviation from the population-weighted citywide mean (54.2°C; Section 5.2). Two points of interpretation, both from the arid-cities literature, are carried through the paper: LST is the temperature of *surfaces*, not of the air people feel (surfaces at midday run far hotter than air), and daytime surface patterns in desert cities can invert intuitions formed in temperate ones [40][41]. LST is used here strictly as a *relative* exposure ranking across districts under identical conditions. Heat is deliberately measured at the summer peak: that is the season in which heat harms people and in which shade is meant to relieve them, and the within-season stability of the thermal ranking has been verified (Section 6.4, E6).

4.5 The Shade Equity Score

The score is one formula, adapted from the Tree Equity Score [18][19] and computed identically for all 69 districts. We state it in full:

Step 1 — Goal. Every district's green-cover goal is **9%** of its area, adopting Green Riyadh's citywide target [5] rather than the US desert-biome baseline of 15% [18]. The reasoning: 9% is the nationally validated, irrigation-costed benchmark for a Saudi desert capital; the American 15% desert figure was calibrated to Sonoran-desert cities with different water arrangements, and American Forests itself warns against transplanting canopy targets across contexts [20]. The score's sensitivity to this choice is examined in Section 6.4.

Step 2 — Gap. For each district *i*: $GAP_i = \max(0, 9 - green\_frac_i)$, then **$GAPscore_i = \min(1, GAP_i / 9)$** — the gap divided by the 9% goal itself, capped at 1. This *fixed-goalpost* normalization (a distance-to-target device in standard composite-indicator practice [55][56]) anchors the scale to the policy goal rather than to whichever district happens to carry the city's largest gap in a given year, making scores comparable across years and across cities that share the goal; the equation-validation study (Section 6.5) verified that within Buraydah it is exactly rank-invariant (Spearman $\rho = 1.000$ against the city-relative alternative). GAPscore is a 0–1 fraction.

Step 3 — Priority index. E is built from the two need indicators that are both *measurable from open data* and *defensible in the Saudi context*:

- **Summer heat** — the district's mean summer LST (Section 4.4), min–max normalized across the city. Hotter districts need shade more urgently. This is the direct analogue of TES's "heat severity" indicator, its strongest transferable component.
- **Population density** — residents per km², min–max normalized. Denser districts put more people within reach of each planted tree.

E = 0.1 + 0.9 × mean(LST_norm, density_norm), retaining the TES v2 floor of 0.1 so that no district's need is ever zeroed out [19].

The US indicators we **dropped, and why**: *race* has no Saudi analogue (the census records nationality, not race, and using nationality as an equity axis would be ethically fraught); *income below the poverty line* does not exist as small-area public data in Saudi Arabia; *health burden* has no open district-level morbidity source. Rather than approximate these with weak proxies, we restrict the priority index to two variables that are directly measured, transparent, and meaningful to a heat-stressed desert city. This is the same pattern the UK followed when it dropped race and substituted air quality on adaptation [22]: the formula travels; the indicators localize.

Step 4 — Score and rank. Shade Equity Score = round(100 × (1 − GAPscore × E)). A district at or above the 9% goal scores 100. **The lower the score, the higher the planting priority.** Districts are then ranked sequentially and uniquely from 1 to 69 by the **exact score before rounding**: displayed scores are rounded to integers for readability, which is the only reason two districts can show the same number, while the ranking follows the precise underlying values — so no rank number repeats and no secondary criterion is needed.

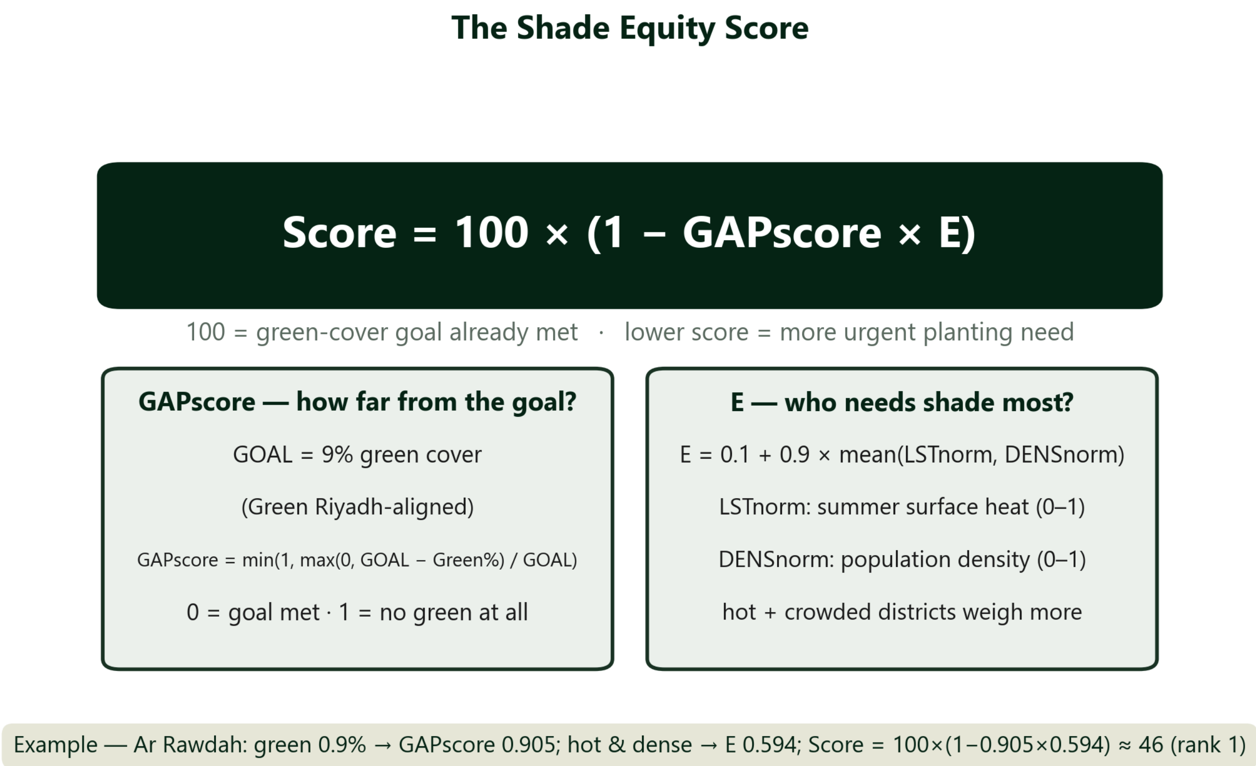

Figure 11: The Shade Equity Score — one formula, four ingredients.

That is the entire method. It contains no weights to tune, no black-box model, and no data a reviewer cannot download. A change of 2019 baseline green fraction (same window, same thresholds) supports trend reporting, and the recommended monitoring cadence is an **annual scorecard computed from the September–October window plus the summer LST composite** — matching Qassim Green Land's October planting phase — with monthly dashboard refreshes treated as indicative only (Section 7), and multi-year trends interpreted cautiously until roughly ten annual observations accumulate [43].

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5. Results

5.1 Citywide picture

Across the 69 districts (total analyzed area ≈ 444 km^2), vegetated cover in September–October 2025 was **6.71% of district area** (area-weighted; the unweighted district mean is 7.3%). Buraydah therefore sits **2.29 percentage points below the 9% goal** adopted from Green Riyadh — closer to the goal than Riyadh's 1.5% starting point, unsurprisingly for a city embedded in an agricultural oasis, but clearly short of it. **50 of 69 districts are below the 9% goal**, and those districts house about **427,000 people — 74.8% of the city's population**. At the severe end, **18 districts have less than 3% green cover**; roughly **158,000 residents (27.7% of the city)** live in them.

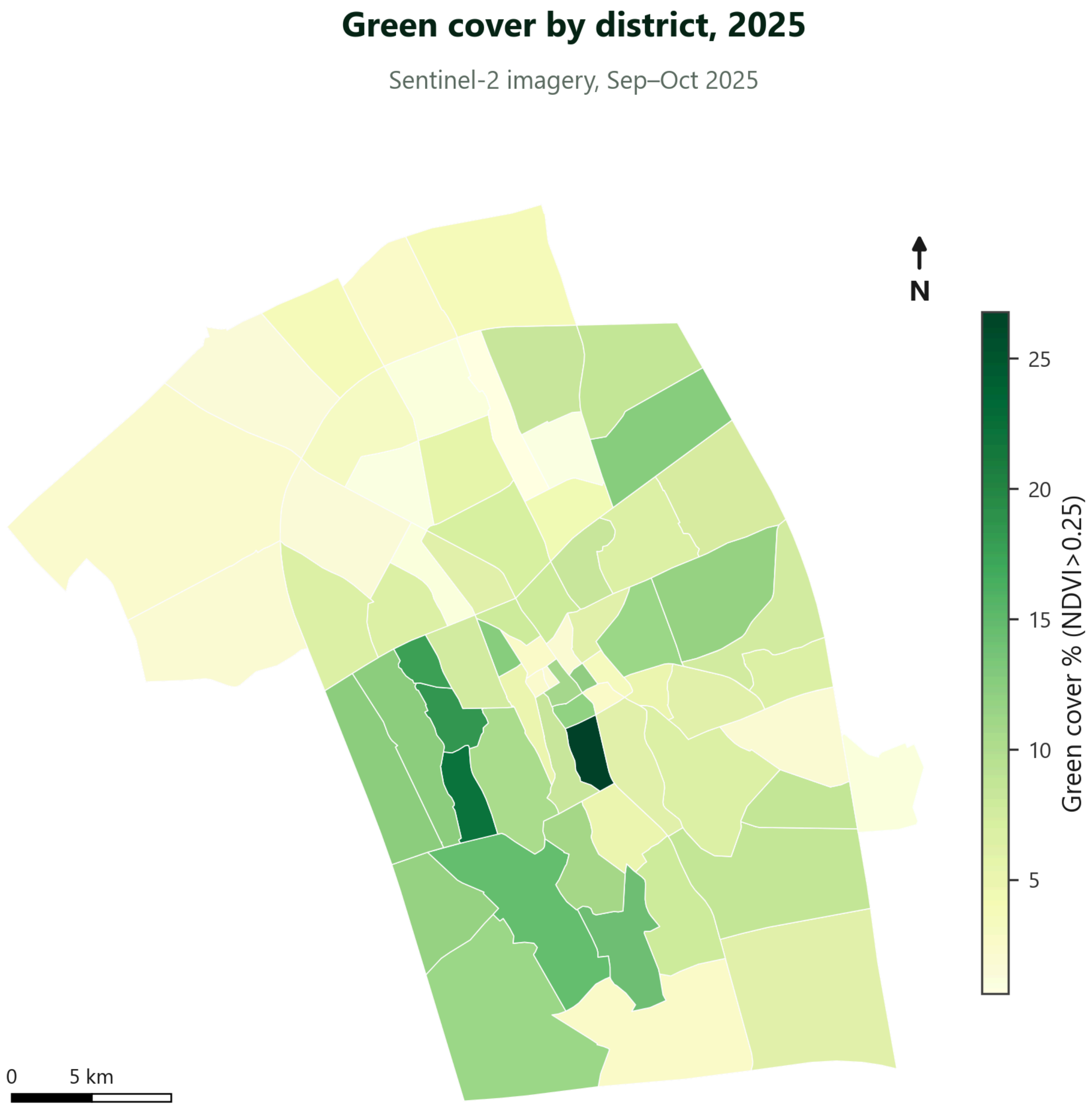


Figure 3: Green cover by district, September–October 2025 (percent of district area with NDVI > 0.25).

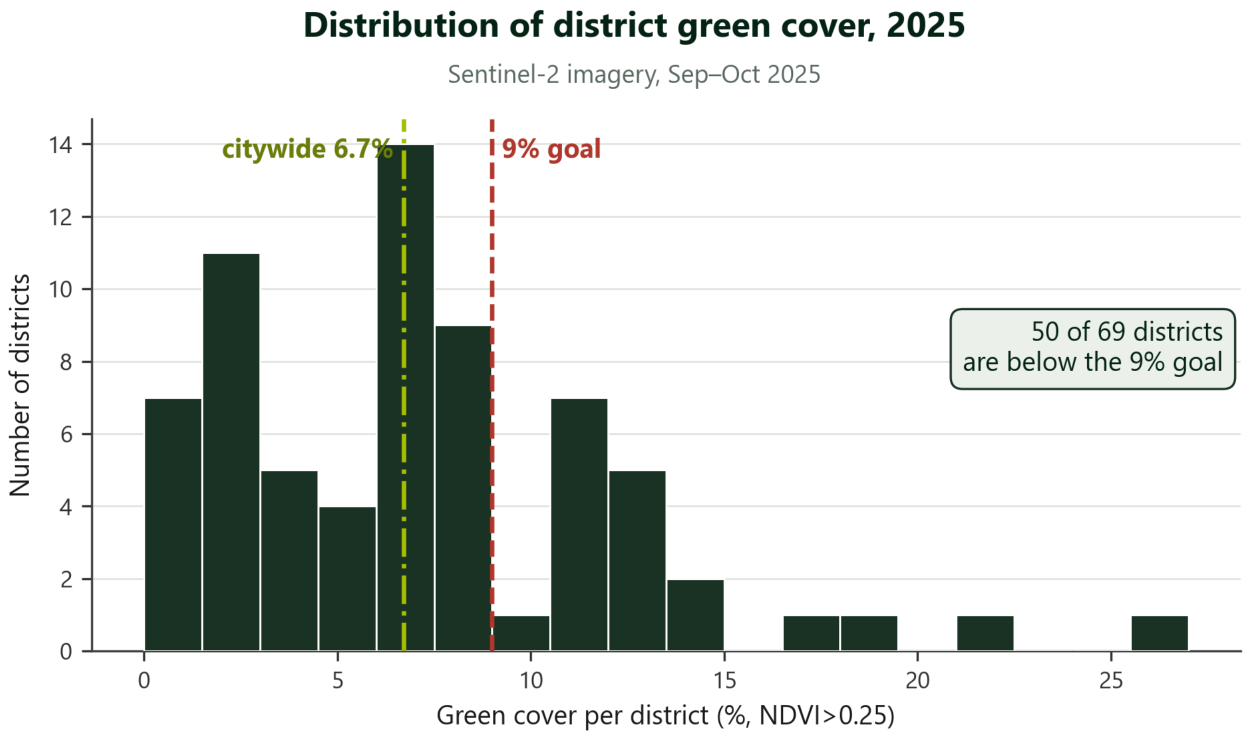


Figure 6: Distribution of district green cover, with the 9% goal marked.

The distribution is strongly skewed (Figure 6). The greenest districts are those that contain agricultural land within their boundaries — As Sabbakh (26.8%), Huwailan (22.3%), Khub Al Buraydi (18.5%), Khub Ath Thanyan (17.6%) — while a long tail of dense residential districts sits below 3%. The minimum is Al Ufuq at 0.64%.

5.2 Summer heat

Mean summer 2025 daytime LST ranges from **51.1°C (Al Khabib) to 58.0°C (Al Yarmouk)** across districts — a spread of nearly 7°C within one city under identical weather. The population-weighted citywide mean is 54.2°C. These are surface temperatures at the ~10:30 satellite overpass, not air temperatures; but a nearly 7°C spread in surface heat load is a material difference in what residents' streets, roofs and courtyards absorb and re-radiate.

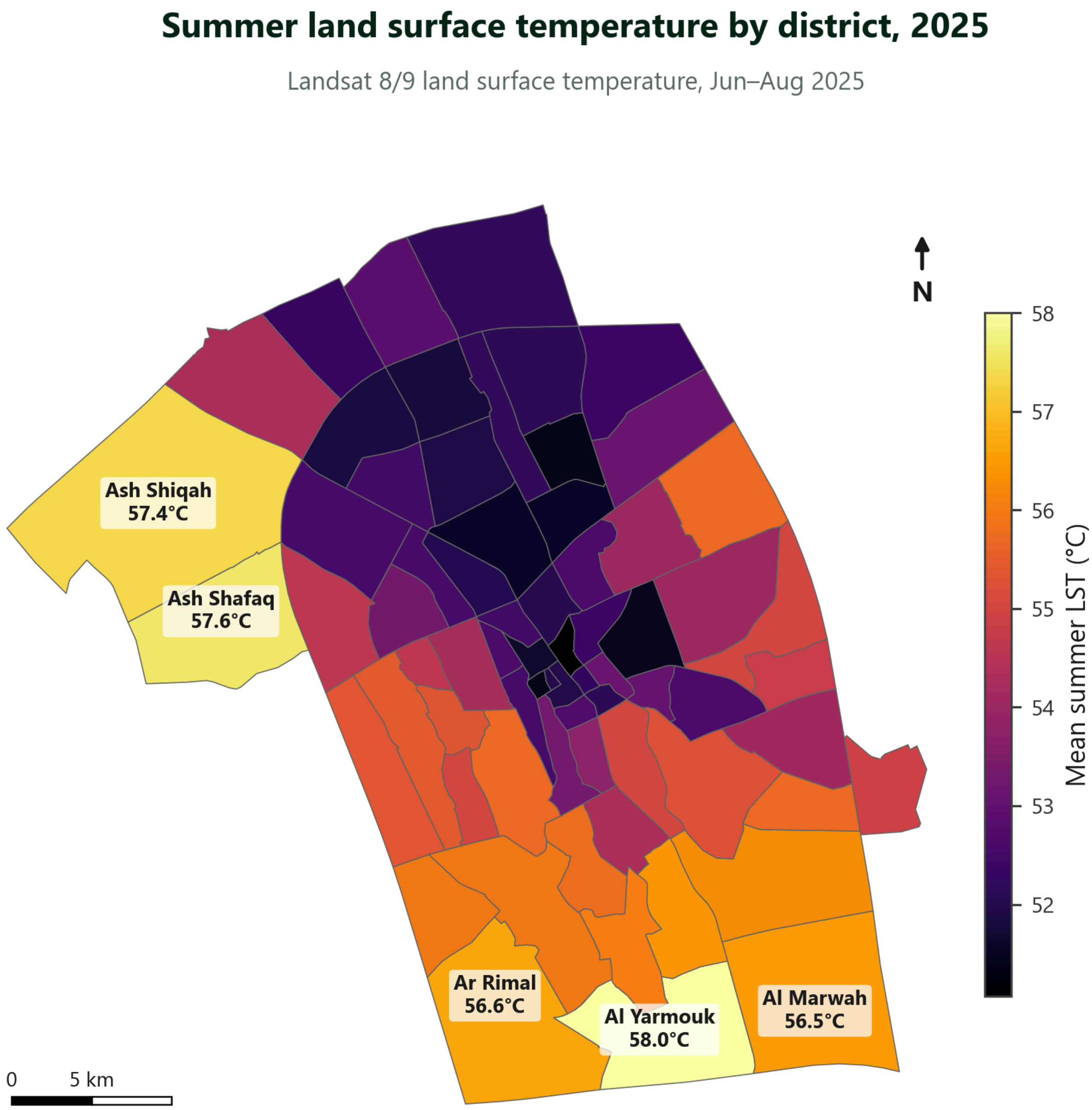


Figure 4: Mean summer land-surface temperature by district, June–August 2025 (Landsat 8/9).

The spatial pattern deserves careful reading, because it confirms the arid-cities caveat flagged in Sections 3.4 and 4.4. Across districts, greener does **not** mean cooler in the daytime surface data: the computed correlation between district green fraction and mean LST is weakly **positive** (r ≈ +0.27, and +0.51 against mean NDVI), while **denser districts are cooler** (r ≈ −0.45 against population density). The hottest districts (Al Yarmouk, Ash Shafaq, Ash Shiqah, all >57°C) are large, low-density peripheral districts containing extensive bare ground, whose exposed soil bakes at midday; several of the coolest districts are compact built-up neighborhoods whose roofs, shade and thermal mass read cooler at the overpass hour. This is the documented desert pattern — weak or inverted daytime NDVI–LST relationships and a daytime surface cool-island tendency [40][41][38] — observed locally in Buraydah's own data. It does not mean vegetation fails to cool (the Buraydah-specific evidence is that it cools strongly, by ~4.5°C at vegetated sites [39]); it means bare desert soil is the hottest surface of all, and that district mean LST must be treated as a measure of *exposure*, not as a simple inverse of greenness. This is exactly why the score uses LST as an independent priority indicator rather than assuming it follows from the green fraction.

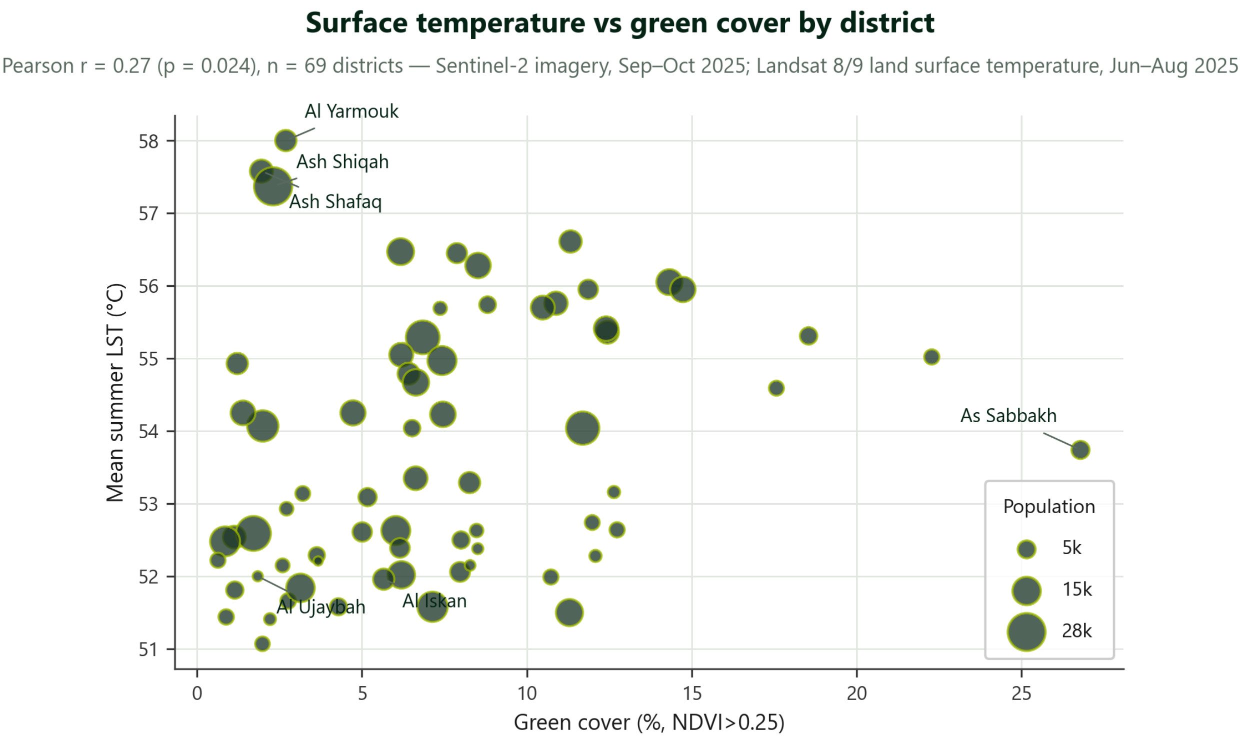
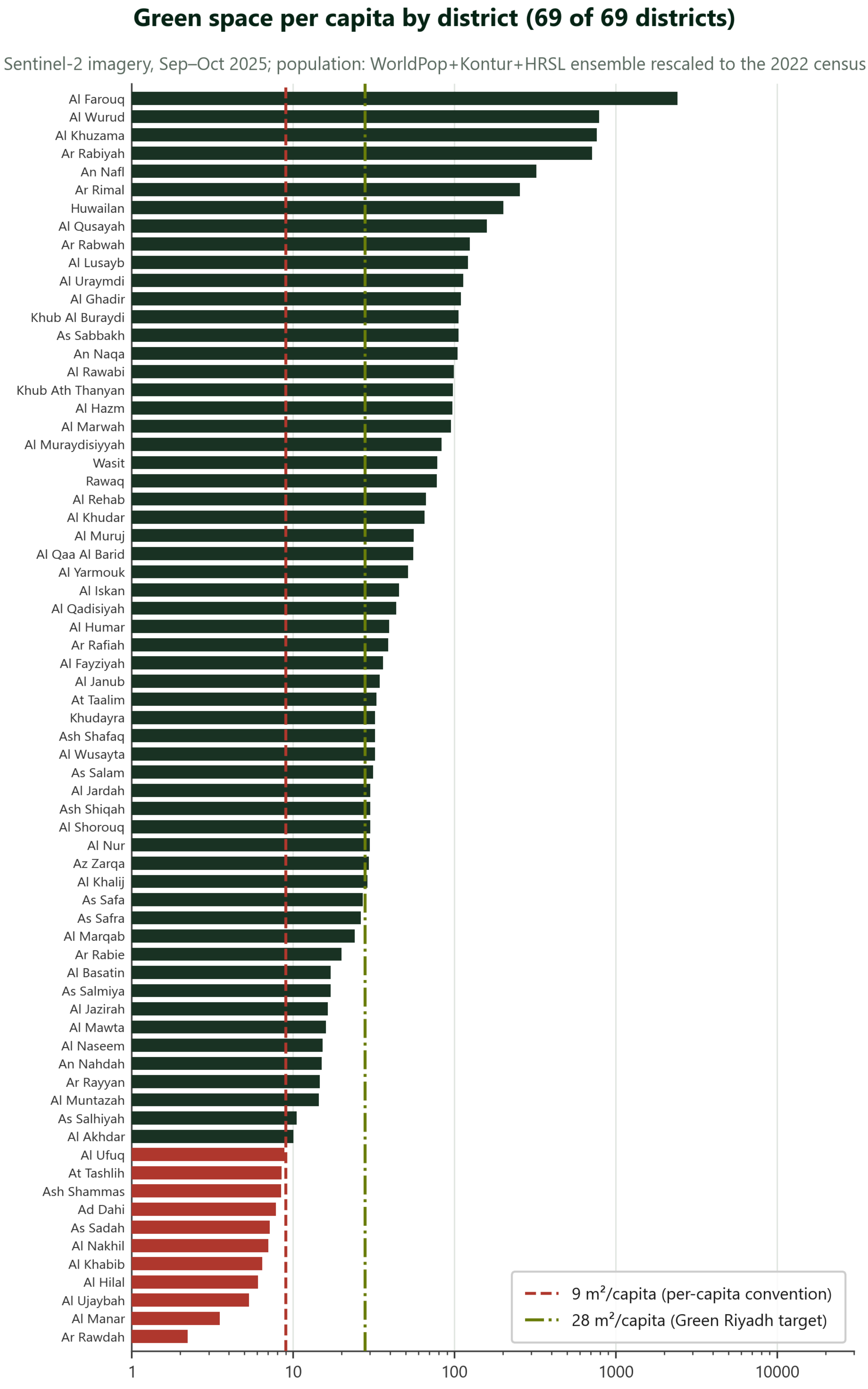


Figure 7: District mean summer LST versus green cover (bubble size = population). The relationship is weak and slightly positive — the documented arid-city pattern.

5.3 Per-capita green space — and how *not* to read it

Dividing each district's vegetated area by its estimated population yields the per-capita figures in Figure 8. Citywide, the number is **52.2 m² of vegetation per resident** — comfortably above Green Riyadh's 28 m² target and the (apocryphal) "9 m² convention."

This number must not be read as green-space provision. The satellite measures *all* vegetation, and in Buraydah a large share of it is **private palm groves and farms inside district boundaries** — precisely the in-city farmland UN-Habitat describes as "private and inaccessible," compounding rather than relieving the public open-space deficit [12, p. 82]. The distortion is visible in the data: agricultural districts post per-capita values in the hundreds of square meters (Al Wurud 789 m², Al Khuzama 763 m², Ar Rabiyah 712 m²), and the extreme case of Al Farouq — a 14 km² northern-edge district whose sparseness is genuine, with all three population sources agreeing on an estimate of roughly 218 residents — posts a statistically meaningless 2,419 m². Meanwhile **eleven populated districts fall below even 9 m² per resident of *total* vegetation** — public or private — and about 39% of the city's population lives in districts below the 28 m^2 line. The honest summary is: *Buraydah as a whole contains substantial vegetation per resident, but it is concentrated in private agricultural land; the public, accessible green space that per-capita benchmarks are meant to measure remains scarce and fragmented, exactly as UN-Habitat found* [12, p. 98]. A proper public-green-space per-capita figure would require a parks inventory, which does not yet exist for the city (regional press reports suggest on the order of 57–72 parks and squares, but no official registry has been published); building one is among our recommendations.


Green space per capita by district (69 of 69 districts)
Sentinel-2 imagery, Sep–Oct 2025; population: WorldPop+Kontur+HRSL ensemble rescaled to the 2022 census
Al Farouq
Al Wurud
Al Khuzama
Ar Rabiyah
An Nafl
Ar Rimal
Huwailan
Al Qusayah
Ar Rabwah
Al Lusayb
Al Uraymdi
Al Ghadir
Khub Al Buraydi
As Sabbakh
An Naqa
Al Rawabi
Khub Ath Thanyan
Al Hazm
Al Marwah
Al Muraydisiyyah
Wasit
Rawaq
Al Rehab
Al Khudar
Al Muruj
Al Qaa Al Barid
Al Yarmouk
Al Iskan
Al Qadisiyah
Al Humar
Ar Rafiah
Al Fayziyah
Al Janub
At Taalim
Khudayra
Ash Shafaq
Al Wusayta
As Salam
Al Jardah
Ash Shiqah
Al Shorouq
Al Nur
Az Zarqa
Al Khalij
As Safa
As Safra
Al Marqab
Ar Rabie
Al Basatin
As Salmiya
Al Jazirah
Al Mawta
Al Naseem
An Nahdah
Ar Rayyan
Al Muntazah
As Salhiyah
Al Akhdar
Al Ufuq
At Tashlih
Ash Shammas
Ad Dahi
As Sadah
Al Nakhil
Al Khabib
Al Hilal
Al Ujaybah
Al Manar
Ar Rawdah
9 m²/capita (per-capita convention)
28 m²/capita (Green Riyadh target)
1
10
100
1000
10000

Green space per capita (m², log scale)

Figure 8: Vegetated area per resident by district, with the 28 m² (Green Riyadh target) and 9 m² (convention of uncertain provenance) lines. Values include private farmland and must not be read as public green-space provision.

5.4 The Shade Equity Score and the priority ranking

Scores range from **46 to 100**, with a median of 89. Nineteen districts meet or exceed the 9% goal and share the top score of 100, and the ten districts at the head of the priority ranking score between 46 and 62. Ranks are sequential and unique (1–69), following the rule of Section 4.5: the ordering tracks the exact score before rounding, and rounding for display is the only reason two districts can show the same score. Following the robustness analysis (Section 6.4), which shows that the *exact* composition of any top-10 list is sensitive to defensible alternative indicator weightings while the ranking as a whole is stable, we present the **ranked list as the operational roadmap**, to be worked from the top downward. One caution carries through: adjacent districts whose scores differ by only a few points are statistically near-tied — the validation shows that exact ordering near the top is sensitive to reasonable parameter choices — so neighboring ranks may be treated as equal priority when that is operationally convenient. The Monte Carlo analysis of Section 6.5 quantifies this caution district by district: the top-10 table below therefore carries a **P(top-10)** column — the probability, across 3,000 joint perturbations of the measurements, the weights, and the formula itself, that the district belongs in the top ten — and three districts (Ar Rawdah, Al Manar, Ad Dahi) are top-10-certain at $P > 0.92$, while the rest of the band is genuinely borderline and should be read as such. The full 69-district table accompanies this paper as open data; Figure 5 maps the scores.

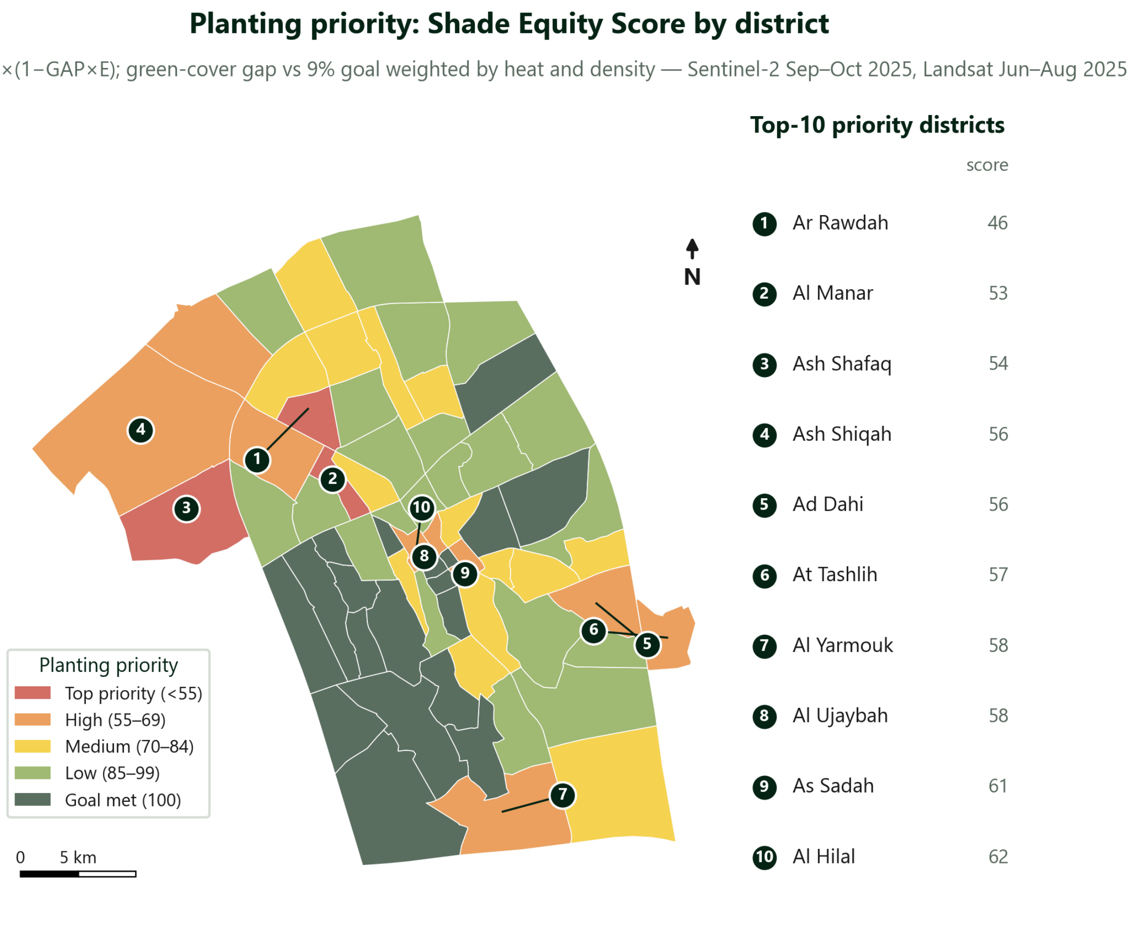


Figure 5: Shade Equity Score by district (lower = higher planting priority), with the top-10 priority districts labeled.

The top of the ranking is shown below. The six lowest-scoring districts together house about **91,000 residents (16% of the city)**, and the top of the list splits cleanly into the method's two structural types: *dense central districts* with almost no vegetation (Ar Rawdah, Al Manar, Ad Dahi) and *hot peripheral districts* whose daytime heat exposure is extreme (Ash Shafaq, Ash Shiqah, At Tashlih).

Rank	District	Score	P(top-10)	Green cover	LST (Δ from city mean)	Density (p/km²)	Population
1	Ar Rawdah (الروضة)	46	99%	0.9%	52.5°C (−1.7)	3,835	16,974
2	Al Manar (المنار)	53	96%	1.1%	52.5°C (−1.6)	3,219	9,201
3	Ash Shafaq (الشفق)	54	76%	2.0%	57.6°C (+3.4)	609	9,442
4	Ash Shiqah (الشقة)	56	74%	2.3%	57.4°C (+3.2)	768	28,668
5	Ad Dahi (الضاحي)	56	93%	2.0%	54.1°C (−0.1)	2,553	18,767
6	At Tashlih (التشليح)	57	88%	1.2%	54.9°C (+0.8)	1,439	7,876
7	Al Yarmouk (اليرموك)	58	62%	2.7%	58.0°C (+3.8)	521	7,915
8	Al Ujaybah (العجيبة)	58	75%	1.8%	52.0°C (−2.2)	3,461	635
9	As Sadah (السادة)	61	63%	2.6%	52.2°C (−2.0)	3,622	2,455
10	Al Hilal (الهلال)	62	47%	2.2%	51.4°C (−2.8)	3,661	1,400

Displayed scores are rounded to integers; the ranking follows the exact score before rounding, which is why adjacent districts can show the same displayed score. P(top-10) is the probability of top-10 membership across the 3,000-draw Monte Carlo uncertainty analysis of Section 6.5.

Brief profiles of the leading districts:

- **Ar Rawdah (rank 1, score 46)** — the clear leader and most consequential entry: 16,974 residents at ~3,800/km² with just **0.9% green cover and 2.2 m² per**

resident, the lowest green cover of any district of more than 10,000 residents. A flagship candidate for the pilot.

- **Al Manar (rank 2, score 53)** — 9,201 residents, 1.1% cover, 3.5 m² per resident; the same dense, low-canopy profile as Ar Rawdah at smaller scale.
- **Ash Shafaq (rank 3, score 54)** — the other type: a large (15.5 km²) southern district of 9,442 people whose mean LST of **57.6°C is 3.4°C above the city mean** — among the hottest inhabited districts in the city. Its 32.1 m² per resident shows how large bare-land districts can look "adequate" per capita while offering little usable shade; here heat exposure, not density, drives the priority.
- **Ash Shiqah (rank 4, score 56)** — the largest population in the top six: **28,668 residents** across 37.4 km², with 2.3% cover and a mean LST of 57.4°C (+3.2). Per tree planted, few districts would shade more residents.
- **Ad Dahi (rank 5, score 56)** — 18,767 residents, 2.0% cover, 7.8 m² per resident: a populous district combining a large green gap with near-average heat, bridging the central belt and the southern exposure zone.
- **At Tashlih (rank 6, score 57)** — 7,876 residents, 1.2% cover, and hotter than the city mean (+0.8°C); an industrial-margin profile combining low greenery with elevated heat.

Next on the list sit **Al Yarmouk** (rank 7, score 58), **Al Ujaybah** (rank 8, score 58), **As Sadah** (rank 9, score 61), **Al Hilal** (rank 10, score 62), and **Al Nakhil** (rank 11, score 63) — the natural continuation of the roadmap, and a live illustration of why neighboring ranks should be read as near-ties: the validation analysis (Section 6.4) shows that ordering at exactly these margins swaps under defensible alternative weightings and from one annual snapshot to the next. Al Ujaybah (0.18 km², 1.8% cover, 5.3 m² per resident, and a *declining* trend since 2019), As Sadah, and Al Hilal extend the dense central belt — each under 1 km², at 3,400–3,700/km² — consistent with UN-Habitat's finding that the green-space shortage is most acute in the central districts [12, p. 98]; Al Yarmouk, whose 58.0°C mean is the city's hottest district surface, extends the exposure belt.

The composite behaves as designed: it elevates both the dense, low-canopy type (which a heat-only ranking would miss, since central districts read relatively cool at the satellite's morning overpass) and the extreme-heat type (which a greenness-only ranking would miss). This complementarity between the gap term and the priority term is the practical argument for a composite score over any single metric.

5.5 Change 2019 → 2025

Comparing identical September–October windows six years apart: **38 districts gained green cover and 31 lost it**, with district changes ranging from **−9.9 to +6.4 percentage points**. Area-weighted citywide cover moved from 7.4% (2019) to 6.71% (2025) — a modest net *decline* of about 0.7 points, driven by large losses in a handful of big agricultural districts (Al Marwah −9.9 pp, Al Ghadir −6.7, An Naqa −6.6, Ar Rabwah −6.3) that are consistent with farmland conversion or fallowing — echoing UN-Habitat's warning that in-city farms are "increasingly fragmented" [12, p. 86]. The largest gains (Al Rawabi +6.4, At Taalim +5.6, Ar Rimal +3.7) are consistent with new development landscaping and planting programs. Interannual agricultural variation contributes noise to any two-year comparison, so these figures are presented as descriptive; the direction of the signal, however, is policy-relevant: **municipal planting gains are running alongside, and partly being offset by, losses of agricultural greenery** — precisely the dynamic UN-Habitat's farmland-preservation action (3.1) targets [12, p. 122].

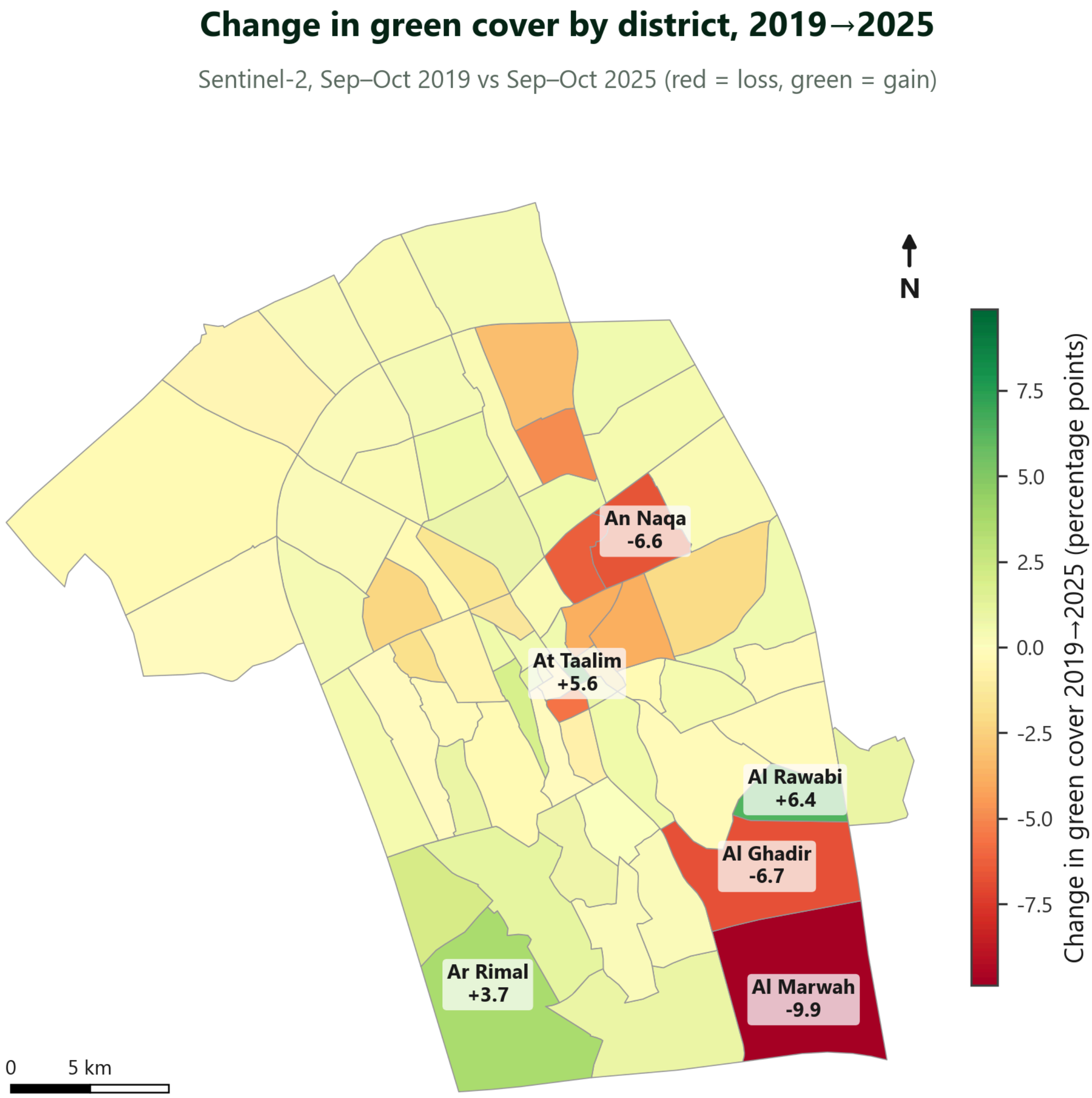


Figure 9: Change in green cover by district, September–October 2019 to September–October 2025 (percentage points).

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6. Discussion

6.1 What the ranking means for Buraydah

Three findings carry direct planning weight.

First, the deficit is concentrated, and therefore tractable. Buraydah does not need to green 444 km² to change most residents' daily experience. The ten districts at the head of the priority ranking score between 46 and 62 (Section 5.4); the six lowest-scoring districts alone contain about 91,000 residents, and the next central districts on the list (Al Ujaybah, As

Sadah, Al Hilal) are each under 1 km². The central priority belt is contiguous, which favors a connected design — linked pocket parks and shaded corridors rather than isolated plots — consistent with UN-Habitat's call for a *hierarchy* of open spaces linking districts [12, pp. 122–123].

Second, the score's two faces demand two products. For the dense central tier, the deliverable is shade where people already are: street trees, shaded sidewalks (explicitly proposed for Buraydah in UN-Habitat's Action 1: "الأرصفة المظللة" [12, p. 118]), courtyard and mosque planting — the same asset-class approach Green Riyadh applies to streets, mosques, and schools [5], and which the Amanah has already piloted with mosque-courtyard greening in Buraydah neighborhoods. For the hot peripheral tier (Ash Shafaq, Ash Shiqah, At Tashlih, and the >57°C belt), the deliverable is cooling mass and dust damping at the urban edge, where the Buraydah Oasis model applies directly.

Third, the change analysis warns that planting alone may not move the citywide number. If agricultural attrition continues at the 2019–2025 pace, municipal planting will be filling a draining basin. UN-Habitat's Action 3.1 (legally binding farmland preservation) and 3.3 (rehabilitating in-fabric farmland as green-blue connectors "with positive urban-climate effects") address the loss side of the ledger [12, pp. 122–123]; a monitoring platform that reports both sides annually (Section 7) makes the trade-off visible to decision-makers.

6.2 Alignment with the UN-Habitat vision

The prioritization maps almost point-for-point onto the *Buraidah Comprehensive Urban Vision*'s Priority Action 3, "preserving natural assets and reconnecting the blue and green networks" [12, pp. 122–123]:

- **White land**: 37% of the built-up area is vacant [12, p. 64], and UN-Habitat recommends selectively reserving white land for green public space, especially in densification zones [12, p. 122]. Several of the highest-priority districts contain vacant parcels where the never-built neighborhood central open spaces [12, p. 122] could finally be delivered; the white-land fee framework provides a policy lever.
- **Wadi linear parks**: reopened wadis are envisioned as "new linear parks citywide" [12, p. 98]. The southern priority districts near Wadi Al-Rummah would gain accessible green space from exactly this intervention.
- **Shaded sidewalks and walkability**: the BRT-and-boulevard action pairs road diets with shaded, rest-equipped sidewalks [12, p. 118] — the fastest way to convert street trees into usable pedestrian shade in the central priority belt.

- **The agro-ecological city**: the report's closing recommendation ("نحو مدينة بريدة الزراعية البيئية") lists reduced urban temperatures and dust capture among the benefits of green space [12, pp. 130–132] — the same outcomes the score is designed to maximize per tree.

to an alarming situation. Buraidah pumps water from the Saq aquifer, whose boundaries and capacities are changing due to its negligent recharge. Data shows that water consumption in the city is about 250 l/day per capita, and is double the average water consumption in developed countries. Shifting this consumption pattern is an urgent concern to ensure the durability of the water supply. The Saq aquifer, which is depleting at an approximate rate of 1.1 million litres per year, provides Buraidah with water-bearing soils. Additionally, the city is edged to the East by Wadi Al Rummah, its primary environmental feature.

Protecting these water features is essential, not only for its ecological importance but also because they support agricultural production, which is the cornerstone of the city's economy. In Saudi Arabia, 30% of the crops and vegetables are produced by greenhouse cultivation. Traditional farming produces the remaining 70%. These conventional farms will be affected by the above-mentioned increase in temperature, the changes in precipitation, the higher evapotranspiration, and the low water reserves. In Buraidah, agriculture is mainly developed within the Development Protection Boundary. Approximately 400 square kilometres of land is currently under cultivation. Now, the leading agriculture technique is through sprinkler irrigations systems, which has proven to be unsustainable. Given the hyper-arid climatic conditions with high rates in air temperature and evapotranspiration, there is a high risk of losing an extensive amount of water.

All of the above showcase the importance of relating the green and blue infrastructure in the city, in a mutually supportive way, to build socio-economic and environmental resilience. For this purpose, the blue and the green system have been mapped. The mapping analysis shows that although the two systems were traditionally linked, due to new development patterns, this is no longer the case. Re-linking blue and green infrastructure systems is, therefore, crucial for a more sustainable future development of Buraidah. Open public spaces could play a key role in supporting the linkages between the blue and green systems. The network of green public areas can become a structural element linked to the water system and hold productive landscape characteristics while increasing the livability of the city.

Fig. 41. Existing green network

Figure: The green and natural network of Buraydah (UN-Habitat Figure 41, "Existing green network"). Source: Ministry of Municipal and Rural Affairs & UN-Habitat, Buraidah Comprehensive Urban Vision, Future Saudi Cities Programme, 2019, English edition, p. 72.

6.3 The irrigation constraint

No Buraydah greening plan is credible without a water answer. The city's domestic consumption is substantial (≈250 L/person/day, among the highest rates internationally, per the urban review) and the Saq aquifer is depleting [12, pp. 73–74]. The answer, fortunately, is already operating locally: **Buraydah Oasis irrigates one million trees with treated wastewater** through a dedicated network and storage lake fed by the city's treatment plant [9], Green Riyadh is scaling the same TSE model to 100% of its irrigation [5], and UN-Habitat's Action 3.2 for Buraydah specifically calls for irrigating urban green space with treated wastewater [12, p. 122]. District prioritization helps here too: concentrating early planting in a contiguous central belt and along defined corridors shortens TSE distribution runs compared to scattering the same trees citywide.

6.4 Robustness and validation

Every methodological choice in Section 4 was stress-tested in a **seven-experiment validation battery** run on the production data with the production pipeline code; the full protocol, scripts, and numeric outputs are published with the platform as a validation annex. In summary:

- **Score sensitivity (E1).** Varying the 9% goal across 7–15% mainly changes how many districts are declared "at goal" (from 31 down to 3), not who ranks first: the full ranking correlates ρ = 0.92–0.97 with the baseline across that entire range, so the goal operates as the policy anchor it is meant to be. Re-weighting the two priority indicators (LST : density, from 100:0 to 0:100) keeps full-ranking ρ ≥ 0.93 — but top-10 *membership* swaps by up to half under defensible tilts, which is precisely why neighboring ranks near the top should be treated as near-ties rather than a hard ordering. The NDVI > 0.25 threshold is the single most sensitive parameter (ranking ρ falls to 0.909 at 0.20): it defines the *level* of green cover even though the ranking survives, so it is stated beside every green-cover figure and retained on the ground-truth evidence of E4 below. Substituting MSAVI2 > 0.18 for NDVI > 0.25 changes nothing material (99.1% pixel agreement; ranking ρ = 0.985) — at district aggregation the two indices are the same measurement in Buraydah (Figure 13).

- **Seasonal window (E2).** A spring (15 February – 30 April 2025) composite was built with identical machinery and empirically rejected as a KPI window: it inflates district green fractions by ×1.36 on average — rain-fed ephemeral vegetation, concentrated in the palm-grove and wadi belts — and perturbs the ranking more than any score parameter tested (ρ = 0.82 against the autumn baseline; one district would move from deep in the priority list to "at goal" on ephemeral spring greening alone). In short, **spring measures rainfall, not policy**; the autumn window measures what a planting program actually creates. The spring composite is retained in the dashboard only as a separate descriptive layer (Figure 14).

- **Interannual stability and cadence (E3).** Anniversary composites for 2021 and 2023 extend the record to four snapshots (2019–2025). Year-to-year priority rankings correlate ρ ≈ 0.9, with 2–3 districts swapping at the top-10 margin at each re-rank — a stable top tier around an unstable exact ordering. Median interannual noise in district green cover is ~9% of its level, so single-year changes of roughly 0.5–1.5 pp are within noise for typical districts. The monitoring consequence: re-rank annually and work down the refreshed list; treat Theil–Sen trend slopes as provisional from **five or more annual snapshots**; and reserve Mann–Kendall significance claims for **ten or more** — with four snapshots the minimum achievable exact p-value is 0.083, so no district trend computable today can honestly be called statistically significant. Backfilling the 2017–2024 anniversary composites (computationally cheap) would close most of that gap immediately (Figure 15).

- **Ground truth against parks and green spaces (E4).** Across 70 OSM-mapped park and green-space polygons in the city, mean pixel NDVI is **0.285 versus 0.101** for the urban background, and **40.4% of their area exceeds the 0.25 threshold versus 6.3% of background — a 6.4× enrichment**; 64 of 70 sites show a detectable green core. Lowering the threshold to "capture" more green area would more than double the background false-positive rate over an area ~100× larger than all sites combined — exactly the arid bright-soil failure mode the method is designed to avoid. The threshold is retained (Figure 16).

- **No double-counting (E5).** The three score inputs are statistically distinct: all variance inflation factors are below 1.4, and the strongest pairwise correlation among the inputs is |r| ≈ 0.45 (LST–density). The LST–green correlation is weakly *positive* (r ≈ +0.27) — the arid inversion documented in Sections 3.4 and 5.2 — confirming that LST enters the score as an independent exposure weight, not as a proxy for barrenness.

- **Within-season LST stability (E6).** Splitting the 34 summer Landsat scenes into early- and late-summer halves and re-compositing reproduces the district heat ranking at ρ = 0.964, with a maximum anomaly disagreement of ~1.1°C against a ~7°C inter-district range. The heat ranking is a stable property of the urban fabric; a single-summer composite suffices for the score.

- **Soil-brightness drift (E7).** Across 2,695,188 bare-class pixels (ESA WorldCover) inside the districts, NDVI's mean reading drifts by **0.074** between the darkest and brightest soil-brightness deciles — an error organised by the colour of the ground rather than by its vegetation — against only **0.045** for the soil-adjusted MSAVI2: **1.65× less**. This drift touches the level of the published percentage, not the ranking: test E1c above shows that substituting MSAVI2 for NDVI reproduces the classification at 99.1% pixel agreement and a rank correlation of ρ = 0.985, and E4's ground-truth calibration anchors the level (Figure 20).

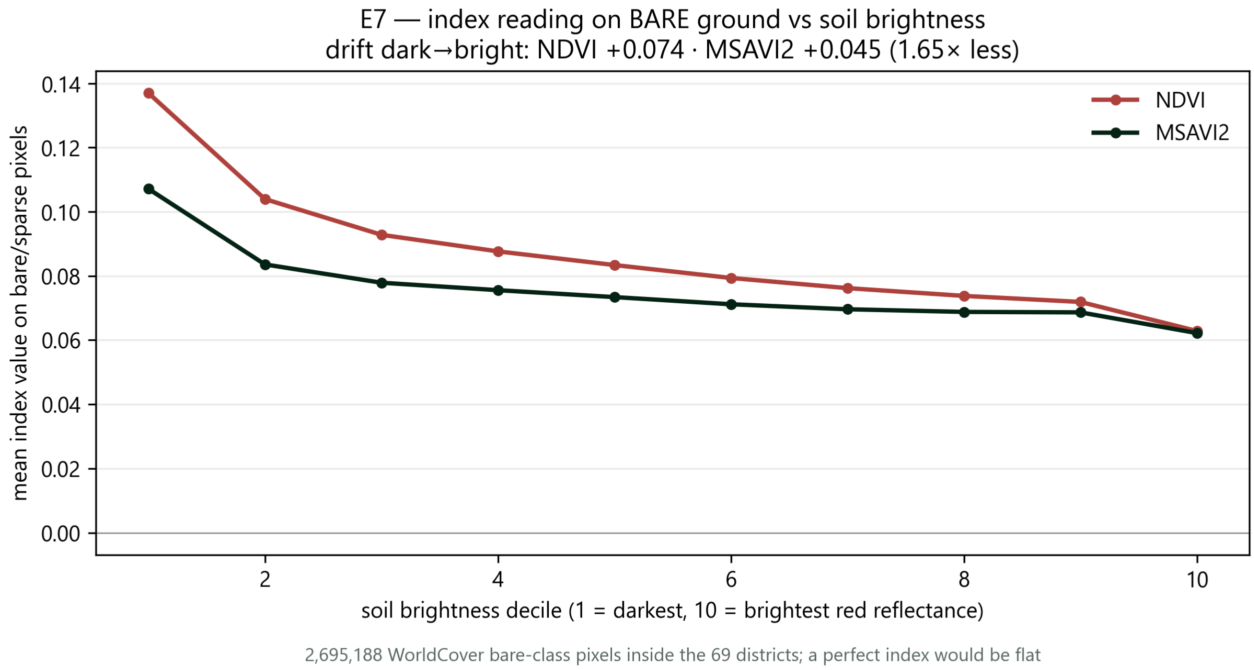

Figure 20: both indices' mean reading on bare ground across soil-brightness deciles — NDVI drifts 1.65× more than MSAVI2, and tests E1c and E4 show the drift does not reach the ranking (validation annex figure).

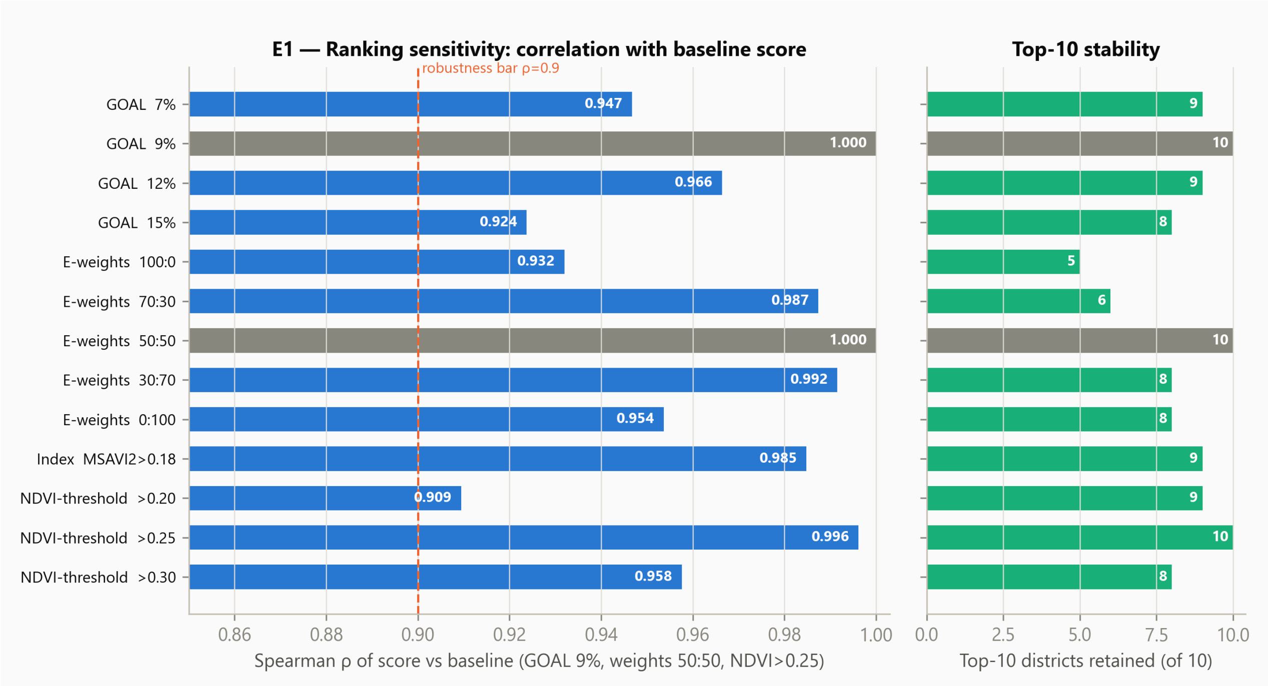

Figure 13: Score sensitivity to goal, indicator weights, index, and threshold choices (validation annex figure).

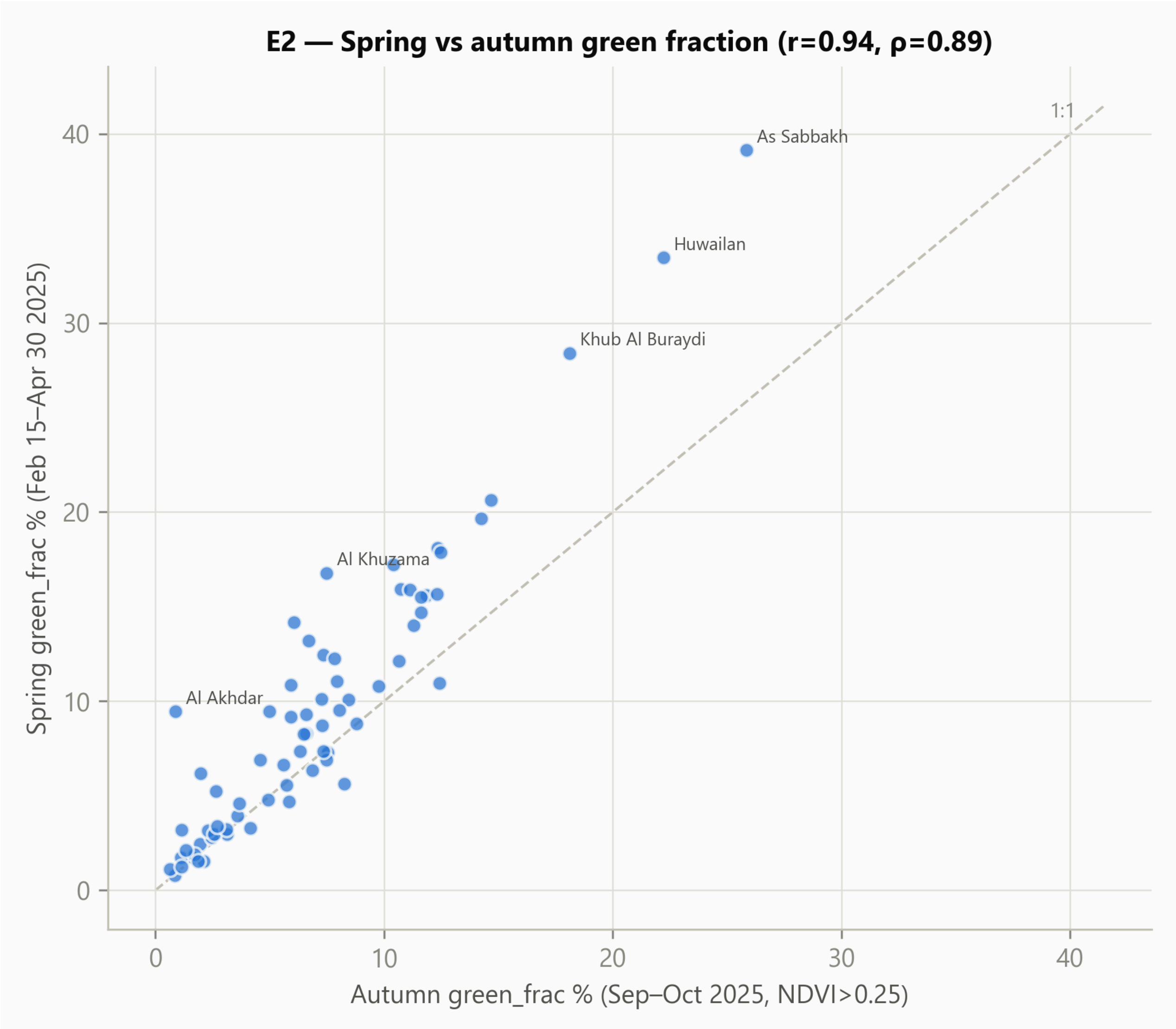

Figure 14: Spring versus autumn green fractions — the ×1.36 ephemeral inflation that disqualifies spring as the KPI window (validation annex figure).

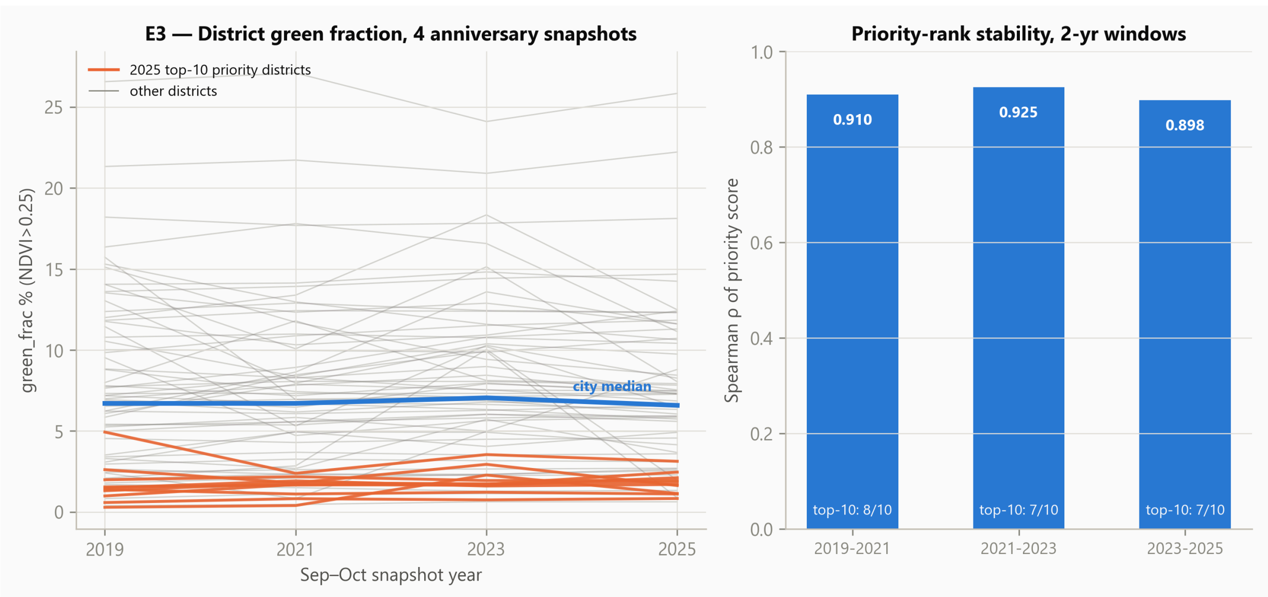

Figure 15: Interannual stability of green cover and priority ranking across the 2019–2025 anniversary snapshots (validation annex figure).

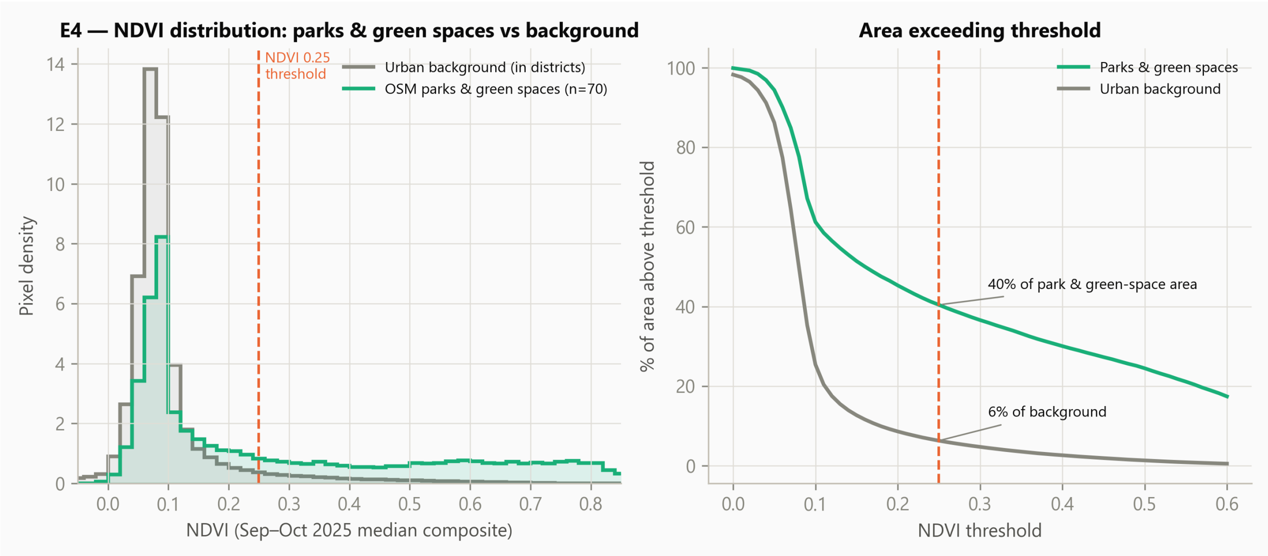

Figure 16: NDVI in OSM-mapped parks versus urban background, supporting the 0.25 threshold (validation annex figure).

The bottom line: the validation confirmed every baseline parameter and changed none — but it did change *presentation* (a deterministic tie-break yielding unique sequential ranks; near-tied scores flagged so neighboring ranks are not over-read) and it strengthened the data: the audit's quality-assurance pass surfaced and repaired one invalid source polygon and motivated the three-source population ensemble of Section 4.2, both incorporated in all numbers reported here.

6.5 Equation validation: alternative formulas, Monte Carlo uncertainty, and a second city

The seven experiments above stress-tested the *parameters* of the score; a second, dedicated study stress-tested the *equation itself* — the functional form, its normalization, and its transferability — following the OECD/JRC composite-indicator methodology for uncertainty and sensitivity analysis [55][57]. Its full protocol, scripts, and outputs are published with the validation annex; the findings:

- **Seven candidate formulas agree on who is priority (E8).** The TES-style multiplicative form was compared against six alternatives spanning the standard aggregation families — an additive weighted composite, two geometric-mean variants, a weighted rank-sum (Borda), TOPSIS, and a no-floor multiplicative variant — on identical inputs. All 21 pairwise rankings correlate at Spearman ρ = 0.87–0.996, every form's top-10 shares 7–10 members with every other's, and six districts are top-10 under all seven forms. The result does not depend on the choice of equation; it depends on the data (Figure 17).

ID	Form	Definition (identical inputs)
F1	TES-style multiplicative (**adopted**)	`100·(1 − GAPscore·E)`
F2	Additive weighted composite	`w₁·GAPscore + w₂·LSTn + w₃·DENSn`
F3a	Geometric mean (gap, LST, density)	`(GAPscore·LSTn·DENSn)^(1/3)`
F3b	Geometric mean (gap, E)	`(GAPscore·E)^(1/2)`
F4	Weighted rank-sum (Borda)	mean of per-indicator ranks
F5	TOPSIS	distance to ideal/anti-ideal point
F6	F1 without the 0.1 E-floor	`100·(1 − GAPscore·E₀)`

- **The multiplicative gap-gate is the *right* form for an oasis city — now positively evidenced, not merely inherited.** Because of the arid-oasis inversion (green cover correlates *positively* with daytime surface temperature: r ≈ +0.27 in Buraydah, +0.32 in Unayzah), any additive (compensatory) form lets heat and density buy out a zero canopy gap — systematically leaking planting priority toward already-green farm-belt districts. The multiplicative gate structurally blocks that failure mode: an at-goal district can never outrank one far below the goal for *planting*, which is the mandate semantics of a program with a stated canopy goal [56]. TOPSIS was additionally rejected on behavior: its geometry drops the three hottest high-gap districts (Ash Shafaq, Ash Shiqah, Al Yarmouk) from its top-10, and it cannot be recomputed by a municipal engineer in a spreadsheet.

- **A 3,000-draw Monte Carlo separates certainty from noise (E9).** Jointly perturbing green fractions (±1.5 pp, the measured interannual noise), LST (±0.5°C), populations (±15%), the indicator weights (30:70 to 70:30), and the functional form itself shows that **measurement noise in the green fraction dominates: it contributes roughly four times the rank variance of any other assumption, including the choice of equation**. Three districts are top-10-certain under every perturbation tested jointly — Ar Rawdah (P = 0.99), Al Manar (0.96), Ad Dahi (0.93) — while thirteen more are borderline; the paper and platform therefore publish each district's P(top-10) beside its rank (Section 5.4), and exact ordered positions below the top band should not be over-read (Figure 18). The full simulation specification: 3,000 joint draws (plus an independent adjudication re-run with a different random seed); each draw perturbs green fraction ±1.5 pp, LST ±0.5 °C, each district's population ±15%, samples the LST:density weights across 30:70–70:30, and randomly selects among the three strongest forms; per-district outputs are the median rank, the 90% rank interval (5th–95th percentiles), and the top-10 probability — the fields published with the data (`p_top10` , `rank_p5` , `rank_p95`). The highest-value robustness investment is multi-year averaging of the green fraction, not further formula engineering.

- **A fixed goalpost replaces the city-relative gap denominator.** The one change the study *did* mandate is the Step-2 normalization of Section 4.5: GAPscore = min(1, GAP/9) instead of GAP/GAPmax. Dividing by the city's largest gap made every district's score depend on the single largest-gap district of that city and year — scores were not comparable across years or cities. Dividing by the 9% goal itself (a distance-to-target normalization in standard practice [55]) fixes both, and was verified to change *zero* ranks within Buraydah (Spearman ρ = 1.000; scores shift by about +1 to +4 points). All scores in this paper use the fixed-goalpost form.
- **The pipeline transfers: a full second-city trial on Unayzah (E10).** The complete production pipeline — population, vegetation, heat, score — was run end-to-end on Unayzah (عنيزة, Al-Qassim) with **zero algorithmic changes and exactly two city-specific inputs: district boundaries and the 2022 census total (183,319)**. The 90-district run produced physically coherent output on the first pass: the historic palm-orchard quarters (Al Masif 30.4%, Ar Rahmaniyah 27.9%) are the greenest and score 100, the hot, sparsely vegetated periphery and market districts top the priority list, 34 of 90 districts meet the 9% goal (38%, vs Buraydah's 28%), scores span 45–100 with a nearly identical distribution, and the arid-oasis LST inversion reproduces (r = +0.32). Transfer to other Saudi cities is thereby an engineering exercise — with the honest caveats that Unayzah shares Buraydah's climate and UTM zone, and that cross-city score comparisons require the fixed-goalpost normalization above.

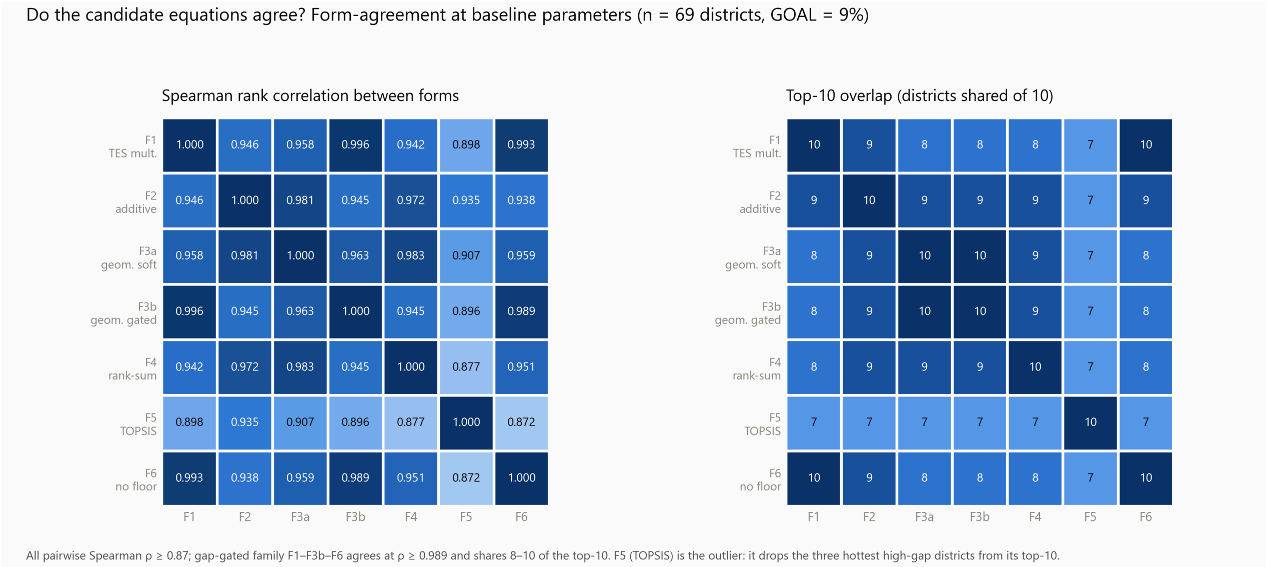

Figure 17: Agreement among seven candidate scoring formulas — Spearman correlations and top-10 overlap (validation annex figure).

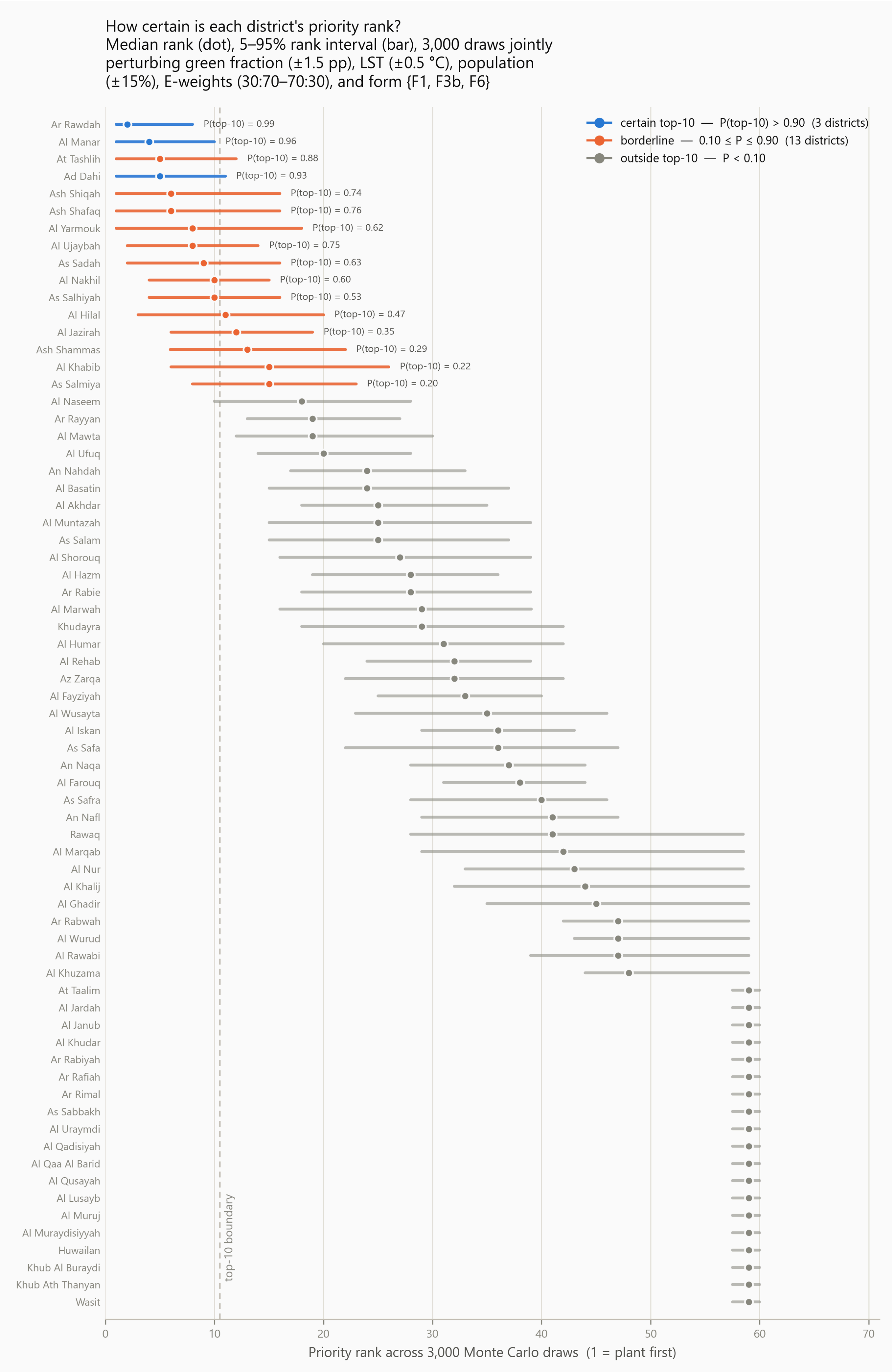
How certain is each district's priority rank?
Median rank (dot), 5–95% rank interval (bar), 3,000 draws jointly perturbing green fraction (±1.5 pp), LST (±0.5 °C), population (±15%), E-weights (30:70–70:30), and form {F1, F3b, F6}
certain top-10 — P(top-10) > 0.90 (3 districts)
borderline — 0.10 ≤ P ≤ 0.90 (13 districts)
outside top-10 — P < 0.10
Ar Rawdah
P(top-10) = 0.99
Al Manar
P(top-10) = 0.96
At Tashlih
P(top-10) = 0.88
Ad Dahi
P(top-10) = 0.93
Ash Shiqah
P(top-10) = 0.74
Ash Shafaq
P(top-10) = 0.76
Al Yarmouk
P(top-10) = 0.62
Al Ujaybah
P(top-10) = 0.75
As Sadah
P(top-10) = 0.63
Al Nakhil
P(top-10) = 0.60
As Salhiyah
P(top-10) = 0.53
Al Hilal
P(top-10) = 0.47
Al Jazirah
P(top-10) = 0.35
Ash Shammas
P(top-10) = 0.29
Al Khabib
P(top-10) = 0.22
As Salmiya
P(top-10) = 0.20
Al Naseem
Ar Rayyan
Al Mawta
Al Ufuq
An Nahdah
Al Basatin
Al Akhdar
Al Muntazah
As Salam
Al Shorouq
Al Hazm
Ar Rabie
Al Marwah
Khudayra
Al Humar
Al Rehab
Az Zarqa
Al Fayziyah
Al Wusayta
Al Iskan
As Safa
An Naqa
Al Farouq
As Safra
An Nafl
Rawaq
Al Marqab
Al Nur
Al Khalij
Al Ghadir
Ar Rabwah
Al Wurud
Al Rawabi
Al Khuzama
At Taalim
Al Jardah
Al Janub
Al Khudar
Ar Rabiyah
Ar Rafiah
Ar Rimal
As Sabbakh
Al Uraymdi
Al Qadisiyah
Al Qaa Al Barid
Al Qusayah
Al Lusayb
Al Muruj
Al Muraydisiyyah
Huwailan
Khub Al Buraydi
Khub Ath Thanyan
Wasit
top-10 boundary
0
10
20
30
40
50
60
70
Priority rank across 3,000 Monte Carlo draws (1 = plant first)

Figure 18: Monte Carlo rank intervals and P(top-10) per district, 3,000 draws (validation annex figure).

6.6 Limitations

We state these plainly, because the credibility of a decision tool depends on knowing what it cannot see.

1. **10 m pixels miss young street trees.** A newly planted sapling does not register at Sentinel-2 resolution until its canopy approaches pixel scale — typically one to two growing seasons for detectability, longer for full effect. The score therefore under-credits very recent planting; this is also why the annual scorecard, not the monthly refresh, is the official comparison basis.
2. **District populations are model estimates.** No public district-level census exists, so populations come from gridded models rescaled to the city total. The three-source ensemble (Section 4.2) hedges single-model artifacts, but the sources genuinely disagree at intra-urban scale (mean absolute share differences of roughly a quarter between WorldPop and the building-footprint-based sources), and citywide accuracy does not guarantee district accuracy. Extreme values are extreme for real reasons — Al Farouq's estimated 218 residents are genuinely sparse, with all three sources agreeing on the order of magnitude — but rankings driven by density should still be re-checked against Amanah service records before funds are committed.
3. **The exposure normalization is single-city.** The gap term is now anchored to the fixed 9% goal (Sections 4.5, 6.5), so gap scores are stable across years and comparable across cities that share the goal — but the exposure index E remains min–max normalized *within* Buraydah, like the Tree Equity Score itself [18]: a 46 here and a 46 in another city share the same gap scale but not the same exposure scale, and adding or redrawing districts still shifts E. The score therefore remains primarily a within-city allocation instrument; the Unayzah trial (Section 6.5) shows the *method* transfers cleanly, while inter-city score league tables should still be read with caution.
4. **The score is sensitive to the 9% goal.** Raising the goal toward the US desert baseline of 15% would push more districts below goal and compress score differences among the worst-off; lowering it would shrink the priority tier. The *ordering* of the most deficient districts is robust to moderate goal changes ($\rho \geq 0.92$ across goals of 7–15%; Section 6.4), but the size of the "meets goal" group is a direct function of this policy choice — which is why we anchored it to a published national target rather than choosing it ourselves.
5. **LST is surface, not air, temperature**, measured at a mid-morning overpass. It ranks districts' radiative heat load; it is not the afternoon air temperature or thermal

comfort of pedestrians, and nighttime heat — where desert urban heat islands are strongest [41] — is not captured by this daytime product.

6. **Ground truth is partial.** The NDVI > 0.25 threshold has now been checked against the city's OSM-mapped parks and held up well (Section 6.4, E4) — but OSM's park inventory for Buraydah is incomplete and community-mapped, so the check is relative, not exhaustive. A field verification campaign against known parks and groves (or the region-scale tree-detection dataset now available for Qassim [49]) would tighten it further.
7. **Short trend record.** The 2019–2025 headline comparison uses two matched windows; the validation's 2021 and 2023 snapshots extend the record to four, which is enough to characterize noise (median interannual variation ≈ 9% of a district's level) but not significance — with four points no district trend can reach $p < 0.05$ (Section 6.4, E3). District-level changes smaller than ~1 pp should not be over-read, and formal trend claims should wait for ~10 annual observations [43].

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7. The Platform

The analysis is delivered not as a static report but as the **Shade (ظِلّ) platform**: an open dashboard presenting the score map, the full 69-district table, per-district profiles (green cover, MSAVI2, LST, per-capita and change figures), and the underlying data for download. The pipeline re-runs automatically each month against newly acquired imagery, so the Amanah can watch planting appear in the data. Monthly values are **indicative** — vegetation indices fluctuate with irrigation cycles and atmospheric conditions — and the **annual September–October composite remains the official comparison basis**, published each autumn together with the summer LST map as the district scorecard. The architecture is fully open (open data in, open code, open outputs), so the method can be audited, corrected, or extended by any party — and replicated for Unayzah, Ar Rass, or any Saudi city with the same free inputs.

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8. Recommendations

Addressed respectfully to the Emirate of Al-Qassim Region, Amanat Al-Qassim, and the municipality of Buraydah, as a technical contribution to programs already in motion.

1. Begin at the top of the ranking (two planting seasons). Work the ranked list from the top downward. The top tier — the first six districts (Section 5.4): Ar Rawdah, Al Manar, Ash Shafaq, Ash Shiqah, Ad Dahi, At Tashlih, which the sensitivity analysis shows are clearly the most urgent under any reasonable weighting — is a natural first phase, scaled to roughly the size of one Bahjah cycle [10], with the next districts on the list (Al Yarmouk, Al Ujaybah, As Sadah, Al Hilal, Al Nakhil) following in order. Treat the two structural types differently: in the dense central districts (Ar Rawdah, Al Manar, Ad Dahi, and the central districts that follow), prioritize street trees, shaded sidewalks, mosque and school courtyards, and pocket parks on white-land parcels; in the hot-exposure districts (Ash Shafaq, Ash Shiqah, At Tashlih), prioritize perimeter groves and corridor planting for cooling and dust damping. Time planting to the established October regional phase of Qassim Green Land [6], and refresh the ranking from each year's scorecard rather than freezing today's list (Section 6.4).

2. Secure treated-wastewater irrigation before planting. Extend the Buraydah Oasis TSE model [9] to the pilot districts, sizing distribution from the treatment-plant network as the National Water Company did for the Oasis's million trees. No pilot street tree should depend on potable groundwater; this is both Green Riyadh's model [5] and UN-Habitat's Action 3.2 for Buraydah [12, p. 122].

3. Plant native and drought-adapted species. Follow the species guidance already institutionalized nationally: the Royal Commission's *Manual of Arriyadh Plants* (99 species selected for Green Riyadh's climate, closely comparable to Buraydah's) [50] and NCVC's native-species programs for the region (ghada saxaul, athl tamarisk, arak, and the salam and samr acacias — the species used in the Emir's Qassim National Park campaign) [8][51].

4. Align delivery with UN-Habitat Action 3.3. Reserve white-land parcels in the priority districts for the neighborhood central open spaces their plans always promised [12, p. 122]; advance wadi linear parks where priority districts touch the wadi system [12, p. 98]; and pair street planting with the shaded-sidewalk standard of Action 1 [12, p. 118] so trees become walkable shade, not only greenery.

5. Adopt a measurement protocol. (a) Publish the annual district scorecard (September–October green fraction and MSAVI2, summer LST, score and rank) each autumn; (b) treat monthly dashboard updates as indicative early-warning only — the platform's live layer uses a trailing 60-day composite displayed primarily as a year-over-year anomaly, a configuration selected empirically in a dedicated window study (60 days is the shortest window that never falls below four usable scenes in any month of 2025, while a 90-day window carries spring rain-greening — up to ×1.36 inflation — into late April; a November–December scorecard alternative was likewise tested and rejected at ×1.52 inflation and rank correlation 0.787, further confirming September–October); (c) commission a one-time parks and public-green-space inventory so that *public accessible* green space per capita can be reported separately from total vegetation — closing the interpretive gap identified in Section 5.3; (d) field-verify the NDVI threshold against a sample of known parks and groves in the first year, extending the OSM-parks check of Section 6.4; (e) hold trend judgments until five annual scorecards exist, and formal significance claims until about ten; (f) backfill the 2017–2024 September–October anniversary composites — a modest one-time computation — so the defensible trend series arrives years earlier (Section 6.4).

6. Measure both sides of the ledger. Track agricultural-greenery loss alongside planting gains (Section 5.5), so that farmland-preservation policy (UN-Habitat Action 3.1) and planting policy are steered by one consistent picture.

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9. Acknowledgment

This study exists because of, not despite, the national and regional programs it hopes to serve. The Saudi Green Initiative established the ambition and the measurement culture; Green Riyadh established the benchmarks and the delivery model; the Emir of Qassim's initiatives — Qassim Green Land, the million-tree campaign, Buraydah Oasis — established that this region plants earlier, and at larger scale, than almost anywhere in the Kingdom; and the Amanah's Bahjah and park programs improve the city visibly year by year. The Shade platform and this study claim no share of that credit. They offer one narrow, technical contribution: a transparent way to decide *where first* — and a free, repeatable way to watch the answer change as the trees go in. The platform complements, and can never replace, the official efforts of the state, the Emirate, and the Amanah. Responsibility for any errors rests with the Shade platform alone, and corrections from the municipality's engineers — who know these districts street by street — are welcomed and will be incorporated.

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Analysis datasets: 69 district polygons (National Address via [46], January 2022 snapshot; geometry-validated, one polygon repaired); Sentinel-2 L2A, 30 scenes, 6 September – 29 October 2025 and 29 scenes, 11 September – 31 October 2019 [44]; Landsat 8/9 C2L2 surface temperature, 34 scenes, 1 June – 31 August 2025 [44]; district populations from a three-source ensemble — WorldPop constrained 2020 BSGM [48], Kontur Population 2023 [53], Meta/CIESIN HRSL 2020 [54] — each rescaled to the GASTAT 2022 city total of 571,169 [16]. Full district table, pipeline metadata, validation annex, and code are published with the Shade platform.