

Urban archetypes reveal disparities in green cooling efficacy, residential access, and distributional equity across Singapore

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Urban archetypes reveal disparities in green cooling efficacy, residential access, and distributional equity across Singapore

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Abstract

Urban greening is widely promoted for heat mitigation, yet its benefits depend on cooling efficacy, residential accessibility, and alignment with thermal need, all of which vary across environmental contexts. Here, we develop an urban archetype framework that connects multidimensional residential environments with the performance of green cooling services. Across 94,076 residential postcodes in Singapore, 1,600,260 dwelling units, we integrated 124 indicators of greenery, heat, pollution, park accessibility and built environment, and identified four spatially reproducible consensus archetypes. Cooling efficacy did not consistently translate into accessible cooling or alignment with residential need. Archetypes differentiated the volume of accessible cooling, with nonlinear green-cooling relationships. Housing & Development Board (HDB) housing comprised 11.2% of residential postcodes but represented 71.3% of dwelling units. Citywide, modelled accessible cooling was absent for 62.9% of HDB dwellings and 55.4% of other residential dwellings; corresponding Gini coefficients were 0.879 and 0.845, and need-service mismatch indices were 0.752 and 0.724. Among high-thermal-need dwellings, priority-deficit prevalence varied markedly across archetypes: the largest HDB-other residential disparity occurred in the Green-Cool archetype, whereas the direction reversed in the two low-green archetypes. These findings show how urban archetypes reveal context-dependent relationships between environmental resources, service performance, accessibility, and residential need.

Keywords: Urban archetypes; Environmental exposome; Green infrastructure; Heat mitigation; Cooling accessibility; Thermal equity.

1 Introduction

In tropical, high-density Singapore, mitigating residential heat is an important climate and health challenge. Green infrastructure is widely used to moderate local thermal conditions by reducing radiant and surface heat through shade, evapotranspiration and changes in the surface energy balance [1–3]. However, the cooling benefits of greening for urban residents depend not simply on the vegetation coverage, but on whether it produces functional cooling where people live and whether that cooling is accessible to people experiencing greater thermal burden. Understanding green heat mitigation at the fine residential scale is therefore important for evaluating how urban greening supports more human-centred and equitable thermal environments [4, 5].

Green cooling benefits are environmentally context-dependent [6–8]. Their magnitude and spatial reach emerge from interactions among background thermal conditions, vegetation, urban morphology and local atmospheric processes [9–12]. Building configuration and surface characteristics influence heat storage, shading and airflow [13], with recent evidence from Singapore showing nonlinear and spatially heterogeneous effects of urban morphology on physiologically relevant heat stress [14]. Vegetation can simultaneously provide shade and evaporative cooling, modify ventilation and intercept airborne particles, creating context-dependent thermal and air-quality effects [3, 15]. Moreover, cooling that is produced locally is not directly linked to accessibility; its potential residential benefit depends on the spatial built environment extent of the cooled footprint and its connection to homes through the pedestrian network [16–18]. These interactions motivate a multi-dimensional view of residential context spanning heat, pollution, greenery, accessibility, built environment and other exposure contexts.

Thermal equity concerns the distribution of the cooling service across geospatial residential and socioeconomic groups [19–23]. Higher thermal burdens commonly coincide with socioeconomic or demographic vulnerability, concentrating heat exposure and limited adaptive capacity within the same residential settings [24]. This creates a distributive mismatch: places with the greatest thermal need may require more cooling to achieve comparable protection, yet the available service may be disproportionately limited [25–28]. Thus, these dimensions distinguish the distribution of cooling resources from their correspondence with need and the populations most exposed to potential service deficits.

Recent research has increasingly moved beyond vegetation quantity to examine how green-space cooling varies across urban environments, how cooling benefits extend beyond

green-space boundaries, and how access to green amenities differs across population groups [17, 18, 21, 29–32]. In addition, urban-exposome approaches, which characterize multiple co-occurring environmental conditions around residential locations, have increasingly been used to identify recurring residential environmental profile [33, 34]. UrbanX combines dimensionality reduction with geographically constrained clustering to identify shared exposomic settings, while Wang et al. derive residential environmental profiles from a large set of co-occurring exposures and relate them to behavioural outcomes [35, 36]. More broadly, the spatial-signatures framework of Fleischmann and Arribas-Bel demonstrates how fine-scale urban heterogeneity can be summarized into interpretable spatial typologies [37]. Together, these studies support a context-based view of the urban environment. Existing typologies characterize where environmental conditions co-occur, while cooling studies typically examine thermal performance, spatial reach or accessibility as separate outcomes.

Here, we address this gap by developing an exposome archetype framework for a complete green cooling assessment on residential postcode locations and dwellings across Singapore. Singapore provides a tropical residential setting in which to examine this question across heterogeneous urban forms and housing sectors [38–42], and recent research has identified inequalities in green-space heat-mitigation services [43]. We analyse 94,076 residential postcodes, including 10,535 Housing & Development Board (HDB) postcodes and 83,541 other residential postcodes. Approximately 11.2% of HDB residential postcode locations represented 71.3% of all dwelling units. Within these contexts, we distinguish three stages of green cooling: the local cooling efficacy associated with greenery, the spatial extent and footprint of cooling from green patches, and the cooling potentially accessible to residences through the pedestrian network. Finally, we examine service inequality, dwelling-weighted need–service mismatch and housing-group over-representation in high-need cooling deficits.

This study advances a service-based interpretation of urban greening: cooling efficacy, cooling accessibility and service-need alignment are related but distinct dimensions of residential adaptation concepts (Fig. 1). Methodologically, it combines domain-balanced classification, stage-specific cooling-service analysis and need-referenced housing comparisons in a reproducible residential framework for urban climate research. Empirically, the Singapore application examines whether cooling-service relationships and housing deficits vary across environmental contexts in a fine-scale residential assessment. Our work is particularly relevant to Singapore’s *City in Nature* objectives under the Singapore Green Plan 2030, which combine expanded greenery with improved park connectivity and a target of bringing every household within a ten-minute walk of a park [44]. Assessing accessible cooling within the environmental exposome framework can complement these provision and proximity targets by identifying where service remains limited relative to residential need. This approach identifies where cooling services may be insufficient to

meet residents' needs due to either limited cooling production or limited access, providing a basis for targeted fine-scale climate-health actions.

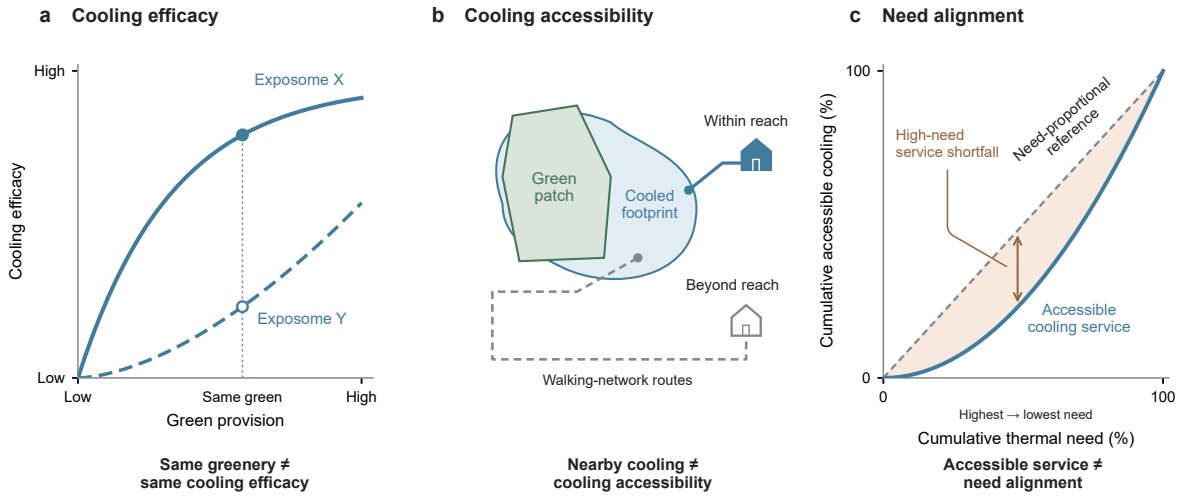


Figure 1: **Cooling efficacy, accessibility and need alignment represent distinct dimensions of residential green cooling.** **a**, The same level of green provision can be associated with different cooling efficacy across residential environmental contexts. **b**, Cooling can extend beyond the boundary of a green patch, while its potential accessibility depends on whether cooled environments fall within pedestrian-network reach of residences. **c**, Accessible cooling is compared with thermal need using a need-proportional reference. Departure below the diagonal represents a relative shortfall in cooling service compared with thermal need; the shaded region illustrates this mismatch rather than an absolute threshold of cooling sufficiency.

2 Results

2.1 Urban archetypes identify heterogeneous and recurring residential environmental exposome

The analytical frame contained 94,076 official residential postcodes: 10,535 HDB postcodes and 83,541 other residential postcodes located in residential or mixed-residential land-use parcels. The 124 environmental indicators spanned heat, fine particulate matter (PM_{2.5}), greenery, park accessibility and built environment. To reduce within-domain redundancy while preventing more densely measured domains from dominating the classification, we performed principal component analysis (PCA) separately within each domain and balanced the retained components before clustering (Methods). This yielded 12 principal components, with each domain contributing approximately 20% of the variance in the

108 clustering space. A 23-partition consensus across K-means, diagonal-covariance Gaussian
109 mixture models and partitioning around medoids was then evaluated from $K = 2$ to
110 $K = 20$ (Fig. 2b–d, Supplementary Table S3).

111 Four archetypes provided the most balanced and spatially reproducible representation
112 of the residential exposome. Among the candidate solutions, $K = 2$, $K = 4$, and $K = 5$
113 satisfied the prespecified internal and spatial validation criteria, but $K = 4$ offered the
114 strongest overall compromise between cluster separation, resampling stability, minimum
115 cluster size, and spatial reproducibility (Fig. 2). The $K = 4$ solution had a mean silhouette
116 width of 0.174, bootstrap adjusted Rand index (ARI) of 0.991, weakest-cluster Jaccard
117 similarity of 0.994, and a minimum cluster share of 15.97%. It also remained highly
118 recoverable when complete planning areas were withheld, with a mean blocked ARI of
119 0.826, minimum-fold ARI of 0.704, and weakest pooled cluster recall of 0.903. Although
120 $K = 5$ achieved slightly higher silhouette width (0.180) and mean blocked ARI (0.844),
121 its weakest spatial fold was substantially less stable, with a minimum-fold ARI of 0.509
122 and weakest pooled recall of 0.782. $K = 2$ showed high weakest-class recall (0.916) but
123 provided a substantially coarser representation and lower separation and mean blocked
124 recovery. We therefore retained $K = 4$ as the primary solution, balancing parsimony with
125 internal stability and spatial reproducibility.

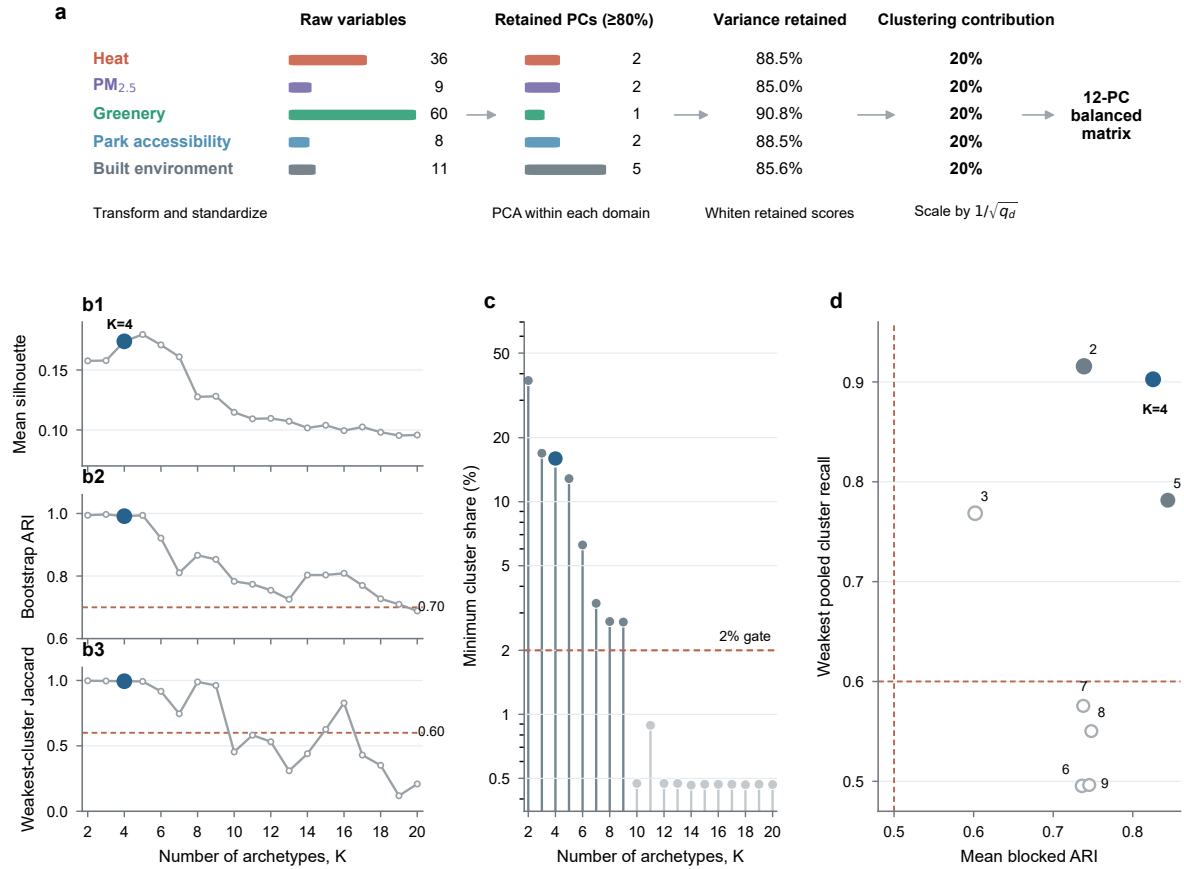


Figure 2: **Domain balancing and spatial validation support a four-archetype representation of the residential environmental exposome.** **a**, The 124 standardized environmental variables were reduced separately within heat, fine particulate matter (PM_{2.5}), greenery, park-accessibility and built-environment domains. The minimum number of principal components explaining at least 80% of within-domain variance was retained and whitened, yielding 12 components. **b1–b3**, Internal diagnostics across $K = 2$ –20: mean silhouette width, bootstrap adjusted Rand index (ARI) and weakest-cluster Jaccard recovery. **c**, Minimum algorithm-specific cluster share of the postcodes. **d**, Spatial recovery when complete planning areas are withheld. Analyses used 94,076 residential postcodes with equal postcode weights

The archetype framework captured recurrent structure in the multidimensional residential exposome (Fig. 3). Within-domain redundancy was substantial in the raw 124 variable datasets: the 60 greenery indicators were highly correlated across time, spatial scales and metric families, with a median pairwise Spearman correlation of 0.94 (interquartile range IQR, 0.85–0.97), supporting compression of repeated measurements before clustering (Fig. 3a). In contrast, cross-domain information often remained distinct; the selected five-domain exemplar had a mean absolute pairwise correlation of 0.03, indicating that the major environmental domains could not be reduced to a single common exposure axis

134 (Fig. 3b).

135 The exact 12-component representation occupied 398 of 400 self-organizing map (SOM)
 136 nodes, with a quantization error of 1.042 and topographic error of 0.155. Of 753 adjacent
 137 occupied-node pairs, 85.4% shared the same dominant consensus archetype. Median node
 138 purity was 1.00 (IQR, 0.89–1.00), and the postcode-weighted mean purity was 0.904. The
 139 consensus archetypes therefore occupied coherent, although not perfectly discrete, regions
 140 of the continuous multidimensional exposome topology.

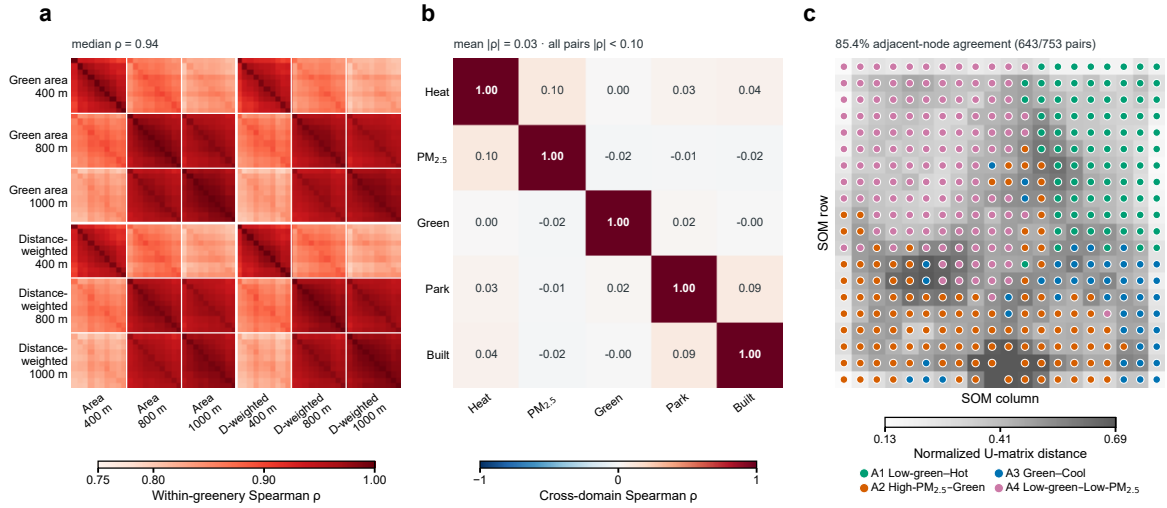


Figure 3: **Multidimensional environmental structure motivates an archetype representation of the residential environmental exposome.** **a**, Spearman correlations among 60 raw greenery indicators, illustrating within-domain redundancy. **b**, Descriptive cross-domain correlation matrix using five environmental domains. Mean absolute pairwise correlation was 0.03 and all $|\rho| < 0.10$, illustrating complementary information across domains. **c**, Self-organizing map (SOM) of the 12-component domain-balanced exposure space. Grey shading shows normalized U-matrix distance, reflecting dissimilarity between neighbouring nodes. Coloured symbols denote the most frequent consensus archetype among residential postcodes mapped to each occupied node.

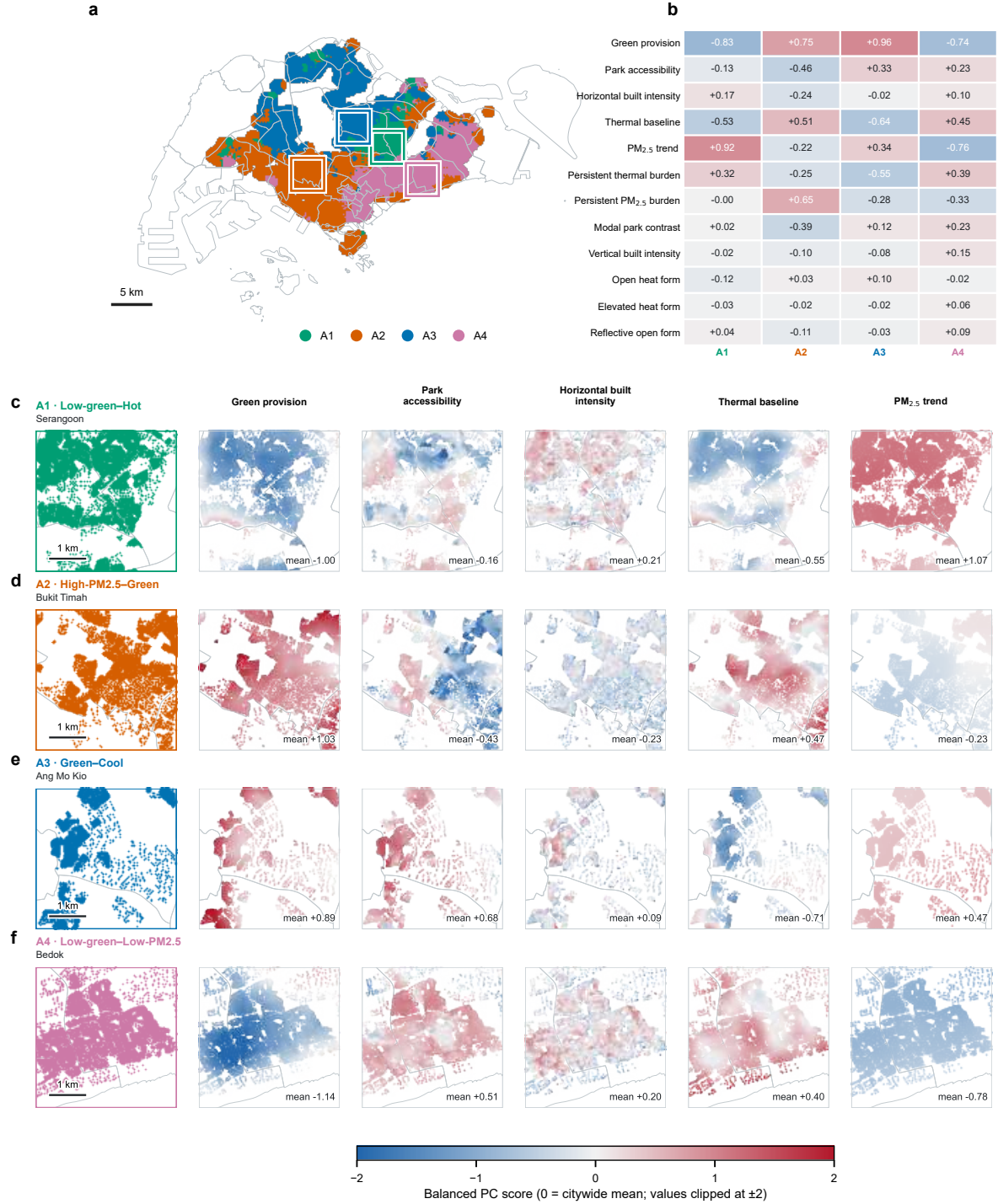


Figure 4: Residential environmental exposome archetypes resolve citywide and local environmental contrasts across Singapore. **a**, Spatial distribution of four consensus archetypes across 94,076 residential postcodes. Boxes identify representative, 4×4 -km local windows. **b**, Archetype centroids for the 12 domain-balanced principal components used in clustering. Each value represents the mean component score across residential postcodes within an archetype. **c–f**, Local views of A1 Low-green–Hot (**c**), A2 High-PM_{2.5}–Green (**d**), A3 Green–Cool (**e**) and A4 Low-green–Low-PM_{2.5} (**f**).

The four archetypes showed distinct multidimensional environmental profiles and clear spatial organization across Singapore (Fig. 4a,b). Archetype sizes, housing composition and complete component centroids are provided in Supplementary Table S4. Their citywide distribution revealed geographically coherent concentrations, while the 12-component centroid profiles showed that each archetype was defined by a combination of environmental characteristics (Fig. 4b).

A1, Low-green–Hot, comprised 21,073 postcodes (22.4% of the analytical frame). It combined the lowest green provision (-0.83) with above-average persistent thermal burden ($+0.32$), below-average park accessibility (-0.13) and elevated horizontal built intensity ($+0.17$). Persistent fine particulate matter ($\text{PM}_{2.5}$) burden was close to the cohort mean, indicating a profile characterized primarily by low greenery and thermal disadvantage rather than uniformly adverse environmental conditions. A1 was concentrated particularly in Serangoon and Hougang, where the representative window illustrated the co-occurrence of sparse greenery and higher built intensity (Fig. 4c).

A2, High- $\text{PM}_{2.5}$ –Green, included 23,672 postcodes (25.2%). High green provision ($+0.75$) coincided with the highest persistent $\text{PM}_{2.5}$ burden ($+0.65$) and the lowest park accessibility (-0.46), while persistent thermal burden was below average (-0.25). A2 therefore illustrates that greener residential surroundings can coexist with relatively high particulate pollution and limited access to designated parks. It was concentrated particularly in Bukit Timah, with additional concentrations in Novena, Clementi and Tanglin (Fig. 4d).

A3, Green–Cool, comprised 21,267 postcodes (22.6%). It combined the highest green provision ($+0.96$) with the lowest persistent thermal burden (-0.55), the highest park accessibility ($+0.33$) and below-average persistent $\text{PM}_{2.5}$ burden (-0.28); horizontal built intensity was close to the cohort mean. Although both A2 and A3 are relatively green, their pollution and accessibility profiles differed markedly, showing that greenery alone did not distinguish these residential contexts. A3 had its largest concentrations in Ang Mo Kio and Yishun, while the representative northern window retained substantial local variation within the shared archetype (Fig. 4e).

A4, Low-green–Low- $\text{PM}_{2.5}$, contained the largest number of residential postcodes, with 28,064 postcodes (29.8%). Low green provision (-0.74) coincided with the lowest persistent $\text{PM}_{2.5}$ burden (-0.33), while persistent thermal burden remained elevated ($+0.39$). Park accessibility was above average ($+0.23$) and vertical built intensity was the highest among the four archetypes ($+0.15$). A4 therefore differed from A1 despite their similarly low-green and relatively hot conditions, principally through lower pollution, better park accessibility and a different built-form profile. It was concentrated particularly in Bedok, Geylang and Marine Parade (Fig. 4f).

Overall, 97.1% of analysed geographic neighbour connections joined postcodes assigned to the same archetype, approximately 3.8 times the 25.4% proportion expected from the archetype shares. Yet the matched 4 × 4-km views showed substantial variation within each class, indicating that the archetypes summarize recurrent combinations of environmental conditions rather than environmentally uniform zones. Most importantly, the classification separated two relatively green settings with contrasting pollution and accessibility profiles, and two low-green, hotter settings that differed in pollution, accessibility and built form. These contrasts provided the environmental contexts for subsequent analyses of cooling function, accessibility and equity.

2.2 Cooling efficacy and accessibility across exposome contexts

We characterized the cooling service associated with urban greenery through two complementary dimensions, cooling efficacy and cooling accessibility. Cooling efficacy describes how strongly local greenness produces coolness, whereas accessible cooling describes the amount of modelled coolness potentially reachable from a residence through the pedestrian network. Specifically, cooling efficacy was expressed as the reduction in Universal Thermal Climate Index (UTCI) associated with a 10-percentage-point increase in green share. Accessible cooling combined the magnitude and area of positively modelled cooled cells reachable within 400 m on the pedestrian network, normalized by a reference catchment area.

The two dimensions showed distinct spatial patterns (Fig. 5a,b). Across the 94,076 official residential postcodes, 41.5% had positive accessible cooling within the pedestrian-network catchment. Coverage ranged from 27.4% in A4 and 28.7% in A1 to 52.4% in A2 and 60.4% in A3. Based on the local derivative of the green-cooling response, mean cooling efficacy was 0.034, 0.106, 0.089, and 0.087 °C per 10-percentage-point increase in green share in A1–A4, respectively. A3 and A4 provide a particularly clear contrast: despite nearly identical mean cooling efficacy, the proportion of postcodes with reachable cooling was 60.4% in A3 but only 27.4% in A4. Thus, similar local cooling efficacy did not necessarily translate into similar potential residential access to cooling services.

The spatial distributions of cooling efficacy and accessible cooling were considered alongside HDB dwelling concentration to distinguish locations with similar environmental performance but different residential concentrations. Within-archetype associations between exposome components and modelled cooling efficacy differed in direction and magnitude across A1–A4 (Fig. 5c). These contrasts do not identify independent effects on cooling efficacy, but describe how environmental profiles co-occur with green cooling efficacy. An interquartile-range contrast in green provision was associated with lower efficacy in A1, by 0.084 and 0.086 °C per 10 percentage points of greenery for HDB and other residential

postcode locations, respectively. The corresponding associations were positive in A2, at 0.073 °C for HDB postcode locations and 0.095 °C for other residential postcode locations, and strongest in A3. In A3, the efficacy contrast was 0.113 °C for HDB postcode locations (95% confidence interval, 0.093–0.132) and 0.175 °C for other residential postcode locations (0.158–0.191). Associations in A4 were comparatively small, with the largest displayed contrast being the positive green-provision association of approximately 0.006 °C in both housing groups. Higher horizontal built intensity co-occurred with lower efficacy in both housing groups in A3. Among other residential postcode locations, however, its association was positive in A1 and negative in A2. Higher thermal baseline co-occurred with lower efficacy among other residential postcode locations in A1, but greater efficacy in both housing groups in A2.

The associations with accessible cooling differed from those observed for efficacy (Fig. 5d). In A1, greater green provision was associated with more accessible cooling in both housing groups, despite its negative association with marginal efficacy. In A2, an interquartile-range increase in green provision was associated with 0.00707 °C-equivalent more accessible cooling among other residential postcodes (95% confidence interval, 0.00290–0.01125), whereas the HDB estimate was 0.00038 °C-equivalent (95% confidence interval, –0.00256 to 0.00332). The housing-group interaction did not meet the false-discovery-rate threshold ($q = 0.052$). Conversely, A3’s strong green-provision association with efficacy was not accompanied by a clearly resolved association with accessible cooling. In A4, park accessibility was positively associated with accessible cooling among HDB postcode locations, despite the near-constant efficacy estimates.

We further separated the probability of receiving cooling service from its accessible cooling volume (Fig. 5e,f). The fitted coverage curves varied across the greenness gradient, with evidence of heterogeneity among archetypes (global interaction $P = 0.0145$; Fig. 5e). A3 maintained a comparatively high probability across intermediate levels of greenness, whereas A1, A2 and A4 generally occupied lower ranges over their respective empirical support. A4 retained strong evidence of nonlinearity after false-discovery-rate correction ($q = 3.87 \times 10^{-11}$; Fig. 5e), indicating that additional greenery was not associated with a simple monotonic increase in service coverage in this low-green context.

The amount of accessible cooling among postcode locations that are served differed strongly across archetype-specific green-response functions (global interaction $P = 1.15 \times 10^{-12}$; Fig. 5f). Accessible cooling volume increased sharply at higher green shares in A2 and A3, while A3 showed significant nonlinearity after correction ($q = 0.00330$). A4 also showed significant nonlinearity ($q = 3.73 \times 10^{-6}$), with its response occurring over a lower and narrower greenness range. The A1 response was likewise confined to a lower and narrower greenness range and showed a substantially weaker increase over its observed support. Thus, environmental context differentiated the amount of cooling generated among served

252 postcode locations more clearly than the probability of receiving any service.

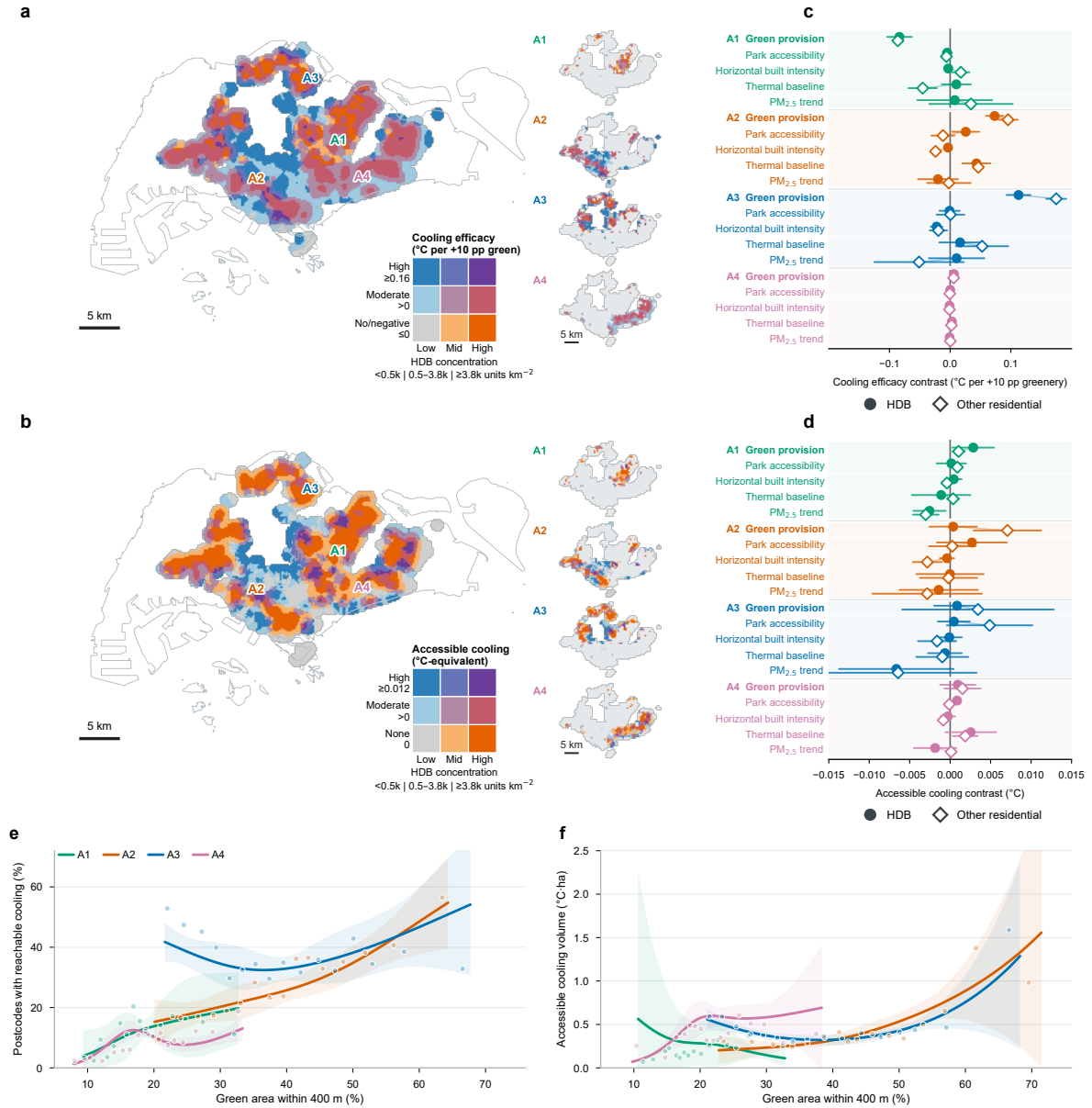


Figure 5: Environmental exposome context differentiates cooling efficacy and accessible cooling. **a,b**, Distributions of cooling efficacy (**a**) and network-accessible cooling (**b**) with HDB dwelling concentration; insets show A1–A4. **c,d**, Within-archetype co-pattern of five exposome components with cooling efficacy (**c**) and accessible cooling (**d**); points show interquartile-range contrasts and lines 95% confidence intervals. **e,f**, Archetype-specific relationships between green share and the probability of any reachable cooling (**e**) and accessible cooling volume among served postcode locations (**f**). Curves show standardized predictions with 95% confidence bands; points show empirical binned estimates.

2.3 Cooling inequity and need–service gaps across housing and exposome contexts

The context-dependent differences in cooling function and potential access raised a further distributional question: how the resulting accessible cooling service was shared across residential dwellings and whether it reached places with greater need. We therefore moved from cooling performance to cooling equity, examining whether accessible cooling was concentrated and aligned with thermal need within residential and socioeconomic contexts.

Housing composition differed substantially across archetypes when expressed using official dwelling counts (Fig. 6a). HDB dwellings represented 76.7% of dwelling units in A1, 68.6% in A2, 79.0% in A3 and 63.2% in A4. Citywide, 21.8% of HDB dwelling units and 16.6% of other residential dwelling units were located in the highest quintile of the socioeconomic-context score. The contrast was largest in A2 (34.0% versus 16.7%), followed by A3 (11.0% versus 4.7%), with smaller differences in A1 (9.7% versus 8.5%) and A4 (31.1% versus 26.3%). Among postcodes classified as having high socioeconomic vulnerability, the dwelling-weighted mean local share of residents aged 65 years or older was 22.0% for HDB and 19.4% for other residential postcodes. The corresponding archetype-specific estimates were 21.0% versus 18.9% in A1, 22.3% versus 16.8% in A2, 22.5% versus 21.1% in A3 and 21.8% versus 20.7% in A4.

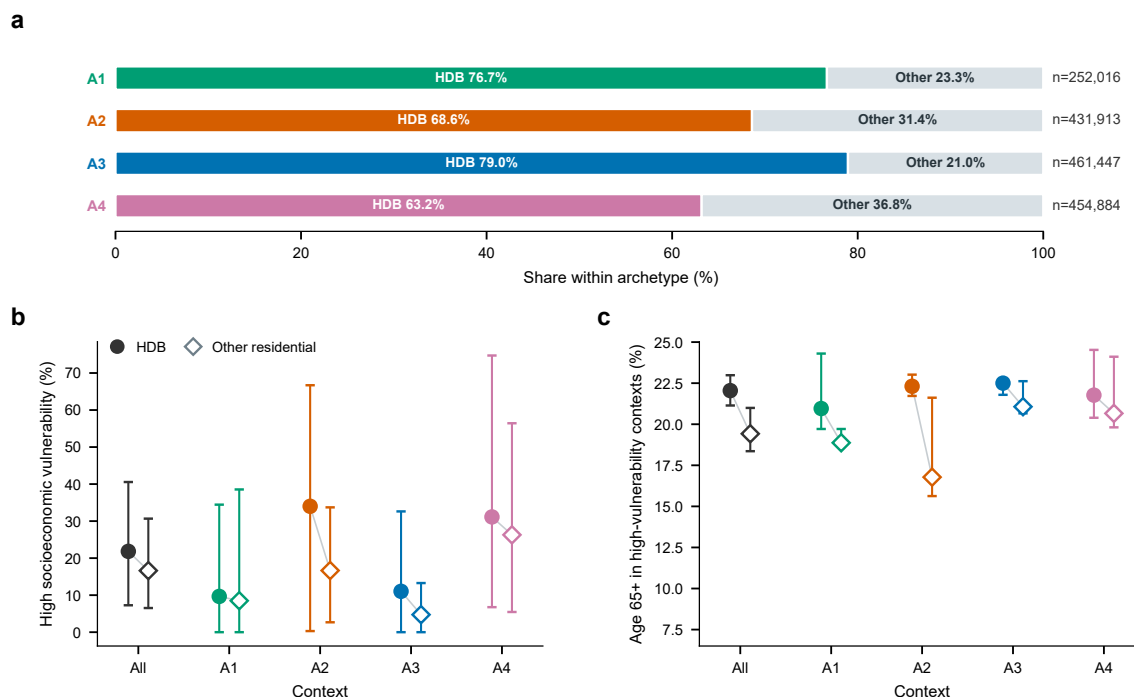


Figure 6: **Housing composition and contextual vulnerability vary across residential environmental exposome archetypes.** **a**, Composition of HDB and other residential dwelling units within archetypes A1–A4. **b**, Percentage of dwelling units in the highest citywide dwelling-weighted quintile of contextual socioeconomic vulnerability, defined from small-home, economic, ageing, and social-isolation components using a common all-residential 80th-percentile threshold. **c**, Dwelling-weighted mean of the local Census population share aged 65 years or older, among residential postcodes classified as high socioeconomic vulnerability.

In the dwelling-weighted primary comparison, 62.9% of HDB dwelling units and 55.4% of other residential dwelling units had an accessible-cooling value of zero (Fig. 7a). The Lorenz curves consequently remained on the horizontal axis through most of the residential distribution before rising steeply among the minority of dwelling units receiving service. The HDB Gini coefficient was 0.879 (95% planning-area bootstrap interval, 0.837–0.913), compared with 0.845 (0.805–0.877) for other residential dwelling units. Bootstrap uncertainty for the principal equity estimates is reported in Supplementary Table S10.

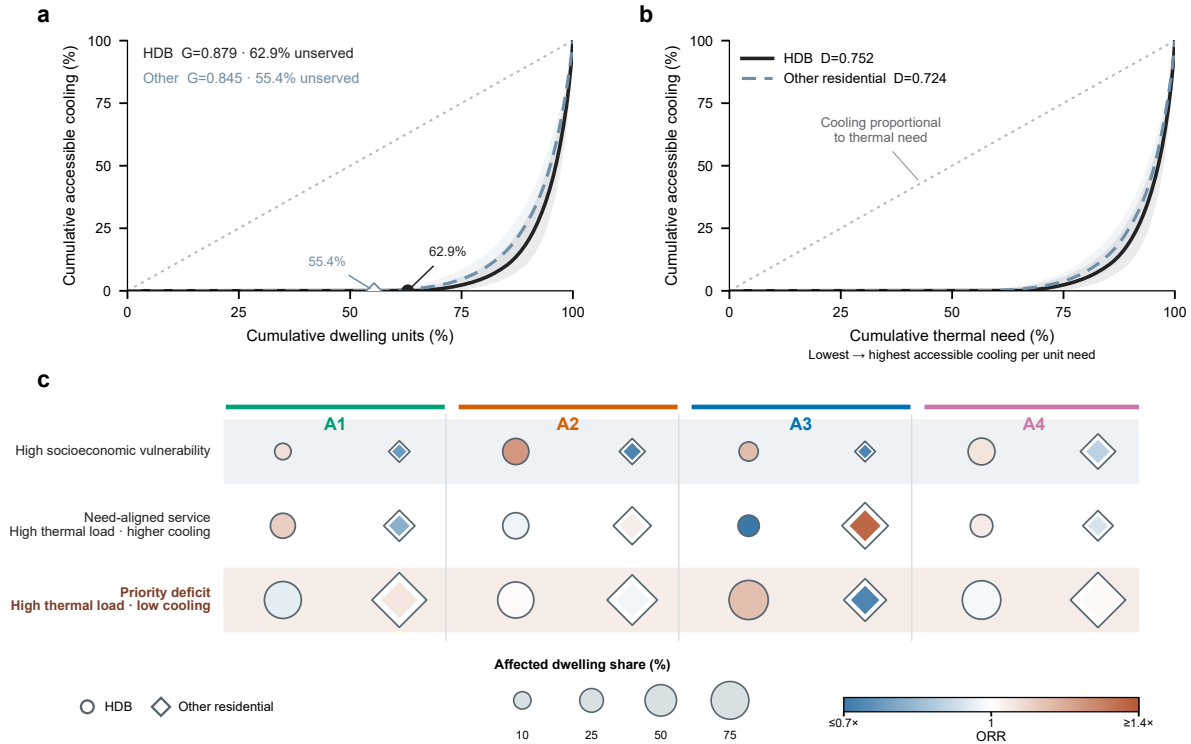


Figure 7: **Accessible cooling is unequal, poorly aligned with thermal need, and shows context-specific housing disparities across urban archetypes.** **a**, Dwelling-weighted Lorenz curves of the accessible-cooling index for HDB and other residential units. Ribbons show pointwise 95% intervals from planning-area bootstrap resamples. **b**, Need-weighted Lorenz curves comparing cumulative accessible cooling with cumulative thermal need, defined as mean monthly positive UTCI exceedance above 26 °C. Ribbons show pointwise 95% intervals from planning-area bootstrap resamples. **c**, Context-specific over-representation of socioeconomic vulnerability and high-need cooling states by housing group. Colour encodes the observed-to-expected over-representation ratio (ORR) within the same archetype and eligible dwelling units, with $ORR = 1$ denoting proportional representation. Symbol size indicates the affected dwelling percentage within each eligible housing–archetype group.

The distribution of cooling was also poorly aligned with dwelling-weighted thermal need (Fig. 7b). Dwelling-weighted need–service mismatch was high in both groups: the mismatch index was 0.752 (95% interval, 0.700–0.801) for HDB and 0.724 (0.678–0.768) for other residential dwellings.

Exposome stratification revealed substantial variation in cooling deficits that was obscured by the citywide aggregate comparison (Fig. 7c). Among dwelling units located at high-thermal-need postcodes, priority cooling deficits affected 75.2% of HDB dwelling units and 72.4% of other-residential dwelling units citywide. Priority deficits comprised high-need

dwelling units with either no accessible cooling or low positive accessible cooling, with low positive cooling defined as values at or below the dwelling-weighted 20th percentile of the citywide positive accessible-cooling distribution. The largest housing-group difference in priority-deficit prevalence occurred in A3, where deficits affected 81.3% of eligible HDB dwelling units compared with 45.3% of other-residential dwelling units, a difference of 36.0 percentage points. The corresponding over-representation ratios were 1.15 (95% interval, 1.06–1.40) for HDB and 0.64 (0.53–0.80) for other residential dwellings, indicating over-representation of HDB and under-representation of other-residential dwellings in the priority-deficit state relative to their respective expected shares within A3. In A2, the housing-group difference was much smaller, with deficits affecting 68.1% of HDB and 65.8% of other-residential dwelling units. In contrast, deficit prevalence was slightly lower for HDB than for other residential dwellings in both A1 (71.4% versus 79.4%) and A4 (78.3% versus 80.7%). Thus, similar citywide deficit prevalence between the two housing groups concealed marked context-specific heterogeneity, most notably the large HDB–other residential disparity in A3 despite its comparatively favourable overall cooling profile. Complete inequality and need–service mismatch estimates are reported in Supplementary Table S8, and socioeconomic vulnerability by archetype and housing group is reported in Supplementary Table S9.

Archetype stratification revealed context-specific housing disparities that were obscured by citywide comparisons, demonstrating its value for locating and interpreting unequal cooling-service burdens. Socioeconomic vulnerability and high-need cooling deficits were not distributed in parallel across archetypes. A2 showed the strongest HDB–other residential contrast in the prevalence of high socioeconomic vulnerability, while priority-deficit prevalence was similar between the housing groups. A3 showed a different pattern: the socioeconomic-vulnerability contrast was smaller, but the housing-group difference in priority-deficit prevalence was substantially larger, with HDB dwellings much more frequently in the deficit state and other-residential dwellings more frequently in the need-aligned higher-cooling state. These contrasting patterns indicate that socioeconomic vulnerability and cooling-service deficit capture distinct dimensions of residential disadvantage.

3 Discussion

This study links the 124 multidimensional environmental variables surrounding 94,076 residential postcodes to the function, potential accessibility and distribution of green cooling. The Singapore application shows why these dimensions should be evaluated separately: environmental settings with favourable average cooling performance can still contain high-need dwelling units with limited accessible service. Urban exposome

archetypes make these differences interpretable by clustering locations according to recurring combinations of heat, pollution, greenery, accessibility, and built form.

Exposome archetypes make multidimensional environmental variation interpretable without reducing it to a single exposure or deprivation score [33–37]. Within-domain PCA addresses redundant indicators, while domain balancing prevents heavily measured domains from dominating the classification. The resulting archetypes provide a common basis for comparing cooling performance and housing disparities across recurring environmental settings. These archetypes summarize continuous environmental variation. Integrating these environmental dimensions within a residential framework reveals differences that are concealed by citywide averages.

This study separates three outcomes that a greenness-only assessment would conflate: local cooling efficacy, potential network access and the distribution of service among high-need dwellings. Efficacy describes the local thermal function associated with greenery, whereas accessible cooling additionally depends on the magnitude and spatial extent of cooling and its connection to residences through the pedestrian network [21, 30, 31]. These dimensions diverged across exposome contexts: A3 and A4 had numerically similar mean efficacy but markedly different residential coverage. Recent Singapore studies similarly show that the thermal contribution of greenery depends on surrounding morphology [38, 45, 46]. Together, these findings indicate that local cooling efficacy alone is insufficient to characterize the potential cooling service available to residents.

Archetype stratification also reveals disparities that citywide distributional summaries do not resolve. Although aggregate inequality and need–service mismatch characterize the overall distribution of cooling, they do not identify the environmental settings in which particular housing groups are disproportionately underserved (Fig. 7). A1 showed broadly limited accessible cooling, whereas A2 combined comparatively greater access with elevated particulate-pollution burden and contextual socioeconomic vulnerability. A3’s favourable environmental profile and high overall coverage coexisted with the largest observed housing disparity in priority deficits, demonstrating that a favourable archetype average does not establish equitable service within it. In A4, widespread deficits across both housing groups showed that a small housing gap does not imply adequate service. This contextual perspective extends recent Singapore evidence of unequal green-space heat-mitigation services [43] by distinguishing broadly shared underservice from housing-specific disadvantage. Archetypes therefore complement, rather than replace, aggregate equity measures, providing interpretable settings for assessing planning priorities according to residential thermal need and potentially accessible cooling rather than greenery provision alone.

These distinctions have practical value because different service deficits imply different

planning questions. Limited vegetation, weak thermal performance of existing greenery, poor pedestrian access to cooled environments and misalignment between cooling and thermal need are not the same problem. They may motivate investigation of vegetation provision, green-space design and surrounding morphology, pedestrian connectivity and public access, or the spatial targeting of adaptation resources, respectively. This context-specific perspective complements previous Singapore assessments of green-space availability and ecosystem-service equity [40–43]. Recent city-scale modelling in Singapore similarly indicates that vegetation cooling depends strongly on surrounding urban morphology [45], reinforcing the need to interpret green resources within their local environmental context. The framework therefore supports diagnosis before intervention selection, while recognising that greening decisions also require attention to displacement, affordability and other dimensions of environmental justice [47, 48]. These findings also suggest a service-based complement to Singapore’s *City in Nature* objectives under the Singapore Green Plan 2030, including the target for every household to be within a ten-minute walk of a park by 2030 [44]. Park proximity remains an important planning objective, but does not establish the magnitude of accessible cooling or its alignment with residential thermal need. The present framework could support differentiated priorities within existing estate-renewal programmes. In Hougang, where A1 is concentrated, low green provision and limited cooling-service coverage suggest the need to assess where additional cooling service is most needed, together with its cooling efficacy and accessibility. In Bedok, where A4 is concentrated, relatively high modelled cooling efficacy coexists with low service coverage and substantial thermal and socioeconomic burden, shifting attention towards the spatial distribution and reach of cooled environments. HDB’s *Remaking Our Heartland* programme, which includes Hougang and East Coast–Bedok, provides an existing mechanism through which such assessments could inform neighbourhood renewal [49]. For example, the proposed Outdoor Play Corridor in Bedok connects the town centre with Bedok Reservoir Park and East Coast Park [50]. Its connections could be evaluated against postcode-level cooling deficits to identify locations where additional entrances, shaded links, or smaller cooled spaces warrant further investigation.

The same service-based interpretation is relevant in greener environmental contexts. In Ang Mo Kio, where A3 is concentrated, comparatively high archetype-level cooling coverage coexists with a pronounced housing-group disparity among high-thermal-need dwellings. Priority deficits are substantially more prevalent among HDB than among other residential dwellings. This provides a basis for considering both cooling destinations and underserved residential origins when prioritising pedestrian improvements. The Friendly Streets pilot at Ang Mo Kio illustrates an existing implementation approach through barrier-free crossings and safer connections to neighbourhood amenities [51]. In Bukit Timah, where A2 is concentrated, high green provision coexists with higher particulate-pollution burden and

relatively low park accessibility, suggesting that proposed connections could be assessed jointly for cooling accessibility and wider environmental exposure conditions. Additional access points along the Rail Corridor (Central) provide one example of an intervention whose cooling-service implications could be evaluated using this framework [52]. Across these programmes, evaluation could complement infrastructure-delivery targets with changes in high-need service exclusion and need-service mismatch. These applications should be interpreted as priorities for investigation rather than evidence of the effectiveness of particular upgrading projects; pedestrian-access audits and thermal measurements would be needed to evaluate intervention performance.

Several limitations define the scope of these conclusions. The five exposome domains were selected to represent complementary environmental conditions. Leave-one-domain-out analyses showed substantial changes in archetype assignments when greenery or PM_{2.5} was removed, but smaller changes when built form was omitted (Supplementary Table S11). Our results do not establish that all five domains are necessary to identify the four archetypes. Domain selection and cluster number should therefore be reassessed when applying the framework elsewhere. The study is cross-sectional and ecological, so the estimated green-cooling relationships do not represent causal effects of planting, and socioeconomic indicators describe area-level context rather than individual factors. The environmental variables also span different periods and therefore form an assembled residential environmental profile rather than a contemporaneous individual exposome. Moreover, official dwelling counts were used for both housing groups, enabling dwelling-weighted comparisons. However, dwelling units are not resident counts. Household occupancy, household size and individual cooling exposure were not measured. Cooling estimates are also sensitive to the representation of green-space sources, cooling footprints, network structure and selected catchment scales. Potential accessibility should not be interpreted as experienced thermal comfort, which additionally reflects perceptual, behavioural and streetscape conditions [53]. Future work may therefore connect the present spatial framework with observed experience. Fixed and mobile thermal measurements, pedestrian-level radiation and airflow observations, route and time-activity data, and improved building-level population estimates could validate both cooling function and potential access. Because cooling performance and thermal need were evaluated using 2019 UTCI, the estimated magnitudes may vary under different meteorological years, although the archetype framework itself incorporates multiyear environmental information. Methodologically, comparisons with continuous exposure models and alternative spatial classifications would help establish when archetype-based stratification provides additional value. In other cities, the environmental contexts will differ, but the analytical framework remains transferable: characterize multidimensional residential environments, separate resource from function and access, and evaluate the resulting service against physical need

and social context.

In conclusion, we developed a transferable residential urban-exposome framework for evaluating how environmental context shapes the performance of accessible cooling. The framework could help planners identify residential settings where high thermal need coincides with limited accessible cooling and investigate which stage of the service chain lacks attention. Our framework suggests that urban greening can advance climate and health goals when the cooling it provides is accessible to residents and aligned with thermal need across diverse urban exposome contexts.

4 Methods

4.1 Study design and residential environmental data

We conducted a cross-sectional study of residential environmental conditions across Singapore. The analytical unit was a geocoded six-digit postcode.

The official residential frame was defined as the union of 10,535 Housing & Development Board (HDB) postcodes and 83,541 postcodes from URA’s postcode-level No. of Dwelling Units layer for private residential properties, including landed, non-landed and executive-condominium properties. The resulting frame comprised 94,076 unique residential postcodes and 1,600,260 dwelling units, including 1,141,285 HDB and 458,975 other residential dwelling units. Although HDB accounted for only approximately 11.2% of residential postcode locations, these postcodes represented 71.3% of all dwelling units. We therefore retained postcode locations as the spatial analytical unit while using official dwelling counts to represent the residential population at risk in distributional and equity analyses.

Residential environmental conditions were represented by 124 indicators in five domains: heat, air pollution, greenery, park accessibility and built environment, with multiscale data across recent ten years. These comprised 36 monthly Universal Thermal Climate Index (UTCI) measures, annual PM_{2.5} surfaces, multiyear and multiscale vegetation measures, park-accessibility measures and built-environment measures. Prespecified right-skewed greenery, park-accessibility and selected built-environment variables were transformed using $\log(1 + x)$ before standardization. The final clustering cohort was complete for all 124 variables. Complete variable definitions, periods, spatial operations, units and transformations are provided in Supplementary Table S1.

4.2 Construction of residential environmental contexts

Spearman correlations were first used to characterize redundancy within environmental domains and complementarity across domains. Principal component analysis (PCA) was conducted within each domain [54]. For domain d , we retained the smallest number q_d of components explaining at least 80% of cumulative variance. To prevent domains containing larger numbers of correlated indicators from dominating the classification, retained scores were whitened and scaled as

$$\mathbf{U}_d = \frac{\mathbf{Z}_d \mathbf{V}_{d,1:q_d} \mathbf{\Lambda}_{d,1:q_d}^{-1/2}}{\sqrt{q_d}}. \quad (1)$$

Here $\mathbf{Z}_d$ is the standardized data matrix for domain d . Whitening gives the retained components approximately unit variance, while division by $\sqrt{q_d}$ gives each domain approximately equal total variance in the combined clustering space. Domain-specific PCA retention, balancing factors and component interpretations are reported in Supplementary Table S2.

Candidate clustering solutions from $K = 2$ to $K = 20$ were evaluated using K-means, diagonal-covariance Gaussian mixture modelling and partitioning around medoids. The consensus ensemble combined the three full-data partitions with 20 additional partitions obtained from ten 80% resamples fitted using K-means and Gaussian mixture models, reducing dependence on a single algorithm or initialization [55]. Candidate solutions were evaluated using cluster separation, agreement and resampling stability, minimum cluster size, and recovery when complete planning areas are spatially withheld [56].

A self-organizing map (SOM) of the same balanced component representation was used to visualize exposure topology and correspondence with the consensus labels [57]. Complete clustering diagnostics across $K = 2$ –20 are reported in Supplementary Table S3.

4.3 Cooling efficacy and pedestrian-network accessibility

First, postcode-level cooling efficacy described the local association between greenery and thermal conditions with green resource represented by mean green-area share within 400 m, and the thermal outcome by annual-mean 2019 UTCI:

$$T_i = \alpha + \sum_{a=1}^4 \mathbb{I}(A_i = a) \left(\beta_{1a} G_i + \beta_{2a} G_i^2 \right) + \boldsymbol{\gamma}^T \mathbf{Z}_i + \eta_{p(i)} + \varepsilon_i, \quad (2)$$

$$E_i = -0.10 \left(\hat{\beta}_{1a} + 2\hat{\beta}_{2a} G_i \right). \quad (3)$$

Here T_i is annual-mean UTCI, G_i is green share and E_i is the modelled UTCI reduction associated locally with a 10-percentage-point increment in green share for a postcode location in archetype a . Larger positive values therefore indicate stronger modelled cooling efficacy. The model used HC3 heteroskedasticity-robust covariance. We kept the thermal year 2019 fixed as the resulting estimates describe spatial differences, not long-term average cooling or temporal trends. This estimand represents a cross-sectional association evaluated at observed greenness rather than a causal planting effect [3, 6–8]. Full archetype-specific green–UTCI estimates and the finite-difference sensitivity analysis are reported in Supplementary Table S5.

We separately estimated the spatial cooling associated with green patches because cooling magnitude and cooling extent represent distinct green-space functions [17, 18]. Official park and open-space geometries were divided into contiguous patches and retained when patch area was at least 1 ha and mean vegetation fraction was at least 0.10. UTCI and morphology covariates were aggregated to a 100-m grid. After adjusting the hottest monthly-mean 2019 UTCI for urban morphology and broad spatial trend, the patch-referenced cooling contrast was

$$C_{pj} = \text{median}_{\ell: 400 \leq d_{p\ell} \leq 1200}(r_\ell) - r_j, \quad (4)$$

where r_j is residual UTCI for cell j . Positive C_{pj} indicates that a cell was cooler than the patch-specific background 400–1,200 m from patch p , after morphology and spatial adjustment. External cooling footprints were extended through consecutive 100-m distance bins while patch-referenced cooling remained at least 0.10 °C, up to a maximum external radius of 300 m. Within the retained footprint, cell-level cooling service was $\max(C_{pj}, 0)$. Positively cooled cells were then linked to residential postcode locations through the pedestrian network. For network radius R , distance-weighted accessible cooling volume and the normalized Accessible Cooling Index (ACI) were defined as

$$\text{ACV}_i(R) = \sum_{j: d_{ij} \leq R} C_j A_j \exp \left[-\ln(5) \left(\frac{d_{ij}}{R} \right)^2 \right], \quad (5)$$

$$A_{\text{ref}}(R) = \frac{\pi R^2 (1 - w_R)}{-\ln(w_R) 10,000}, \quad w_R = 0.2, \quad (6)$$

$$\text{ACI}_i(R) = \frac{\text{ACV}_i(R)}{A_{\text{ref}}(R)}. \quad (7)$$

Here d_{ij} is shortest pedestrian-network distance, C_j is positive modelled cooling and A_j is cell area in hectares. ACI is expressed in °C-equivalent and represents potential

network access to modelled cooling. We defined local accessible cooling using a primary pedestrian-network catchment of 400 m. This 400-m walking threshold was informed by the park-accessibility criterion in the NParks Handbook on the Singapore Index on Cities' Biodiversity [58]. Accessible-cooling estimates under alternative pedestrian-network catchment radii are reported in Supplementary Table S6.

4.4 Context-specific green-cooling co-occurrence patterns

The probability of reaching any positive cooling was modelled using a binomial generalized linear model with logit link, while positive accessible cooling volume among served postcode locations was modelled using a Gamma family with log link [21, 30, 59]. Green share entered both models as an archetype-specific restricted cubic spline with knots at its 5th, 35th, 65th and 95th percentiles [60]:

$$\text{logit Pr}(R_i = 1) = \alpha_R + f_R(G_i, A_i) + \gamma_R^\top \mathbf{Z}_i, \quad (8)$$

$$\log E(V_i | R_i = 1) = \alpha_V + f_V(G_i, A_i) + \gamma_V^\top \mathbf{Z}_i. \quad (9)$$

Here R_i indicates any service and V_i positive accessible cooling volume. The adjustment set included housing and planning-area terms. Predictions were standardized over the observed covariate distribution and displayed only within the archetype-specific 2.5th–97.5th percentile range of green share. Joint Wald tests assessed archetype-by-green heterogeneity, and Benjamini–Hochberg correction was applied to context-specific nonlinearity tests [61].

We additionally examined five prespecified balanced components within each archetype: Green provision, Park accessibility, Horizontal built intensity, Thermal baseline and PM_{2.5} trend. Each component was analysed separately in relation to cooling efficacy and accessible cooling fitted at the postcode level. Component scores were centred at the within-archetype median and scaled by their interquartile range, describing how environmental profiles co-occur with cooling performance. For outcome Y_i , the model was

$$Y_i = \alpha_a + \beta_a P_i + \gamma_a H_i + \delta_a(P_i H_i) + \xi_1 X_i^{\text{coord}} + \xi_2 Y_i^{\text{coord}} + \eta_{p(i)} + \varepsilon_i, \quad (10)$$

where P_i is the centred, IQR-scaled component score, and H_i equals 1 for HDB postcodes and 0 for other residential postcodes. The interaction allowed separate HDB and other-residential contrasts, expressed as the change between the 25th and 75th percentiles of the component. Archetype-specific nonlinearity tests, Benjamini–Hochberg-adjusted q -values, planning-area counts and spline knots for the green-accessible-cooling models are reported in Supplementary Table S7.

4.5 Thermal need, housing context and cooling equity

Thermal need was defined independently of accessible cooling as positive monthly UTCI exceedance above the 26 °C boundary for moderate heat stress [62]:

$$N_i = \frac{1}{12} \sum_{m=1}^{12} \max(T_{im} - 26, 0) \quad (11)$$

where T_{im} is mean UTCI in month m of 2019.

Cooling equity was assessed along three complementary dimensions: distributional inequality, alignment of cooling with thermal need, and housing-specific concentration of deficits.

Distributional inequality was summarized separately for HDB and other residential housing using dwelling-weighted unserved shares, Lorenz curves and Gini coefficients of ACI. Gini coefficients were also calculated among dwelling units associated with postcodes having positive accessible cooling.

Need-service mismatch was evaluated using a need-weighted Lorenz curve. Within each housing group, residential postcode locations were ordered by increasing S_i/N_i , where S_i is accessible cooling and N_i thermal need. High thermal need was defined as the dwelling-weighted upper quintile of N_i across all residential postcodes.

Let

$$n_i = \frac{w_i N_i}{\sum_j w_j N_j}, \quad s_i = \frac{w_i S_i}{\sum_j w_j S_j} \quad (12)$$

denote normalized need and service shares within a housing group. Here w_i is the official dwelling count associated with postcode i . The dwelling-weighted need-service mismatch index for each housing group was

$$D = \frac{1}{2} \sum_{i=1}^n |s_i - n_i| = \max_k (X_k - Y_k) = 1 - B, \quad (13)$$

where X_k and Y_k are cumulative need and service shares under the increasing- S_i/N_i ordering, and B is the overlap between the two normalized distributions. Because postcode locations with relative service deficits precede those with relative surpluses under this ordering, the maximum vertical distance below the diagonal equals the total unmatched share D . Thus $D = 0$ denotes identical normalized need and service shares at every postcode location, while larger values indicate greater mismatch, with 1 the complete non-overlap limit. The identity in equation (13) was verified against all observed and bootstrap curves.

Housing and socioeconomic characteristics from Census 2020 summaries were used only for downstream contextual profiling. A four-component contextual vulnerability score combined ageing, small-home, economic and one-person-household components and was used for the vulnerability over-representation analysis.

Housing-specific over-representation was evaluated within each archetype and eligible population:

$$E_{gca} = n_{ga} \frac{O_{ca}}{N_a}, \quad (14)$$

$$\text{ORR}_{gca} = \frac{O_{gca}}{E_{gca}}, \quad (15)$$

Here O_{gca} is dwelling units associated with postcodes in housing group g , state c and archetype a ; n_{ga} is the corresponding eligible dwelling-unit total; O_{ca} and N_a are, respectively, the affected and eligible dwelling-unit totals across both housing groups within the same archetype and row-specific analytical subset. E_{gca} is the expected affected dwelling count.

4.6 Spatial uncertainty, sensitivity and reproducibility

Spatial uncertainty was estimated using 499 whole-planning-area bootstrap resamples, preserving within-area dependence. For Lorenz curves, Gini coefficients and unserved shares retained the prespecified group-specific resampling procedure. For housing comparison, each bootstrap replicate applied the same planning-area multiplicities to both housing groups, preserving shared-area covariance. Each joint replicate recomputed within-group denominators, complete need-weighted Lorenz curves, mismatch indices and the HDB–other difference. Pointwise curve intervals and scalar 95% intervals were defined by the 2.5th and 97.5th percentiles of the bootstrap distributions. These intervals are not simultaneous tests of curve dominance and do not propagate uncertainty from the upstream cooling models.

Regression-based within-archetype contrasts used planning-area-clustered covariance where specified, while the cooling-efficacy model used HC3 covariance. Sensitivity analyses additionally examined alternative pedestrian-network radii and the finite-difference cooling-efficacy estimand. False-discovery-rate control used the Benjamini–Hochberg procedure for families of context-specific nonlinearity tests. Bootstrap uncertainty for the principal equity estimates is reported in Supplementary Table S10. We tested domain dependence by refitting and rebalancing the remaining domain PCs, then repeating fixed- $K = 4$ consensus clustering after each omission (Supplementary Table S11).

Data and Code availability

Analysis scripts and model diagnostic code are made publicly available at https://github.com/sdgresearch/Archetype_ORA. The environmental, housing, census, and spatial datasets used in this study were obtained from the sources documented in Supplementary Tables.

Ethics

The study used area-level environmental, housing and aggregate open-source spatial records and did not include identifiable individual participants or individual records.

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Author contributions

Haiwei Li: Conceptualization, Methodology, Data curation, Software, Formal analysis, Visualization, Writing – original draft. Rudi Stouffs: Supervision, Funding acquisition, Writing – review & editing. Ronita Bardhan: Supervision, Funding acquisition, Writing – review & editing.

Competing interests

The authors declare no competing interests.

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