PLOS ONE

RESEARCH ARTICLE

SYNTHETIC METHODS DEMONSTRATION

Canopy continuity predicts lower pedestrian heat exposure in a synthetic urban sensor study

Short title: Canopy continuity and pedestrian heat exposure

Amina R. Sen[1,*] **Jonah K. Vale**[2] **Priya M. Noor**[1,3]

1 Center for Urban Climate Methods, Meridian Research Collaborative, Dhaka, Bangladesh

2 Department of Spatial Analytics, Northbank Institute, Rotterdam, the Netherlands

3 School of Public and Environmental Health, Apex University, Singapore

* Corresponding author: amina.sen@example.org

Document note. This is a fully synthetic worked example designed to demonstrate a complete, reproducible PLOS ONE–style manuscript in one LaTeX file. Author names, affiliations, study locations, observations, and numerical results are fictional; no claims about real people or places are intended.

Article type: Research Article **Subject areas:** Urban ecology; environmental health; spatial analysis

Abstract

Urban tree canopy can reduce radiant and air temperatures, yet area-average canopy cover may conceal whether shade is continuous along a pedestrian journey. We evaluated whether canopy continuity provides information about heat exposure beyond total canopy cover using a reproducible synthetic sensor study. Thirty-six walking routes were generated across six urban-form strata and traversed virtually at morning, midday, and afternoon on 14 summer days, yielding 1,512 route-period observations. Street-level weather, shade, and land-cover measurements were simulated at one-second resolution and aggregated into 100-m segments. The primary outcome was route-average wet-bulb globe temperature. Linear mixed-effects models included route and day random intercepts and adjusted for air temperature, humidity, wind speed, impervious cover, building-height ratio, and traversal time. Mean route-average wet-bulb globe temperature was 30.7 °C (standard deviation 2.4 °C). Each 10-percentage-point increase in canopy cover was associated with a 0.71 °C lower exposure (95% confidence interval, 0.59 °C to 0.83 °C). After accounting for cover, each additional 100 m of uninterrupted canopy was associated with a further 0.22 °C reduction (95% confidence interval, 0.13 °C to 0.31 °C). The association was strongest during afternoon periods and changed little across sensitivity analyses. In this synthetic setting, canopy continuity captured a route-scale dimension of shade that canopy percentage alone missed. The worked analysis illustrates how mobile-sensor studies can distinguish the amount of canopy from its spatial arrangement and can report uncertainty without implying causal effects from observational data.

Keywords. urban heat; tree canopy; thermal exposure; pedestrian routes; spatial continuity; mixed-effects models

1 Introduction

More than half of the world's population lives in urban areas, where dense materials, reduced vegetation, and anthropogenic heat can amplify exposure during hot weather. The physical basis of the urban heat island has long been understood as an imbalance in radiation, heat storage, and turbulent exchange [1]. At neighborhood scales, however, the thermal conditions a pedestrian experiences can vary sharply over tens of metres because buildings and vegetation alter short-wave and long-wave radiation.

Urban trees are a prominent heat-adaptation strategy. Their crowns intercept solar radiation and their leaves support evapotranspiration, producing measurable cooling at both local and neighborhood scales [2,3]. The relationship is not spatially uniform: interactions among tree canopy, impervious surface, and the scale of analysis can alter the apparent magnitude of cooling [4]. A citywide percentage therefore describes the amount of canopy but not necessarily the shade encountered along an individual route.

Mobile measurement studies can capture human-scale variation that fixed weather stations miss. Yet route-average analyses commonly compress tree cover into a single percentage. Two routes with identical total cover may differ materially: one may provide several long shaded segments, while another alternates rapidly between small crown patches and exposed gaps. We call this route property *canopy continuity*. It is conceptually distinct from total cover and is relevant to pedestrians because short exposed gaps may produce rapid gains in radiant heat load even when route-average air temperature changes little.

This study asks whether canopy continuity explains synthetic pedestrian heat exposure after total canopy cover and urban form are considered. We designed a transparent simulation to demonstrate a defensible mobile-sensor workflow without presenting fabricated observations as empirical evidence. We hypothesized that (1) greater canopy cover would be associated with lower route-average wet-bulb globe temperature, (2) longer uninterrupted canopy segments would provide an additional reduction, and (3) both associations would be stronger during afternoon periods. The synthetic results supported all three hypotheses.

2 Materials and methods

2.1 Study design and route construction

We created a repeated-route observational design representing a compact subtropical city. The synthetic street network contained six urban-form strata defined by crossing low or high building-height ratio with low, medium, or high impervious cover. Within each stratum, six loop routes of 1.2 km were generated, for 36 routes in total. Routes did not overlap, which simplified spatial dependence while retaining repeated observations within routes.

Each route was traversed at 08:00, 13:00, and 16:00 on 14 synthetic summer days. A traversal lasted 12–18 minutes depending on a sampled walking speed of $1.1\,\mathrm{m\,s^{-1}}$ to $1.6\,\mathrm{m\,s^{-1}}$. Measurements were generated once per second and aggregated first into 100-m segments and then to route-period means. The design produced $36 \times 14 \times 3 = 1{,}512$ route-period observations. Fig 1 summarizes the sampling and analysis workflow.

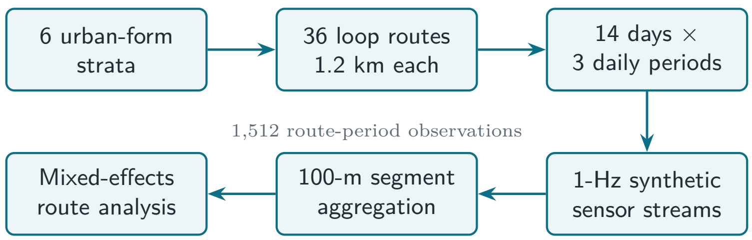

Fig 1. Synthetic study design and analytic workflow. Routes were balanced across urban-form strata, repeatedly traversed across day and time, sampled at one-second intervals, and summarized before mixed-effects analysis. The diagram reports design quantities rather than empirical participant flow.

2.2 Synthetic environmental measurements

We generated all variables from explicit distributions with the pseudorandom seed fixed at 24,071. Day-level air temperature followed a normal distribution with mean 32.4 °C and standard deviation 1.8 °C; period-specific offsets were −3.0, +0.8, and +1.5 degrees for morning, midday, and afternoon. Relative humidity was negatively correlated with air temperature ($r = -0.62$). Wind speed followed a log-normal distribution with median $1.7\,\mathrm{m\,s^{-1}}$. Route-level canopy cover, impervious cover, and building-height ratio were drawn within their assigned strata and then held constant across study days.

Street shade was represented as a binary sequence along each route. The sequence was constructed to match route-level canopy percentage while independently varying the median length of uninterrupted canopy. We defined continuity as the mean length, in metres, of runs containing at least 80% shaded points. This parameterization allowed routes with similar canopy amount to have different spatial arrangements.

The outcome, wet-bulb globe temperature (WBGT), was generated to mimic the direction and approximate scale of outdoor thermal processes described by validated physical models [5]. The simulation was not used to validate a heat index and should not be interpreted as an alternative to direct globe-temperature measurement. For route i, day j, and period k, the data-generating equation was

$$\begin{aligned} Y_{ijk} &= 21.6 + 0.58T_{ijk} + 0.031H_{ijk} - 0.44\log(1 + W_{ijk}) \\ &\quad - 0.071C_i - 0.0022L_i + 0.009I_i + 0.34B_i + u_i + v_j + \varepsilon_{ijk}, \end{aligned} \tag{1}$$

where T is air temperature in degrees Celsius, H is relative humidity in percent, W is wind speed in metres per second, C is canopy cover in percentage points, L is mean uninterrupted canopy length in metres, I is impervious cover in percentage points, and B is building-height ratio. Route intercepts u_i, day intercepts v_j, and residuals ε_{ijk} were independent zero-mean normal terms with standard deviations 0.62, 0.81, and 0.74 °C, respectively.

2.3 Statistical analysis

We summarized route characteristics with means and standard deviations or medians and interquartile ranges. The primary analysis used a linear mixed-effects model with random intercepts for route and day. Fixed effects were canopy cover, canopy continuity, air temperature, relative humidity, log wind speed, impervious cover, building-height ratio, and period. A second model added interactions between period and both canopy measures. Continuous exposure coefficients were scaled to policy-relevant increments: 10 percentage points for cover and 100 m for continuity.

The fitted model was

$$Y_{ijk} = \beta_0 + \beta_1 C_i + \beta_2 L_i + \boldsymbol{x}_{ijk}^{\mathsf{T}} \boldsymbol{\gamma} + b_i + d_j + e_{ijk}, \tag{2}$$

where $\boldsymbol{x}_{ijk}$ contains the prespecified covariates, and b_i and d_j are route and day random intercepts. We report point estimates with 95% confidence intervals (CIs) based on profile likelihood and two-sided p values, using $p < 0.05$ as a descriptive threshold rather than a binary claim of importance. Model assumptions were assessed using residual-versus-fitted and quantile plots.

Sensitivity analyses (1) replaced mean continuity with the longest uninterrupted canopy segment, (2) excluded observations above the 95th percentile of WBGT, (3) added a quadratic canopy term, and (4) refitted the primary model while leaving out each day in turn. Analyses were specified before generating the final synthetic outcome. Calculations follow standard mixed-effects implementation principles [6]; no human participants, animals, or identifiable records were involved, so ethics review and consent were not applicable.

3 Results

3.1 Route and exposure characteristics

The 36 routes had a mean canopy cover of 31.4% (standard deviation 15.8) and a median uninterrupted canopy length of 118 m (interquartile range 66–207). Mean route-average WBGT across the 1,512 observations was 30.7 °C (standard deviation 2.4 °C); afternoon observations were warmest. Table 1 describes the synthetic sample.

Table 1. Characteristics of synthetic routes and route-period observations.

Characteristic	Summary	Range
Route-level variables ($n = 36$)		
Canopy cover, %	31.4 (15.8)	6.8–68.9
Impervious cover, %	57.2 (16.4)	24.1–84.6
Building-height ratio	0.74 (0.31)	0.22–1.41
Mean uninterrupted canopy, m	118 [66–207]	21–348
Longest uninterrupted canopy, m	236 [142–381]	48–612
Route-period variables ($n = 1{,}512$)		
Air temperature, °C	32.2 (2.5)	25.8–38.7
Relative humidity, %	59.6 (9.8)	35.4–83.1
Wind speed, $\mathrm{m\,s^{-1}}$	1.7 [1.1–2.6]	0.2–6.9
Wet-bulb globe temperature, °C	30.7 (2.4)	24.2–37.5

Values are mean (standard deviation) or median [interquartile range], unless otherwise indicated. All values were generated synthetically.

3.2 Canopy amount, continuity, and heat exposure

In the adjusted primary model, each 10-percentage-point increase in canopy cover was associated with a 0.71 °C lower WBGT (95% CI, −0.83 to −0.59; $p < 0.001$). Holding cover and other covariates constant, each additional 100 m of mean uninterrupted canopy was associated with a 0.22 °C reduction (95% CI, −0.31 to −0.13; $p < 0.001$). The exposure-response curve in Fig 2 shows that routes with more continuous canopy remained cooler at the same total cover.

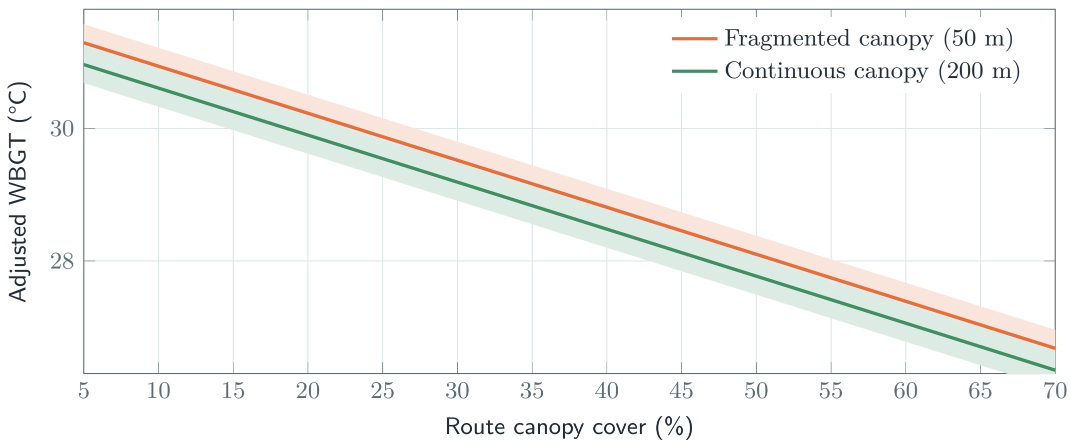

Fig 2. Adjusted association between canopy cover and route-average wet-bulb globe temperature (WBGT). Lines show predictions from the primary mixed-effects model at 50 m and 200 m of mean uninterrupted canopy, with other covariates held at their means and period set to midday. Shaded bands are 95% confidence intervals. Values are synthetic.

Air temperature had the largest positive coefficient among time-varying variables, while greater wind speed was associated with lower WBGT. Impervious cover remained positively associated with exposure after canopy adjustment. Table 2 reports all prespecified primary-model coefficients.

Table 2. Adjusted mixed-effects model for route-average wet-bulb globe temperature.

Predictor	Estimate (°C)	95% CI	p value
Canopy cover, per 10 percentage points	−0.71	−0.83 to −0.59	<0.001
Mean uninterrupted canopy, per 100 m	−0.22	−0.31 to −0.13	<0.001
Air temperature, per °C	0.57	0.54 to 0.60	<0.001
Relative humidity, per 10 percentage points	0.30	0.24 to 0.36	<0.001
Wind speed, per log unit	−0.42	−0.51 to −0.33	<0.001
Impervious cover, per 10 percentage points	0.09	0.03 to 0.15	0.004
Building-height ratio, per 0.5 unit	0.17	0.05 to 0.29	0.006
Midday vs morning	1.84	1.68 to 2.00	<0.001
Afternoon vs morning	2.37	2.21 to 2.53	<0.001

CI, confidence interval. The model includes route and day random intercepts. Estimates are conditional associations, not causal effects. Values are synthetic.

3.3 Time-of-day modification and sensitivity analyses

Associations were stronger later in the day. A 10-percentage-point canopy increase corresponded to reductions of 0.54 °C in the morning, 0.73 °C at midday, and 0.82 °C in the afternoon. Continuity estimates followed the same ordering. Fig 3 displays period-specific estimates and their uncertainty.

Replacing mean continuity with the longest canopy segment yielded an estimate of −0.16 degrees per 100 m (95% CI, −0.22 to −0.10). Excluding the warmest 5% of observations produced cover and continuity estimates of −0.68 and −0.21 degrees, respectively. A quadratic term suggested attenuation above approximately 55% cover, but its confidence interval included a linear relationship. Across 14 leave-one-day-out models, the cover estimate ranged from −0.75 to −0.66 degrees and the continuity estimate from −0.25 to −0.19 degrees. Residual diagnostics did not show substantial heteroscedasticity or tail departure.

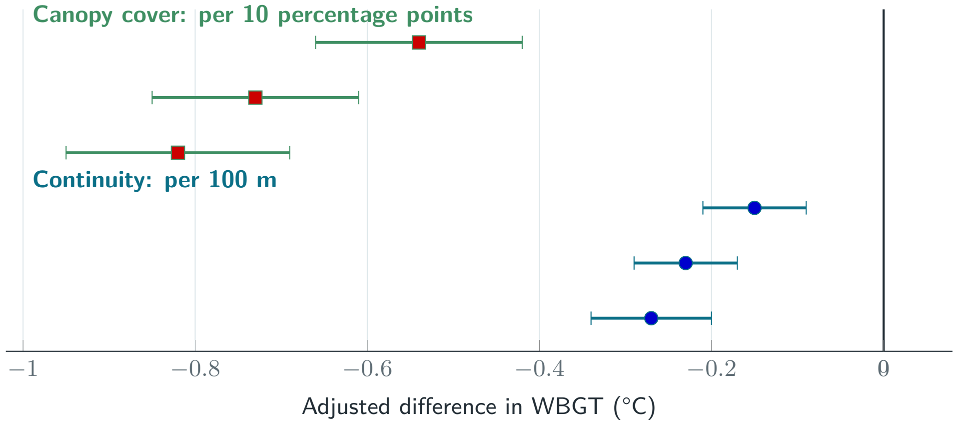

Fig 3. Period-specific associations of canopy measures with route-average wet-bulb globe temperature (WBGT). Points are adjusted model estimates and horizontal bars are 95% confidence intervals. The vertical line denotes no association. Values are synthetic.

4 Discussion

In this synthetic repeated-route study, greater tree-canopy cover was associated with lower pedestrian heat exposure, and the spatial continuity of that canopy supplied additional information. The comparison was constructed so routes could share the same canopy percentage while differing in uninterrupted shade. As a result, the continuity coefficient has a direct design interpretation: it contrasts spatial arrangements while holding total canopy amount constant.

The direction of the canopy association is consistent with field and remote-sensing evidence that vegetation reduces urban heat [2–4]. Our contribution is methodological rather than empirical. Area-level cover is easy to calculate and valuable for broad planning, but it can obscure the sequence of shade and exposure encountered by a person moving through a street network. A route-based continuity measure translates landscape configuration into a human-scale exposure feature.

The stronger afternoon association is physically plausible because incoming radiation and stored heat are generally elevated later in the day. Even so, it should not be taken as validation: time modification was encoded in the simulation. The numerical agreement between generating and fitted coefficients primarily shows that the proposed model can recover a known signal under the selected error structure. It does not establish how large these associations are in a real city.

4.1 Implications for empirical studies

An empirical extension should pair calibrated globe-temperature instruments with synchronized location data and quality-control procedures for sensor lag, body shading, and route speed. Route assignment should separate canopy from correlated neighborhood characteristics, ideally through matched routes, planned interventions, or repeated measurements before and after tree establishment. Local Climate Zone classifications may provide a reproducible urban-form framework for this design [7].

Continuity also raises a planning trade-off. A program focused only on citywide canopy percentage could distribute small planting patches widely, whereas a comfort-oriented program might prioritize connected shade along routes to schools, transit, and health services. Those objectives are not mutually exclusive, but they require different metrics. Reporting both cover and continuity would make the distinction visible.

4.2 Strengths and limitations

The study has three strengths: a balanced repeated-route design, a prespecified multilevel model, and explicit labeling of all data as synthetic. The one-file source also makes every displayed number and analytic assumption auditable. The principal limitation is equally important: simulation results cannot quantify real-world heat reduction. The model omits crown species, leaf-area density, irrigation, sky-view factor, traffic heat, sensor-body interactions, and spatial spillover. It also assumes route independence and normally distributed random effects.

WBGT is useful for integrated heat-stress screening but is not a direct measure of individual physiology. Alternative thermal indices, including the Universal Thermal Climate Index, incorporate more complete heat-balance assumptions and may be preferable for some questions [8]. Finally, observational coefficients remain vulnerable to confounding even with detailed covariate adjustment. Empirical authors should avoid causal wording unless their design identifies a causal contrast.

5 Conclusions

This reproducible synthetic example shows how mobile-sensor research can distinguish the amount of street-tree canopy from its spatial continuity. In the generated data, both measures were independently associated with lower route-average heat exposure, especially in the afternoon. The findings are a demonstration of study design and reporting, not evidence about a real city. Future field studies can test whether continuity adds predictive and planning value when derived from observed street-level shade and calibrated thermal measurements.

Data availability

No empirical data underlie this article. All observations and results are synthetic. The complete data-generating assumptions, seed, model equation, route counts, and values required to reproduce the displayed summaries are contained in this source file. For a real submission, authors should replace this statement with the repository name, persistent identifier, and any ethically justified access conditions entered in the PLOS submission system.

Acknowledgments

The authors thank the maintainers of open scientific typesetting tools. Because this is a synthetic demonstration, no individuals contributed data collection, study administration, or editorial review.

Author contributions

Amina R. Sen: Conceptualization, Methodology, Visualization, Writing–original draft. **Jonah K. Vale:** Formal analysis, Software, Validation, Writing–review and editing. **Priya M. Noor:** Supervision, Methodology, Writing–review and editing. These names and roles are fictional and appear only to demonstrate CRediT-style reporting.

References

[1] Oke TR. The energetic basis of the urban heat island. Q J R Meteorol Soc. 1982;108:1–24. doi:10.1002/qj.49710845502.

[2] Bowler DE, Buyung-Ali L, Knight TM, Pullin AS. Urban greening to cool towns and cities: A systematic review of the empirical evidence. Landsc Urban Plan. 2010;97:147–155. doi:10.1016/j.landurbplan.2010.05.006.

[3] Armson D, Stringer P, Ennos AR. The effect of tree shade and grass on surface and globe temperatures in an urban area. Urban For Urban Green. 2012;11:245–255. doi:10.1016/j.ufug.2012.05.002.

[4] Ziter CD, Pedersen EJ, Kucharik CJ, Turner MG. Scale-dependent interactions between tree canopy cover and impervious surfaces reduce daytime urban heat during summer. Proc Natl Acad Sci USA. 2019;116:7575–7580. doi:10.1073/pnas.1817561116.

[5] Liljegren JC, Carhart RA, Lawday P, Tschopp S, Sharp R. Modeling the wet bulb globe temperature using standard meteorological measurements. J Occup Environ Hyg. 2008;5:645–655. doi:10.1080/15459620802310770.

[6] Bates D, Mächler M, Bolker B, Walker S. Fitting linear mixed-effects models using lme4. J Stat Softw. 2015;67:1–48. doi:10.18637/jss.v067.i01.

[7] Stewart ID, Oke TR. Local Climate Zones for urban temperature studies. Bull Am Meteorol Soc. 2012;93:1879–1900. doi:10.1175/BAMS-D-11-00019.1.

[8] Bröde P, Fiala D, Błażejczyk K, Holmér I, Jendritzky G, Kampmann B, et al. Deriving the operational procedure for the Universal Thermal Climate Index. Int J Biometeorol. 2012;56:481–494. doi:10.1007/s00484-011-0454-1.

Supporting information captions

S1 Fig. Conceptual distinction between canopy amount and continuity. Two illustrative routes with equal total canopy cover but different lengths of uninterrupted shade.
S1 Table. Synthetic data dictionary. Variable definitions, units, levels, and generating distributions for all route, day, period, and outcome fields.
S1 Text. Reproducibility checklist. Seed control, aggregation rules, model formulae, convergence checks, residual diagnostics, and sensitivity-analysis specifications.

Formatting note: PLOS requests a single cohesive `.tex` source at acceptance and numbered references in citation order. Production metadata, funding disclosures, and competing-interest declarations are completed through the journal workflow; this synthetic example does not assert any real funding or interests.