



# Modeling the Shading Effect of Vancouver's Urban Tree Canopy in Relation to Neighborhood Variations

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**Abstract.** Background: Cities consume a disproportionate amount of energy for internal temperature regulation. Being able to reduce cities' cooling load on hot summer days can decrease energy consumption while improving occupants' thermal comfort. The urban canopy is an effective shading agent, adding cooling benefits to existing buildings and streets while providing other ecological and physiological values. Yet the building and street shading dynamic is a highly complex system that involves micro-level building components and macro-level variables. Introducing urban canopy to such a complex system creates another challenge, as urban canopy variables can also interact with buildings at both micro- and macro-levels. In order to accurately represent the urban canopy shading effect, it is necessary to account for the interactions among buildings, streets, and urban canopies. Methods: This study simulates the shading effect of urban canopy measured by aerial laser scanning (ALS) in the City of Vancouver, Canada, through the integration of a Radiance daylight simulation engine and geographic information system (GIS) data. All trees detected by ALS were included in the analysis. Results: The results indicate that street surfaces receive more solar irradiance reduction than building roofs and façades (i.e., exterior walls). Neighborhoods with less density and lower buildings were shaded noticeably better than areas with higher density and taller buildings. Among Vancouver's 22 neighborhoods, 2 neighborhoods, Kitsilano and the West End, demonstrated a promising sign where both building density/height and urban canopies are maintained. There was evidence of high canopy shading and high-density urban morphologies. Conclusion: Overall, this work provided an authentic canopy assessment from single building to city scale, creating opportunities to investigate intracity urban canopy variations, equality, and the balance between urban greening and urban densification.

**Keywords.** 3D Tree Canopy Mode; Aerial Laser Scanning; Canopy Shading; Radiance Model; Street Trees; Urban Forestry.

## INTRODUCTION

Covering approximately 3% of the terrestrial surface, cities consume a disproportionate amount of energy and are therefore a major emitter of greenhouse gases (GHGs). In Canada, cities are responsible for over 42% of the GHG emission (Torrie 2015). As a result, local municipalities have included various measures to reduce GHG emissions through either improving operational efficiency (i.e., higher building performance standards), reducing energy demand (i.e., discourage private vehicle usage), or both. Cities tend to have higher air and land surface temperatures than surrounding landscapes (known as the urban heat island, or UHI, effect), with a difference ranging from 1 to 3 °C (Rosenfeld et al. 1995), but sometimes can exceed 10 °C (Stone et al. 2010; Stone et al. 2012). Climate change, along with fast urbanization, has

caused cities more intense and frequent heat waves, which are periods with exceptionally high temperatures (Li and Bou-Zeid 2013).

Currently, over 60% of the urban population is experiencing above-average temperatures in cities compared to nonurbanized areas (Estrada et al. 2017). City dwellers face increased heat-related health and safety risks due to the synergetic relationship between UHI and heat wave effects (Li and Bou-Zeid 2013), adversely impacting not only local and regional climates but also ecosystem function and human health (Grimm et al. 2008). For example, in the United States, extreme heat events have caused the highest number of climate-related fatalities (Stone et al. 2010). Climate change is only expected to exacerbate heat risk in the urban environment, which will lead to the use of space cooling technologies and consequently

higher energy demand and GHG emissions (Sailor and Pavlova 2003). Urban canopy, including street, park, and private trees, is well known for its ecological values (Krayenhoff et al. 2020), its social values (Kweon et al. 1998; Laforteza et al. 2009; Nesbitt et al. 2017), and its contribution to regulate microclimates and even lower cities' GHG emissions (Palme et al. 2020; Pigliatile et al. 2020; Sabrin et al. 2021) due to its cooling and shading effects (Huang et al. 1987; Tooke et al. 2012; Morakinyo et al. 2017).

### Key Characteristics of Urban Canopies in the Context of Shading

Urban canopy can lower air and surface temperature through evapotranspiration (Metselaar 2012) and casts shade that prevents solar radiation from heating the air and land surface (Bowler et al. 2010; Yu Q et al. 2020). As a natural cooling device for building occupants and pedestrians, urban canopy offers up to 9 °C reduction in building surface temperature, potentially lowering up to 30% of the overall cooling energy demand (Akbari et al. 1992; Berry et al. 2013).

In general, there are 4 key urban canopy characteristics that can influence shading ability. Firstly, the coverage and height of the canopy (i.e., canopy cover hereafter) directly determine the shaded area cast by a given tree crown. Ziter et al. (2019) suggested that a nonlinear relationship exists between temperature reduction and canopy cover size in a midsized city in the Upper Midwest United States. Middel et al. (2015) found that an increase in canopy cover from 10% to 25% can potentially reduce its surrounding air temperature by 2 °C in a residential neighborhood in the City of Phoenix, Arizona. Secondly, canopy cover density can interplay with shading, as trees closer together tend to have a lower solar permeability and therefore offer better shading quality (Aminipouri et al. 2019). Thirdly, the location of canopy can indirectly impact the overall shading quality (Palme et al. 2020). For example, in Melbourne, Australia, east-west oriented street trees often provide better shading (Norton et al. 2015), and trees located closer to a building or streets cast more direct shade than trees located farther away (Berry et al. 2013). Lastly, canopy shading ability can vary across different physiological traits of an urban canopy, such as its species, age, health condition, and height. Deciduous trees, compared to coniferous trees, can also have seasonal fluctuations between leaf-on and leaf-off months.

### Modeling Thermal Dynamics of Built Environment and Urban Canopy

The thermal dynamics of the built environment (i.e., building and street) is highly complex, including both micro-level building components and macro-level variables (e.g., building locations, street width/density, climate conditions, etc.). Additionally, urban canopy characteristics (e.g., size, density, location, species, etc.) are interwoven with micro- and macro-level urban built elements, creating additional complexity for researchers and urban planners. As a result, the majority of the previous research on urban canopy cooling focused on limited spatial extent (Yu Q et al. 2020). Even fewer empirical studies have been conducted to focus on canopy shading on both building and street level due to expensive field study costs, and they were often limited by small sample sizes and the ability to set up proper control experiments (Berry et al. 2013). The lack of reliable data and models therefore hinders the possibilities for future temporal studies.

Tree shade changes spatially across urban environments, yet there is no consistent method to effectively quantify the spatial variations of canopy shade, as it strongly depends on various complex factors such as spatial scale, location, and solar geometry (Yu X et al. 2020). Spectral information (e.g., the normalized difference vegetation index) from remotely sensed images has been commonly used to investigate the spatial (Jin et al. 2020) and temporal variations (Czekajlo et al. 2020) of urban vegetation. In general, remote sensing data are more consistent and temporally stable compared to manually collected field data (Shahtahmassebi et al. 2021). Yet multispectral or even hyperspectral data offer limited information on detailed 3D urban canopy structure (e.g., tree height) sensitive to the shading effect (Yu X et al. 2020).

Other remote sensing technologies such as aerial laser scanning (ALS, or commonly known as LiDAR) have become increasingly common in modeling urban canopies (Tooke et al. 2012; Plowright et al. 2017) and solving other urban vegetation-related challenges. Compared to multispectral remote sensing images, ALS is an attractive tool due to its capability of measuring urban canopy in 3D at a fine spatial resolution (e.g., sub 1 m). ALS also enables researchers to generate accurate digital surface models (DSMs) and individually delineated single canopy crowns in complex urban settings (Chance et al. 2016; Plowright et al. 2016; Plowright et al. 2017). Yet despite the

advancement of ALS, understanding thermal dynamics between urban built environment and urban canopy still requires additional modeling capability to decode the interwoven relationships among buildings, streets surfaces, canopies, and local solar and climate conditions. Solely relying on ALS and other remote sensing data therefore cannot create an authentic model to simulate canopy shading effect accurately.

There is a need for a model capable of reconciling buildings, streets, and urban canopies when simulating canopy shading effect. This study uses ALS remote sensing to create a comprehensive 3D model of the urban canopy in Vancouver, British Columbia, Canada. Using a Radiance-based simulation engine (Ward 1994; Roudsari and Pak 2013), the shading impact of the modeled canopy is studied on various horizontal and vertical urban surfaces under local climate conditions. This work consolidates urban canopy modeling through the integration of building energy modeling, remote sensing, and urban design, offering practical planning and research opportunities in understanding urban canopy shading dynamics. The complete data coverage (citywide with over 245,000 trees modeled) and spatial resolution ( $< 1$  m) also provide a solid foundation for researchers interested in urban greenness inequity, gentrification, and species adaptation (Gould and Lewis 2016; Nesbitt et al. 2019).

## MATERIALS AND METHODS

The following sections introduce the study site, the processing of ALS, and solar irradiance simulation.

### Study Area: Vancouver, BC

Located in the lower mainland of British Columbia (BC), Canada, the City of Vancouver (Vancouver hereafter) has a population of 675,000 and a size of 115 km<sup>2</sup>. The city has 2,645 ha of tree cover, giving its residents appropriately 23% canopy cover citywide. This canopy is distributed unevenly across the city, with a general east-west divide of low/high canopy cover (Vancouver Board of Parks and Recreation 2020).

Vancouver experiences a mix of an oceanic climate (Köppen climate classification *Cfb*) and a warm-summer Mediterranean climate (*Csb*). Its summer is typically dry with an average of 8 hours of sunlight, 18 °C in day temperature, and 9.3 °C at night in August (Environment and Climate Change Canada 2021). As summers become increasingly warmer, the use of air conditioning (AC) in BC has tripled to 34%

since 2001, costing British Columbians around \$300 in annual electricity bills per household (BC Hydro 2018). Shading from urban canopy can potentially eliminate the use of AC or at least allow a moderate AC usage (Akbari and Taha 1992). For every degree lower that an AC unit is set, the approximate cooling cost can increase by up to 3% (BC Hydro 2018). With its unique climate profile, variations of intracity canopy cover, and increasing energy demand for cooling, Vancouver is an ideal case study.

There are 22 neighborhood planning areas defined by the City of Vancouver. They vary in size from 217 to 907 ha. Building density and height are highest in and near Downtown areas, with the lowest-density neighborhoods being along the south and west edge of the city. Building heights range from 2 to 190 m, with the majority of buildings over 30 m located in the Downtown area.

### Data Acquisition and Processing

In order to accurately simulate individual canopy shading effects on buildings and streets, 3 primary data layers were generated to represent buildings as a 3D model (including their location, heights, and orientation), streets as a 2D polygon (including their widths, lengths, and location), and lastly urban trees as a 3D model (including their height, crown sizes, densities, and shapes). A 3D building layer was derived by extruding the existing building footprints by their heights using Microsoft's open building data (GitHub 2021) and BC Assessment Data (BC Assessment 2021). A 2D street raster surface was generated using Vancouver's latest land cover and land use classification at 2-m spatial resolution (Metro Vancouver 2014). The advantage of using a raster-based street layer over a conventional vector-based (i.e., polylines) layer was to offer accurate measurement on the right-of-way (ROW), as a wider street will have more exposed surface than a narrow one. In addition, by including both a 3D building layer with building height information and a street ROW layer, the model can also take into account the aspect ratio (AR) defined by building height divided by the street width (H/W). Being able to accurately account for various ROWs was therefore critical to this model.

A 3D tree canopy model was generated using a set of aerial laser scanning (ALS) point clouds (City of Vancouver Open Data Portal 2013). In 2013, Vancouver acquired a citywide ALS for the extent of its legal jurisdiction with a minimal point density of 12 points/m<sup>2</sup>

and an average 50% overlap among flight paths. The resulting data have an overall accuracy of 18 cm (vertical) and 36 cm (horizontal) at 95% confidence level, respectively. The raw ALS point clouds were classified into 5 categories: bare earth and low grass, low vegetation, high vegetation, buildings, and water (Figure 1). Individual treetops and canopy crowns were identified and delineated based on Matasci et al. (2018) with an object-based image analysis approach relying on a DSM derived from the point clouds. As they offered minimal shading, low vegetation points were removed from subsequent analysis to boost processing speed.

### Urban Canopy Cover Density

In this project, one key attribute to accurately simulating canopy shading was canopy cover density. Canopy cover density determines the shading intensity cast by a given tree canopy. Based on the processed ALS point clouds and individual canopies delineated by Matasci et al. (2018), a simple yet intuitive canopy cover density measure was generated for each tree crown. Figure 2 illustrates this process where for individual crown, the return points classified as vegetation (> 3 m) and the total ground return points were used to estimate the amount of laser beams from LiDAR disrupted by the presence of a canopy, which in turn indicated the overall canopy cover density. For example, for a given canopy with 100 returns detected

by LiDAR—20 of which were returned from the ground ( $G = 20$ ), while 80 laser points were returned to the sensor because of leaves and branches within this canopy ( $V = 80$ )—the overall estimated canopy cover density would be 80% (i.e., 80/100). This procedure was applied to all trees except those in large forests located within the Pacific Spirit Park and Stanley Park, where only limited built structures and streets were present and therefore not relevant in this project. The canopy cover density metric (Figure 2) proposed in this work can act as a proxy to sky view factor without conducting manual field measurements. Our canopy cover density, unlike a leaf area index (LAI), directly accounted for the amount of the laser pulses that reached the ground and the laser pulses blocked by the canopy structure (e.g., branches and leaves). In other words, this metric is a measure of how much light can be seen under the canopy.

### Honeybee: A Radiance Engine

The aforementioned 3D buildings (roof and walls), 2D street surfaces, and 3D urban canopy layers were input into a Radiance engine to simulate the shading impact on buildings and streets from urban canopies. The simulation was performed using Radiance, a validated ray-tracing tool, through an environmental analysis program, Honeybee versions 0.66 and 0.69 (Radiance 2021). Honeybee is an open-source

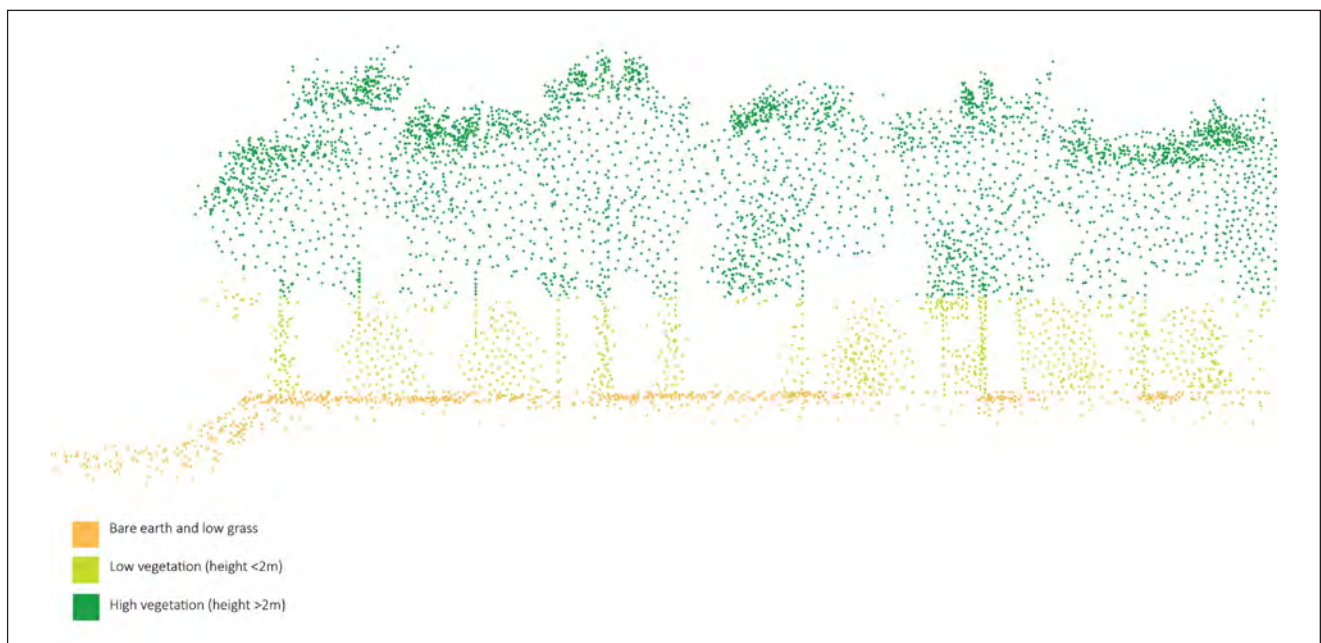


Figure 1. Illustration of sample ALS (LiDAR) point cloud classes.

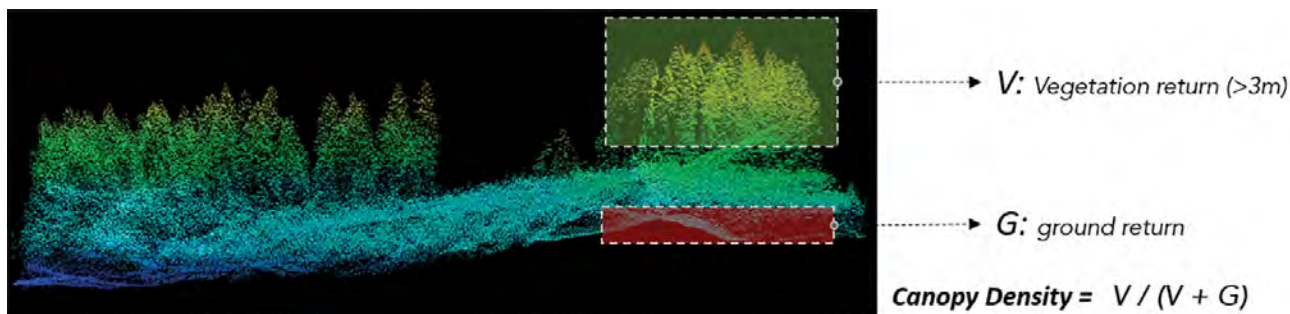


Figure 2. Canopy cover density calculation illustration.

extension of the Ladybug toolkit developed by Roudsari and Pak (2013), which allows users to create, simulate, and visualize energy and daylight with validated building performance simulation (BPS) tools including Radiance, Daysim, and EnergyPlus/OpenStudio. Honeybee is highly customizable with modular components for users to set their desired parameters (Aksamija 2018).

Honeybee was developed in Rhino’s visual scripting interface Grasshopper, providing high efficiency in simulation workflow and design feedback. To perform a daylight simulation, Honeybee offers precise thermal zone surface adjacency solutions and flexibilities to substitute the window-to-wall ratio (WWR)(Lin et al. 2019) and simulated irradiance of surfaces of all build-

ings (i.e., roofs, façades/walls) and streets (Figure 3).

To run Honeybee, this study first utilized geometries described above to develop the wall and roof geometries. Honeybee subdivided extruded building footprints by a standard floor height of 2.7 m. These subdivided masses were then assigned window areas based on the percentage of openings for each façade orientation (e.g., North = 20% WWR). This type of input setting is particularly well suited for urban-scale simulations, where the actual position of windows on façades is usually unknown, while their influence on the energy balance is still relevant (Peronato et al. 2017). The information of each input attribute can be displayed through synchronous graphics on the 3D model in Grasshopper, allowing the user to check the



Figure 3. Surfaces (façades, roofs, and streets) simulated in this work. The amount of solar radiation with and without urban canopies will be generated and compared for each surface type.

accuracy of their input prior to executing the simulation. In simulating irradiance, users generate test points on surfaces of interest, such as the roof of a building, defined as a grid with an adjustable density assigned to the surface and parameters specific to the Radiance engine that define the physical intersection of simulated photons, such as the number of bounces allowed for a beam of light, or the sampling density of the beams per time step (Roudsari and Pak 2013). For the surfaces in this study, a density of 1 sample point per 0.5 m<sup>2</sup> was assigned and simulation parameters were set to more than accurate according to Radiance documentation, with the exception of ambient bounces (number of times a ray of light bounces from surface to surface before dissipating).

While Honeybee provides an interactive mode for the use of Radiance, it comes with drawbacks regarding computation resources. This can lead to lengthy simulation times in large simulation sets and, specifically in the case of this study, if using processing hardware with low RAM (< 32 GB), failed simulations were experienced. To compensate for lengthy processing times, ambient bounces were set to 1 to reduce overall simulation time without compromising the study aim of analyzing the impact canopy cover has on direct solar radiation. Ambient bounces control the amount of times a ray that has been cast is allowed to bounce across surfaces in the model. A higher value leads to more bounces and more ambient light resolution but does not impact measured radiation as a result of the initial canopy cover. A sample of key radiance parameters is shown in Table 1.

The engine used hourly solar data, referenced from an EnergyPlus Weather (EPW) file for Vancouver's

climate (EnergyPlus 2016). This file was used to generate a cumulative sky to simulate hourly solar irradiation within the model (Robinson and Stone 2004). EPW files are constructed representative annual weather sets that typically describe a location's climatologically typical weather parameters (National Renewable Energy Laboratory 2020). The simulation utilizes the location of the sun for every hour of the chosen analysis period to cast light rays onto the test surfaces and queries the EPW's solar irradiance values to determine how much solar radiation the exterior surfaces may receive given any shading objects that obstruct their view of the sky type, grid size, grid distance off surface, and legend (low and high bound) (Aksamija 2018). After setting up the input parameters, the user can run the simulation from Grasshopper. Following the simulation run, users can visualize and customize the results in several different ways with Honeybee's components (Roudsari and Pak 2013). For example, results can be displayed with intuitive colors on the surfaces (e.g., street, roof, and walls of the 3D model). Although hourly output could be generated for the entire year, the scope of this project considered a peak heat and an unobstructed direct sunlight week (mid-July). Surrounding buildings and context such as tree canopies were considered during this analysis as a baseline case of shading. Input parameters were kept consistent between the baseline cases (only building and context shading) and the experiment cases (including the urban canopy as a shading element). The scope of this project focuses on canopy shading, therefore shading cast by buildings on other buildings and street surfaces is not included when comparing solar irradiance reductions.

## RESULTS

### Canopy Cover Density

As expected, neighborhoods showed considerable variations in terms of canopy cover (total canopy area/total neighborhood area) and total number of trees (Figure 4). A total of 245,645 trees were processed with an average canopy cover density of 53% (standard deviation of 22%) for the entire City of Vancouver.

Well-treed neighborhoods such as Shaughnessy, Dunbar-Southlands, and Kerrisdale had over 20% canopy cover and over 20,000 trees, while neighborhoods such as Downtown, Strathcona, and Sunset had less than 10% canopy cover with about 5,000 trees. There

**Table 1. Radiance parameters were set to the "High" quality in Honeybee, with the exception of ambient bounces. Key parameters are shown here.**

Radiance parameter	Value
Ambient accuracy	0.1
Ambient bounces	2
Ambient divisions	4,096
Direct certainty	0.75
Specular threshold	0.15
Limit weight	0.005
Ambient super-samples	4,096
Ambient resolution	128
Limit reflection	8

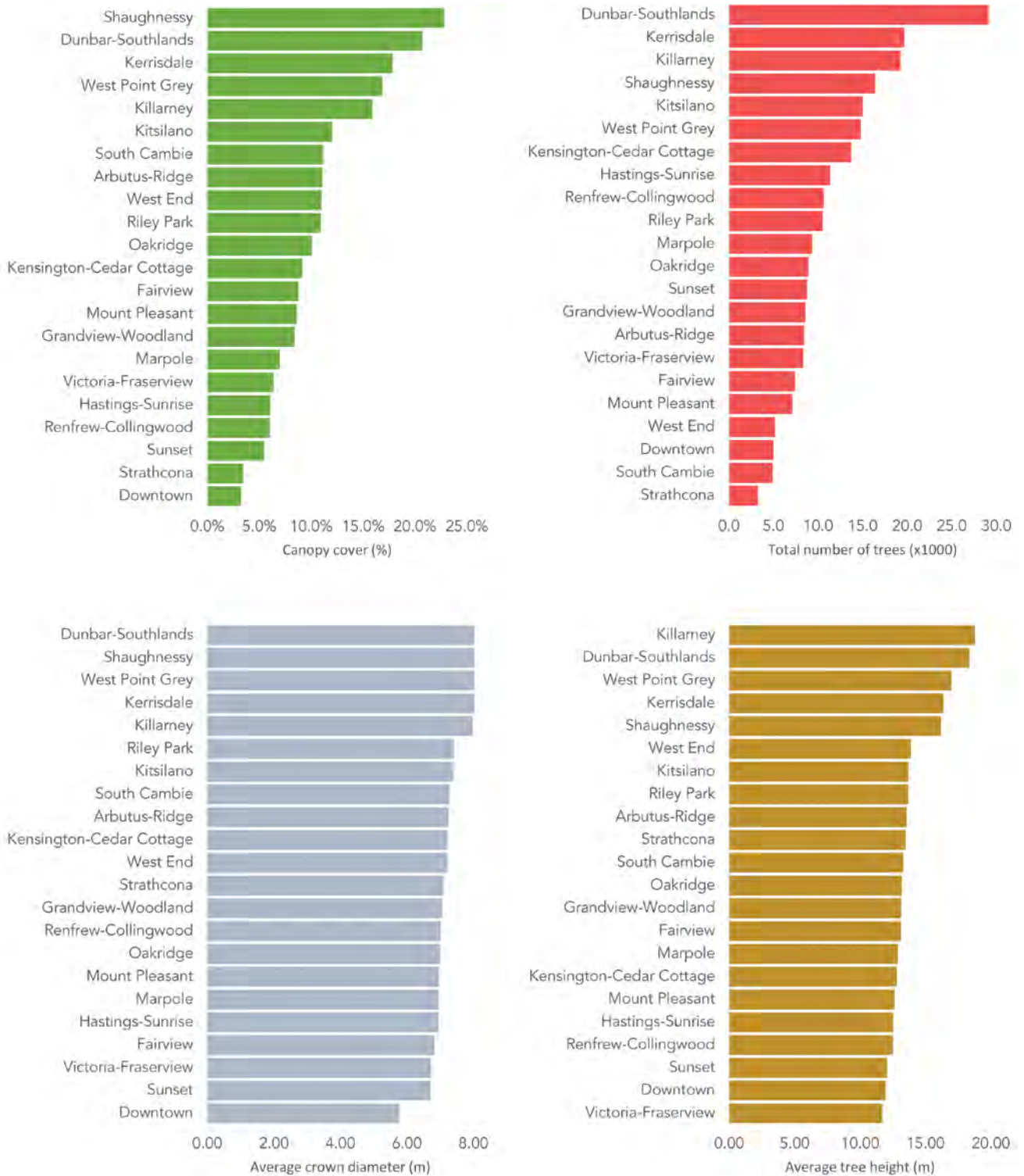


Figure 4. An overview of urban canopy conditions of Vancouver’s local area neighborhoods.

was less variation in terms of average canopy crown diameter and tree height (Figure 4), however, poorly treed neighborhoods appeared to have slightly smaller trees.

Figure 5 illustrates samples of estimated ALS-derived canopy cover density from 4 distinctive neighborhoods. Typically, Downtown (Figure 5a) was representative of neighborhoods of dense and tall buildings with limited canopy cover. Downtown West End (Figure 5b), on the other hand, represented neighborhoods with both high population density and canopy cover. Victoria-Fraserview and Shaughnessy (Figure 5c and 5d) portrayed 2 distinctive urban canopy characteristics found in areas predominantly occupied by single-family and low-rise housing.

### Canopy Shading Impact: Streets

Average solar irradiance reduction (%) on street surfaces was summarized for each neighborhood (Figure 6). As expected, reductions on street surfaces varied from neighborhood to neighborhood in Vancouver. After

adding canopy into the simulation, a street surface could receive up to 78% reduction in incoming solar irradiance. Typically, neighborhoods with more street trees (e.g., West Point Grey, Dunbar-Southlands) appeared to have more canopy shading on its street surface. Note that reduction values in Figure 6 did not necessarily mean such neighborhoods were shaded more than places such as Downtown, as shades cast by tall/large buildings (often seen in Downtown) could also provide shading but were not illustrated here.

### Canopy Shading Impact: Roofs

Similar to street surface, Figure 7 demonstrates shading differences on roofs while taking into account the overall building height, as taller buildings were less likely to receive shading from trees. This reveals contrasting roof shading characteristics among neighborhoods. Generally speaking, shading impact on roofs was influenced by a combination of both building height and overall canopy cover. For example, the majority of roofs in the east part of the city (e.g., Riley

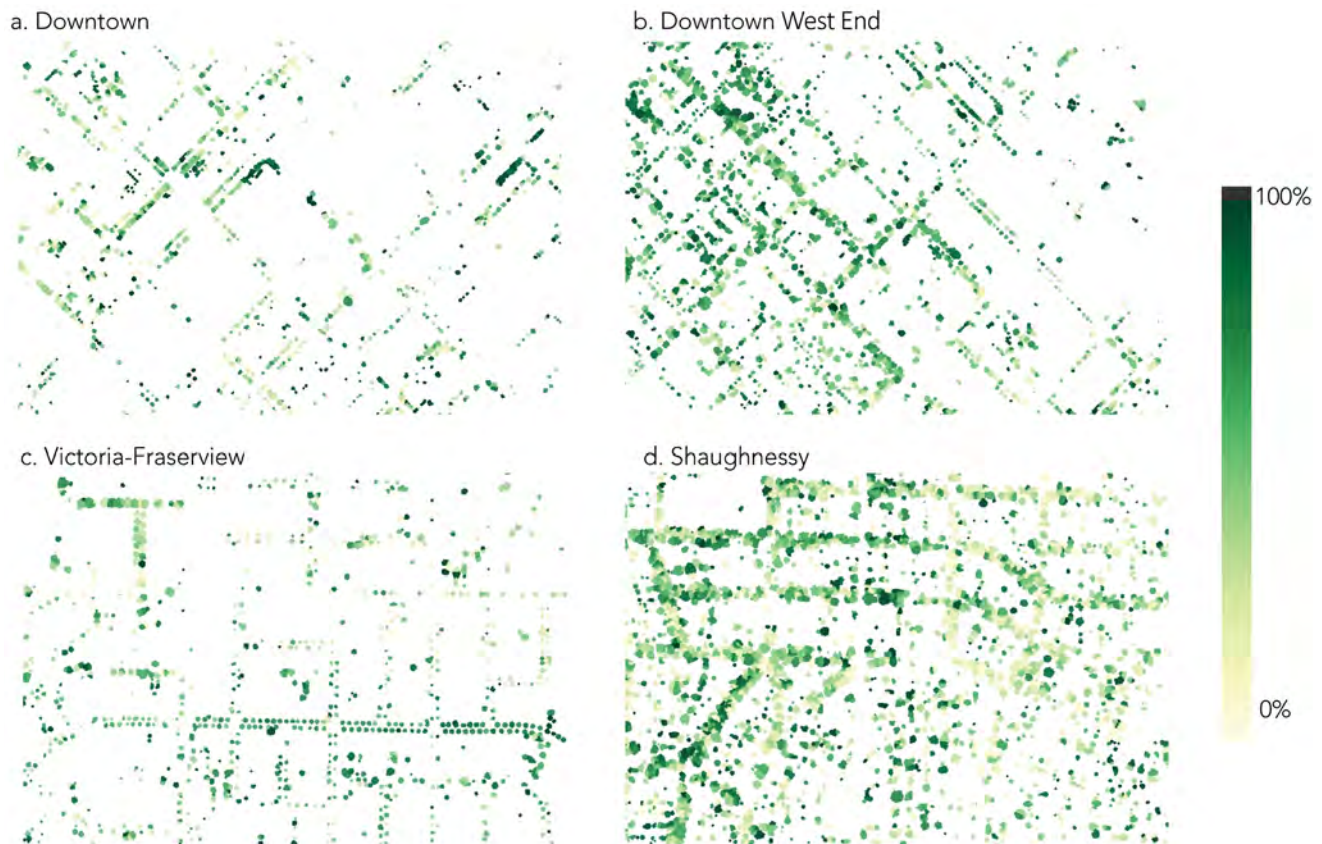


Figure 5. Sample canopy density estimates of (a) Downtown, (b) Downtown West End, (c) Victoria-Fraserview, and (d) Shaughnessy. Each polygon is an individual canopy delineated using ALS points and colored based on its measured canopy density (0% to 100%).

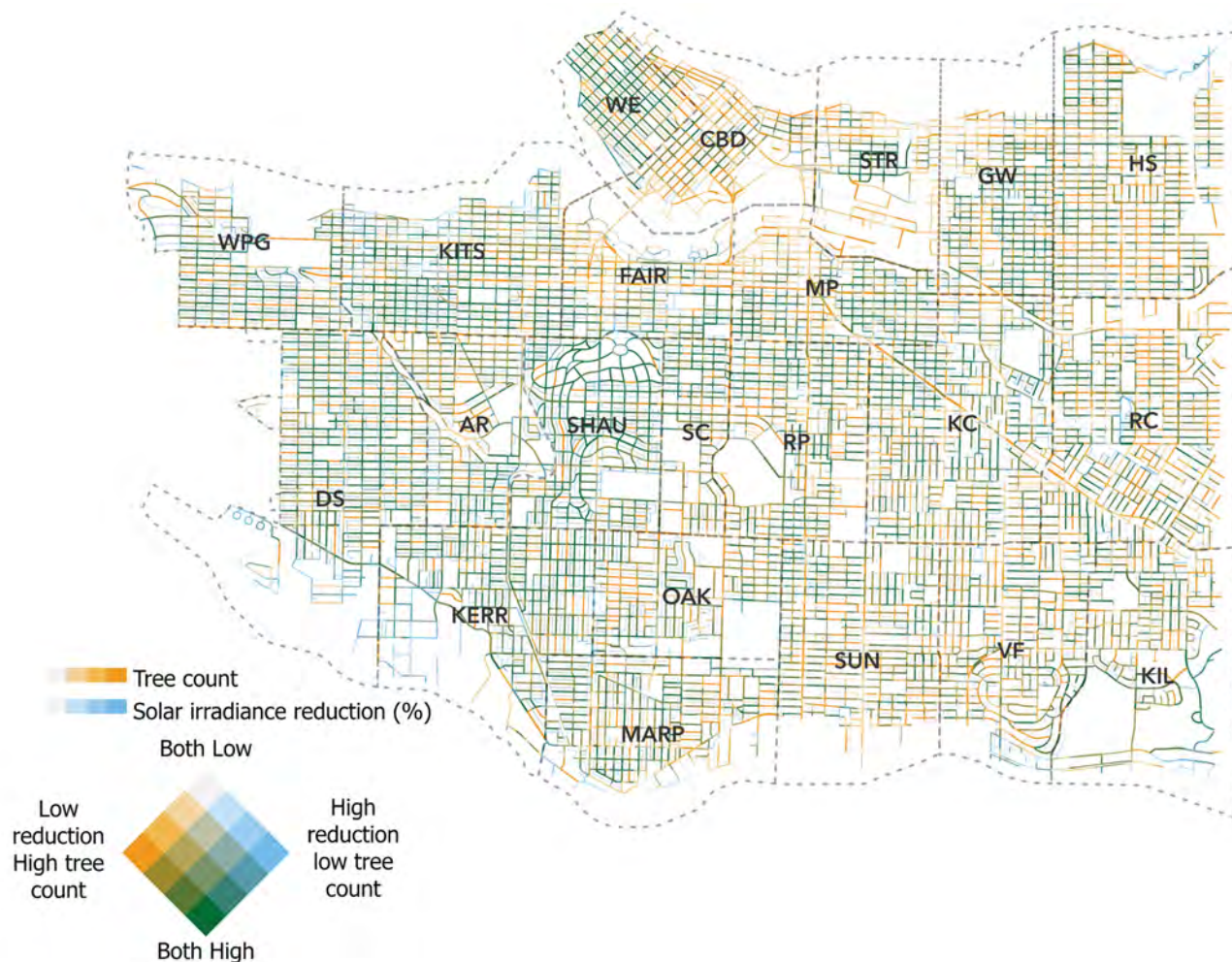


Figure 6. A bivariate (tree count and relative solar irradiance reduction) summary map of street-level solar irradiance changes (%) due to urban canopies. WPG = West Point Grey. DS = Dunbar-Southlands. KITS = Kitsilano. AR = Arbutus Ridge. KERR = Kerrisdale. WE = West End. FAIR = Fairview. SHAU = Shaughnessy. OAK = Oakridge. MARP = Marpole. CBD = Downtown. MP = Mount Pleasant. SC = South Cambie. RP = Riley Park. SUN = Sunset. STR = Strathcona. KC = Kensington-Cedar Cottage. VF = Victoria-Fraserview. HS = Hastings-Sunrise. RC = Renfrew-Collingwood. KIL = Killarney.

Park, Sunset) were not shaded nearly as well as the west-side neighborhoods (e.g., Dunbar-Southlands, Shaughnessy) despite having similar building heights. Roofs located in neighborhoods such as Kitsilano, Kerrisdale, and West End set an unusual example where both building height and shading reduction were relatively high (i.e., taller buildings yet with noticeable shading benefit from trees).

### Canopy Shading Impact: Façades

Solar irradiance reduction was also simulated for all building façades in Vancouver. Figure 8 visualizes average reduction and the general building style/size in each neighborhood. Neighborhoods primarily with

larger building façades (e.g., Downtown, Fairview) received relatively less irradiance reduction (%) than neighborhoods with shorter building façades.

It was also noticeable that not all neighborhoods with small buildings were shaded equally. For example, Victoria-Fraserview, an area largely occupied by comparably sized buildings found in Dunbar-Southlands and Shaughnessy, received less than 10% irradiance reduction. There were, however, places where larger buildings also benefited up to 20% reduction in solar irradiance, namely Kitsilano, Mount Pleasant, Kerrisdale, and West Point Grey. Overall, the Downtown area, including West End, and Victoria-Fraserview were among the worst neighborhoods in terms of façade shading.

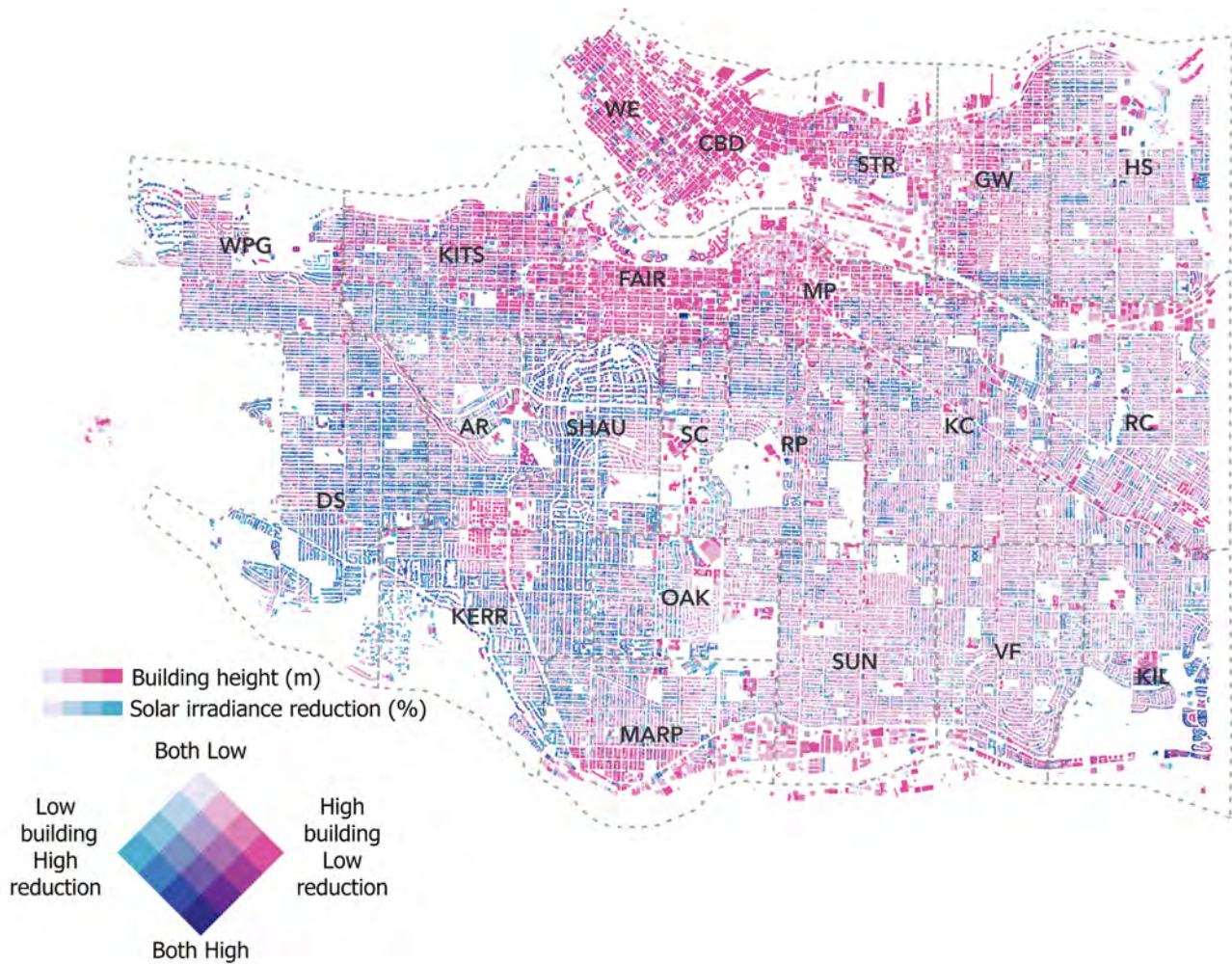


Figure 7. A bivariate (building height and relative solar irradiance reduction) summary map of roof-level shading results. WPG = West Point Grey. DS = Dunbar-Southlands. KITS = Kitsilano. AR = Arbutus Ridge. KERR = Kerrisdale. WE = West End. FAIR = Fairview. SHAU = Shaughnessy. OAK = Oakridge. MARP = Marpole. CBD = Downtown. MP = Mount Pleasant. SC = South Cambie. RP = Riley Park. SUN = Sunset. STR = Strathcona. KC = Kensington-Cedar Cottage. VF = Victoria-Fraserview. HS = Hastings-Sunrise. RC = Renfrew-Collingwood. KIL = Killarney.

## Neighborhood Comparison

Figure 9 summarizes solar irradiance reduction on all surfaces for all 22 neighborhoods in Vancouver. Street surfaces (Figure 9a) showed the strongest correlation ( $r = 0.94$ ) between relative irradiance reduction and average canopy cover in all neighborhoods. Expectedly, irradiance reduction on wall surfaces (Figure 9b) also highly correlated with canopy cover ( $r = 0.90$ ). Such pattern, however, was less evident for roofs (Figure 9c,  $r = 0.84$ ), where minimal solar irradiance reduction was observed regardless of the canopy cover, even for well-treed neighborhoods. Overall, Figure 9d revealed that poorly canopied neighborhoods—particularly those with higher population density—did not enjoy

as much shading benefits for their streets and building façades.

## DISCUSSION

Urban canopy offers not only ecological and social benefits to urban dwellers and wildlife, but it is increasingly being recommended as a shading agent to lower street temperature and overall building cooling load. Akbari et al. (1992) demonstrated that peak electricity load would increase 1.5% to 2% for every 1 °F (0.56 °C) increase in temperature in American cities with more than 100,000 residents. Preserving and/or enhancing urban canopy shading in already dense urban areas requires comprehensive and

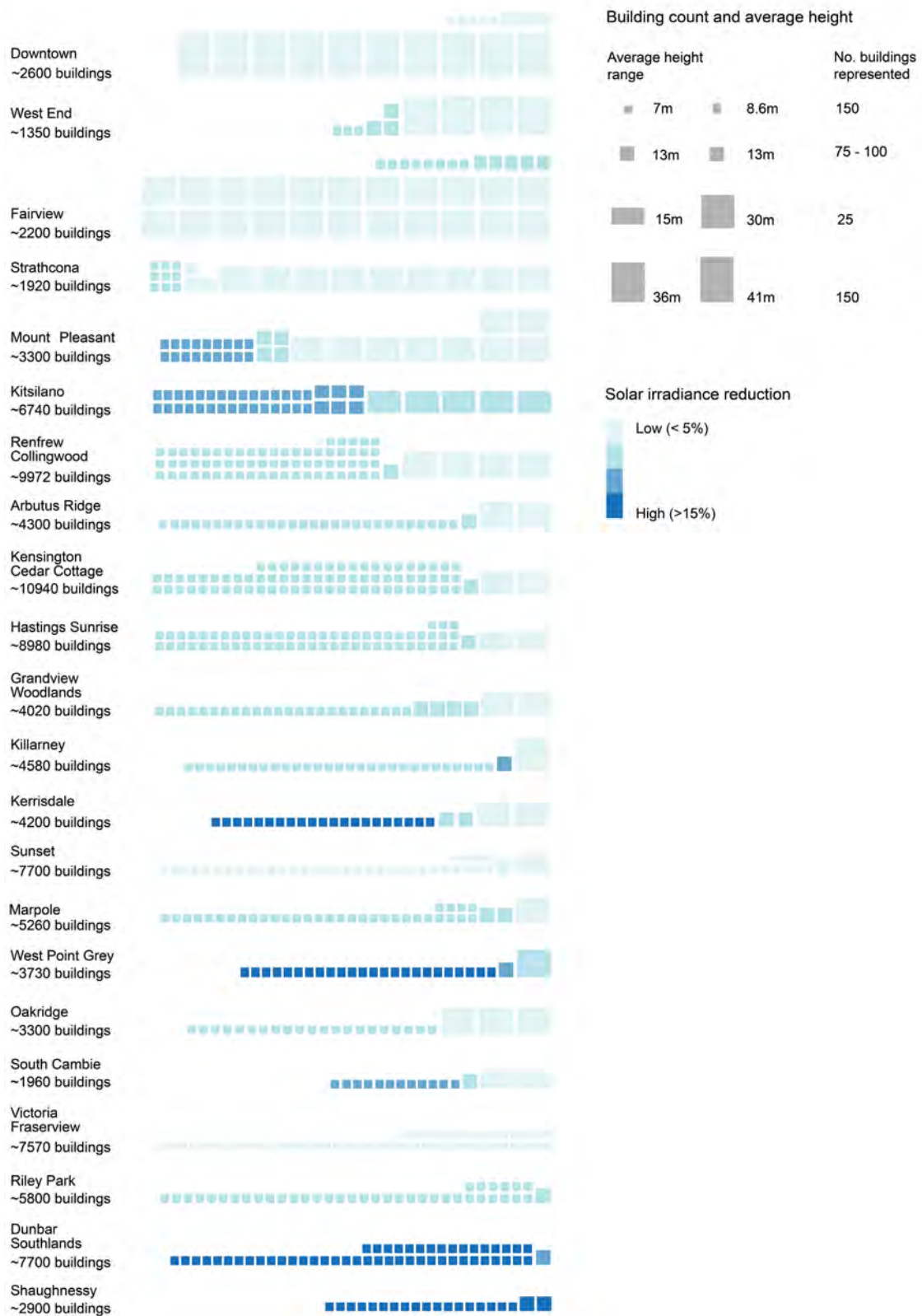
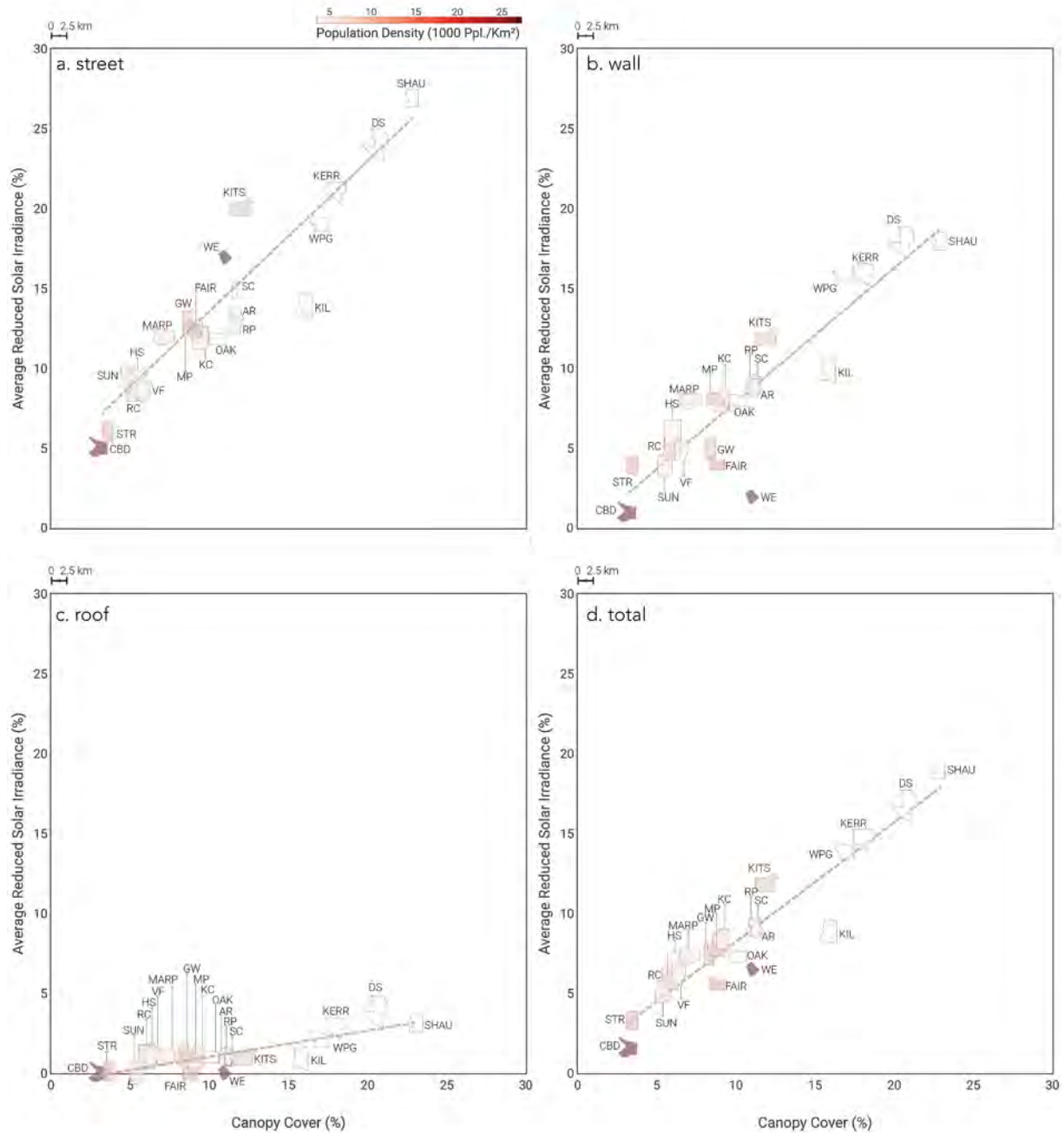


Figure 8. Average solar irradiance reduction on walls/façades by neighborhood. Building frontal views are used to illustrate the distribution of building types, amount of buildings, and reduction (%).



**Figure 9. Scatter maps comparing total neighborhood cover (%) to average solar irradiance reduction on (a) street, (b) wall (façade), (c) roof, and (d) all surfaces. Polygons are scaled to size and colored based on population density (1,000 people/ha).**

effective planning, which should be guided by informed and careful selection of planting locations, sufficient standards and robust legal framework, and collaborative decision-making processes. These all require innovative techniques to understand the complex relationships between urban canopy and the built environment. This work presents an attempt in building a long-term collective modeling environment by

integrating remotely sensed ALS data with a Radiance engine to simulate urban canopy's shading ability to guide science-based planning and urban design.

With cities growing larger, denser, and at a faster pace, compact urban forms with increased density have been consistently considered to be more sustainable than urban sprawl. Density is encouraged because it limits adverse impacts of urban expansion

on surrounding natural areas while promoting accessibility and walkability, reducing driving mileages, and creating efficient use of urban land (Haaland and van den Bosch 2015). Yet densification often competes against other needs such as urban canopy and green spaces, in particular. Densification intensifies UHI due to increased impervious surfaces, lowered albedo, altered urban geometry, and reduced green spaces (Erlwein and Pauleit 2021). Such development patterns are evident in this work, and they present a major threat to urban canopy health such as loss of green spaces and urban canopy shading quality due to insufficient soil volume and competition with utilities below ground and above ground, compacted and degraded soil, and limited access to water (Haaland and van den Bosch 2015).

The outcome of this research can inform planners, urban foresters, and policy makers to better address urban densification and urban green space. Previous research has suggested that dense areas are not necessarily less green (Guo et al. 2019). (Re)development of properties occurring alongside the densification process might be one of the main culprits of the urban tree canopy decline due to its impacts on soil quality and volume, surface paving, and aerial and underground space available for trees (Haaland and van den Bosch 2015; Jim 2017; Guo et al. 2018; Guo et al. 2019). However, Metro Vancouver (2019) has indicated an increasing trend for tree canopy in newer and higher-density residential areas, while tree canopy on low-density existing housing parcels has declined from 36% in 1970 to 18% in 2000 on average. There has also been a declining trend in the levels of impervious surface in high-density housing parcels since the 1950s in Metro Vancouver (Metro Vancouver 2019). Although this study found some good examples of areas that can be both green and dense, it should be noted that the causes of urban canopy decline are complex. Managing urban canopy requires robust policy and community support, proactive planning and design, and adequate management, especially in cities that are going through densification. Densifying cities can also learn from the practices of cities and countries that manage to maintain a high level of both urban canopy and density, such as Hong Kong (Tan Z et al. 2016) and Singapore (Tan PY et al. 2013).

In addition, the modeling framework and outcome from this work demonstrate many potential research and planning implementation opportunities. For example, being able to systematically identify surfaces

with limited shading, particularly on façades and roofs, planners and builders can prioritize constructions such as green roofs or walls (e.g., vertical greeneries) to improve overall shading quality and quantity. Green roofs, if applied at the city scale, may reduce the average ambient temperature by 0.3 to 3 °C. Vertical greeneries are another technique that has been increasingly adopted in cities for thermal comfort and energy conservation. Both green roofs and vertical greeneries provide an excellent opportunity to mitigate urban heats, enhance indoor thermal comfort, and potentially reduce building energy consumption for cooling. They also present new ways to increase green areas with various ecological and social co-benefits in underutilized spaces like roofs and walls, especially in densely populated areas where space is a major limiting factor (Alexandri and Jones 2008). Urban form, land use patterns, and even local social conditions can also play a role in overall shading efficacy. We found that although neighborhoods with lower building height (e.g., single-family residential areas) appear to benefit from more canopy shading, it was possible to maintain both residential density and tree canopy, and consequently, canopy shading benefits in some neighborhoods. This was mainly caused by the Vancouverism architectural style that features high floor area ratio (i.e., small lot sizes with tall buildings), preserving pervious surface for trees and other vegetation (Metro Vancouver 2019). According to an interview of Vancouver's staff, neighborhoods like Kitsilano and West End are also older neighborhoods where native (although disturbed) soil has been preserved. However, there are no regulations to preserve native soil, which might be a contributing factor in some neighborhoods with limited canopy cover.

Moving forward, the authors have identified current caveats and future research directions that can further improve the current project and modeling capability. Firstly, this model currently uses constant weather and climate without considering the seasonal variations or other urban form features that could impact tree shading performance. Middel et al. (2021) presented possible research opportunities for this work and proposed a series of shade performance curves that characterize various urban tree shading efficacy for the City of Tempe, Arizona, offering a more comprehensive assessment of urban tree shade performance. Secondly, the canopy evapotranspiration was not included in the current modeling parameter, which likely caused an underestimation of the

current shading impact on heat mitigation (Wong et al. 2010). Thirdly, current results were expressed in solar irradiance (e.g., kWh). Given the reduced solar exposure, it would also be beneficial to estimate the potential outdoor and indoor temperature differences by utilizing microclimate models. Lastly, the newest ALS acquired by the City of Vancouver during peak summer conditions (currently unreleased at the time of this project) can also improve the accuracy of canopy cover density measures and include smaller trees and tree species information that was previously omitted (the True Positive rate of ALS crown detection is 76.6%, Matasci et al. 2018).

## CONCLUSION

Urban canopy, when implemented appropriately, can become an effective shading agent for the built environment, in particular for streets and building façades. This work integrated remotely sensed ALS point clouds with a Radiance daylight simulation engine (Honeybee) to simulate the potential shading impact of urban canopies on Vancouver's streets, building roofs, and façades. The results indicated that street surfaces received the most solar irradiance reduction compared to roofs and façades. Neighborhoods with less density and lower-rise buildings were shaded noticeably better than areas with higher density. Among Vancouver's 22 local neighborhoods, Kitsilano and West End demonstrated a promising sign where both building density/height and canopy shading can be relatively high at the same time. This work not only generated a detailed citywide simulation on existing shading conditions for over 200,000 trees in Vancouver but also offered useful insights to planners and builders for implementing innovative urban green infrastructures such as green roofs and vertical greeneries. One key future research direction is that one should evaluate how a changing climate will impact the health of existing and/or future urban trees as well as the need for cooler streets and internal environments in extreme hot summer days.

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#### **Conflicts of Interest:**

The authors reported no conflicts of interest.

**Résumé.** Contexte: Les villes consomment une quantité disproportionnée d'énergie pour le contrôle de la température interne. La capacité de réduire la charge de refroidissement des villes pendant les chaudes journées d'été peut diminuer la consommation

d'énergie tout en améliorant le confort thermique des citoyens. La canopée urbaine est un pourvoyeur d'ombrage efficace, permettant de rafraîchir les bâtiments existants et les rues tout en offrant d'autres valeurs écologiques et physiologiques. Cependant, la dynamique de l'ombrage des bâtiments et des rues est un système très complexe impliquant des éléments de bâtiments au niveau micro et des paramètres sur le plan macro. Introduire la canopée urbaine dans un système aussi complexe crée un autre défi, car les variables de la canopée urbaine peuvent également interagir avec les bâtiments aux niveaux micro et macro. De manière à décrire avec précision l'effet d'ombrage de la canopée urbaine, il est nécessaire de tenir compte des interactions entre les bâtiments, les rues et les canopées urbaines. Méthodes: Ce projet simule l'effet d'ombrage de la canopée urbaine mesurée par balayage laser aérien (BLA) dans la ville de Vancouver au Canada, par l'intégration d'un outil de simulation de la lumière du jour Radiance et de données d'un système d'information géographique (SIG). Tous les arbres détectés par BLA ont été inclus dans l'analyse. Résultats: Les résultats indiquent que les surfaces des rues montrent une plus grande réduction de l'irradiation solaire que les toits et les façades des bâtiments (c'est-à-dire les murs extérieurs). Les quartiers de moindre densité avec des bâtiments moins hauts ont été nettement mieux ombragés que les secteurs où la densité est plus élevée et les bâtiments plus hauts. Parmi les 22 quartiers de Vancouver, deux d'entre eux, Kitsilano et le Westend, ont montré un résultat prometteur lorsque la densité et la hauteur des bâtiments ainsi que la canopée urbaine sont maintenues. Il y a avait des preuves d'ombrage du fait de la canopée élevée et de morphologies urbaines à haute densité. Conclusion: Dans l'ensemble, ce travail a permis une véritable évaluation de la canopée que ce soit à l'échelle d'un seul bâtiment ou d'une ville entière, créant ainsi des opportunités pour étudier les variations de la canopée urbaine au sein d'une ville, et la recherche d'égalité et d'équilibre entre le verdissement et la densification urbaine.

**Zusammenfassung.** Hintergrund: Städte verbrauchen eine unverhältnismäßig große Menge an Energie für die interne Temperaturregulierung. Wenn es gelingt, die Kühllast der Städte an heißen Sommertagen zu verringern, kann der Energieverbrauch gesenkt und gleichzeitig der thermische Komfort der Bewohner verbessert werden. Das städtische Kronendach ist ein wirksamer Beschattungsfaktor, der bestehende Gebäude und Straßen kühlt und gleichzeitig andere ökologische und physiologische Werte bietet. Die Dynamik der Beschattung von Gebäuden und Straßen ist jedoch ein sehr komplexes System, das Gebäudekomponenten auf Mikroebene und Variablen auf Makroebene umfasst. Die Einbeziehung der städtischen Überdachung in ein solch komplexes System stellt eine weitere Herausforderung dar, da die Variablen der städtischen Überdachung mit den Gebäuden sowohl auf der Mikro- als auch auf der Makroebene interagieren können. Um den Beschattungseffekt von Stadtvordächern genau darstellen zu können, müssen die Wechselwirkungen zwischen Gebäuden, Straßen und Stadtvordächern berücksichtigt werden. Methoden: Diese Studie simuliert die Beschattungswirkung von städtischen Baumkronen, die durch Laserscanning aus der Luft (ALS) in der Stadt Vancouver, Kanada, gemessen wurden, durch die Integration einer Radiance-Tageslichtsimulationsmaschine und geografischer Informationssystemdaten (GIS). Alle von ALS erfassten Bäume wurden in die Analyse einbezogen. Ergebnisse: Die

Ergebnisse zeigen, dass Straßenoberflächen eine stärkere Reduzierung der Sonneneinstrahlung erfahren als Gebäudedächer und -fassaden (das heißt, Außenwände). Stadtteile mit geringerer Dichte und niedrigeren Gebäuden wurden deutlich besser beschattet als Gebiete mit höherer Dichte und höheren Gebäuden. Unter den 22 Stadtvierteln von Vancouver zeigten 2 Stadtteile, Kitsilano und das Westend, ein vielversprechendes Anzeichen, in denen sowohl die Gebäudedichte/-höhe als auch die städtischen Vordächer beibehalten wurden. Es gab Anzeichen für eine starke Beschattung durch Vordächer und eine städtische Morphologie mit hoher Dichte. Schlussfolgerung: Insgesamt lieferte diese Arbeit eine zuverlässige Bewertung der Baumkronen von einem einzelnen Gebäude bis hin zur Stadt. Dadurch wurden Möglichkeiten geschaffen, die Variationen der Baumkronen innerhalb der Stadt, die Gleichheit und das Gleichgewicht zwischen Stadtbe-grünung und Stadtverdichtung zu untersuchen.

**Resumen.** Antecedentes: Las ciudades consumen una cantidad desproporcionada de energía para la regulación interna de la temperatura. La capacidad de reducir la carga de refrigeración de las ciudades en los calurosos días de verano puede disminuir el consumo de energía al tiempo que mejora el confort térmico de los ocupantes. El dosel urbano es un agente de sombreado efectivo, que agrega beneficios de enfriamiento a los edificios y calles existentes al tiempo que proporciona otros valores ecológicos y fisiológicos. Sin embargo, la dinámica de sombreado de edificios y calles es un sistema altamente complejo que involucra componentes de construcción de nivel micro y variables de nivel macro. La introducción del dosel urbano en un sistema tan complejo crea otro desafío, ya que las variables del dosel urbano también pueden interactuar con los edificios tanto a nivel micro como macro. Para representar con precisión el efecto de sombreado del dosel urbano, es necesario tener en cuenta las interacciones entre edificios, calles y marquesinas urbanas. Métodos: Este estudio simula el efecto de sombreado del dosel urbano medido por escaneo láser aéreo (ELA) en la ciudad de Vancouver, Canadá, a través de la integración de un motor de simulación de luz diurna Radiance y datos del sistema de información geográfica (SIG). Todos los árboles detectados por ELA se incluyeron en el análisis. Resultados: Los resultados indican que las superficies de las calles reciben más reducción de irradiancia solar que los techos y fachadas de los edificios (es decir, paredes exteriores). Los vecindarios con menos densidad y edificios más bajos fueron sombreados notablemente mejor que las áreas con mayor densidad y edificios más altos. Entre los 22 vecindarios de Vancouver, 2 vecindarios, Kitsilano y el Westend, demostraron un signo prometedor donde se mantienen tanto la densidad / altura del edificio como las marquesinas urbanas. Hubo evidencia de alto sombreado del dosel y morfologías urbanas de alta densidad. Conclusión: en general, este trabajo proporcionó una auténtica evaluación del dosel desde un solo edificio hasta la escala de la ciudad, creando oportunidades para investigar las variaciones del dosel urbano dentro de la ciudad, la igualdad y el equilibrio entre la ecologización y la densificación urbana.