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RESEARCH

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Impact of 2050 tree shading strategies on building cooling demands

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ABSTRACT

As urban heatwaves become more severe, frequent and longer, cities seek adaptive building cooling measures. Although passive building design, energy-efficient materials and technologies and mechanical means are proven cooling methods, the potential of nature-based solutions (particularly trees as shading elements) has been understudied despite its significant opportunity. Using a new framework to explore this at the neighbourhood level, three future (2050) potential tree planting strategies are modelled for increasing tree volume and canopy cover and their impacts assessed for summer building-level solar radiation absorption (SRA) and building cooling energy demand (BCED) for a densifying neighbourhood in Vancouver, Canada. The boldest tree planting strategy, with 287% more trees than baseline and 16% canopy cover, reduced neighbourhood-scale total SRA (22%) and BCED (48%) over a no-trees scenario. BCED reductions of up to 64% for retrofitted/redeveloped buildings and 53–79% for low/medium-height buildings (mostly single-family residential) were associated with targeted south-side tree planting. Taller/larger buildings (predominantly mixed use) and buildings along north–south-oriented streets (mainly commercial and mixed use) encountered more tree shading challenges and would require more site-specific interventions. The methodology presented provides a framework to assess current and potential future shading and cooling energy benefits through various tree planting strategies.

PRACTICE RELEVANCE

This research illustrates the tree shading and cooling potential to improve indoor liveability, reduce energy demand and reduce vulnerabilities amidst mounting extreme heat risks. This novel framework and method can be used by planners and urban designers to understand the potential cooling reduction and to develop tree planting and management strategies for effective shading and indoor cooling at the neighbourhood scale. Based on a case study neighbourhood in Vancouver for 2050 climate scenarios, this

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research shows increased tree volume and canopy cover can significantly reduce building SRA and BCED during the summer. The level of tree shading impact on buildings' SRA and BCED was associated with the intensity and location of tree planting, but also the relative amount of lower height (and smaller) buildings. The boldest tree planting strategy yielded a 48% reduction in energy demand for cooling.

1. INTRODUCTION

1.1 MITIGATION AND ADAPTATION TO EXTREME HEAT EVENTS

Cities are getting warmer as the initial impacts of climate change have already produced dangerous extreme heat events (Tong *et al.* 2021; Wang *et al.* 2021). Meanwhile, climate projections indicate that extreme heat events will become more common and potentially more severe. Cities are at particular risk as extreme heat events will be amplified by the urban heat island (UHI) effect (Santamouris 2014; Zhao *et al.* 2018) due to the prevalence of impervious surfaces and high-density building arrangements (Akbari *et al.* 2016), as well as the reliance on air-conditioning systems (Zhao *et al.* 2018). For example, in Metro Vancouver in British Columbia (BC), Canada, the number of typical hot summer days of approximately 25°C (22–55 days/year) is expected to double, and extreme heat values (34–38°C) are expected to increase in the 2050s (Metro Vancouver Regional District 2016: 80).

Under the current pace of climate mitigation efforts, all urban inhabitants, but especially vulnerable populations, including racial minorities, those living in poverty (Hsu *et al.* 2021), the elderly, pregnant individuals, those with mental illness or pre-existing conditions, and those living or working in thermally stressful environments (Petkova *et al.* 2014), will more likely experience negative health outcomes and potentially death. For example, 619 deaths were attributed to the 2021 heatwave across BC (Egilson 2022), and were associated with high indoor temperatures (30–40°C), as well as the absence of air-conditioning and lower neighbourhood greenness (Henderson *et al.* 2022).

Evidence of increased heat intensity and duration in cities globally, and their impacts on human health and wellbeing, has prompted more attention on cooling urban environments. While cool, outdoor urban refuges exist as parks and other public spaces, city dwellers and visitors also require liveable indoor spaces. However, as advancements in sustainable, energy-efficient building design practices have not been widely applied to date, the current Canadian building stock is outdated and ineffective for handling projected cooling energy demands (Haley & Torrie 2021: 85). Existing heat mitigation strategies also rely on air-conditioning systems, resulting in increased greenhouse gas (GHG) emissions that exacerbate climate change and UHI (Wang *et al.* 2021; Zhao *et al.* 2018), and contribute to the positive feedback loop of rising energy demands and associated costs (BC Hydro 2018). In BC, the use of air-conditioning has tripled (to 34%) since the early 2000s, and is linked to an average 120–370% increase in summer energy costs (BC Hydro 2018). Compounded, air-conditioning and other building operations currently account for up to 18% of Canadian GHG emissions (about 122 Mt CO2-eq) (Environment and Climate Change Canada 2022; Government of Canada 2021).

1.2 NATURE-BASED SOLUTIONS TO WARMING CITIES

In the face of mounting climate change-related heat stress, cities may look to nature-based solutions (NBS) that can provide alternative, effective and less energy-demanding cooling methods through activities that protect, sustainably manage, or restore natural or modified ecosystems, and also promote human wellbeing and biodiversity (Cohen-Shacham *et al.* 2016; van den Bosch & Ode Sang 2017). In urban areas, NBS may include the provision of green spaces or green infrastructure, such as parks, street trees and green roofs, that foster temperature regulation (Saaroni *et al.* 2018) among other ecosystem services such as flood mitigation and air purification (Jones *et al.* 2022;

Livesley *et al.* 2016). Trees can cool cities at extents that reduce the UHI effect (Armson *et al.* 2012; Bowler *et al.* 2010), as well as contribute to building cooling and energy demand reductions (Akbari *et al.* 1997; Moss *et al.* 2019)—often more efficiently and cost-effectively than technical methods (Bauduceau *et al.* 2015).

The adoption of NBS, particularly strategies for urban greening (*i.e.* the incorporation of trees and other vegetation or natural elements in cities), is accelerating as one of many approaches to mitigate the impact of climate change-related increasing temperatures. Across Canada, municipalities are increasingly incorporating urban forestry and greening programmes as part of their climate plans and actions (Ordóñez & Duinker 2013). However, alongside underreported urban tree and vegetation losses nationally (Czekajlo *et al.* 2020; Lantz *et al.* 2021), and the increasing threat of extreme heat events and other climate change-related impacts, cities need more data-driven strategic plans to ensure tree planting and management efforts are successful. Gaps in knowledge also exist in current urban forestry and climate plans about how existing and future urban tree inventories could contribute to specific climate mitigation and adaptation approaches—such as building cooling (Cheng *et al.* 2021). Additionally, as many disadvantaged urban populations in Canada tend to live in low tree canopy neighbourhoods (Quinton *et al.* 2022), municipalities have a responsibility and opportunity to directly address social and environmental inequities and improve resiliency to extreme heat events through well-designed, equitable and evidence-based urban greening projects (Nesbitt *et al.* 2019; Sax *et al.* 2022).

1.3 TREES IN BUILDING ENERGY MODELLING

Current energy modelling is often limited to focusing on either trees or buildings individually, or at coarse or small spatial scales, which makes estimating the potential indoor cooling benefits of specific NBS approaches at a neighbourhood scale difficult. Building energy modelling has become a complex and diverse field that requires the integration of geospatial, supply and/or demand factors, modelled for different scopes and objectives, and applied through a multitude of input data sources, software and methods (Gao *et al.* 2019; Johari *et al.* 2020; Pereira *et al.* 2021). Previous energy models and examples are plentiful at the individual building level (Ahmad *et al.* 2018; Harish & Kumar 2016), and their aggregation at neighbourhood and city scales has also been demonstrated (Buckley *et al.* 2021; Johari *et al.* 2020; Mosteiro-Romero *et al.* 2020). These models require data about location, weather, building design, energy sources, heating, ventilation and air-conditioning (HVAC) systems, and operation schedules (Harish & Kumar 2016). Building energy model outputs typically include heating/cooling loads and energy demands (Corrado & Fabrizio 2019), as well as may include information about solar radiation absorption (SRA) (Fonseca *et al.* 2016). A building's total SRA can be influenced by time of day and year, weather conditions, interceptions by neighbouring objects, as well as the reflectivity of building materials and form (Chwieduk 2014). Building cooling energy demand (BCED) is related to heat gain via a function of the solar incidence received and absorbed directly by the building envelope (*i.e.* windows, walls and roof), as well as indirectly through transmittance (*e.g.* via windows) and subsequent absorption by indoor air and objects (Leftheriotis & Yianoulis 2012).

Shading the building envelope through passive building design, energy-efficient materials and technologies, and mechanical means can reduce cooling demands (Pacheco *et al.* 2012; Valladares-Rendón *et al.* 2017). More recent investigations have also found significant incremental cooling benefits of trees, green walls and roofs, as well as other greenery via shading or insulating buildings across climates (Mari *et al.* 2019; Priya & Senthil 2021; Wang *et al.* 2016). However, while extensive research has been conducted to model BCED with various applications of green roofs and walls (Besir & Cuce 2018; Zhang *et al.* 2022), models that include trees and other vegetation are limited by form (Gómez-Muñoz *et al.* 2010; Lindberg *et al.* 2015) or spatial scale (Mosteiro-Romero *et al.* 2020). Advances in modeling three dimensional (3D) trees has also been conducted using light detection and ranging technology (*i.e.* lidar or aerial laser scanning—ALS) (Hofierka *et al.* 2017; Zhang *et al.* 2015). For example, Lu *et al.* (2022) used ALS-based tree and building models to assess the tree canopy shading effect on roofs and exterior walls for Vancouver. However, lidar is costly to acquire and tree models directly extracted from lidar represent current or previous conditions due to limitations in individual tree growth modelling (Pretzsch *et al.* 2015). As a result, the impact of tree shading on SRA and subsequent BCED has not been widely applied for future building energy assessments and heat reduction recommendations at local scales.

Other methodologies to estimate tree shading effects can be found in the field of urban forestry. For example, longstanding and commonly used i-Tree software[1] can use urban forest inventories to quantify the tree shading impact on buildings and subsequent energy savings. However, critiques of i-Tree have included inflexibility with missing tree inventory information (*e.g.* diameter at breast height) or altering methods (Cimburova & Barton 2020; Steenberg *et al.* 2017; Walters & Sinnett 2021). Similarly, integrations with building energy modelling software are limited and may produce uncertain or inapplicable results as i-Tree is based on generalised US-based data about climate types, energy uses and emissions factors (i-Tree Eco International n.d.; Nowak *et al.* 2008, 2017).

1.4 RESEARCH QUESTIONS

Despite ample evidence for the cooling benefit of urban trees and other vegetation, little research has been conducted to assess their potential future, local impact. This gap in knowledge leaves policymakers and practitioners speculating about prospective indoor cooling benefits of urban forest and greening strategies. This study address three research questions:

- How do three future tree planting strategies of variable intensity impact SRA and BCED?
- How do tree-related reductions in SRA and BCED vary across building ages and retrofit/ redevelop status?
- At what building height are trees an ineffective shading and indoor cooling solution?

A new methodology is presented to generate comparative estimates of current and potential future tree shading impacts on building energy at neighbourhood scale. It uses projected climate, develops 3D building and tree model sets, and open-source building energy software. Specifically, this study analysed tree shading effects on SRA and resulting BCED during typical hot, summer months (21 June–22 September) in a modelled Vancouver neighbourhood with low density and low canopy cover in 2020, as well as three potential tree planting strategies and increased density in 2050.

2. METHODS

SRA and BCED in the summers of 2020 and 2050 were estimated using spatial models of three future tree planting scenarios for a proxy neighbourhood. The methods of this work included:

- the development of the proxy 'sandbox' neighbourhood models for 2020 and 2050
- the generation of three future (2050) tree planting spatial models and
- the modelling of SRA and BCED for building groups based on retrofit/redevelop status and height.

Using methods and data detailed in prior work (Lu *et al.* 2021, 2023), a 1600 × 1600 m spatial proxy model (named 'sandbox' by the authors) was created to represent a neighbourhood-scale area in Vancouver in 2020. The sandbox model provides an approximation of spatial (2D and 3D) and non-spatial attributes of a real neighbourhood at a given time by typifying its urban form, population density, parcel density, street patterns, parcel and block sizes, and building-use proportions. Input data used to create the sandbox model for 2020 include: available street, building and parcel use data (Metro Vancouver Regional District 2020), additional building information (including type, age, occupancy, height, and construction type and date) (BC Assessment 2019), and local census population data (Statistics Canada 2017, 2019). The Vancouver study area population growth rate was estimated to be 10% per decade for the future 2050 models, and used to determine appropriate building developments (Lu *et al.* 2023).

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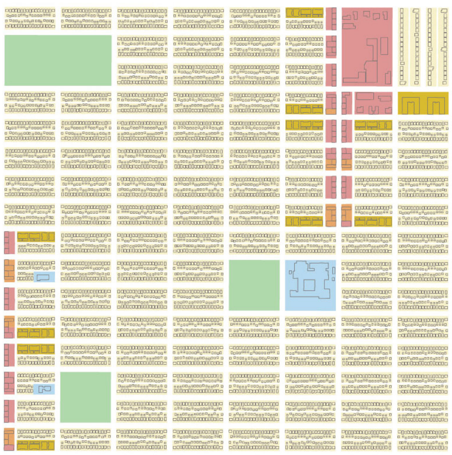
Two versions of the 2050 sandbox model were developed (Figure 1). Both future building model versions represent 2050 development with increased residential and commercial floor areas, as well as associated resident counts. Some buildings, placement and corresponding land uses (including a new park) differed between the two 2050 buildings model versions. The baseline 2020 sandbox model included 7125 buildings and 15,164 residents, while each of the 2050 models included 7019 buildings, accommodating a 34% greater population (20,389 residents).

Baseline (2020) "Sandbox"



Building use	2020	2050 v1	2050 v2
Single-family	80%	80%	79%
Multi-family	4%	4%	5%
Mixed use	1%	2%	1%
Commercial	6%	4%	4%
Civic	1%	3%	3%
Park	8%	8%	9%
Buildings			
Area (ha)	260	260	260
Parcels	3,647	3,595	3,595
Dwelling units	6,021	8,299	8,299
Residents	15,164	20,389	20,389

Future (2050) "Sandbox": version 1

Future (2050) "Sandbox": version 2

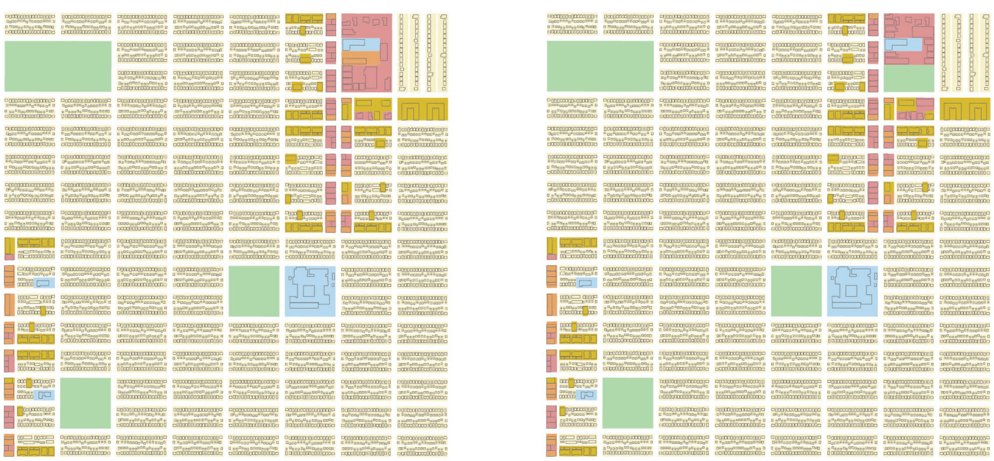


Figure 1: Building-use maps and details of the baseline (2020) and two versions of the future (2050) sandbox models.

Note: White spaces between parcels indicate streets.

2.2 BASELINE AND FUTURE TREE MODELS

2.2.1 Baseline (2020) trees

Baseline 2020 tree planting geolocations (approximate), heights and canopy spreads were derived from Vancouver's 2013 ALS dataset of the real neighbourhood area (City of Vancouver Open Data Portal 2013) via an object-based image analysis approach (Matasci *et al.* 2018). Street tree species were identified using the Vancouver street tree inventory (City of Vancouver and Vancouver Park Board 2023), whereas private and park tree species were randomly assigned using a list of common trees compiled through observations in the real neighbourhood area using Google Street View imagery.

2.2.2 Future (2050) tree planting scenarios

Three future potential tree planting scenarios for 2050 were created using current policy and best practices research, which also guided the rules-based generation of associated spatial tree data (see Czekajlo *et al.* 2023 for more details). The rules used to develop the future tree models focused on the following policy actions: (1) tree planting rates on public and private lands; (2) tree replacement of 'aged out trees' (*i.e.* trees removed between baseline and future scenario models due to mortality or development purposes); (3) locations of trees on private parcels; (4) proportions of large (mature tree height > 15 m), medium (mature tree height = 10–15 m) and small trees (mature tree height < 10 m); (5) proportions of deciduous trees versus coniferous trees; and (6) tree diversity proportions based on genus and species. The policy and best practices based rules were applied using *R* software (R Core Team 2017), and included the packages *raster* (Hijmans *et al.* 2022), *rgdal* (Bivand *et al.* 2022), *sf* (Pebesma *et al.* 2022) and *tidyverse* (Wickham *et al.* 2019).

The intensity of Future 2050 tree planting and management strategies (with a sustainability and building energy focus) increased sequentially. EP followed the existing city planting goals (City of Vancouver and Vancouver Park Board 2018) and species list (City of Vancouver 2011: 37), while TBS and Maximize Tree Canopy (MTC) applied a climate-adapted tree species list (Diamond Head Consulting 2019a, 2019b), but varied in tree planting strategy and intensity. To target shading potential, TBS focused the planting of one tree to the south-west corner of each occupied private building, while MTC strategically placed two trees along the southside of occupied private buildings. EP and TBS used 2050 building model version 1, while MTC used version 2 (Figure 1). MTC also incorporated additional green space features such as partial afforestation of two parks and two additional rows of trees on proposed blue–green infrastructure streets (Figure 2).

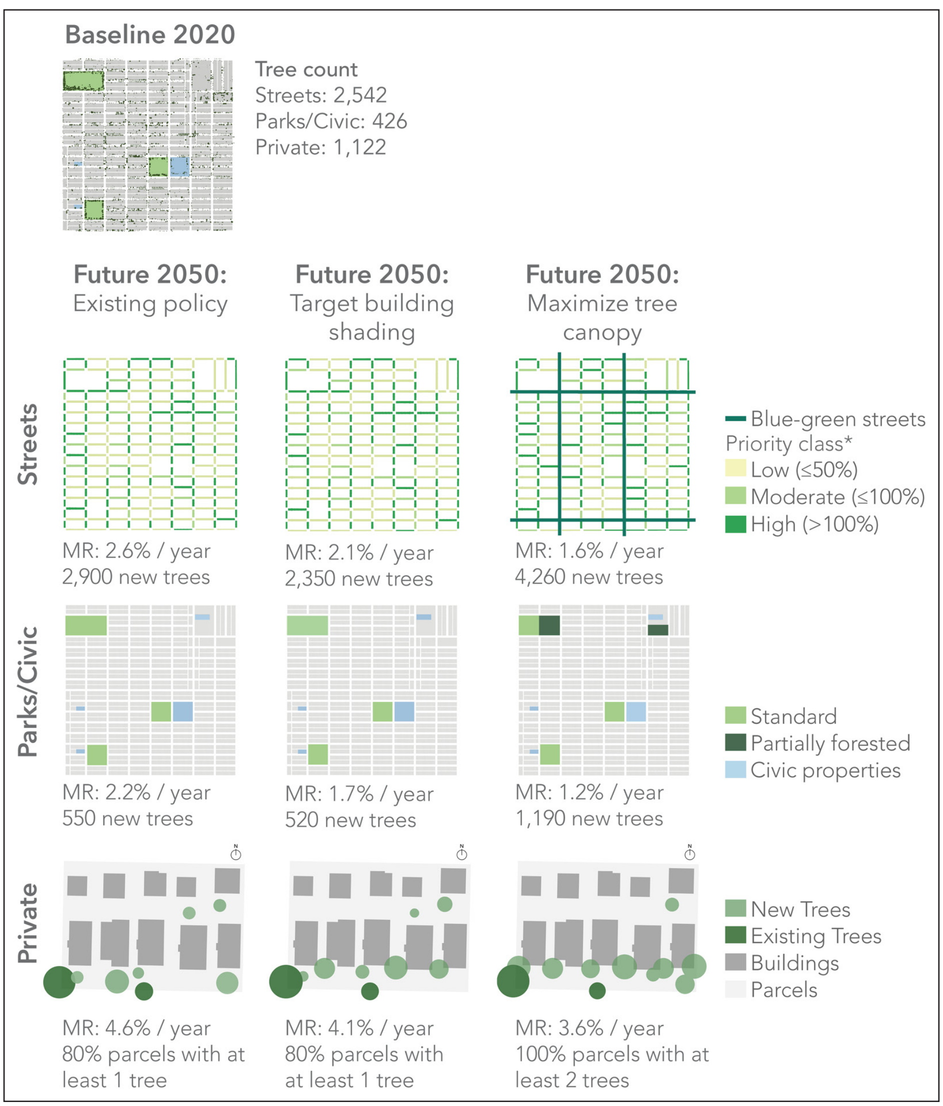


Figure 2: Summary of future urban forest scenarios, including: mortality rates (MR), proportion or quantity of new (*i.e.* additional and replacement) trees, and their general placement.

Note: General rules across scenarios include: one-to-one tree mortality/replacement, and diversity goals of no more than 30% per family, 20% per genus and 10% per species (as per Santamour 1990). Priority class for streets was determined as the increase (%) in the number of trees since baseline.

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Tree height and crown radius in 2050 were modelled to represent 30-year sizing, based on mature tree height values acquired from open and accessible databases (primarily by Oregon State University,[2] Kwantlen Polytechnic University,[3] Missouri Botanical Gardens,[4] and Plants For A Future[5] used for missing information). Thirty-year tree heights were calculated as two-thirds of average mature tree height; associated crown diameter was estimated as 45% of average mature tree height. Details about tree count and sizing, in total and per planting location are provided in Section 3.1.

2.3 BUILDING ENERGY MODELLING

Building energy demand was modelled using City Energy Analyst (CEA) (The CEA Team n.d.) for the 2020 baseline condition as well as the three 2050 future tree planting strategies and associated sandbox models. CEA integrates urban planning and energy systems engineering in an open-source urban building simulation platform for assessing shading, energy use and other aspects of building performance (Fonseca *et al.* 2016). Outputs from the CEA modelling included the SRA of walls and windows (*i.e.* combined as facade; per cardinal direction: north, east, south, west), roofs, and in total, as well as cooling energy demand (BCED). Energy modelling was performed for each scenario with and without trees, for which the differences in SRA and BCED outputs determined the explicit effect of trees. Modelling was conducted for summer months (21 June–22 September) in Vancouver using projected climate models. CEA uses DAYSIM for dynamic daylight simulations and ArcGIS for geometries.

CEA imports building geometry and spatial arrangement information (*e.g.* footprint, heights above and below ground, and number of floors), and connects with building template data about the envelope's thermal properties, orientation-specific window to wall ratios, building occupants, fuel sources, as well as HVAC systems to provide a customised profile for each building (Table 1). Buildings in the sandbox model were categorised by type, age and construction methods to create the template files (Lu *et al.* 2021, 2023). Construction standard was based on year of construction and the associated building standards, which influenced archetypes of envelope, and HVAC and supply systems. Occupancy type (associated with building use) determined internal occupancy loads, equipment and lighting efficiencies, and indoor comfort level.

CATEGORY	INPUT PARAMETER	ASSEMBLY	DESCRIPTION
Construction standard	Air-conditioning system	HVAC assemblies	Properties of a building's HVAC system
	Architecture	Envelope assemblies	Properties of a building's envelope; including window to wall ratio, structure material and thermal properties of floors, roof, facades and windows
	Supply systems	Supply assemblies	Properties of a building's energy supply
Use types	Internal loads	n.a.	Properties of a building's internal thermal loads
	Indoor comfort	n.a.	Properties of a building's thresholds of thermal comfort

Table 1: Summary of City Energy Analyst (CEA) input parameters and their associated category, assembly and description

Note: HVAC = heating, ventilation and air-conditioning; n.a. = not applicable.

For additional details, see ***Table S1*** in the supplemental data online.

Although this is not true in the existing neighbourhood in Vancouver, it was assumed that all buildings were equipped with cooling systems to determine the effect of BCED reductions with the addition of trees to the model. Building internal heat loads were calculated by summing the heat capacities of all building elements in direct thermal contact with the internal air of the zone under consideration. The energy supply systems for modelled standard buildings included natural gas-fired boilers and water/water heat pumps. HVAC systems included radiators, floor heating and mini-split air-conditioning, as well as window ventilation for all buildings.

Based predominantly on age, some 2020 buildings were selected to be retrofitted with new technology (heating, cooling, water heating, lighting and/or appliances) and/or envelope upgrades, or for redevelopment in 2050 (Lu *et al.* 2021). These buildings followed the BC Energy Step Code

(Energy Step Code Council 2019). Redeveloped (new) buildings accommodated added population. Envelope retrofitting was applied to the 2050 models for 50% of buildings at least 30 years old. Retrofitted and redeveloped buildings achieved a BC Step Code of 2 or higher (Energy Step Code Council 2019) (for additional details, see ***Table S2*** in the supplemental data online).

3D spatial tree models developed for the baseline (2020) and three future (2050) tree planting scenarios were inputted in CEA as objects. At the time of analysis, CEA did not include a method to simulate intricate or semi-transparent objects. Consequently, trees in this study were treated as 3D opaque cylindrical extrusions. The cylinder extrusion representing each tree was sized using the crown radius and tree height.

Hourly climate information (*i.e.* dry-bulb temperature, relative humidity, solar radiation, cloud cover, wind speed and atmospheric pressure) for 2020 and 2050 was derived from a Vancouver EnergyPlus Weather file (EnergyPlus 2005) developed by Ek *et al.* (2018). Both 2020 and 2050 climates simulate the RCP8.5 'high emission future without effective climate change mitigation policies' scenario (Ek *et al.* 2018); this included an increase in daily high temperatures > 25°C from 14 days in 2020 to 56 days in 2050, and an increase of 0 to 5 days at > 30°C. A digital elevation model (DEM) representing a homogeneous 1 m elevation above sea level was included in the CEA modelling to exclude any topographical influences.

2.4 LINKING CANOPY COVER, BUILDING PROPERTIES AND ENERGY RESULTS

Canopy cover (%) was calculated by using a merged polygon of 2D crown radius-buffered tree points. SRA (gigawatts; GW) by building facade (*i.e.* wall and window) of each cardinal direction (north, east, south, west), roofs, and in total, as well as BCED (megawatt-hours; MWh), for the summer period were outputted for buildings with regular occupants (*e.g.* not garages). BCED per occupant (kWh/occupant) was calculated using the sum of residents and commercial space users in the sandbox model, and BCED per gross floor area (GFA; kWh/m^2) was calculated using the sum of GFAs of each building in the sandbox model. Reductions (%) in SRA and BCED due to trees (*i.e.* difference between 'no trees' and 'with trees' modelled conditions of each scenario) were calculated on the building level. Scenario-wide reductions due to trees were calculated using the sum of each of building-level 'no trees' and 'with trees' values, for SRA and BCED.

Comparisons of SRA and BCED results were conducted between buildings with any envelope and technology upgrades ('retrofit/redevelop') and those without changes since baseline ('no change') across future scenarios. SRA and BCED results were also summarised by building height groups: low (3–6 m; one to two storeys), medium (> 6–11 m; three to five storeys), and tall (> 11–58 m; six or more storeys). Due to high relatability, building use was referenced alongside building height results (for details, see the supplemental data online).

Kruskal–Wallis tests (Kruskal & Wallis 1952; McKight & Najab 2010)—reported via Chi-square statistic (χ^2)—and pairwise Wilcoxon rank sum tests (Wilcoxon 1945) were performed to assess building-level variation in SRA and BCED, per scenario as well as per retrofit/redevelop status and building height groups. Only significant differences ($p < 0.05$) were reported; detailed results are included in the supplemental data online. Statistical analyses were performed using *R* software (R Core Team 2017) and the *rstatix* package (Kassambara 2023). Manual edits, spatial analysis and mapping were performed using *ArcGIS Pro* (versions 2.9/3.0).

3. RESULTS

3.1 SUMMARY OF TREE PLANTING IMPACTS

Impacts of trees on building shading and cooling energy demand for this study stem from the nature of the three future (2050) tree planting strategies. Table 2 provides a summary of relevant tree planting and urban forest indicators for the baseline (2020) and future (2050) scenarios. All future scenarios increased canopy cover from baseline by 2.2–9.1%. MTC observed the highest canopy cover (15.6%) while scenario EP the lowest (8.7%). Future scenario models of EP and MTC encompassed opposing tree planting strategies; EP used fewer but typically larger trees, while MTC incorporated more trees that were climate-adapted but tended to be smaller. As a result, MTC included about 55% more trees and almost 80% greater canopy cover than EP.

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Table 2: Summary of the relevant urban forest and tree form indicators for the baseline (2020) and future (2050) scenarios, per planting location

Note: SD = standard deviation.

INDICATOR	PLANTING LOCATION	BASELINE 2020	FUTURE 2050: EXISTING POLICY	FUTURE 2050: TARGET BUILDING SHADING	FUTURE 2050: MAXIMIZE TREE CANOPY
Tree count	Private	1,122	5,397	5,400	8,505
	Street	2,542	4,054	4,054	5,830
	Park/civic	426	777	774	1,488
	Total	*4,090*	*10,228*	*10,228*	*15,823*
Canopy cover (%)	Private	1.7%	3.2%	4.1%	6.6%
	Street	3.9%	4.1%	4.3%	6.4%
	Park/civic	1.0%	1.4%	1.2%	2.4%
	Total	*6.5%*	*8.7%*	*9.5%*	*15.6%*
Average tree height ± 1 unit SD (m)	Private	12.1 (± 4.6)	6.4 (± 2.5)	7.3 (± 2.4)	7.6 (± 2.4)
	Street	10.9 (± 4.0)	8.6 (± 6.0)	8.3 (± 3.4)	8.9 (± 3.7)
	Park/civic	17.3 (± 5.9)	13.1 (± 8.2)	10.7 (± 4.1)	10.8 (± 3.4)
	Total	*11.9 (± 4.8)*	*7.8 (± 5.1)*	*7.9 (± 3.2)*	*8.3 (± 3.2)*
Average crown diameter ± 1 unit SD (m)	Private	6.7 (± 2.7)	4.2 (± 1.6)	4.8 (± 1.6)	5.0 (± 1.6)
	Street	6.6 (± 2.7)	5.2 (± 2.8)	5.4 (± 2.3)	5.7 (± 2.5)
	Park/civic	8.6 (± 3.5)	7.6 (± 3.8)	7.1 (± 2.8)	7.2 (± 2.3)
	Total	*6.8 (± 2.9)*	*4.9 (± 2.5)*	*5.2 (± 2.1)*	*5.4 (± 2.1)*

3.2 BUILDING SRA AND COOLING ENERGY DEMAND

3.2.1 Neighbourhood scale

Cumulatively, trees added to the 2050 sandbox model resulted in at least a 10% reduction in total SRA (for EP), and up to 22% with the most progressive tree planting strategy, MTC (Table 3). MTC, which incorporated planting two additional trees on the southern side of buildings, observed the greatest SRA reduction due to trees for southern facades; 43% greater southern facade reduction than TBS (which included strategic planting of one tree on the south side) and 63% greater than the EP scenario (no strategic planting). In comparison, random planting in EP resulted in the north side of buildings receiving the greatest shading, with an 18% greater SRA reduction due to trees than the next leading facade (*i.e.* south). Western facades also observed substantial SRA reduction due to trees, particularly for scenarios TBS and MTC, both of which included strategic planting at the south-western corner of buildings. Roof SRA reductions due to trees were minimal (up to 4%) across all scenarios.

Total summer cooling energy demand without trees increased by 73% (EP) to 77% (MTC) over baseline in 2050 scenarios due to significantly hotter summer temperatures. Nonetheless trees mitigated these effects. Resulting total BCED reductions due to trees followed a similar pattern as total SRA: EP observed the lowest total BCED reduction due to trees (19%) while the total BCED reduction due to trees for MTC was about 2.5 times that of EP. All future scenarios experienced greater tree-related reductions in BCED than baseline, except for EP. Similar trends were observed for total BCED per occupant and per GFA. Again, MTC observed the greatest reductions due to trees in BCED per occupant and GFA (45% more reduction than the next leading scenario (TBS); 60% more reduction than EP).

SCENARIO	CONDITION	SUMMER SRA (GW)						SUMMER COOLING ENERGY DEMAND		
		FACADE				ROOF	TOTAL	TOTAL (MWH)	TOTAL PER OCCUPANT (kWh)	TOTAL PER GFA (kWh/m²)
		NORTH	EAST	SOUTH	WEST					
Baseline 2020	No trees	17.6	29.9	46.6	39.5	148.4	281.9	9,407.6	620.4	13.8
	With trees	14.4	26.8	40.5	34.9	144.0	260.7	7,522.5	496.1	11.0
	Reduction due to trees	*21.5%*	*11.5%*	*15.0%*	*13.0%*	*3.0%*	*8.1%*	*25.1%*	*25.1%*	*25.1%*
Future 2050: Existing policy	No trees	27.3	46.2	77.5	63.4	219.5	433.7	16,254.6	797.2	13.7
	With trees	21.1	39.5	63.1	53.7	212.6	390.0	13,645.8	669.3	11.5
	Reduction due to trees	*22.7%*	*14.5%*	*18.6%*	*15.3%*	*3.1%*	*10.1%*	*19.1%*	*19.1%*	*19.1%*
	No trees	27.3	46.2	77.5	63.4	219.5	433.7	16,254.6	797.2	13.7
Future 2050: Target building shading	With trees	21.5	37.4	55.1	48.5	214.6	377.1	12,877.3	631.6	10.9
	Reduction due to trees	*21.2%*	*19.0%*	*28.9%*	*23.5%*	*2.2%*	*13.1%*	*26.2%*	*26.2%*	*26.2%*
Future 2050: Maximize tree canopy	No trees	27.7	45.8	77.4	63.1	219.3	433.3	16,611.0	814.7	14.5
	With trees	20.2	32.5	38.3	38.7	210.5	340.1	11,245.8	551.6	9.8
	Reduction due to trees	*27.1%*	*29.0%*	*50.5%*	*38.7%*	*4.0%*	*21.5%*	*47.7%*	*47.7%*	*47.7%*

Table 3: Summary of summer building-level solar radiation absorptions (SRA) and building cooling energy demand (BCED) results for each scenario and condition (*i.e.* 'no trees' or 'with trees'), per facade, roof and total

Note: Reductions due to trees (%) use the following calculation: {('no trees' – 'with trees')/('no trees')} × 100%.

3.2.2 Retrofitted and redeveloped buildings

The reduction of SRA for buildings that were retrofitted or redeveloped (*i.e.* received envelope and/or technology upgrades), versus those without changes since baseline (*i.e.* 'no change'), were impacted by tree planting strategies (Table 4). Total SRA and BCED reductions were comparable for both 'retrofit/redevelop' and 'no change' buildings in EP and TBS, while MTC observed up to five times greater reductions in SRA and BCED than other future scenarios per status.

Most notable tree shading impacts were southern and western facades of non-retrofitted/redeveloped buildings. Trees on the southern facades of MTC, in particular, reduced SRA by 128% compared with 67% for retrofitted/redeveloped buildings. Southern facades of TBS 'no change' buildings also performed relatively well in terms of SRA reduction due to trees (45% greater than next leading facade (west) of the same group; 21% greater than southern facades of TBS retrofitted/redeveloped buildings). EP observed relatively low reductions in SRA across facades for both groups, with the 'no change' group consistently observing lower reductions across facades, roofs and in total. Roof SRA did not experience much reduction overall. Total SRA reduction was greatest for MTC 'no change' buildings; however, these building-level results were not significantly different from the 'retrofit/redevelop' group. Both 'retrofit/redevelop' and 'no-change' buildings of TBS and EP observed about 50% decreases in total SRA reductions compared with MTC 'no change' buildings.

SCENARIO	BUILDING STATUS	COUNT[a]	SUMMER SRA REDUCTION DUE TO TREES (%)					
			FACADE				ROOF	TOTAL
			NORTH	EAST	SOUTH	WEST		
Future 2050: Existing policy	Retrofit/redevelop	1,016	29.9%	18.1%	24.1%	20.9%	4.5%	13.1%
	No change	3,067	28.9%	14.7%	21.7%	15.3%	2.2%	10.0%
Future 2050: Target building shading	Retrofit/redevelop	1,016	28.8%	24.1%	35.9%	30.0%	2.8%	15.4%
	No change	3,067	25.7%	22.1%	43.4%	30.0%	2.2%	15.2%
Future 2050: Maximize tree canopy	Retrofit/redevelop	1,042	41.0%	42.6%	67.1%	52.9%	4.2%	24.4%
	No change	3,067	34.7%	39.8%	128.0%	69.8%	4.4%	29.8%

Table 4: Solar radiation absorptions (SRA) reductions for 'retrofit/redevelop' versus 'no change' buildings due to trees (%), per facade, roof and total

Note: Reductions due to trees (%) use the following calculation: {('no trees' – 'with trees')/('no trees')} × 100%.

[a]Count reflects buildings used to derive reported values. Total building numbers will vary between tables due to some missing data.

Reductions in BCED followed a similar pattern to total SRA (Figure 3). BCED reductions for MTC 'no change' buildings were 97% greater than buildings in the same scenario that were retrofitted or redeveloped. Comparing 'no change' buildings across future scenarios, total BCED reductions for MTC were 112–226% greater; meanwhile, differences between 'retrofit/redevelop' buildings across scenarios was only 42–71% greater. Differences in total BCED reductions between status groups in other future scenarios were also lower (TBS 'no change' was 31% greater; EP 'no change' was 3% greater).

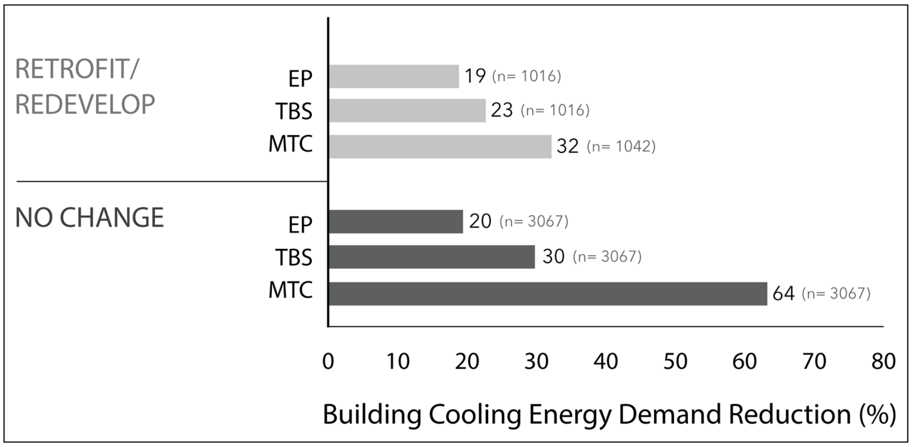

Figure 3: Total summer building cooling energy demand (BCED) reduction due to trees (%) per 'retrofit/redevelop' or 'no change' status for each scenario.

Note: Reductions due to trees (%) use the following calculation: {('no trees' – 'with trees')/('no trees')} × 100%. The count of buildings is included for each group (*n*); it reflects buildings used to derive reported values (total building numbers will vary between tables due to some missing data).

3.2.3 Building height

Trees can provide considerable shading and subsequent cooling energy demand benefits for buildings; however, their impacts were diminished for taller buildings. Table 5 summarises SRA results per facade, roofs and in total for building height groups: low (3–6 m; one to two storeys), medium (> 6–11 m; three to five storeys) and tall (> 11–58 m; six or more storeys). For all future 2050 scenarios, tree shading had the greatest effect on low- and medium-height buildings. The most notable result was a 127% reduction due to trees on the south facades, and 70–74% reductions on the west facades of MTC—with 30% total reductions. Tall buildings showed far less SRA reduction: only 20% on south facades, 27% on the west and 16% total. TBS also showed far more SRA reduction on south and west facades and in total for the low- and medium-height buildings as compared with tall buildings. One unexplained anomaly in the results—tall buildings in the EP scenario showed greater reductions in SRA on the west facades than lower buildings, but the total reductions were less for tall buildings. Baseline showed less difference in SRA between the differing heights of buildings.

SCENARIO	BUILDING HEIGHT GROUP	COUNT[a]	SUMMER SRA REDUCTION DUE TO TREES (%)					
			FACADE				ROOF	TOTAL
			NORTH	EAST	SOUTH	WEST		
Baseline 2020	Low	1,544	23.2%	11.8%	16.4%	13.5%	3.5%	8.8%
	Medium	841	25.2%	12.6%	15.7%	14.1%	3.0%	8.4%
	Tall	45	22.9%	12.5%	13.7%	10.8%	3.4%	8.4%
Future 2050: Existing policy	Low	2,584	29.3%	18.0%	24.0%	15.5%	4.1%	11.2%
	Medium	1,451	33.1%	15.1%	26.1%	16.9%	2.5%	11.3%
	Tall	70	19.2%	18.8%	8.0%	26.2%	1.4%	10.7%
Future 2050: Target building shading	Low	2,584	27.3%	23.2%	48.9%	32.0%	3.7%	16.1%
	Medium	1,451	29.4%	25.2%	44.5%	32.7%	1.5%	16.0%
	Tall	70	19.1%	20.0%	8.5%	20.0%	0.0%	9.4%
Future 2050: Maximize tree canopy	Low	2,583	37.4%	38.0%	127.2%	69.7%	6.6%	29.4%
	Medium	1,452	38.3%	45.3%	126.9%	73.6%	2.4%	30.0%
	Tall	70	31.4%	34.8%	20.3%	26.6%	0.1%	15.5%

Table 5: Solar radiation absorptions (SRA) reductions per building height group due to trees (%), per facade, roof and total

Note: Reductions due to trees (%) use the following calculation: {('no trees' – 'with trees')/('no trees')} × 100%.

[a]Count reflects buildings used to derive reported values. Total building numbers will vary between tables due to some missing data.

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BCED followed similar patterns as total SRA (Figure 4), with MTC reductions 52–70% greater for low buildings and 49–64% greater for medium buildings, than tall buildings. Although baseline observed the lowest (and comparable) total SRA reductions due to trees across building height groups, baseline tall buildings observed the greatest significant tree-related BCED reduction of all scenarios' tall building groups (61% greater than MTC; 70% greater than lowest value (TBS)).

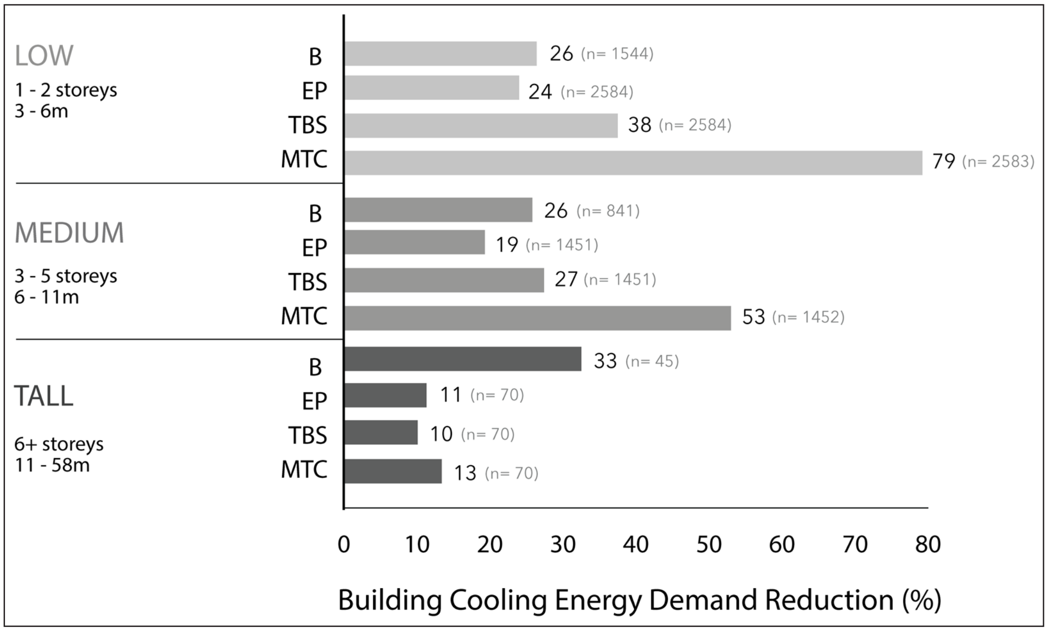

Figure 4: Total summer building cooling energy demand (BCED) reduction due to trees (%) per building height group for each scenario: Baseline 2020 (B) and Future (2050) scenarios: Existing Policy (EP), Target Building Shading (TBS) and Maximize Tree Canopy (MTC).

Note: Reductions due to trees (%) are the sum of building-level reductions calculated between 'no trees' and 'with trees' conditions, using the following calculation: {('no trees' – 'with trees')/('no trees')} × 100%. The count of buildings is included for each group (n); it reflects buildings used to derive reported values (total building numbers will vary between tables due to some missing data).

4. DISCUSSION

4.1 RESEARCH IMPLICATIONS

Considering minimal changes associated with the retrofitting, height, placement and orientation of select buildings between future (2050) building model versions, the findings show that trees in the future scenario which maximised tree planting and canopy cover (MTC; 16% canopy cover) had significantly greater shading and subsequent cooling energy demand impacts than other future scenarios. Across scenarios, shorter/smaller or older buildings that were not retrofitted or redeveloped (*i.e.* no envelope or technological improvements) benefitted the most from tree shading in terms of total SRA and BCED. Tree-based shading and cooling demand reductions resonated across all building height and retrofitting status groups, where MTC mostly outperformed EP and TBS. In particular, two additional trees planted on the south side of buildings in MTC provided substantial reductions in SRA due to trees on the south facade compared with EP (no targeted planting) and TBS (one additional tree planted on the south side). Compounded, total MTC tree shading was 10–13% greater than the other future scenarios; considerable compared with the negligible total SRA difference between EP/TBS and MTC sandbox models without trees. Similar effects followed for tree-related BCED reductions; MTC trees reduced total BCED by 13–18%.

Tree-related reductions in sandbox-wide total SRA and BCED were greater than associated increases in canopy cover. A 44% increase in canopy cover from EP to MTC was associated with a 53% greater reduction due to trees in total SRA and a 60% greater reduction in BCED due to tree shading. MTC observed a 39% increase in canopy cover compared with TBS, which translated into increased tree-related reductions in total SRA and BCED of 39% and 45%, respectively. These results emphasise the impact of increased tree planting (55% more trees in MTC compared with EP or TBS), despite overall smaller tree sizes (due to the use of climate-adapted species). The double-effort and targeted private tree planting strategy, focusing on the south-western and southeastern corners of buildings, was also crucial to the substantial reductions in total SRA and BCED of MTC. These planting strategies translated into substantially greater SRA reductions due to trees in MTC on south facade of low- and medium-height buildings (127% for each)—which included mainly single-family residential overall (96% of all buildings). In support of our findings, previous research by Privitera & La Rosa (2018) found that trees planted along the western–southern–eastern or western–eastern sides of the buildings effectively reduced energy consumption in Catania, Italy.

When building heights exceed tree heights, shading effects are minimised. In all future scenarios, but especially in TBS and MTC, taller buildings (predominantly mixed use, and with a larger footprint) underperformed in terms of tree-based reductions in total SRA and BCED. This observation is supported by other modelling research noting lower cooling effects in areas with tall buildings despite increasing trees (by 30% or 60%; Chen *et al.* 2020). The lower tree shading impact for these taller/larger buildings in TBS and MTC can also be attributed to the generally smaller tree sizes associated with the climate-adapted species used. Taller/larger buildings may require more fine-tuned tree selection (*e.g.* consider size) or placement than was applied for this study, and should be considered in practice.

Reductions in total SRA and BCED may also be impacted by the location and orientation of buildings. For example, all commercial and mixed-use buildings (also majority of tall height group), which observed relatively lower tree-related reductions in total SRA and BCED (see ***Table S3*** and ***Figure S1*** in the supplemental data online), were placed along north–south running streets. In these cases, the addition of street trees predominately targeted shading of eastern and western facades for these buildings across future scenarios. However, shading the eastern facade in Vancouver (and our study area) does not provide the most efficient strategy to reduce total SRA. Previous work by Aboelata and Sodoudi (2020) also found that street and building orientations and aspect ratios influenced the degree of energy demand in Cairo, Egypt. Other studies have also noted the different cooling effect of the same vegetation on various street sizes and orientations (Lee *et al.* 2020; Ng *et al.* 2012).

Due to the projected increases in summer temperature and numbers of extreme heat days in 2050, summer cooling energy demand will increase. Using the RCP8.5 'high emission future without effective climate change mitigation policies' climate projection, our future scenarios illustrate the level of investment into urban forestry and greening initiatives that may be required for effective shading and indoor cooling at neighbourhood scale. Compared with EP and TBS, baseline (2020) showed comparable tree-related reductions in total SRA and BCED despite having 60% fewer (but generally larger) trees, and a 25–32% lower total canopy cover. Only the 16% canopy cover future scenario (MTC) showed tree-related reductions in BCED to levels close to baseline. Relatively lower impacts of tree shading on BCED for future scenarios are likely associated with the projected increase in dry-bulb temperature and relative humidity at the study location. However, additional compounding or contradictory shading effects in future versus baseline scenarios may also be due to tree selection, the increased density (*i.e.* building footprint and height), and retrofitting/redevelopment. For example, in baseline, the lack of trees for shading was compensated with generally less building surface area available for the absorption of solar radiation. Accounting for climatic factors and planning decisions, this research underscores the potentially substantial energy-related benefits of strategic tree planting and the inadequacy of inaction or half-measures in urban forestry and greening initiatives for addressing future liveability concerns such as indoor cooling.

4.2 MODELLING APPROACH, LIMITATIONS AND FUTURE RESEARCH

A novel mixed-methods approach was presented to spatially model tree shading effects in relation to SRA of buildings and subsequent BCED that uses future climate models. These methods complement analyses involving existing and potential future urban form, climatic and other environmental conditions, for comparative analyses that can provide potentially meaningful, data-driven guidelines for municipalities and stakeholders to address increasing urban heat. Other methodologies exist for creating 3D tree and building models as well as building energy analysis (Lindberg *et al.* 2015; Zhang *et al.* 2015); however, these methods have only been tested with data about current or previous conditions. Simulated, potential future urban form (3D) and using projected climates have been limited before this research, especially coupled with urban forest scenarios in the field of building energy. Using a building model set enabled systematic comparative estimates of various tree planting and resulting shading impacts on summer BCED at a neighbourhood scale.

Limitations to the research outlined in this paper are largely due to the modelling software, as well as balancing building and tree models' complexities alongside applicability. Thus, the limitations of this work include the following:

- Some differences in SRA and BCED results between 2020 and 2050 could be due to differing tree size data sources, *i.e.* lidar versus database (*i.e.* standardised sizes).
- Building models were simplified to fit predetermined archetypes that characterised the real neighbourhood and are not a direct one-to-one replica.
- CEA integrates spatial and highly detailed building information, but methods to incorporate trees are lacking. As a result, trees could only be modelled as opaque cylindrical extrusions, which greatly generalises their shape and canopy density. This impacts solar radiation transmissivity and ventilation, among other factors, and likely overestimates shading potential.
- The bottom-up approach for building energy modelling used does not represent post-occupancy performance as it neglects to account for human behaviour and economic contexts (Kavgic *et al.* 2010). Results of this study generate comparative estimates rather than predict actual energy use.
- Energy performance data from the modelled real neighbourhood were not available; future work should conduct additional testing and evaluation if possible.
- This paper focused on summer building energy due to the pressing concern of extreme heat events; however, long-term impact assessment should consider nighttime, seasonal (*e.g.* winter), annual and cumulative effects.

Opportunities for additional research include the following:

- The scale of this study and current building energy software capabilities prohibited the integration of microclimate analysis here, but the field is quickly advancing (Brozovsky *et al.* 2022; Mosteiro-Romero *et al.* 2020) and could be instructive for fine-scale tree planting scenarios.
- Optimal tree planting configurations for urban heat reduction should be systematically investigated with respect to building form and density (Lobaccaro & Acero 2015; Morakinyo *et al.* 2017), sky view factor (Tan *et al.* 2016, 2017), dimensions and orientations (Fu *et al.* 2022; Langenheim *et al.* 2020; Lee *et al.* 2020), and other built environment factors.
- Integrating additional environmental variables (*e.g.* outdoor air circulation and cooling, air pollution, *etc.*) into future scenario models would promote the further understanding of co-beneficial tree selection and planting strategies—such as the effect of morphologies (He *et al.* 2023), sizes and spatial configurations (Berry *et al.* 2013; Fu *et al.* 2022).
- Tree shading impacts heating and other building energy demands, energy-related carbon equivalent emissions as well as potential trade-offs (*e.g.* volatile organic compounds and reduced air quality, maintenance costs, potential hazards) should be studied for a more holistic cost–benefit assessment of extensive tree planting (Erker & Townsend 2019; McCarty *et al.* 2021).
- Comprehensive benefit assessments that incorporate, but are not limited to, social–ecological, cultural, equity and accessibility factors (Bibby *et al.* 2021; Nesbitt *et al.* 2019) should be conducted for localised tree planting and management models.

5. CONCLUSIONS

Effective tree planting strategies to maximise tree canopy and target building shading and cooling are especially crucial to incorporate in urban plans alongside densification and inevitable increases in summer temperatures due to climate change. The proposed framework incorporated current (2020) and projected future (2050) climates, as well as standardised building and tree spatial models, to develop future tree planting and development scenarios and assess multi-scale solar radiation absorption (SRA) and building cooling energy demand (BCED). The boldest tree planting strategy (Maximize Tree Canopy—MTC), with 175% more trees and 150% greater canopy over the baseline condition (2020), resulted in a 22% increase in neighbourhood-scale total building shading and a 48% reduction in BCED. Non-retrofitted/non-redeveloped or low/medium-height buildings (mostly single-family residential) benefited the greatest from targeted tree planting on southern facades. Trees had less impact on SRA and BCED reductions of taller/larger buildings (predominantly mixed use) and buildings along north–south-oriented streets (mainly commercial and mixed use). Site-specific interventions via tree species selection and fine-tuned tree planting strategies could produce more substantial and successful cooling energy reductions. The developed framework can benefit from future research that investigates multi-temporal effects and holistic cost–benefit implications, as well as integrated dynamic and fine-scale tree models for microclimate analyses.

NOTES

1 See www.itreetools.org/.

2 See https://landscapeplants.oregonstate.edu/.

3 See https://plantdatabase.kpu.ca/.

4 See http://www.missouribotanicalgarden.org/plantfinder/plantfindersearch.aspx/.

5 See https://pfaf.org/user/Default.aspx/.

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COMPETING INTERESTS

The authors have no competing interests to declare.

DATA AVAILABILITY

The freely available data used include: (1) census data from Statistics Canada 695 (https://www12.statcan.gc.ca/census-recensement/index-eng.cfm); (2) reference street, building and parcel information from Metro Vancouver (https://open-data-portal-metrovancouver.hub.arcgis.com/); (3) lidar and tree inventory data from the City of Vancouver (https://opendata.vancouver.ca/pages/home/); and (4) additional online databases (see Section 2.2.2). The BC Assessment data used in this project for building information were obtained under licence from the British Columbia

Assessment Authority. Use of the data was restricted to the researchers and therefore cannot be shared. For additional information, see the Urban Greening & Urban Densification dashboard at https://experience.arcgis.com/experience/011b5cf2809a4c79b02b112629a826ae.

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SUPPLEMENTAL DATA

Supplemental data for this paper can be found at: https://doi.org/10.5334/bc.353.s1.

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