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Synthesizing the evidence on green and blue infrastructure for urban temperature mitigation in Canada

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Abstract

Urban green and blue infrastructure (UGBI) is increasingly integrated into cities for its numerous benefits, particularly their cooling effects. As the body of evidence on UGBI cooling ability grows, systematic reviews are essential; however, Canadian studies have been notably absent from global reviews. This study synthesizes the evidence on UGBI cooling effect in Canadian cities, addressing gaps on cooler climates by examining the geographic, climatic, methodological, and UGBI-specific dimensions of the Canadian evidence. Following PRISMA guidelines, we retrieved 1062 articles from Scopus and Web of Science, and after rigorous screening and data extraction, analyzed 43 studies using a systematic review approach. The results reveal a significant increase in studies over time, with a concentration on major cities such as Toronto, Vancouver, and Montreal. Central Canada overwhelmingly represents the evidence base. Most research was conducted in cold climate zones and primarily focused on green infrastructure elements, such as trees, vegetation, and green roofs, primarily focusing on their abundance rather than configurational or functional attributes. Thermal impacts were mainly measured through air temperature, land surface temperature, and energy savings, with cooling effects generally higher during the daytime. Among UGBI types, trees and parks exhibited the strongest cooling effects. Methodologically, simulation and observational approaches dominated, with a significant focus on micro-scale analyses. The review highlights important gaps, including the underrepresentation of smaller cities and regions such as Atlantic Canada, limited research on blue infrastructure, and minimal integration of health outcomes. Addressing these gaps is critical for developing robust guidelines to enhance urban resilience.

Key words: green infrastructure, blue infrastructure, urban heat island, systematic review, Canada

1. Introduction

The growing recognition of the challenges posed by elevated temperatures to urban infrastructure (Dwivedi and Soni 2024) and public health (Ebi et al. 2021) has made temperature mitigation a central focus across a range of disciplines (Akbari et al. 2016). Cities in colder climates were once considered immune to the challenges associated with high temperatures. However, this assumption does not hold anymore. Climate change and continued urbanization is making heatwaves more frequent, intense, and longer in duration, even in predominantly cold regions such as Sweden (Wilcke et al. 2020), Russia (Shaposhnikov et al. 2014), and Finland (Votsis et al. 2021).

For example, in Moscow, the 44-day-long heatwave in 2010 led to over 11 000 deaths, exacerbated by increased air pollution from wildfires (Shaposhnikov et al. 2014). In Sweden, the summer of 2018 was exceptionally warm compared to historical climatic records causing wildfires (Wilcke et al. 2020), and a strong association between mortality and increasing temperatures has been observed in Stockholm (Oudin Åström et al. 2013). Helsinki saw a record high in 2022 that resulted in increased hospitalizations for respiratory and cardiovascular conditions (Votsis et al. 2021). In addition to health impacts, cities in cold climates face significant infrastructure challenges as their various systems (e.g., energy, water resource) are often not designed to withstand thermal stress (Dwivedi and Soni 2024).

Canadian cities are also increasingly experiencing the far-reaching impacts of global warming (Casati et al. 2013; Zhang et al. 2019). In 2021, a heatwave in western Canada caused over 600 deaths in British Columbia (BC) and overwhelmed emergency rooms (British Columbia Coroners Service 2022). Wildfires destroyed approximately 90% of Lytton village in BC (Schmunk 2021; Jain et al. 2024), while blackouts are becoming increasingly likely due to rising demand on the power grid in part from increased air conditioning use (Aziz

2024). Rail tracks expanded and softened, causing delays in Toronto during a 2024 heatwave (National Post 2024). Atlantic Canada has also faced more frequent heatwaves in recent years. In June 2024, temperatures in Atlantic Canada were 10.6 °C higher than the daily average (Environment and Climate Change Canada 2024). These examples demonstrate that high temperatures and their associated negative impacts are no longer limited to warm climates, and that even cities in cold regions should adapt to the impacts of rising temperatures to protect their populations and infrastructure.

Urban green and blue infrastructure (UGBI)—defined in this study to include trees, shrubs, grasses, parks, green roofs, and other vegetation, as well as wetlands, rivers, and lakes, blue roofs, and water bodies—has emerged as a critical tool for off-setting urban heat and improving thermal comfort in cities (Marquez-Torres et al. 2025).

Blue infrastructure (BI) is an efficient thermal regulator due to a combination of higher heat capacity and relatively low thermal conductivity, giving it a relatively high thermal admittance compared to most urban materials, as well as facilitating evaporation removing heat from the surrounding environment in the form of latent heat (Oke et al. 2017*b*). Green infrastructure (GI), on the other hand, provides cooling through reflection of sunlight, shading that prevents solar radiation from reaching the ground and converting into sensible heat, and evapotranspiration, which enhances latent heat exchange (Erell 2017). UGBI is particularly attractive for urban thermal regulation, because it not only helps cities adapt to rising temperatures but also mitigates climate change by storing carbon (Davies et al. 2011), a major contributor to human-caused global warming. Additionally, UGBI offers numerous co-benefits, such as air purification (Klingberg et al. 2017), stormwater runoff reduction (Berland et al. 2017), biodiversity, and opportunities for recreation and cultural experiences (Nesbitt et al. 2017).

However, effective incorporation of UGBI into urban fabric is complex. Evidence indicates that the cooling ability of UGBI may depend on various attributes. For instance, for GI, factors including their type (e.g., tree, shrub, and grass) (Richards et al. 2020), plant species (e.g., sugar maple, black spruce, and bur oak), irrigation (Tan et al. 2020), plant health (e.g., greenness) (Weng et al. 2004), and spatial arrangement (e.g., fragmentation, connectivity) (Masoudi et al. 2019) could play a role. For BI, variables such as the surface area and shape (Ampatzidis et al. 2023), depth (Deng et al. 2023), and turbidity of the water body (Song et al. 2013) can influence the extent of its cooling effect. This means that the cooling effect of UGBI can be maximized through careful selection of vegetation types and plant species, strategic spatial distribution, proper maintenance, timely irrigation, pollution control in water bodies, and ensuring sufficient vegetation cover or water surface area.

However, the current evidence base remains too limited and inconsistent to support general conclusions regarding integrating UGBI within urban fabric. For instance, factors such as background climate influences the extent of cooling conferred by trees (Tan et al. 2018) and water bodies (Hu et al. 2023). Geological conditions such as soil type (Stumpe et al. 2023) has been shown to significantly influence the cooling performance of GI.

Under thermal stress—largely driven by climatic and weather conditions—trees may, for example, close their stomata, thereby reducing the evaporative cooling benefits from transpiration (Teskey et al. 2015). Background climate also affects transpiration rates in trees; in hot, humid environments where the air is nearly saturated, trees are less effective at cooling through transpiration (Shashua-Bar et al. 2023). This is likely why a 10% increase in vegetation resulted in a 1.4 °C temperature reduction in Phoenix, Arizona, USA (Middel et al. 2015), but only a 0.5 °C reduction in Athens, Greece (Shashua-Bar et al. 2010). Similarly, for BI, the cooling effect of water bodies has been shown to vary significantly across seven climate zones in China, with water bodies in tropical and subtropical regions exhibiting a lower cooling impact than those in arid regions (Hu et al. 2023).

Further complicating matters, studies reveal inconsistencies in how UGBI spatial patterns influence their capacity for cooling, even in cities with similar climates and geological conditions (Masoudi et al. 2019) or within the same city over time (Masoudi and Tan 2019). Spatial scale is another factor that can influence the cooling provided by UGBI (Greene and Kedron 2018). This variability in evidence regarding the impact of spatial pattern and scale of analysis raises the possibility that urban morphology may play a role in shaping UGBI effectiveness, making it even more difficult to establish universal guidelines.

Considering all the points mentioned above, evidence from one city may not be directly transferable to other cities. Therefore, we contend that to develop effective policies, we need evidence from a broad range of climates, geological and ecological regions, and cities with diverse urban morphologies.

A recent scoping review of studies on UGBI and its benefits revealed a significant lack of evidence for low-density and cold continental cities, which are prevalent in Canada (Richards et al. 2019). Specifically, regarding UGBI's temperature mitigation capabilities, Bartesaghi Koc et al. (2018) found no studies from Canada in their review. This omission is notable given Canada's vast extent and diversity of climatic, geological, and ecological regions, as well as urban morphologies. We suspect that the lack of Canadian studies in these reviews reflects narrow keyword selection, as our pre-knowledge suggested a considerable body of Canadian research on this topic. Either way, omitting evidence from countries in predominantly cold climates, such as Canada, weakens our ability to develop universal generalizations about UGBI effectiveness. It should be acknowledged, however, that not all of Canada is classified as a cold climate, as there are other climate types such as temperate (e.g., Cfb) and cold semi-arid (BSk). Nonetheless, since about 88% of Canadian cities and towns with populations over 10 000 are located in cold climates according to the latest update of the Köppen–Geiger climate zone maps (Beck et al. 2023), for brevity and to avoid repeatedly listing multiple climate types, we refer to Canada as a predominantly cold region, while specifying the exact climate zone for studied cities when describing or discussing our results. To address this knowledge gap, we conducted this study to systematically synthesize the evidence of UGBI impacts on thermal environments specific to Canadian cities. Accordingly, this review seeks to answer several key questions with regard to studies that investigate UGBI impacts on urban temperature: (1) What are the geographical and climatic distributions of studies? (2) What spatial scales of analysis were used? (3) What thermal metrics and methodological approaches were employed? (4) Which types of UGBI were studied? (5) What proportion of studies validated their findings? and (6) How many studies explicitly linked UGBI's thermal impacts to human health and well-being?

Answering these questions is crucial for identifying knowledge gaps and guiding future research directions for thermal impacts of UGBI in Canada. In addition, synthesizing the Canadian evidence may also inform studies in cities outside of Canada with comparable climates. Furthermore, this research addresses a significant gap in global knowledge of UGBI thermal regulation in predominantly cold regions, supporting the development of effective policies and practices for building climate change-resilient urban environments.

2. Approach

We conducted this systematic review using the methodology outlined by Xiao and Watson (2019) and reported our findings following the PRISMA guidelines (Page et al. 2021), with Covidence (Covidence Systematic Review Software 2023) employed to enhance consistency, transparency, replicability, and rigor throughout the process. We began this systematic review with a clearly defined protocol that was discussed with the research team, outlining the objectives, scope, and methodologies of the study. The abovementioned research questions were formulated to guide our data extraction on the cooling benefits of UGBI in Canadian cities.

2.1. Development of search strings and strategy

Keywords typifying the concepts targeted by the research questions were determined through an investigation of both contemporary and historical UGBI scientific literature. The focus was on four main components: green and blue infrastructure, thermal regulation, urban contexts, and Canadian locations. These keywords were then translated into search strings to query literature in Scopus and Web of Science, the primary scientific databases indexing research in these areas, on 27 January 2023. The identified keywords for each component are outlined below. Terms within each component were connected using the Boolean operator "OR", while components were linked using the Boolean operator "AND". Table 1 in the Supplementary Information presents the specific search strings designed for each database, which were applied to the title, abstract, and keyword fields of articles. It is worth highlighting that, although not explicitly listed below, commonly used terms such as urban heat island, surface urban heat island, heat mitigation, air temperature, cooling capacity, cooling benefits, and land surface temperature are also captured by the search string.

1) Green and blue infrastructure: vegetation; natural infrastructure; urban forest; nature-based solution; greenspace; green space; tree; park; wetland; river; waterbody; watercourse; lake; ocean; green roof; eco roof; vegetated roof; living roof; green wall; green façade; eco wall; vegetated wall; living wall; rooftop garden; and sky garden.
2) Cooling effect: air temperature; land surface temperature; urban heat island; surface urban heat island; heat mitigation; thermal comfort; and thermal regulation.
3) City: urban; town; and municipality.
4) Canadian locations: Canada; Ontario; Quebec; British Columbia; Alberta; Manitoba; Saskatchewan; Nova Scotia; New Brunswick; Newfoundland and Labrador; Prince Edward Island; Northwest Territories; Yukon; and Nunavut.

2.2. Screening process

The screening process consisted of two stages: a coarse screening, followed by a fine screening stage. During the coarse screening, articles were assessed based on titles and abstracts only, without the need to download full texts. The fine screening stage involved assessing the full text of each article. Throughout both stages and the subsequent data extraction, each article was independently reviewed by two reviewers. Any conflicts were resolved by a third reviewer to ensure impartiality. For particularly challenging conflicts, the entire research team engaged in a discussion to reach a consensus.

The decision to include or exclude an article was guided by predefined criteria. To be included, an article had to meet the following requirements: it must have been peer-reviewed, published in English (none of the authors was fluent in French, the other official language of Canada), and reported original research; it had to address urban case studies located in Canada; and it needed to examine, either directly or indirectly, thermal regulation services provided by UGBI that directly benefit humans.

To assess whether a study was focused on an urban area, we followed the definition of "population centre" by Statistics Canada (2017), which since 2010 used this term instead of "urban". According to this definition, a population centre is an area with a minimum population of 1000 people and a population density of at least 400 people per square kilometre. These population centres are identified and coded by Statistics Canada.

2.3. Data extraction

Data were extracted using a structured codebook, maintained as a living document with updates transparently communicated among the research team. The predefined variables for data extraction were established based on our research questions. After completing the extraction process for all articles, the results were carefully checked and verified by the conflict resolver before being confirmed for analysis.

While most variables in the codebook were straightforward (e.g., whether the simulation results were validated, or if the health impacts were explicitly investigated), some require further explanation. To define the "Background Climate" of cities, we used the updated Köppen-Geiger climate classification (Beck et al. 2023). This system, designed to align with major ecosystem types, classifies zones based on temperature and precipitation patterns and assigns them letters from A to E (five major climate types: A–tropical, B–arid, C–temperate, D–cold, and E–polar), with the second and third letters describing subtypes of the same climate zone based on seasonality and threshold values of temperature and precipitation, resulting in a total of 30 climate zones. Given the importance of time of year and time of day in urban heat island (UHI) studies—where UHI is defined as a phenomenon in which areas with higher concentrations of people and built structures exhibit higher temperatures than less urbanized areas (Oke et al. 2017*d*)—we recorded time at two scales: seasonal and diurnal (day or night) (Oke et al. 2017*d*). To determine the spatial scale of analysis, following Oke et al. (2017*a*), we categorized studies based on the scale at which metrics related to UGBI, and their thermal impacts were reported: (1) micro-scale, representing a horizontal extent of up to approximately 200 m × 200 m; (2) local-scale, encompassing an area of up to approximately 2 km × 2 km; and (3) meso-scale, covering areas up to 100 km × 100 km. We also recorded whether the study design was cross-sectional or longitudinal (Bartesaghi Koc et al. 2018).

Although categories for each variable were predefined prior to data extraction, they were refined during the review process as needed. For instance, using Oke et al.'s (2017*c*) framework, we initially categorized methods of inquiry as observational (distinguishing between fixed and mobile sensors), physical modeling or experimental, and simulation (subdivided into numerical modeling and empirical or statistical modeling). However, a separate "observational-proxy variables" category was later introduced for studies that indirectly assessed thermal variables, such as through health emergency visits (Graham et al. 2016) rather than direct temperature measurements.

Similarly, we initially sought to extract information on the "Type of UHI" categorizing it into Canopy Layer UHI (air temperature), Surface UHI (land surface temperature), Boundary Layer UHI, and Subsurface UHI (Oke et al. 2017*d*). However, during the review process, we determined that renaming this variable to "Thermal Variable" would better encompass a broader range of relevant metrics, such as thermal comfort and turbulent latent heat flux. The study that did not directly examine a thermal variable but instead assessed health emergency visits as a proxy for the thermal benefits of UGBI (Graham et al. 2016) was retained, leading us to include this as an additional category under the "Thermal Variable" designation.

For the type of UGBI, we initially predefined categories such as trees, grass, shrubs, lakes, rivers, green roofs, and green walls. During the review process, additional categories such as vines, hedgerows, and agriculture were incorporated. We also extracted information on the aspect of UGBI studied, categorizing it into three major groups informed by the latest advancements in landscape and urban ecology literature (Forman and Godron 1986; Wentz et al. 2018; McGarigal et al. 2023). The first category, Composition, includes aspatial attributes such as type (captured as a separate variable due to its significance as mentioned earlier), abundance, and plant species (e.g., sugar maple vs. black spruce). The second category, Configuration, encompasses spatial attributes in two dimensions (calculated using indicators such as landscape metrics, surface metrics, or user-defined metrics, such as distance to specific features) and three dimensions (e.g., height). The third category, Physical and Functional Characteristics, involves metrics such as albedo, evapotranspiration, and emissivity. While physical and functional characteristics could be considered part of composition, we chose to create a separate category for these measures to better align with the relevant literature.

2.4. Analysis and reporting

The extracted data were systematically analyzed using suitable visualization techniques—such as bar and pie charts—and summary statistics to uncover patterns, identify trends, and highlight research gaps.

3. Findings

In this section, we present our findings in relation to the research questions that guided this study.

3.1. Literature search and screening process

A total of 1062 articles were initially retrieved: 545 from Web of Science and 517 from Scopus. Among these, 310 duplicates were identified and removed, leaving 752 articles for title and abstract screening.

During the coarse screening stage, 655 articles were excluded based on the inclusion criteria, leaving 97 articles for full-text review. Following the full-text review, 40 additional articles were excluded as they did not meet all the inclusion criteria, resulting in 57 articles advancing to the data extraction stage.

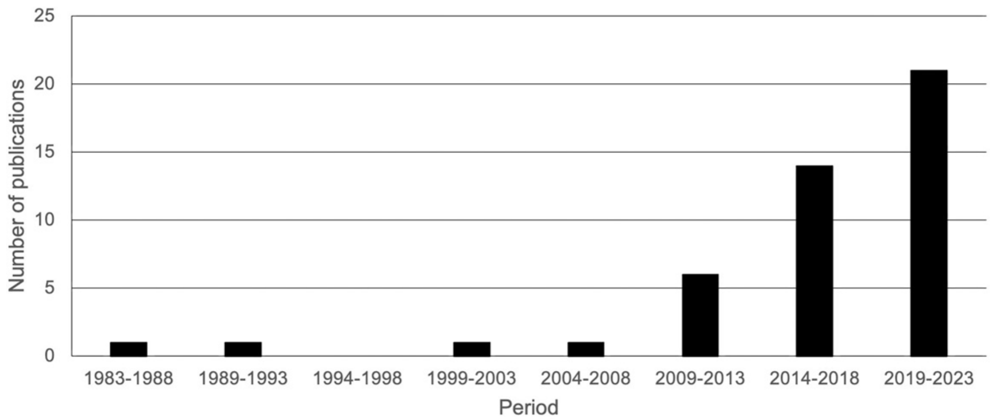
During the final compilation of articles selected for review, a duplicate not identified by Covidence or the reviewing team in earlier stages was discovered.

Further detailed examination during the data extraction led to the exclusion of 13 more articles for the following reasons:

- One article was effectively a science communication piece reporting on the cooling effects of various GI projects.
- Two articles included case studies combining Canadian and non-Canadian locations, which could not be parsed based on the reported information.
- One article was a peer-reviewed conference paper, not a journal article.
- The remaining articles were excluded either because it was not possible to relate any thermal variable (even via proxy) to GI or BI or because the studied elements were not considered GI or BI within the scope of this study. For example, one article examined the role of pumping cold water from a lake to cool buildings, which did not align with our definition of GI in this study.

Ultimately, 43 articles (Table 2 in the Supplementary Information) were analyzed in the final data extraction stage.

Fig. 1. Increase in the number of articles that have examined the thermal regulation ability of urban green or blue infrastructure in Canada, for the period of 1983 to 2023.



3.2. Temporal trend in publications

The number of articles published from 1983 to 2023 (27 January), was counted in 5-year intervals and plotted to better illustrate the publication trend on the topic over time (Fig. 1). Plotting of the articles reveals a considerable increase in publications, particularly after 2010. From the early 1980s to the mid-2000s, the number of articles remained consistently low. However, following this period the number of publications steadily increased with each 5-year interval, peaking at 21 articles during the 2019–2023 period.

3.3. Geographical and climatic distribution of studies

A total of 51 case study urban areas were examined across the 43 articles we analyzed, as some studies investigated multiple cities. As shown in Fig. 2, most studies focused on Toronto (17), Vancouver (12), and Montreal (6), accounting for approximately 69% of the research on Canadian cities. Three studies examined Quebec City, while Edmonton and Brampton each appeared in two studies. The remaining cities—Caledon, Windsor, Nanaimo, London, Ottawa, Halifax, Calgary, Saskatoon, and the Credit River Watershed (included in the analysis due to its urban areas)—were each represented by only one study.

From a regional perspective, the distribution of case study cities highlights significant variations across Canada's regions. Central Canada leads, with Ontario (24 studies) and Quebec (nine studies) accounting for the majority of the analyzed literature. The Canadian West Coast follows with 13 studies from British Columbia. The Prairie Provinces are represented by three studies from Alberta and one from Saskatchewan. Atlantic Canada is underrepresented, with only one study from Nova Scotia and none from New Brunswick, Newfoundland and Labrador, or Prince Edward Island. Northern Canada (Yukon, Northwest Territories, and Nunavut) has no representation.

Regarding the climate zones of the urban areas examined in the articles we analyzed, the majority of cities fall within the Dfa climate zone (47%), which is characterized by a cold overall climate, with no dry season, and hot summers (average temperature of the warmest month $\geq$22 °C). The Dfb climate zone, also a cold climate with no dry season but with warm summers (average temperature of the warmest month <22 °C and at least 4 months with a mean temperature above 10 °C), accounts for 27% of the studied cities. Cities in the Cfb climate zone, a temperate climate with no dry season and warm summers, make up to 24% of the total. The Csb climate zone, a temperate climate with dry (precipitation in the driest summer month below 40 mm and less than one-third of that in the wettest winter month) and warm summers, was minimally represented, with only one case study city, contributing 2% of the evidence. For detailed definitions of the climate zones, see Beck et al. (2023).

3.4. What types and aspects of UGBI were studied?

Figure 3 illustrates the types of UGBI studied in the analyzed articles. Since some studies considered multiple types of GI and BI, there were a total of 71 UGBI types examined. GI dominated the analysis, comprising about 86% of all UGBI types studied. BI accounted for 4%, while hybrid GI–BI, classified as UGBI, made up 10% of the total. Approximately, two thirds of the studies (65%) focused only on the thermal impacts of a single type of UGBI, while the remainder investigated multiple types of UGBI, ranging from two to four.

Among the various types of GI, trees ($n = 23$) were the most frequently studied, followed by vegetation ($n = 14$) and green roofs ($n = 9$). Together, these three types accounted for 75% of all GI types investigated in the articles. The GI type "vegetation" was defined differently across studies, but for consistency, any aggregated analysis of vegetation without distinguishing between specific types such as green roof, tree, or shrub, was categorized as "vegetation". For instance, studies that quantified vegetation using measures like Normalized Difference Vegetation Index (NDVI)—a remote sensing index used to distinguish vegetation from non-vegetation and to differentiate green from stressed vegetation (Sun et al. 2011)—were grouped under this category.

Fig. 2. Geographical distribution of Canadian urban areas studied. The proportional size of the circles represents the frequency of each urban area.

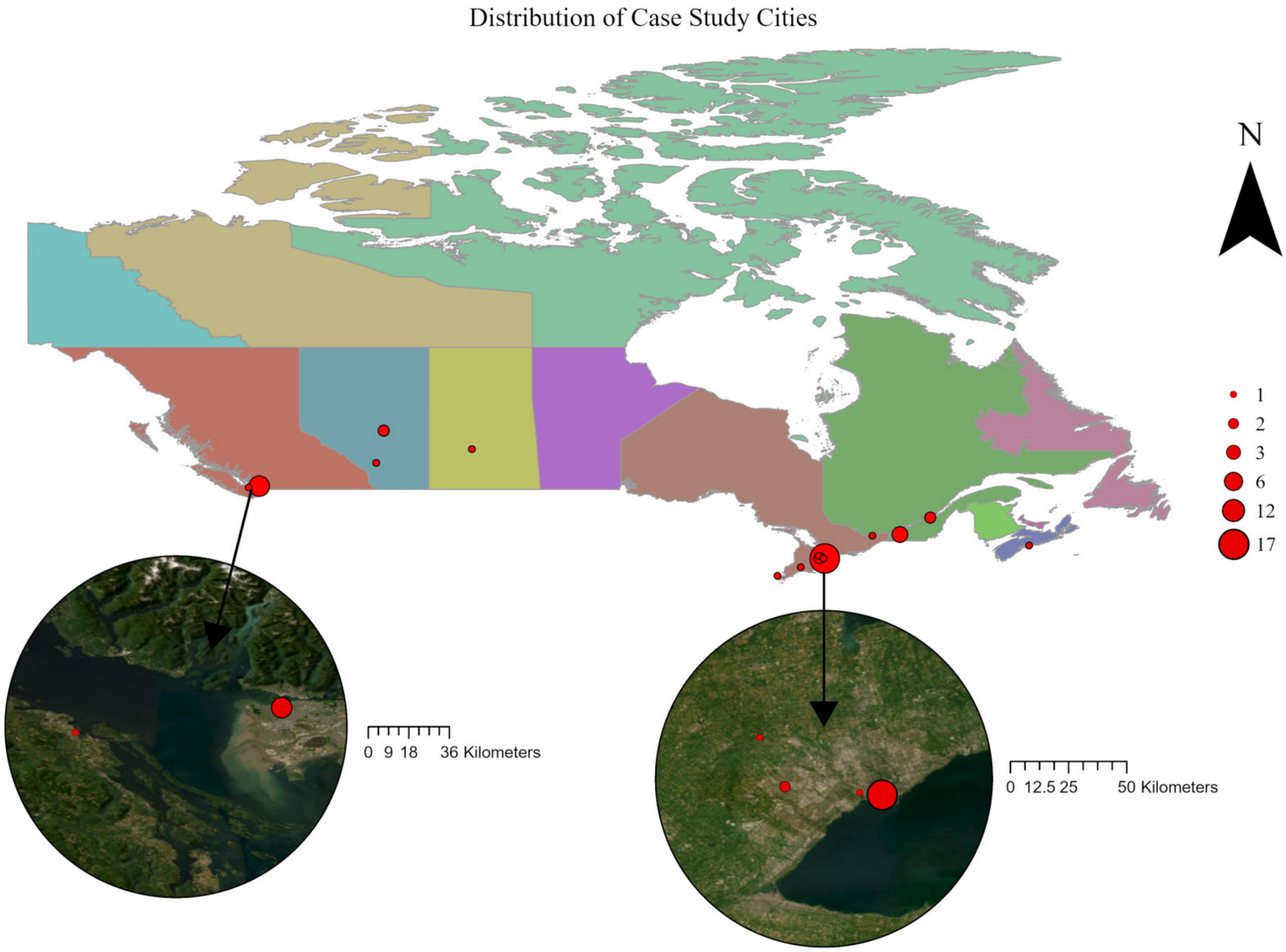


Fig. 3. The different types of green infrastructure (GI), blue infrastructure (BI), and urban green and blue infrastructure (UGBI) examined in the articles.

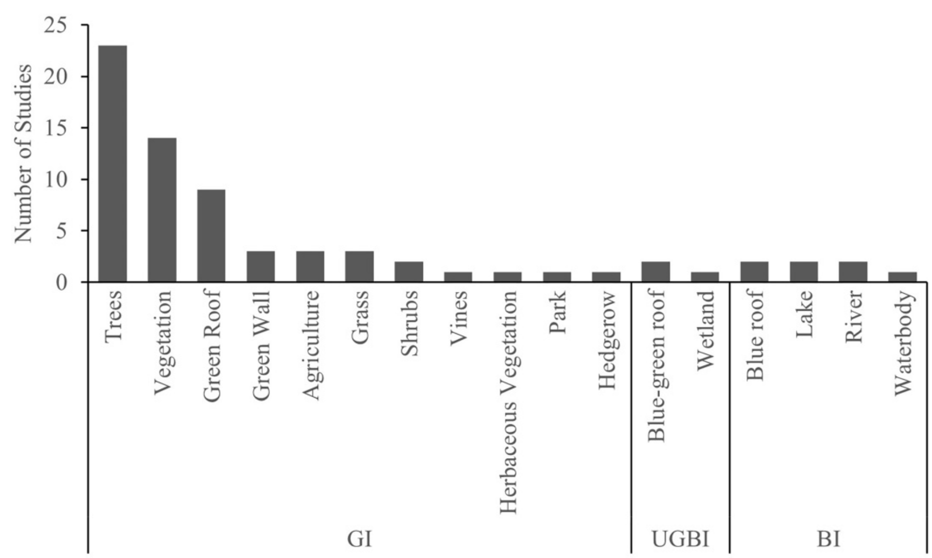
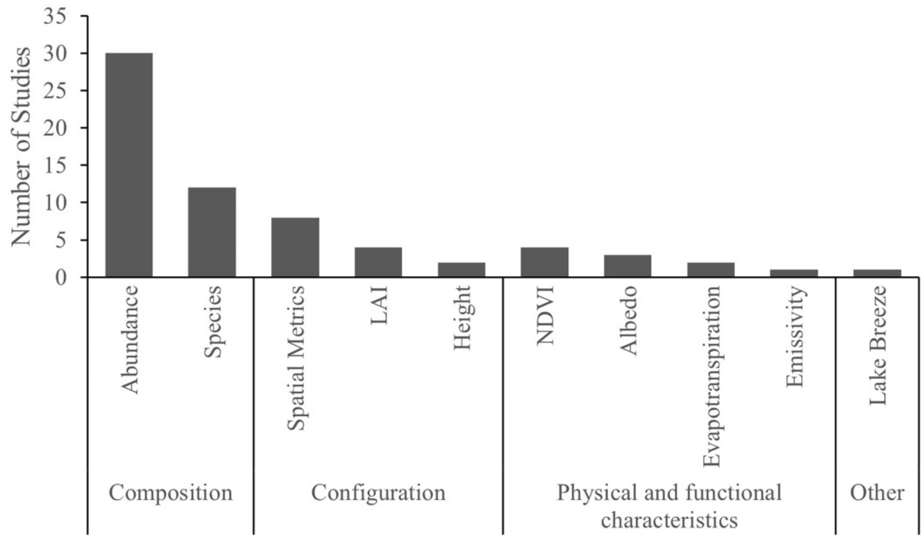


Fig. 4. The different aspects of urban green and blue infrastructure examined in the articles. NDVI, Normalized Difference Vegetation Index.



For BI, water bodies (a term used collectively to refer to lakes, rivers, and similar features), lakes, rivers, and blue roofs were the BI types studied. Each of these was analyzed in two studies, except for water bodies, which were included in only one study.

Hybrid GI–BI types were rarely studied, with only three articles examining them in total. Green–blue roofs were investigated in two studies, while wetlands were analyzed in one study.

Approximately 70% of the studies focused on a single attribute of UGBI, while the remaining studies analyzed two to five attributes (Fig. 4), resulting in a total of 67 attributes examined. The most commonly studied attributes of UGBI were composition, which accounted for 63% of the analyses, followed by configuration at 21%, and physical and functional characteristics at 15%. One study examined an attribute that did not fit neatly into these categories—lake breezes—which was placed in a new category labeled “Other”.

Among composition-based metrics, the abundance of UGBI types was the most frequently studied attribute ($n = 30$), followed by species ($n = 12$). For configuration-based metrics, spatial metrics were analyzed in eight studies, while other measures such as LAI and height were examined in fewer than five studies each. The number of articles analyzing the physical and functional characteristics of UGBI was relatively limited. Among these measures, NDVI was the most frequently studied, appearing in four articles, followed by albedo in three articles, evapotranspiration in two, and emissivity in just one article.

3.5. What are the thermal impacts of UGBI?

Of the 43 studies analyzed, 34 explicitly and intentionally measured the thermal benefits of UGBI. The remaining studies did not have this as a stated objective, though some assessed thermal benefits incidentally. Among the analyzed articles, 36 provided explicit numerical values for the thermal impact of UGBI, either through direct thermal measurements or proxy variables such as energy savings.

The reviewed articles assessed the thermal impact of UGBI using a range of thermal and proxy variables, with some studies utilizing multiple measures. Air temperature was the most frequently analyzed variable, appearing in 25 studies. Land surface temperature was used in 17 articles, followed by energy savings, used as a proxy variable, in eight articles. Other variables included various thermal comfort indices ($n = 7$) and mean radiant temperature ($n = 4$). The least frequently studied variables were the frequency of heat-related medical emergencies, used as a proxy in two studies, and boundary layer temperature and turbulent latent heat flux, which were considered in one study.

Due to the wide variation in measured thermal variables, methodologies for assessing relationships between UGBI attributes and thermal indicators, UGBI types and characteristics, and the very limited number of studies with directly comparable results, conducting a reliable meta-analysis was not feasible. Nevertheless, we provided a general summary of the reported cooling impacts of UGBI where possible (Table 1). Given the substantial variability across studies, any direct comparison of numerical values in Table 1 should be approached with caution, and focus should instead be directed toward broad patterns rather than precise estimates. For example, previous research has demonstrated that the choice of regression method (e.g., ordinary least squares vs. spatial error models) can substantially alter the observed relationships between vegetation attributes and LST—sometimes rendering a previously significant variable insignificant or even cause a relationship to change direction (Masoudi et al. 2019). As Table 1 shows, in terms of thermal variables, the largest cooling effects were observed when measured using mean radiant temperature (MRT) (up to 17.3 °C) and land surface temperature (LST) (up to 15 °C), followed by air temperature (up to 6 °C). Energy savings from reduced cooling demand due to green roofs reached a maximum of

Table 1. The UGBI's cooling effect.

Grouping criteria			Range of cooling effects
Thermal variable	Air temperature		0.44 °C (Anderson and Gough 2022) to 2.92 °C (Almaaitah and Joksimovic 2022) (mean), up to 6 °C (Vanos et al. 2012)
	LST		5 °C (Francoeur et al. 2021), up to 15 °C (Anderson et al. 2022; Boiné et al. 2022)
	MRT		3.2–17.3 °C (mean) (Aminipouri et al. 2019)
	Energy savings		Energy saving of 1.8 (Berardi 2016) to 5.2% (Moradi et al. 2022) (overall), up to 36% (at the roof level) (Berardi 2016)
	Heat-related emergencies		About 80% reduction in ambulance calls for 5% increase in canopy cover (Graham et al. 2016)
	Thermal comfort		UTCI: 5.9 °C (Berardi and Graham 2020); 32 W/m^2 (Vanos et al. 2012); PET: 2.1 °C (Wang and Akbari 2016)
Type of GI	Trees	Air temperature	Up to 5.5 °C (Boiné et al. 2022)
		LST	Up to 15 °C (Anderson et al. 2022; Boiné et al. 2022)
		MRT	Up to 17.3 °C (2Aminipouri et al. 019)
		Thermal comfort	Up to 32 W/m^2 (Vanos et al. 2012)
		UTCI	Up to 5.9 °C (Berardi and Graham 2020)
	Green-blue roofs (air temperature)		Up to 2.92 °C (Almaaitah and Joksimovic 2022)
	Park	Air temperature	Up to 6 °C (Vanos et al. 2012)
		Thermal comfort	Up to 20 W/m^2 (Vanos et al. 2012)
	Water bodies		Cooling effect within 500 m of rivers (Shen et al. 2014) 2.1 ± 0.2 °C (air temperature) (Mariani et al. 2018)
Time of day	Daytime	Air temperature	Up to 6 °C (Vanos et al. 2012) *0.2 to 0.3 °C (Wang and Akbari 2016)
		LST	Up to 15 °C (Anderson et al. 2022; Boiné et al. 2022)
		MRT	Up to 17.3 °C (Aminipouri et al. 2019)
		PET	*0.6–2.1 °C (Wang and Akbari 2016)
		UTCI	0.54 °C (mean) (Berardi and Graham 2020), up to 5.9 °C (Berardi and Graham 2020)
	Nighttime	Air temperature	*0.03 to 0.19 °C (Wang and Akbari 2016)
		LST	About 4 °C (warmer) (Richards and Oke 2002)
		MRT	Up to 8 °C (HosseiniHaghighi et al. 2020)
		PET	*0.1–0.4 °C (Wang and Akbari 2016)

Note: LST, land surface temperature; MRT, mean radiant temperature; UTCI, universal thermal climate index; PET, physiological equivalent temperature.
*Indicates that the values are from the same study, using consistent methods, and therefore comparable.

5.2% on average for the building envelope, with savings of up to 36% at the roof level. Thermal comfort was assessed using various indices, including the universal thermal climate index (UTCI) and the physiological equivalent temperature (PET).

Regarding UGBI type, parks appeared in the analyzed articles to provide the greatest cooling effect, followed by trees, green-blue roofs, and water bodies. The largest reported cooling effect for parks was 6 °C, compared to 5.5 °C for trees. Green-blue roofs showed an average cooling effect of approximately 2.9 °C, while water bodies were reported at around 2.1 °C. The general pattern noted earlier regarding differences across thermal variables also applies here. For example, the cooling effect of trees measured using MRT and LST was substantially higher than that when measured using air temperature. However, it should be noted that this pattern appears to apply only during the daytime. At night, air temperature was higher than LST. When focusing on the time of day (daytime vs. nighttime), pairwise comparisons based on the same thermal variables consistently indicate that the cooling effect of UGBI is greater during the day than at night. For example, one study that assessed cooling effects during both day and night using consistent methodologies—ensuring comparability—reported a daytime cooling effect of approximately 0.2–0.3 °C, compared to 0.03–0.19 °C at night (based on air temperature). Similarly, when measured using PET, a maximum thermal comfort change of 2.1 °C was estimated during the day and only 0.4 °C at night.

3.6. Spatial scale of analysis of studies

Figure 5 illustrates the spatial scales of analysis used in the studies. Among the 43 studies reviewed, six conducted their investigations at two different scales: three at the micro and local scales, two at the local and meso scales, and one article at the micro and meso scales. The remaining studies focused on a single spatial scale. Of these, the micro scale was the most common ($n = 21$), followed by the meso scale in nine studies, and the local scale in seven studies.

Fig. 5. The spatial scale of analysis used in studies.

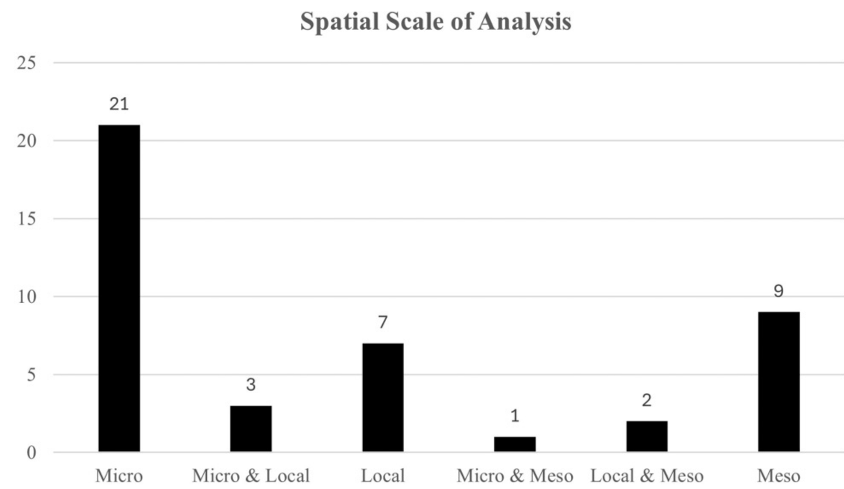


Fig. 6. The methodological approach adopted by the analyzed articles.

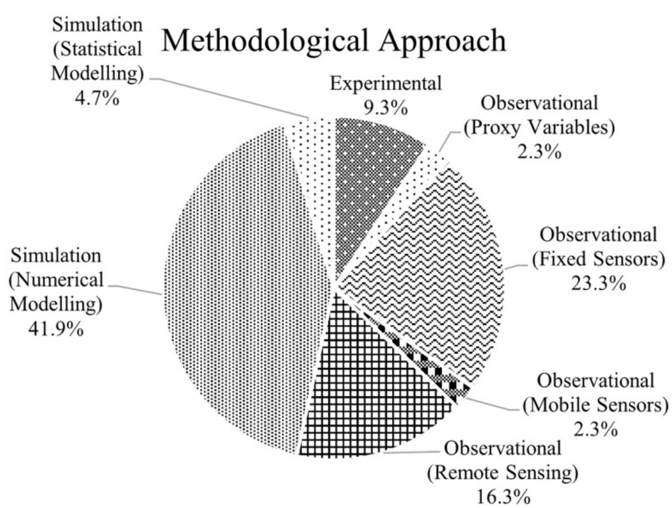
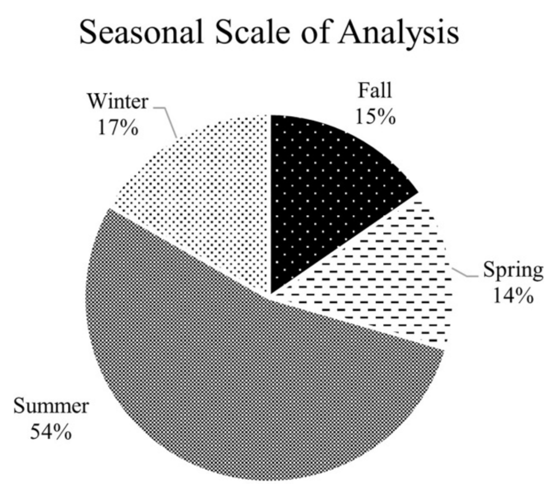


Fig. 7. The seasonal temporal scale of analysis.



3.7. Methodological approaches adopted in the studies

In terms of the general study design, 32 studies employed a longitudinal approach, while 11 studies used a cross-sectional design, examining the subject at a single point in time.

Regarding methodological approaches, as Fig. 6 illustrates, simulation was the most frequently used, adopted by 47% of the studies, followed by observational approaches at 44%, and experimental approaches at 9%. Among the studies using an observational approach, fixed thermal sensors were the most commonly utilized ($n = 10$), followed by remote sensing methods ($n = 7$), and mobile sensors ($n = 1$). For studies employing simulation approaches, numerical modeling was predominant ($n = 18$), while two studies relied on empirical modeling. Of the 20 studies that employed simulation approaches, 11 validated their results.

3.8. Temporal scale of analysis of studies

Sixteen out of the 43 analyzed articles focused on the thermal impact of UGBI during the daytime, one examined nighttime, and 25 investigated both. One study did not involve a diurnal temporal scale, as it simulated a statistical model independent of the time of day.

On a seasonal scale, 29 studies focused on a single season. Figure 7 illustrates the frequency of analysis for each season of the year. As shown, most studies were conducted during the summer months (54%), followed by winter, fall, and spring, each with a much lower but similar frequency of around 16%. In total, 14 studies investigated the thermal impacts of UGBI across multiple seasons: three studies covered two seasons, one study covered three seasons, and 10 studies examined all four seasons.

3.9. Health benefits of UGBI's thermal regulation capacity

Among all the studies, only three explicitly examined the health impacts of UGBI's cooling effect. These studies assessed health effects using various indicators, including the number of ambulance calls for heat-related emergencies (Graham et al. 2016), recorded deaths during heatwaves (Henderson et al. 2022), and general heat-related morbidity (Vanos et al. 2012).

4. Discussion

We identified 43 studies evaluating the thermal regulation capacity of UGBI in Canada, none of which were included in previous global systematic reviews (e.g., Bartesaghi Koc et al. 2018). We believe that synthesizing this evidence for Canadian cities will provide valuable insights, not only for urban areas within Canada but also for cities in in other predominantly cold countries such as Sweden, Finland, Norway, Russia, and parts of the United States.

The temporal analysis of publication trends from 1983 to 2023 reveals a growing emphasis on the cooling benefits of UGBI in Canadian cities, particularly after 2010. This upward trend reflects growing academic focus, likely driven by the rapid urbanization (Statistics Canada 2022) and rising temperatures (Zhang et al. 2019) in Canadian cities, which have amplified the need for planning resilient and sustainable urban environments. Despite the growing body of evidence, our results highlight significant gaps in existing knowledge, providing guidance for future research to develop a more comprehensive understanding of how UGBI can support Canadian cities and other urban areas with similar geographical, climatic, and morphological characteristics in tackling the challenges of climate change and urbanization.

The analyzed articles reveal a notable concentration of research in the large cities of Toronto, Vancouver, and Montreal, which together account for approximately 70% of the studies, revealing a gap in knowledge on UGBI cooling benefits in smaller cities. The predominance of research on these large cities may be expected given greater share of the national population, their economic and political significance, the concentration of universities that create an environment demanding more research, and their experience of intensified heat due to larger and denser built-up areas, higher traffic volumes, and greater building energy consumption that releases waste heat into the urban environment. Other contributing factors include the presence of bylaws, urban planning and forestry policies, and the availability of data—all of which add pressure to conduct more research.

However, we believe that the scale of the imbalance in the literature is not reasonable and should be addressed. Our concern extends beyond representation to the usefulness and applicability of existing evidence. The relationship between the spatial patterns of urban landscapes, including of UGBI, and ecological processes such as temperature regulation varies significantly with changes in spatial scale as demonstrated by previous research (Li et al. 2013; Estoque et al. 2017). For instance, a seminal study by Oke (1973) demonstrated that UHI intensity increases with city size, a finding that has been replicated in more recent research (Zhou et al. 2017). Consequently, the dynamics of scale in the context of UGBI cooling performance is expected to differ substantially between cities of significantly different sizes.

Moreover, smaller cities often face challenges related to infrastructure, economy, and social and political structures, which make them distinct from large cities in ways that have direct implications for vulnerability to heat. For instance, they tend to have fewer heat-mitigation amenities (e.g., splash pads, cooling centres) (Pierce et al. 2025) and a higher median age, with older adults being more vulnerable to elevated temperatures (Bunker et al. 2016). They also face unique challenges that influence how UGBI may be integrated in these urban areas through urban planning and design measures (Back and Collins 2022). These fundamental distinctions make it even more complicated to transfer evidence from large cities, necessitating further research on smaller urban centres to generate a more comprehensive evidence base that can help cities adapt to the adverse impacts of heat. It is also worth noting that a considerable proportion (above 30%) of Canadians live in small- and medium-sized cities, based on the definition used by Statistics Canada (Statistics Canada 2017), which further underscores the importance of addressing the knowledge gap regarding these cities. We also argue that, given the significance of city size in relation to UGBI—thermal microclimate relationships elaborated above, the definitions for city size used by Statistics Canada—classifying urban areas into large (over 100 000), medium (30 000–99 999), and small (1000–29 999) population centres—may not adequately capture the variation within the "large urban centres" category, with important implications for understanding urban environmental and ecological dynamics. For example, Toronto, with a population exceeding 2000 000, is placed in the same category as Windsor, which has just over 200 000 residents. We encourage future studies to systematically examine the influence of city size on the cooling capacity of UGBI and to consider proposing threshold values that are more contextually appropriate.

One key consideration in assessing city size is whether the small- or medium-sized urban centre is located within or outside a larger metropolitan area. Proximity to a larger urban core may influence the extent and intensity of elevated temperatures far more than if the city were isolated from such influence. In addition, small-, or medium-sized urban centre located within a larger metropolitan area—or in proximity to other smaller urban centres—may be able to draw on resources from those nearby cities should the need arise. Future studies could be designed to test this hypothesis. We also encourage researchers to provide more detailed, specific information about their study areas, including potential impacts from neighbouring urban centres.

The regional distribution of studies also highlights significant disparities, with Central Canada (Ontario and Quebec) dominating the literature, followed by the Canadian West Coast (British Columbia). Conversely, the Prairie Provinces, Atlantic Canada, and Northern Canada are markedly underrepresented, with Northern Canada completely absent from the analyzed studies. This uneven representation has important implications for understanding the cooling benefits of UGBI in less-studied regions. Substantial differences in geography, economy, culture, population size, demographics, and historical context across these regions create varying opportunities for integrating UGBI into urban structures. Additionally, regional climatic and geological attributes significantly influence the cooling effects of UGBI. For example, variations in soil texture (Stumpe et al. 2023), sunlight and water availability (Tan et al. 2018), vegetation types (Richards et al. 2020), and plant species (Tan et al. 2020) all affect GI's capacity to reduce temperatures, while the background climate zone shapes BI's cooling impacts (Hu et al. 2023). This underscores the need for more region-specific research.

From a climatic perspective, the dominance of studied cities in the Dfa, Dfb, and Cfb climate zones—which collectively constitute 98% of the existing evidence on Canadian cities—reveals a gap. While these zones account for the vast majority of Canada's urban population, the absence or underrepresentation of cities in other climate zones, such as Dfc, Dsc, and BSk, limits our ability to draw conclusions about how urban ecosystems function across Canada's full range of climatic conditions. Cities such as St. John's, the capital of Newfoundland and Labrador, are located in the Dfc climate zone, a cold climate with no dry season and cold summers (average temperature of the warmest month >10 °C; coldest month ≤ 0 °C; and 1–3 months with mean temperature >10 °C). The Dsc climate zone, also a cold climate with dry summers and cold summers, includes cities like Whitehorse, the capital of Yukon. The BSk climate zone, classified as a cold semi-arid steppe (mean annual precipitation $\geq 5 \times$ precipitation threshold but $< 10 \times$ precipitation threshold, with mean annual temperature < 18 °C), is exemplified by Lethbridge, the third-largest city in Alberta.

Additionally, the similarity of climate zones does not automatically ensure the possibility of directly transferring evidence. For instance, while most urban areas in Atlantic Canada fall within the Dfb climate zone, for which there appears to be comparatively ample evidence, the climate in Atlantic Canada is also shaped by maritime influences (i.e., the moderating effects of large water bodies, resulting in milder winters, cooler summers, and higher humidity and precipitation levels). Furthermore, as noted earlier, cities in Atlantic Canada are on average smaller than those in Ontario and Quebec, which represents another important factor in determining the cooling capacity of UGBI. These differences in size and maritime influences, along with other factors mentioned earlier such as soil type and urban morphology, limit the direct transfer of evidence.

Our analysis reveals a strong focus on GI in the literature, accounting for 86% of the UGBI types studied, compared to just 4% for BI and 10% for hybrid GI–BI. The global analysis by Bartesaghi Koc et al. (2018) of relevant literature reported that 89.7% of studies investigated the thermal impacts of GI, 5.5% examined BI, and 4.8% focused on hybrid GI–BI. While this aligns with our observations of Canadian evidence in terms of the predominant focus on GI, Canadian studies appear to place comparatively greater emphasis on BI than hybrid GI–BI. Nonetheless, the predominant focus on GI highlights a significant research gap in understanding and leveraging the thermal benefits of BI and hybrid GI–BI, such as lakes, ponds, rivers, and wetlands. This gap is particularly relevant for Canadian urban areas, since these elements are relatively common in Canadian urban areas and can provide significant cooling effects through evaporative cooling and by serving as efficient heat sinks due to their higher thermal inertia, which is primarily a result of their high heat capacity (Oke et al. 2017*b*). Given the increasing recognition of BI's cooling effects (Chakraborty et al. 2023), as well as the synergistic roles of GI and BI in providing cooling (Marquez-Torres et al. 2025), we encourage future studies to focus more on BI and assess the complex interactions between BI and GI in generating cooling. Such an approach is key to gaining more comprehensive insights into urban cooling strategies and to better equipping policymakers and planners with the tools needed to create more resilient and livable communities. In particular, future studies should explore how the size of various BI within and near city boundaries may affect temperature. For instance, a study on the cooling benefits of UGBI across 12 U.S. cities demonstrated that the cooling effects of water bodies can extend up to 4 km (Marquez-Torres et al. 2025), while other studies have suggested the possibility of thresholds in the size of BI (and GI) (Yu et al. 2020). However, the exact thresholds in size and distance are likely to differ for Canadian cities given substantial differences in variables such as background climate and soil conditions, warranting further research. Factors such as the depth and turbidity of water bodies (e.g., lakes and ponds), and the maintenance of constructed hybrid UGBI such as rain gardens as well as natural and constructed wetlands, could also be examined in future studies.

Additionally, within the GI types, there appears to be limited exploration of certain key categories, as the vast majority of studies focus on the thermal impacts of trees, general vegetation, and green roofs, mirroring patterns observed in global literature (Bartesaghi Koc et al. 2018). For instance, urban parks, which play a vital role in cooling urban areas (Hwang et al. 2015) while also offering recreational and social benefits (Peters et al. 2010), are significantly understudied. Although three out of the 43 articles that we examined mentioned studying parks, they did not explicitly treat parks as distinct ecosystems—that is, they did not assess the cooling effect of the park as a whole, but instead focused on individual components within the park, such as trees and grasses (Richards and Oke 2002; Boiné et al. 2022). This gap restricts our ability to fully understand the potential of diverse GI in mitigating elevated temperatures.

Our systematic review reveals another noteworthy pattern: most studies (65%) focus on the thermal impacts of a single UGBI type. We argue that this approach is potentially limiting for several reasons. First, incorporating multiple UGBI types within a single study can provide more robust evidence on their relative contributions to cooling effects by accounting for methodological differences that often exist across separate studies. Second, such an approach can more effectively capture interactions among different UGBI types, enabling the identification of synergies and trade-offs. Finally, a more holistic approach would support more effective urban planning and policymaking by providing a comprehensive understanding of how diverse UGBI types work together to mitigate urban heat.

Regarding UGBI attributes, the literature primarily focuses on composition (63% of analyses), followed by configuration (21%) and physical/functional characteristics (15%). While composition metrics—such as the abundance of different UGBI types and plant species—offer valuable insights, the underrepresentation of configuration and physical/functional characteristics highlights key research gaps. For instance, configuration-based metrics, including fragmentation, connectivity, and geometric complexity of UGBI patches, are critical for optimizing spatial arrangements to maximize cooling benefits (Connors et al. 2013; Masoudi et al. 2021). However, studies measuring these factors against temperature remain limited (11% of the studies). As urbanization continues, optimizing UGBI patterns becomes increasingly important, particularly given the constraints on urban expansion.

Similarly, physical and functional characteristics, such as evapotranspiration and albedo, which impact heat transfer via latent heat and energy exchange through radiation, respectively, remain underexplored. Research demonstrates that cooling performance varies, for instance, by plant species due to differences in evapotranspiration rates, and that irrigation can enhance evapotranspiration (Yu et al. 2018). Similarly, the turbidity of urban ponds can influence their cooling impact, as it affects water albedo and, consequently, heat absorption and evaporative efficiency (Solcerova et al. 2019). Expanding investigations into these factors will improve our ability to design and implement UGBI strategies that maximize urban cooling.

As noted in Section 3.5, we were unable to reliably assess the thermal impact of UGBI due to the considerable methodological heterogeneity in the articles. Consistent definitions and methodologies are prerequisites for reliable comparisons and meaningful synthesis.

However, we aimed to identify general patterns where possible. The analyzed articles show that studies measuring cooling impacts using MRT and LST reported substantially higher values compared to those using air temperature (during daytime). This observation is broadly consistent with previous research (Good et al. 2017), and is also expected given the nature of these variables: MRT and LST are directly exposed and influenced by solar radiation, capturing peak thermal stress, whereas air temperature reflects more moderated ambient conditions, influenced by atmospheric mixing. This pattern, however, reverses at night, as the surface cools at a faster rate, while the overlying air retains heat longer through mixing and lower net radiative cooling (Oke et al. 2017*d*).

Among the various types of UGBI studied in the articles we analyzed, parks appeared to provide the greatest cooling effect, which is in agreement with findings from a previous meta-analysis (Bowler et al. 2010). This is not surprising, given that parks are relatively larger than other UGBI types, and also typically contain a combination of trees, grasses, shrubs, and water features. Since each of these individual UGBI types contributes to cooling, their combined presence within a larger spatial unit such as a park would reasonably be expected to result in a greater overall cooling effect. However, only one article evaluated the cooling effect of parks as a whole (Vanos et al. 2012). As noted earlier, additional studies are needed before drawing reliable conclusions about the cooling potential of parks. Trees were associated with the second-largest cooling effect, which is also consistent with previous research (Bowler et al. 2010; Richards et al. 2020), which is likely due to their high rates of transpiration—an important cooling mechanism—and the substantial shade provided by their canopy, especially in comparison to grass (Tan et al. 2018).

Water bodies were reported to have the lowest cooling effect. A study conducted in the Kathmandu Valley, Nepal, observed a similar pattern, with ponds providing the least cooling compared to urban forests and parks, which may be because water bodies are more likely to absorb heat from the surrounding hot urban features (Bhattarai et al. 2025). It is important to note; however, that only three out of the 43 studies investigated BI, and one of those did not explicitly report numerical values for the cooling effect. The 2.1 °C cooling estimate was taken from a study that focused exclusively on BI (Mariani et al. 2018), meaning it was not compared directly to any GI within that investigation. As discussed earlier, caution is warranted when comparing values across studies with differing methodologies. One study did assess both GI and BI simultaneously and reported cooling effects as coefficients in a regression model (Shen et al. 2014). In that study, GI was associated with a larger cooling coefficient (−0.33) compared to BI (−0.22), further suggesting that GI may provide greater cooling benefits. Nevertheless, the existing evidence on BI's cooling ability remains highly limited, and further research is needed to systematically compare the cooling performance of GI and BI. This underscores the current gap in our understanding of the cooling effects of BI, as previously noted.

Moreover, the greater cooling effects observed during the daytime compared to nighttime align with existing evidence and are theoretically expected. For example, a significant part of the cooling provided by tree canopies is due to shading, which becomes irrelevant at night when there is no incoming solar radiation to intercept (Tan et al. 2018). The absence of sunlight at night also leads to a substantial reduction in evapotranspiration (Tan et al. 2018).

The pattern we observed in our analysis regarding the specific indicators used to measure the thermal impact of UGBI aligns with the findings of Bartesaghi Koc et al. (2018). They reported that approximately 70% of studies used air temperature, 52% used LST, and 26% employed thermal comfort indices. Similarly, we found that air temperature was the most frequently studied indicator, followed by LST and thermal comfort indices.

Regarding the spatial scale of analysis, our results highlight a strong emphasis on micro-scale studies, with 21 out of 43 studies (49%) focusing on this scale—identical to the findings reported by Bartesaghi et al. (2018) in their global review. This focus on the micro-scale is perhaps expected, as it aligns with the scale at which people live, work, and play. Similar to Bartesaghi Koc et al. (2018), the meso-scale and local scale were the next most studied in the Canadian literature, with 21% of studies (compared to 23.6% in Bartesaghi Koc et al. (2018)'s analysis) focusing on the meso-scale and 16% (compared to 23%) at the local scale.

In contrast to the global literature (Bartesaghi Koc et al. 2018), where only 4.2% of studies conducted multi-scale analyses, our review of Canadian evidence found that 14% of studies adopted this approach. However, we argue that more multi-scale evidence is needed to effectively inform policymaking, planning, and design interventions. The impact of UGBI on temperature has been shown to be scale-dependent (Li et al. 2013), making it essential to understand how localized cooling benefits translate into city-wide and regional temperature patterns. Without robust multi-scale evidence, UGBI implementation risks being fragmented, potentially limiting its integration into urban climate strategies. Future research should address this gap by adopting multi-scale approaches, which would enhance the ability of urban decision-makers to develop holistic, evidence-based climate adaptation strategies that maximize the cooling potential of UGBI across different spatial scales.

We observed a similar pattern to previous systematic reviews of global literature regarding the temporal scale of analysis. In the Canadian literature, summer was by far the most studied season (54%), aligning with findings from the study by Degefu et al. (2022), which focused exclusively on remote sensing methods (46%) evaluating evidence from megacities (defined as having a population over 10 million), and Bartesaghi Koc et al. (2018) (83%). This is unsurprising, as the cooling effect of UGBI is most pronounced and necessary during summer when temperatures are highest and also when trees and shrubs are in full leaf. Other seasons were studied almost equally. Additionally, 30% of Canadian studies analyzed multiple seasons, a higher proportion than both global analyses—Degefu et al. (2022) (22%) and Bartesaghi Koc et al. (2018) (14%).

Regarding the time of day, our results closely resemble those reported by Degefu et al. (2022). Our analysis revealed that 58% of studies evaluated both daytime and nighttime, comparable to 52% in Bartesaghi Koc et al. (2018)'s review. Daytime-only studies accounted for 37%, almost identical to Bartesaghi Koc et al. (2018) at 38%, and nighttime data were the least used at 2%, similar to Bartesaghi Koc et al. (2018) (1.8%).

Our analysis demonstrates that approximately 75% of Canadian studies employed longitudinal approaches rather than cross-sectional designs. Longitudinal approaches are particularly valuable as they provide repeated measurements over time, enhancing confidence in the observed evidence. We interpret this as a positive trend. The previous global analysis by Bartesaghi Koc et al. (2018) showed only about 50% of studies adopted a longitudinal approach.

Although simulation was the most commonly used methodology in Canadian studies (46.6%), it was closely followed by observational methods (44.2%). Experimental approaches accounted for 9.3% of studies. This general pattern aligns with global trends. The study conducted by Bartesaghi Koc et al. (2018) found that 71% of studies utilized simulation approaches, compared to 69% for observational methods and 20% for experimental approaches. It is worth mentioning that these numbers do not add up to 100%, since several studies used more than one approach.

Slightly over half of the Canadian studies using simulation methods (55%) validated their findings. We argue that validation should be a standard practice in simulation-based studies, as there is no universal model applicable to all urban settings. Models developed for specific cities cannot necessarily be applied directly to other cities with different climatic, geographic, and morphological conditions. Therefore, validating and calibrating models borrowed from other contexts is essential. This approach would enhance understanding of model suitability and accuracy, ensuring that findings are reliable and applicable across diverse urban environments.

A significant gap we observed was that among the 43 studies, only three linked UGBI's cooling impacts to specific health outcomes. This gap is particularly important, as public health and well-being are the ultimate goals of UHI mitigation studies and urban policy interventions. Integrating health indicators into research frameworks of UHI studies would provide policymakers and planners with stronger justification for investing in the implementation and expansion of UGBI as a climate adaptation strategy.

Lastly, although we sought to be inclusive in selecting relevant keywords and aimed to capture as much of the literature as possible, we acknowledge that our list of keywords was neither exhaustive nor comprehensive. For instance, incorporating the names of major cities in each province, abbreviated provincial names, or a more extensive list of specific GI and BI terms might have yielded additional papers. Moreover, restricting our search to scientific articles published in English excluded valuable scholarship written in French or contained in grey literature.

That said, the purpose of this study was to provide a broad scan of the Canadian evidence on the cooling benefits of UGBI, to identify general patterns, and to highlight gaps in the literature. We strongly encourage future studies to expand their search criteria and, given that there is now sufficient Canadian evidence, to consider conducting meta-analyses.

We also recognize that research on heat mitigation by UGBI spans multiple disciplines, including urban ecology, urban forestry, urban planning, and urban climatology. Each of these fields has developed its own terminology–some overlapping, others distinct. Additionally, certain keywords are context-dependent. For example, what is referred to as a "green roof" in one country may be termed "skyrise greenery", "eco-roof", or "living roof" elsewhere. These considerations should be taken into account by future research.

5. Conclusion

This systematic review is the first to comprehensively synthesize the thermal regulation impacts of UGBI in Canadian urban areas, addressing a major gap regarding cold climate cities in the global literature. It should be highlighted that an important limitation of this study was the exclusion of literature published in French.

Our analysis of 43 studies reveals interesting patterns in the existing evidence and highlights areas for future research. Most of what is currently known about UGBI's cooling effects in Canada is drawn from major urban centres (Toronto, Vancouver, and Montreal), particularly in Central Canada. While the literature has grown substantially over time, it is geographically and thematically uneven. GI—especially trees and parks—was shown to provide the greatest cooling benefits, yet smaller cities, Atlantic Canada, BI, and hybrid GI–BI systems remain underrepresented. Emergent properties that are more immediately relevant to public policy, namely health-related outcomes, are also rarely directly examined.

The predominance of micro-scale studies offers valuable insight at the human scale, but underscores the need for more multi-scalar approaches, especially as scale appears to strongly influence outcomes. The focus on abundance-based metrics over configurational or functional attributes indicates another gap in the literature. As urbanization intensifies and space becomes limited, maximizing UGBI's cooling benefit will require exploring more efficient strategies—such as selecting tree species with higher cooling capacity or optimizing spatial configurations (e.g., connected vs. fragmented UGBI patches).

Although methodological inconsistencies limit direct comparisons of cooling magnitudes, some general patterns emerged: cooling effects were greater when measured using MRT and LST than air temperature, and more pronounced during the day. Parks showed the highest potential for cooling, yet only one study examined them as a distinct ecosystem.

Expanding research to include diverse climate zones, urban sizes, and underexplored UGBI types and attributes—while adopting multi-scale approaches—will be essential to improving our understanding of UGBI's cooling ability and supporting more climate-resilient cities.

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Supplementary material

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