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Review

Nature-Based Solutions (NBSs) to Mitigate Urban Heat Island (UHI) Effects in Canadian Cities

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Abstract: Canada is warming at double the rate of the global average caused in part to a fast-growing population and large land transformations, where urban surfaces contribute significantly to the urban heat island (UHI) phenomenon. The federal government released the strengthened climate plan in 2020, which emphasizes using nature-based solutions (NBSs) to combat the effects of UHI phenomenon. Here, the effects of two NBSs techniques are reviewed and analysed: increasing surface greenery/vegetation (ISG) and increasing surface reflectivity (ISR). Policymakers have the challenge of selecting appropriate NBSs to meet a wide range of objectives within the urban environment and Canadian-specific knowledge of how NBSs can perform at various scales is lacking. As such, this state-of-the-art review intends to provide a snapshot of the current understanding of the benefits and risks associated with the implantation of NBSs in urban spaces as well as a review of the current techniques used to model, and evaluate the potential effectiveness of UHI under evolving climate conditions. Thus, if NBSs are to be adopted to mitigate UHI effects and extreme summertime temperatures in Canadian municipalities, an integrated, comprehensive analysis of their contributions is needed. As such, developing methods to quantify and evaluate NBSs' performance and tools for the effective implementation of NBSs are required.

Keywords: nature-based solutions (NBSs); urban heat island (UHI); increased surface reflectivity (ISR); increased surface greenery (ISG); buildings and urban infrastructure

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1. Introduction

Due in part to a rapidly growing population and extensive land transformation, urban surfaces have caused Canada to warm at double the rate of the global average [1]. This is of particular concern in cold-climate cities where heat-vulnerable populations may not be able to adapt to rising temperatures or cooling infrastructure may not be implemented. Through climate change and the UHI effect, the energy balance of urban environments are being altered, resulting in periods of decreased pedestrian thermal comfort. In addition, anthropogenic heat emissions directly impact the energy input to urban environments [2,3]. These additional heat sources can contribute to a feedback loop where increased outdoor temperatures lead to increased cooling loads and peak energy demand used to maintain indoor thermal comfort. Increased outdoor temperatures can also affect the population, from loss of urban environmental quality to increased risk of heat-related mortality and morbidity [1]. The health impacts of rising urban temperatures are being observed across Canada; an estimated 156 people perished in 2009 over an eight day heat wave in British Columbia, and an estimated 280 deaths over five days in 2010 across Quebec [1]. The strengthened climate plan released by the federal government, emphasizes the use of NBSs as opposed to mechanical air conditioning to combat the effects of the UHI phenomenon.

Leveraging synergies of nature within the built environment, NBSs are an approach that Canadian municipalities can take as climate mitigation and adaptation strategies. NBSs are defined as "solutions to societal challenges that are inspired and supported by nature, which are cost-effective, while simultaneously providing environmental, social and economic benefits to help build resilience" [4]. NBSs may contain design elements that mimic, enhance, conserve, or support nature in order to achieve one or more desired ecosystem services [1,5]. NBSs can take the form of increased surface greenery/vegetation (ISG) including green roofs, urban forests, and vegetated vertical surfaces or increasing surface reflectivity (ISR) including reflective or cool infrastructure. NBSs can reduce building energy use and resulting carbon emissions, moderate the microclimate, and lessen the impact of extreme heat events.

Urban planners and policymakers have the challenge of selecting appropriate NBSs in order to meet a wide range of objectives within the urban environment. Challenges include, determining how to balance the synergies and trade-offs that are achieved from NBSs, avoiding the use of heuristics when selecting useful strategies to implement, and obtaining the skills required to design, build, and maintain the selected strategy [5]. As such, this state-of-the-art review presents a current understanding of the benefits and risks associated with the implementation of NBSs on the energy balance of: urban agglomerations, buildings and occupant thermal comfort, and the outdoor environment and pedestrian thermal comfort in cold-climate cities as well as reviewing the current techniques used to model and evaluate the potential effectiveness of UHI under evolving climate conditions.

2. The Urban Heat Island (UHI) and Climate Change

2.1. Overview of UHI and the Energy Balance of Urban Agglomerations

Elevated temperature in urban areas relative to their rural surroundings is known as the urban heat island (UHI) effect and was first introduced by Howard in 1818 [6]. The two most commonly analysed types of UHIs are surface UHIs and air temperature UHIs [1]. Surface UHIs refer to elevated temperatures recorded on urban surfaces such as roads, sidewalks, and building envelopes. While air temperature UHIs refer to the elevated ambient temperatures found within the urban environment caused by the release of thermal energy from urban surfaces and anthropogenic sources (e.g., air conditioning, transportation, etc.). As the resulting effects from the two UHIs are so interconnected on thermal comfort and building performance, this study uses UHI to signify both, unless specific reference to one or the other is made.

The UHI effect is mainly caused by a high density of buildings and impervious materials which significantly affects the energy balance within a city [7]. Typically building materials such as concrete and asphalt have a lower albedo compared with vegetation [8], meaning that these materials only reflect a minor portion of the incoming radiation compared with vegetation. Urban materials also tend to have higher heat capacity compared with vegetation, and because of this, can store more of the absorbed solar energy [9]. In addition, current urban landscapes leave little room for vegetation, which reduces the amount of heat dissipation that would otherwise be achieved through evapotranspiration [10,11]. Through all these factors, significantly more thermal energy is absorbed and retained within the urban environment, causing temperatures to increase faster compared with more natural areas [12].

Not only do urban materials contribute to the UHI effect, but the function and form of the urban space can contribute to the total energy budget and dictate when the greatest effects of the UHI will be experienced. Urban function considers how the urban space is used from residential to commercial, with form defining the shape and quantity of the structures. The function of an area can bring unique occupancy levels, occupancy schedules, and energy use requirements, where heat emissions from sources such as industry and air conditioning directly impact the energy budget within an urban environment [2,3]. These additional anthropogenic sources of heat can create a feedback cycle where increased outdoor temperatures lead to increased cooling load and peak energy demand used to maintain indoor thermal comfort. The urban form is defined by characteristics such as the height-to-width ratios of structures, building densities, and the resulting sky view factor (SVF). The urban form also dictates the complex interactions between elements in a city, such as the reflection of radiation, transfer, and storage of heat, even affecting wind speed, wind direction, cloud cover, and precipitation [13].

When analysing the effects to humans subjected to heightened urban temperatures, two frames of reference are generally used. The first frame of reference considers the energy balance of buildings and how this affects occupant thermal comfort, whereas the second frame of reference considers the energy balance of the urban environment and the resulting effects on thermal comfort of pedestrians. Using both frames of reference, the following sections present an overview of how UHI affects buildings, building occupants and the pedestrians within the urban environment.

2.2. UHI Effects on Buildings and on Occupant Thermal Comfort

With rising urban temperatures, and extreme heat events becoming more prevalent, the likelihood that overheating events will occur within buildings increases. Overheating events are considered periods where elevated indoor temperatures trigger a physiological response and the action of building occupants to restore thermal comfort [14]. Overheating is generally found in free-running or naturally ventilated buildings, buildings with limited capacity or intermittent use of air conditioning, and buildings that experience extended periods of power outages or HVAC failure. In these buildings, the indoor conditions are a direct result of the outdoor conditions and the responses of the building envelope and structure. Persisting warm/hot indoor conditions over several days may strain the human physiological system and therefore lead to serious health injuries or even death, particularly for those vulnerable to heat, including the elderly, sick, and children [1]. To reduce such effects on occupant health, buildings should be designed, retrofitted, and operated to mitigate the risk of overheating under such extreme climatic conditions.

As building codes advance, new builds have a better chance of maintaining occupant thermal comfort compared with existing buildings which may not have the best insulation levels or air conditioning systems [15]. As such, studies should first focus on finding solutions to maintain occupant thermal comfort within our existing building stock. Although designing facades to reduce the effects of UHI in a warming climate is important, creating sustainable façades that account for both occupant thermal comfort and reducing building energy loads must be considered. To achieve this, designers should first make use of the passive design strategies as listed in Table 1, as much as possible before adding additional cooling solutions [16].

2.3. UHI Effects on Outdoor Environment and Pedestrian Thermal Comfort

An outdoor extreme heat event is defined as continuous elevated outdoor temperatures that affect the comfort of people who are directly exposed to such heat events over at least one day [14]. Both the form and function of the urban environment can affect the perceived thermal comfort of those outdoors, and the selection of UHI mitigation strategies should be made with both time of use and location in mind. Considerations may include planning for open space within a city while taking the SVF into consideration. The inclusion of open space within the urban environment can help ensure that wind speeds are maintained and that both pollution and emitted heat can be removed from the city. Residential areas can be designed with larger SVF's to allow for cooling at night, but warmer temperatures during the day, while areas with high daytime occupancy may wish to lower SVF's to create urban canyons and lower street level temperatures during the day but allow warmer temperatures at night. Height-to-width ratios of 0.5 with a building density of around 0.3 are being suggested as a geometry ratio to reduce UHI effects [17]. When considering which UHI mitigation solution to analyse in each urban form, the following characteristics, as presented in Table 2, should be considered.

Table 1. Passive design strategies for sustainable building design based on climate.

Climate Type	Design Strategies
Heating-dominated	• Orientation for solar collection for passive heating; • Using thermal mass for heat storage in the wall; • Improved insulation and air tightness levels; • Use of daylighting.
Mixed	• Selective solar control to protect façade from solar gains in summer and to collect heat during winter; • Use of natural ventilation where possible; • Use of daylighting.
Cooling-dominated	• Protecting the façade from direct solar radiation for passive cooling; • Use of natural ventilation where possible; • Use of daylighting, while using shading devices and light shelves; • Make use of well-insulated opaque façade elements.

Table 2. Characteristics to consider in different urban forms.

Building Type	Characteristics
Residential, single detached or row-houses	• Some property and space surrounding home; • Wider range of roof angles; • Primary occupancy at night.
Mid-rise urban canopy	• Potential for wider range of occupancy hours; • More exposed wall surface compared with residential.
High-rise urban canopy	• Potential for wider range of occupancy hours; • More exposed wall surface area compared with roof area; • Potential for deep urban canyons and low SVF.

The impacts of UHI will be exacerbated in the future due in part to global warming, urban expansion, and increased anthropogenic heat fluxes, all of which will cause a larger gradient to form between the urban center and surrounding rural areas [18,19]. Consequently, cooling energy consumption [20,21] and heat-related mortality [22,23] are both generally expected to increase because of elevated temperatures.

To combat these issues, many strategies have been proposed to mitigate the UHI effect. The next section provides an overview of the many proposed strategies, specifically focusing on ISG to provide cooling through shading and evapotranspiration [24], and ISR to mitigate UHI effects [25].

3. Approaches to Mitigate the UHI Effect

Many strategies have been proposed to mitigate the negative effects that climate change and the UHI effect have on buildings, building occupants, and pedestrian thermal comfort. However, to effectively compare UHI mitigation strategies, comparisons must be made using the same metric or frame of reference. This is especially important considering the fact that many mitigation strategies have the potential to reduce both surface and air UHI effects. Mitigation strategies that modify the boundary conditions (convective and radiative loads) that act upon a structure or individual are said to have “direct effects”, whereas strategies that modify the ambient conditions surrounding a structure or individual (such as temperature or humidity), that, in turn, affects its energy balance are said to have “indirect effects” [26]. The following section of this study presents the direct and indirect effects that ISG and ISR have on the energy balance of urban agglomerations, the energy balance of buildings and their occupants, and the energy balance of the outdoor environment and pedestrians.

3.1. Increased Surface Greenery/Vegetation (ISG)

In general, the shading from leaves provides the main cooling effect achieved by vegetation, where solar radiation that would otherwise be incident on a surface, is blocked from reaching the surface below [27]. Additional cooling is achieved when radiation absorbed by vegetation is dissipated through transpiration from the leaves and/or evaporation from the growing medium. The surface cooling resulting from evapotranspiration is usually less than that achieved from shading; however, the process is effective at reducing ambient air temperatures on a larger scale [28]. Urban vegetation can also alter the convective boundary condition by creating a wind barrier next to a surface. Many surfaces can benefit from added vegetation; however, the urban environment can be a harsh place for plants to grow and survive. As such, unique strategies have been developed to increase the likelihood that vegetation will survive in both horizontal and vertical environments. In addition to their cooling abilities urban vegetation can bring multiple social, economic, and environmental benefits to the urban environment.

3.1.1. Roofs

Green roofs, often referred to as vegetated roofs, eco-roofs (due to ecological benefits), roof gardens, or living roofs, are a system of vegetation planted within a growth medium (substrate). A typical green roof configuration with all the components can be seen in Figure 1. The selection of materials and configuration of each of the components within a green roof dictate how a system responds to local climatic conditions and precipitation events. The structural composition of green roofs provides a convenient way to classify these systems, where green roofs can be classified into intensive, semi-intensive, and extensive categories (Figure 1).

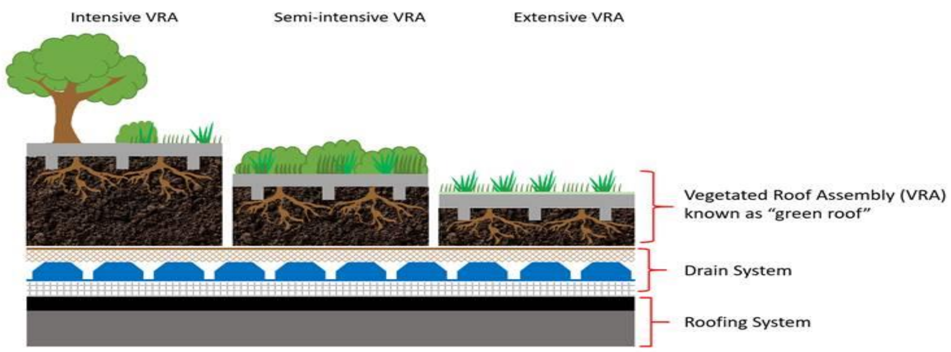

Figure 1. Typical components and configurations of green roofs, based on [29].

Intensive green roofs can accommodate a wide variety of plant species, from grasses and small shrubs to trees, supported by a substrate depth normally greater than 25 cm. Maintenance is required for fertilization, irrigation, and plant accommodation. In comparison, extensive green roofs are constructed with plant species such as herbs and grasses, set on a substrate layer between 8 and 15 cm in depth, requiring lower maintenance and less water. Semi-intensive green roofs are characterized by small plants such as shrubs and grass, supported by a layer of substrate typically varying between 15 and 25 cm in depth. They require more maintenance than an extensive green roof, but less maintenance compared with intensive green roof systems. Of the three types, extensive green roofs are the most common as they are lighter and therefore more easily installed on roofs compared with the other types of green roof. In addition, these systems do not require a dedicated irrigation system to be installed, thus requiring less capital and maintenance compared with other vegetated roof systems.

3.1.2. Facades

Depending on the urban form, vegetated façades can provide a greater cooling potential compared with vegetated roofs. In cases where buildings have large areas of exposed façade, Vertical Greenery Systems (VGS) can provide cooling solutions to multiple floors, whereas vegetated roofing strategies may only cool the spaces directly below the roof [30]. There are many different greenery systems available for vertical surfaces, and each system has its advantages and disadvantages. VGS can be classified into three categories based on their construction and cooling benefits [30]. The three categories include: Green Barrier Systems (GBSs); Green Coating Systems (GCSs); and Green Walls (GWs) (see Figure 2). As the three categories have different constructions, their effects on building energy use, occupant thermal comfort, or UHI reduction vary.

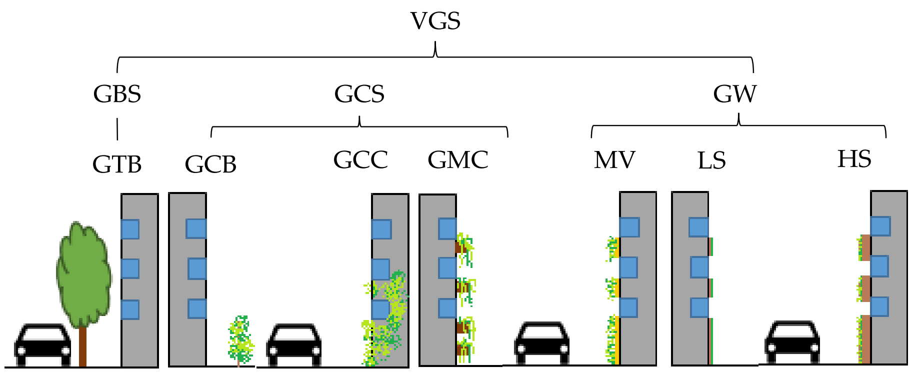

Figure 2. Vertical greenery system classification, based on [30].

The GCS category includes Green Climbing Barrier (GCB) and Green Climbing Coating (GCC) systems where plants grow up from the ground [28], or Green Modular Coating (GMC) systems in which the plants grow from containers attached to the façade [30]. Typically, GCSs alter the thermal performance of a building by shading incoming solar radiation and creating a wind barrier that alters the exterior convective coefficients. Plants used in GCC and GCB systems climb a façade by directly attaching themselves to a surface or climbing a freestanding support structure or a lightweight support system attached to the structure [28]. As GCB and GCC requires little to no support, these vegetated systems can be implemented with little capital compared with other vertical greenery systems and are suited to retrofit applications. An added benefit of GCB and GCC systems is that the vegetation can provide greater shading coverage at a faster rate compared with trees which may take between 10 and 30 years to reach their cooling potential [31]. However, several years of growth may be required in order to reach sufficient levels of coverage [28]. Alternately, GMC systems utilize planters of growing medium suspended across the façade. With increased root placement options, GMC systems can cover more of a façade, compared with plants growing from the ground. During the heating season, VGS can act as a wind barrier to decrease heating loads; however, shading can increase heating loads up to 28%, if the plants remain evergreen throughout the winter (i.e., plants do not shed their leaves), [28]. In a mixed or heating-dominated climate such as Canada, the selection of deciduous plants may provide benefits in both cooling and heating seasons. However, in Canada this may change should the climates become cooling dominated.

Compared with GBSs and GCSs, where plants are grown from the ground or within elevated planters, GW systems have plants growing from a medium suspended in the vertical plane. GW systems have the potential to provide greater levels of cooling compared with GBSs and GCSs due to increased levels of transpiration from the plants and evaporative cooling from the growth medium. The growing medium in which the plants are rooted allows for a convenient way to group and classify the different GW systems as seen in Figure 2. The Mur Vegetal (MV) system has plants rooted, irrigated, and fed from an inorganic membrane, where both the Light System (LS) and Heavy System (HS) have plants rooted in and fed from an organic growing medium. The LS and HS differ from one another based on the depth of the growing medium, where LS typically have growing material less than 15 cm in depth [30]. In addition to shading and evaporative cooling, the growth medium can also provide thermal mass and thermal resistance to a façade. However, the thermal resistance of the growth medium cannot be considered a substitute for conventional building insulation [28].

To maintain the health of plants and the cooling potential of GWs, irrigation must be provided. In the case of GBSs and some GCSs, irrigation can be provided from the ground; however, green walls require irrigation of the entire vertical surface. Despite the potential drought tolerance of plants, in order to achieve the optimum cooling potential from GW systems, a sufficient to high level of irrigation is be required [32]. As plants become stressed from lack of water, their pores close and the rate of transpiration decreases. Between the plants, the growing medium, support structure, and irrigation systems; green walls can become quite heavy compared with other VGS. Because of their weight, GW systems are predominantly integrated into the façade of new construction to accommodate structural requirements.

The use of Green Tree Barrier (GTB) systems within the urban environment can provide cooling potential to both horizontal and vertical surfaces through shading and lowering the ambient air temperature through transpiration from their leaves. It is suggested that a fully grown tree could lose up to 450 L of water per day due to evapotranspiration, thus providing approximately the same level of cooling as five air conditioners [31]. With their cooling potential GTB systems can create an overall cooling effect for pedestrian thermal comfort, despite potentially reducing air speeds and increasing relative humidity [33]. By greatly increasing the amount of shading provided by trees in Montreal, Quebec, a 40 °C reducing in mean radiant temperature may be possible based on simulated results [34]. Where MRT is a metric used to quantify the amount of short- and long- wave radiation fluxes absorbed by the human body and a metric to evaluate thermal comfort on pedestrians. Through careful planning of where GTBs are planted, the ventilation achieved from wind corridors within the urban environments can be maintained.

Although the majority of cooling gained from GTBs occurs from shading during daylight hours, a small amount of transpiration can occur after the sun sets, where up to 20 h of cooling can be achieved by trees [31]. Many urban environments make use of trees to provide shading in areas where high levels of daytime occupancy are expected, where the air temperatures surrounding a row of trees could be reduced by approximately 1 °C, and where the creation of an urban park could reduce air temperatures by up to 6 °C [31]. The effects from urban trees can also be experienced beyond the immediate planted area toward the downwind environment. However, without performing unique simulations for each city, there is no real way of comparing how one strategy implemented in one location may compare to that achieved in another location.

3.2. Increased Surface Reflectivity (ISR)/Cool Systems

Typically, urban materials are darker in colour and have a higher heat capacity compared with vegetation. Because of this, urban areas tend to absorb and store more incoming solar energy compared with its surroundings. Depending on the exposed surface, the absorbed radiation is either transmitted through the façade to a conditioned space by conduction or released back to the urban environment through radiation and convection as seen in Figure 3. Cool materials are those that make use of natural cooling processes, allowing energy to be released from the urban environment [35]. Examples of cooling materials together with their cooling principles are presented in Table 3. Despite all the solutions having the potential to reduce urban surface temperatures provided in Table 3, not all solutions can reduce UHI effects. High inertia and energy harvesting solutions can achieve surface cooling through the day by storing or converting incoming energy. However, these strategies can release stored energy during the evening causing an increase in surface and surrounding air temperature. Solutions that merely shift the timing of when energy is released from the urban surface tend to work best when there is little to no evening occupancy; however, this is becoming more difficult to realise within diverse urban agglomerations. As such, only reflective and evaporative materials are discussed in this study.

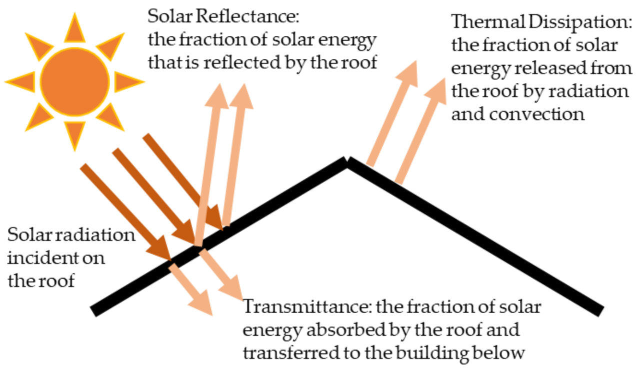

Figure 3. Schematic of roofing surface subject to incident solar energy.

Table 3. Categories of cool solutions.

Solution	Sub-Category	Cooling Principle
Reflective	-	Increased albedo.
Evaporative	Porous pavement, permeable pavement, vegetated surfaces	Release latent heat due to the evaporation of water.
High inertia	Phase-changing materials	Dampening heat transfer to and from the surface by transitioning between a solid and liquid phase of a material.
Energy harvesting	Heat exchanger	Removal of energy through liquid or gas circulated through the material.
	Photovoltaic	Photoelectric effect: is the emission of electrons from a material caused by electromagnetic radiation.
	Thermoelectric	Seebeck effect: where a temperature gradient between dissimilar electrical conductors creates a voltage difference.

3.2.1. Reflective Solutions

Compared with conventional urban materials, high-albedo materials can reduce surface and air temperatures during the day by reflecting incoming solar radiation. Typical urban materials, including asphalt and concrete have albedos in the range of 0.05–0.1 and 0.3–0.4, respectively, where the albedo of reflective surfaces tend to be greater than 0.5. The use of roofing material that reflect short-wave radiation back to the atmosphere results in a decrease in the energy budget for the roof surface and subsequent underlying structure. Based on their expected wear and rate of soiling, high-traffic urban surfaces, such as walkways or roads, will likely require more cleaning in order to maintain their reflectivity over time [36].

By switching from asphalt to concrete in both residential and high-rise areas a ground surface temperature reduction up to 7.9 °C at 12:00 pm may be possible in Toronto, Canada [17]. A drawback to using reflective materials on urban surfaces is that if not accounted for, the reflected radiation can become trapped by the urban form or unintentionally reflected onto adjacent buildings or pedestrians. The reflected energy can affect the overall energy balance of buildings and pedestrians, leading to periods where overheating and or thermal discomfort can occur [17]. In order to reduce the diffuse scattering of radiation reflected from high-albedo surfaces, the use of retro-reflective materials was proposed [37]. Retro-reflective materials are materials that can reflect radiation back along the incident direction. In a review of current retro-reflective materials, prism retro-reflective materials were found to reflect the most incoming radiation; however, due to their critical incident angle for retro-reflection, their effectiveness is limited to periods when incoming radiation is within this angle. As bead and capsule retro-reflective materials have no fixed critical angle, they may be more suited for vertical urban surfaces where the incident radiation is influenced by the sun's path. In terms of durability, the retro-reflective characteristics of prism style materials can be retained after cleaning, whereas bead and capsule systems can lose some of their reflectance over time due to surface degradation [37].

A second potential drawback to using reflective surfaces is that in some instances, high-albedo roofs can increase the energy usage during the heating season due to the reduction in absorbed radiation, often referred to as the winter heating penalty [38]. However, factors such as the sun's lower trajectory across the sky during winter and the accumulation of snow, already minimize the amount of solar energy that would be incident on a building. According to the U.S. DOE [38], in most cases, the winter heating penalty is less than the cooling energy savings. Despite this, a thorough energy and socioeconomic analysis need to be conducted for different Canadian cities [39] to determine whether this is in fact the case.

3.2.2. Evaporative Solutions

Evaporative surfaces release absorbed solar energy through the evaporation of water stored within the material. As the water turns from liquid to gas, thermal energy is absorbed from the surroundings, and the surface is cooled. In order to maintain the cooling effect, a sufficient supply of water must be present. Vegetated surfaces can store water in the plants and growing medium, whereas solid surfaces make use of water reserves. Porous pavers retain water within the cavities whereas permeable paving materials access water from a sublayer below. To a certain degree, these surfaces can be used to absorb and sequester rainwater that, in turn, can help reduce water runoff from otherwise impermeable urban surfaces. However, similar to reflective surfaces, evaporative surfaces require upkeep. In respect to porous and permeable materials, cleaning involves the removal of debris from the pores, whereas plants within the vegetated surfaces require nutrients and care. Vegetated surfaces may work well for open parks, where porous materials may be a cooling solution for areas that experience high rates of traffic.

A drawback to porous surfaces is that when the material is dry, the air within the voids can act as a thermal insulator, which can store thermal energy and prevent cooling [35]. Another concern with permeable and porous surfaces is their ability to withstand winter freeze-thaw conditions. In certain cases, trapped water can cause material failure due to their expansion and contraction as occurs from the freezing and melting process. However, this can be avoided by varying the aggregate components of the porous material [40].

4. Modelling and Forecasting Urban Climate

The urban climate has been substantially modified from its natural state by changes in the physical characteristics of the landscape and the effects associated with a concentrated population. As such, UHI effects will be exacerbated in the future, where global warming, urban expansion, and increasing anthropogenic heat fluxes will result in the formation of a larger thermal gradient between urban centers and surrounding rural areas [18,19]. Consequently, the effects of climate change on the UHI have been extensively studied, where cooling energy consumption [20,21] and heat-related mortality [22,23] has generally been seen to increase given the elevated temperatures achieved within urban agglomerations during extreme heat events. To combat these issues, many strategies have been proposed to help mitigate UHI effects by reducing the overall temperature in urban environments including ISG and ISR.

In order to analyse the potential effectiveness of these UHI mitigation strategies within urban agglomerations, simulations of the urban climate, especially under evolving climate conditions, will need to be conducted. There are many approaches that can be taken to model the climate in and across urban agglomerations; however, the spatial scale of the climate model is a critical aspect to consider, especially when high-resolution climate data in both time and space is required [41].

4.1. At Regional Scales

On the largest scale, global climate models (GCMs) are commonly used to provide projections of climate change over longer time periods [42,43]. These numerical models simulate the major processes and interactions that govern the climate across a spatial resolution of a few hundred kilometers and are useful in studying various degrees of climate change forced by different representative concentration pathways on a global scale [44]. However, urban areas and the mechanisms that cause UHI cannot be simulated in these models because the spatial resolution is too coarse. Despite attempts to incorporate urban canyon models into GCMs [45,46], the scale of these models limits the usefulness of the resulting UHI studies. Thus, it is necessary to downscale the coarse resolution of GCMs to a finer spatial resolution through regional climate models (RCMs).

To improve the output from climate projections to a spatial and temporal scale more appropriate for urban use, statistical, dynamical, and statistical-dynamical downscaling (SDD) methods have been proposed. These methodologies are quite versatile as they can be applied to a large set of climate projections, including different greenhouse gas emission scenarios and long time periods; allowing model and scenario uncertainties to be accounted for. Additionally, these models allow researchers to model regional climates and generate data applicable to entire cities.

Due to the fact that statistical downscaling approaches are limited to historical observations and cannot account for the potential variability in future climates, many researchers have begun to use fully dynamic models which use GCM projections as boundary conditions to reproduce the local climate at a higher resolution [47]. Dynamical downscaling adopts similar physical equations and parameterizations as GCMs but employs them at a much higher spatial resolution. In addition to the higher resolution, RCMs need to explicitly include representations of urban areas and processes to simulate the urban climate accurately.

Recent advances in climate science and climate models such as the Weather Research and Forecasting (WRF) model allows researchers to downscale data to a resolution of 1km with relative accuracy, accounting for urban parameterizations and land use. As such, different urban parameterization schemes and local land cover data and their effects on the local UHI effect can be analysed [48,49]. Additionally, the effects of climate change and further development in urban areas can be studied through dynamic modelling, where global climate models following a climate change scenario can be dynamically downscaled to estimate what fraction of the increase in UHI intensity can be attributed to global warming or to urbanization [50].

More recent experiments have coupled Single Layer Urban Canopy Models (SLUCM) [51] with Weather Research and Forecasting (WRF) models, resulting in numerous studies validating the accuracy of such a model compared with observational data in various climates [52–54]. Although SLUCMs add much-needed complexity to the climate model, they only represent general aspects of the urban environment, and do not take microscale characteristics such as individual buildings into consideration [55]. Multi-level UCMs provide more details about the urban environment and can divide the building facades into a number of patches, each with their own parameters and energy exchanges modelled [56]. Multi-level UCMs are useful in studying the interactions within cities, but their complexity comes at a high computational cost. Studies have found that simpler models are able to produce reliable climate simulations [57]. However, in order to evaluate the magnitude of UHI, it is necessary to apply multi-level UCMs to account for turbulence and multi-reflections within the urban canopy [58].

4.2. At Neighborhood Scales

In addition to downscaled climate data at a regional scale, the effect of UHI can also be analysed down to a sub-meter scale, using detailed computational fluid dynamics

(CFD) models. These CFD models allow researchers to resolve physical phenomena in detail and provide the capacity to reproduce details of the microclimate in a city district, neighborhood, or street canyon, as opposed to the general city-wide effects considered by regional modelling. CFD models can also be coupled with the solar radiation models, heat and moisture conduction, and transport models to analyse the physical environment within a city.

One of the challenges for microclimate modelling is that urban climate models are normally oversimplified [59]. As such, the computational domain should be carefully defined using the best practice guidelines from the Architectural Institute of Japan (AIJ) [60,61] and European Cooperation in Science and Technology (COST) [62,63] to reduce oversimplification. It is also necessary to consider the various environmental elements in the study area, such as anthropogenic heat emission [64,65], vegetation (green infrastructure) [66–68], water bodies (blue infrastructure) [69,70], and expected precipitation levels [71–74]. For NBSs to be analysed as a means of UHI mitigation, the simulation of natural infrastructure needs to be considered, and is a major concern in many studies. The geometry of the plants is always hard to obtain, and the multi-physical process of the plants is very complicated. Even though theoretical and empirical models for plants have been developed by multiple studies, they are not easily implemented in common CFD programs. In addition, studies that attempt to quantify the performance of NBSs usually fail to mention or describe in sufficient detail the parameters that influence the NBSs that would allow others to make quantitative conclusions as to how specific strategies would perform under different climate conditions [28,75].

Performing whole building energy simulations are the most popular option to analyse the potential of overheating in buildings. In these models, contributions from multiple building systems, material properties, building utilities, and the occupants' schedule, can be considered comprehensively. Moreover, these models can be coupled with urban-scale CFD models to determine the impact of UHI and climate change scenarios on buildings. In addition to coupling with building energy models, CFD models can also take the boundary conditions from the Regional Climate Modelling data and simulate the sub-grid environment.

Resolving the interactions between global and urban climate is necessary to generate information on a scale that is relevant to UHI. The ability to produce detailed information regarding global climate change within urban areas will aid practitioners in implementing UHI mitigation strategies. Previous studies have combined large-scale climate models with microscale CFD models to study the local climate in extremely high resolution [76]. However, statistical downscaling approaches are faced with limitations as they can only be calculated based on historical observations and therefore cannot account for the potential variability in future climates [77]. Consequently, to generate data necessary to study UHI and climate change, WRF should be used to dynamically downscale climate projections suitable for building simulations [78].

4.3. Current Challenges Associated with Generating Urban Climate Forecasts

One of the major challenges moving forward is developing approaches to assess the effects of UHI and NBSs at climatological time frames of sufficient breadth such as the now recommended 20 to 30 year length. The studies reviewed before show that majority of previous studies have been performed over several days of extreme weather events or typical summer weather. This is because despite advances in climate modelling, undertaking high resolution regional climate simulations at high spatial resolutions (<4 km) over long time periods is computationally expensive. Long-term climate projections with NBS–UHI effects will allow us to evaluate their impact on urban climate, air quality, human thermal comfort and health, and consequently the effects on indoor building environments.

As such, conducting multi-decadal urban climate simulation at high resolutions, from multiple global climate models, for multiple greenhouse emission scenarios, for different cities, remain a daunting task. At the same time, long-term urban climate projections incorporating the effects of urban form and NBSs at climatological timeframes are necessary to evaluate the long-term risk of overheating in cities accurately. Therefore, there is a need to use statistical-dynamical methods that combine short-term high-resolution urban climate simulations with advanced statistical and data-driven modelling techniques to develop long-term urban climate projections incorporating the effects of urban form and NBSs [79,80].

5. Future Steps

Climate change will only exacerbate the existing UHI conditions if mitigation strategies are not diligently implemented across cities. Modelling studies have shown that the UHI effect in many Canadian cities is expected to increase as a consequence of increasing urbanization and anthropogenic greenhouse gas emissions [48]. ISR and ISG can help to alleviate the UHI, but the degree of their effectiveness is highly dependent on the specific conditions of the city in question. Consequently, the results from one city ought not to be generalized to another. Therefore, to appreciate the impact that NBSs may have on mitigating UHI effects across Canada, it is necessary to thoroughly examine those strategies that may best be suited for each unique climate and urban environment of interest.

There is growing interest from municipalities, building owners, stakeholders, insurers, and building communities to use the vast surface of buildings to mitigate the adverse impacts of UHI, where urban planners and policymakers have the challenge of selecting appropriate NBSs to meet a wide range of objectives within the urban environment. Challenges include but are not limited to: determining how to balance the synergies and trade-offs that are achieved from NBSs; avoiding heuristics and mental shortcutting when selecting strategies to implement; and obtaining the skills required to design, build, and maintain the selected strategy. As such, if NBSs are to be adopted as an effective strategy to reduce carbon emissions and mitigate UHI effects and extreme summertime temperatures in Canadian municipalities, an integrated and comprehensive analysis of their contributions is needed. Canadian specific knowledge of how NBSs will interact with existing and planned buildings and at various scales is lacking. Specifically, methods to quantify and evaluate NBSs' performance and tools for their effective implementation are required.

To fill these knowledge gaps, advanced models will need to be developed to enable the generation of multi-scale urban microclimates with integrated estimation of carbon emissions and sequestration from urban communities in response to current and future climates. Measurements carried out in community-scale projects for model validation and performance evaluation will also be required. Validated models will then be used to assess the performance of UGIs designed for archetype buildings and communities that are adaptive and effective to their physical, social, and economic environment over their life cycle to optimize NBSs. From this research, design suggestions, policy guidelines, and web-based decision-making tools will be developed to enable policymakers and professionals to make informed decisions and implement these solutions with confidence across Canadian communities contributing to the goal of net-zero emissions in Canada by 2050.

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