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Nature Based Solutions to Mitigate Urban Heat Island Effects in Canadian Cities: Literature Review

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Executive Summary

Canada is warming at double the rate of the global average caused in part by a fast-growing population and extensive land transformations, where buildings significantly contribute to the urban heat island (UHI) phenomenon (Jandaghian & Berardi, 2020a). The federal government released a strengthened climate plan in 2020, which emphasizes using Nature Based Solutions (NBS) to combat the effects of the UHI. Accordingly, two NBS techniques are proposed: increasing surface reflectivity (ISR) of horizontal building surfaces (e.g., roofs) and increasing surface greenery/vegetation (ISG) on both vertical and horizontal building envelope components (Berardi, Jandaghian, & Graham, 2020). Figure 1 shows the use of ISR and ISG on rooftops in the City of Toronto, ON.

Figure 1: Examples of ISR and ISG on rooftops – Toronto, ON. Imagery ©2023 CNES/ Airbus, First Base Solutions, Maxar Technologies, Map data ©2023

ISR and ISG lead to a decrease in air temperature and temperature-dependent atmospheric chemistry that controls photochemical reaction rate of ozone production (Jandaghian & Akbari, 2019). Direct benefits of NBS on the built environment include, decreasing cooling loads of buildings in summertime, reducing the rate of heat-related mortality (HRM), and improving urban climate and air quality (Jandaghian & Akbari, 2021). In addition, the implementation of NBS generates a range of co-benefits, such as carbon sequestration, water purification, green growth, biodiversity of habitats, recreational facilities, mental well-being and job creation. Given the apparent accelerating pace of climate change and the need to improve the resilience of buildings and communities, greater efforts and investment are now required to facilitate the uptake of NBS for urban centers located in Canada that are intent on mitigating the effects of UHI in the future.

This literature review presents a snapshot of the current understanding of NBS and how they affect building performance, the simulations conducted to evaluate NBS and UHI effects and modeling approaches used, the primary knowledge gaps as well as the future steps needed to reduce the effects of UHI in urban agglomerations across Canada. Accordingly, the next section provides a condensed summary of previous research on ISR and ISG. Then the modeling approach is described followed by a road map to assist policymakers to take action against the adverse impacts of UHI in cities.

The road map consists of; I) providing approaches to reduce the UHI influences with respect to the implications of warming/changing climate, urban canopy/landscape characteristics and building design; II) development of the best management practices (BMP) for NBS – UHI for Canadian communities; and III) development of guidelines for the design of NBS–UHI solutions to mitigate UHI in accordance with Canadian design climatic load.

1 Introduction

Canada is warming at the double the global average rate caused in part by a fast-growing population and extensive land transformations, with urban surfaces contributing to the urban heat island (UHI) phenomenon. The federal government released a strengthened climate plan in 2020, which emphasizes using Nature Based Solutions (NBS) to combat the effects of the UHI phenomenon.

Harnessing the potential of nature within the built environment, NBS provide an option for Canadian cities to reduce the impact climate change and UHI have on urban agglomerations. NBS are defined as "solutions to societal challenges that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience" (Raymond, et al., 2017). NBS often make use of design elements that mimic, enhance, conserve or support nature in order to achieve one of more desired ecosystem services (Health Canada, 2020; Croeser, Garrard, Sharma, Ossola, & Bekessy, 2021). NBS can take the form of increasing surface greenery and vegetation (ISG) including trees, vegetation, green roofs, and vegetated facades and increasing surface reflectivity (ISR) including reflective or cool infrastructure. NBS can reduce urban CO_2 emissions and support necessary climate change adaptations. While promising an array of cost-effective options for municipal climate action, these NBS provide many public policy co-benefits, such as enhanced urban livability. As well, and though there has been research in the area of holistic urban design through the use of urban modelling software tools, additional work is needed for further developing such tools to permit adapting to and mitigating the effects of climate change in urban agglomerations.

Research that focuses on NBS and UGI for climate-resilient buildings and communities would include research from those involved in:

- Urban landscape architecture and planning;
- Urban development and community level modeling of building energy use and carbon emission calculations of future climate scenarios;
- Urban carbon cycle modeling for carbon sequestration calculations;
- Urban forestry, and; Urban tree mapping growth forecasting;
- Human environmental interactions;
- Urban policy making;
- Urban microclimate modeling;
- Building operations, energy efficiency and indoor environment;
- Building thermal and hygrothermal response and energy use simulation.

What research might be completed in respect to gaining an understanding of how NBS might provide UGI solutions to sequester carbon, mitigate urban heat island effects and reduce GHG emissions? How might such research support the development of NBS and UGI best practices as might be offered in guidelines that enable professionals and policymakers to implement these solutions with confidence across Canada?

This might include, for example:

- Quantifying the contribution of existing and future NBS and UGI to sequester carbon, reduce carbon emission from buildings, and moderate the urban microclimate to reduce urban heat island effects;
- Demonstrating the approach in developing NBS and UGI solutions for carbon-neutral, climate-resilient buildings and communities through simulations that consider current and projected climate and development scenarios.

In this report, the effects of two NBS techniques are reviewed and analyzed for buildings: increasing surface greenery and vegetation (ISG) and increasing surface reflectivity (ISR) on both vertical and horizontal building envelope components. As such, this state-of-the-art review presents a current understanding of the benefits and risks associated with the implementation of NBS on the balance of thermal energy into and out of: urban agglomerations, buildings (and resulting occupant thermal comfort), and outdoor environment (and resulting pedestrian thermal comfort), through a review of current literature, previous modeling, and experimental studies.

2 Climate and the UHI effect on urban agglomerations

Anthropogenic induced climate change is one of the greatest challenges that society will face. Around the world, the challenges associated with 1°C of global warming above pre-industrial levels are already being felt (Revi, et al., 2014) in the form of increased intensity, frequency, and duration of extreme weather events such as warm spells and heat events, drought, heavy rainfall, storm surges, and sea-level rise (Hunt & Watkiss, 2010; Solomon, et al., 2007; Field, et al., 2012). Even if international efforts to limit global warming to 1.5°C are met according to the 2015 Paris Agreement, there will still be significant ramifications to the climate that will require considerable adaption (Masson-Delmotte, et al., 2018). Consequently, substantial changes to the urban environment are required to support a growing urbanized population, which is projected to reach 60% (5 billion) of the world's population by 2030, according to the (Population Reference Bureau, 2005). With an expanding urban population facing climate change, the need to address the urban heat island effect (UHI) is of increasing concern for many cities around the world.

2.1 Urban climate and climate change

The urban climate has been substantially modified from its natural state by changes to the physical characteristics of the landscape and from effects associated with a concentrated population. Elevated temperatures in urban areas compared to their rural surroundings is known as the urban heat island (UHI) effect, where the concept of UHI was first introduced by Howard (1818), who recorded warmer air temperature in a city compared to its surrounding countryside. The urban topography is commonly characterized by higher building densities, and a greater concentration of impervious and dark coloured materials (Oke, Mills, Christen, & Voogt, 2017). These features often lead to warmer temperatures, altered winds, modified cloud cover and precipitation events. Oke T. R. (1981) identified six factors that affect the how much thermal energy is retained with a city, and thus contribute to UHI. These factors include anthropogenic heat, impervious surfaces, thermal properties of materials, surface geometry, urban roughness, and air pollution.

Common building materials such as concrete and asphalt have a comparatively lower albedo than vegetation (Taha, Akbari, Rosenfeld, & Huang, 1988), meaning that only a minor portion of the incoming radiation will be reflected, and more heat will be absorbed. Where an increase in absorbed thermal energy will cause temperatures to increase faster in-built environments (Kolokotroni & Giridharan, 2008). The heating process is further intensified as these building materials have the capacity to store twice as much thermal energy as natural elements (Christen & Vogt, 2004). Additionally, the altered landscape leaves little room for vegetation, which limits the amount of cooling that can be achieved through evapotranspiration (Wilmers, 1990; Jonsson, 2004; Founda & Santamouris, 2017).

Urban climates are not only affected by the transition away from natural surface materials but also by the function and form of an urban space. Urban function considers how the urban space is used, i.e., residential, commercial and industrial, all of which have a unique occupancy level, occupancy schedule and energy use requirement. Urban form is defined by the arrangement, size and density of buildings, and the urban canyons that are created.

The urban form creates complex interactions between elements in a city, such as the reflection of radiation, transfer of heat, wind speed, and wind direction (Pattacini, 2012). For example, the accumulation of thermal energy is driven by tall buildings that absorb more solar radiation during the day while also reducing the natural cooling achieved at night due to a decreased sky view factor (SVF) (Salvati, Monti, Roura, & Cecere, 2019). Local geography can also have substantial effects on the urban climate. For example, where urban centers are located next to bodies of water, an onshore breeze can often cause a cooling effect for the urban space, leading to moderate urban temperatures (Ramamurthy & Bou-Zeid, 2017; Kotharkar, Ramesh, & Bagade, 2018). Consequently, a review conducted by Kotharkar, et al., (2018) showed that sea breeze during the daytime at some cities improves thermal comfort while limiting diurnal warming and atmospheric pollution. Similarly, mountains can induce wind systems that influence the UHI and its variability. For instance, in Stuttgart, Germany, the surrounding hills cause stagnation of air over the city, resulting in poor air quality and intensified UHI (Ketterer & Matzarakis, 2014). On the other hand, cool air from high mountain ranges can flow through city centers and mitigate UHI (Hamada, Tanaka, & Ichinose, 2008).

The activity within an urban space can bring about the addition of anthropogenic heat emissions from industry and air conditioning, directly increasing the energy input into the environment (Ichinose, Shimodozono, & Hanaki, 1999; Fan & Sailor, 2005). These anthropogenic heat sources can create a feedback cycle where elevated outdoor temperatures, lead to increased air conditioning use, which further raise outdoor temperatures. Studies have consistently shown that the cooling energy demand is often elevated in cities compared to their rural surroundings due to the higher temperatures caused by UHI (Palme, Inostroza, Villacreses, Lobato-Cordero, & Carrasco, 2017; Magli, Lodi, Lombroso, Muscio, & Teggi, 2015; Shahmohamadi, Che-Ani, Maulud, Tawil, & Abdullah, 2011). Consequently, a review of UHI impacts on urban energy consumption (Li,, et al., 2019) calculated a median increase of 19% in cooling demand with a wide variation within and among different cities. For instance, Van Hove, et al., (2015) found that UHI in Rotterdam, Netherland resulted in greater number of discomfort hours where Physiologically Equivalent Temperature (PET) exceeded 23°C, compared to the rural reference location.

Indeed, urban development can indirectly affect human health by worsening air pollution (Xu, Yin, & Xie, 2014), altering rainfall patterns (Collier, 2006), and increasing flood risk and decreasing water quality (Hester, & Bauman, 2013). However, the most direct impact of UHI on human health is through the exposure to increased temperatures, particularly by amplifying heat waves where synergistic interactions with UHI were found to magnify the difference between urban and rural temperatures (Li, Bou-Zeid, & Oppenheimer, 2014). Subsequently, Heaviside, et al., (2016) quantified the intensity of UHI in Birmingham, UK and their analysis showed that the increased temperatures caused by UHI could be responsible for up to 50% of the total heat-related mortality during heat waves.

The impacts of UHI will be exacerbated in the future, where global warming, urban expansion, and increasing anthropogenic heat emissions will result in a larger temperature gradient between the urban center and surrounding rural areas (Fujibe, 2011; Varquez & Kanda, 2018). Consequently, the effects of climate change on UHI have been studied extensively, where cooling energy consumption (Kolokotroni, Ren, Davies, & Mavrogianni, 2012; Santamouris, Cartalis, Synnefa, & Kolokotsa, 2015) and heat-related mortality (Luber & McGeehin, 2008; Hajat, Vardoulakis, Heaviside, & Eggen, 2014) is generally seen to increase because of elevated temperatures. To combat these issues, many strategies have been proposed to mitigate the UHI by reducing the overall temperature in urban environments. In order to analyse the potential effectiveness of these UHI mitigation strategies within urban form, simulations analysing the urban climate, especially under evolving climate conditions will need to be conducted. There are many approaches that can be used to model the climate of urban agglomerations. However, the spatial scales of the climate models used to study urban climate is a critical aspect to consider, especially when high-resolution climate data in both time and space are required (Masson, Lemonsu, Hidalgo, & Voogt, 2020). In addition, the spatial scale of the climate model used in the analysis will determine how the built environment is represented in the model.

2.2 Modelling and forecasting urban climate at regional scales

On the largest scale, Global Climate Models (GCMs) are commonly used to provide projections of climate change over longer periods of time (Flato, et al., 2014; Collins, et al., 2013). These numerical models simulate the physical 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 (Van Vuuren, et al., 2011). However, these models are often only available at spatial resolutions that are too coarse to resolve city-scale mechanisms and with a time-step that is usually not frequent enough to study local sub-daily processes. Despite attempts that have been made to incorporate urban canyon models into GCMs (Oleson, 2012; Fischer, Oleson, & Lawrence, 2012), the scale of these models limits their usefulness in 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 that is 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 green-house gas emission scenarios and long time periods; allowing model and scenario uncertainties to be accounted for. Additionally, these models allow researchers to simulate regional climates and generate data applicable to entire cities.

Due to fact that statistical downscaling approaches are limited to historical observations and therefore 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 (Giorgi, 2019). 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.

A study conducted by McCarthy, et al., (2012) coupled a simple urban land-surface scheme with an RCM at 25km resolution for a sensitivity analysis of cities in the UK. The sensitivity of the UHI effect within cities to large-scale climate change, local forcing from urban land use, and anthropogenic heat flux were analyzed. The results indicated that the simple land-surface exchange scheme provided a realistic UHI comparable to observed values over a city scale.

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 parametrization schemes and local land cover data and their effects on the local UHI effect can be analysed (Gaur, Eichenbaum, & Simonovic, 2018; Zhang, Jin, & Leach, 2017). 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 could be dynamically downscaled to estimate the fraction of the increase in UHI intensity that could be attributed to global warming or to urbanization (Adachi, Kimura, Kusaka, Inoue, & Ueda, 2012).

More recent experiments couple a Single Layer Urban Canopy Model (SLUCM) (Kusaka, Kondo, Kikegawa, & Kimura, 2001) with the Weather Research and Forecasting (WRF) model, which have resulted in numerous studies validating the accuracy of such a model when compared to observational data in various climates (Chen, Kusaka, Tewari, Bao, & Hirakuchi, 2004; Imran, Kala, Ng, & Muthukumaran, 2018; Giannaros, Melas, Daglis, Keramitsoglou, & Kourtidis, 2013). Although SLUCMs add much-needed complexity to the climate model, they still only represent general aspects of the urban environment, but do not take microscale characteristics such as individual buildings into consideration (Reder, Rianna, Mercogliano, & Castellari, 2018). Multi-level urban canopy models (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 heat (thermal energy) exchanges (Grimmond, et al., 2010). Multi-level UCMs are useful in studying the thermal energy exchange occurring between urban surfaces, however, the complexity comes with a high computational cost. Fortunately, subsequent studies have found that simplified models are able to produce reliable climate simulations (Best & Grimmond, 2013). However, in order to evaluate the magnitude of UHI, it is necessary to apply multi-level UCMs to account for turbulence and multi-reflections in the urban canopy (Jandaghian & Berardi, 2020b).

2.3 Modelling urban climate at neighborhood scales

In addition to the climate data downscaled at a regional scale, the effect of UHI can also be analyzed at microscales with some detailed models such as computational fluid dynamics (CFD) based models. These models provide the capability of reproducing details of the microclimate in a district, neighborhood, or street canyon, as opposed to the general city-wide effects considered by regional modelling. CFD models can be easily coupled with the solar radiation models as well as heat and moisture transport models so that the physical environment in the city can be resolved in detail. The urban microclimate is exposed to an infinitely large atmospheric space. Therefore, the computational domain should be carefully defined to reduce the effects of simplification. The best practice guidelines (BPG) come from the Architectural Institute of Japan (AIJ) (Tamura, Nozawa, & Kondo, 2008; Tominaga, et al., 2008) and European Cooperation in Science and Technology (COST) (Franke, et al., 2004; Franke, Hellsten, Schlunzen, & Carissimo, 2007), which specifies the requirements of how the computational domain, boundary conditions, wind profiles, and turbulence models should be defined to ensure the quality of the simulation. Blocken & Gualtieri, (2012) also proposed a framework to use CFD for the design and optimization of pedestrian wind comfort. To consider the thermal effects in urban areas, the grid size of the microclimate models can be refined down to a sub-meter scale, which will allow researchers to resolve physical phenomena in detail. To that end, Tsoka, et al., (2018) summarized the publication trend and global distribution of the studies using ENVI-met (a software tool that allows the scientific analysis of the impacts of urban design measures on the local environment), which reported 280 papers in total before March 2018, and most of them came from Europe and Asia. The studies also cover a wide range of Koppen climate zone types.

One of the challenges for microclimate modelling is that urban climate models are normally oversimplified (Mirzaei, 2021). It is necessary to consider the various environmental elements in the study area, such as anthropogenic heat emission (Arnfield, 1990) (Mirzaei & Haghighat, 2010), vegetation (green infrastructure) (Bowler, Buyung-Ali, Knight, & Pullin, 2010; Priya & Senthil, 2021; Jamei, Rajagopalan, Seyedmahmoudian, & Jamei, 2016), water body (blue infrastructure) (Liu, et al., 2021; Manteghi & Remaz, 2015), and rains (Blocken & Carmeliet, 2004); (Blocken, Derome, & Carmeliet, 2013); (Derome, Kubilay, Defraeye, Blocken, & Carmeliet, 2017); (Van den Brande, Blocken, & Roels, 2013). For NBS to urban heat mitigation, the simulation of the natural infrastructure comes to be a major concern. 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 incorporated into common CFD programs.

Despite these challenges, case studies further demonstrate the capability of CFD models. For example, Antoniou, et al., (2019) performed an unsteady-state Reynolds-averaged Navier-Stokes (RANS) simulation for a highly heterogeneous district in Nicosia, Cyprus, over a four-day period in July 2020. The simulation was validated by a high-resolution experimental dataset (Neophytou, et al., 2011; Neophytou, et al., 2013) which included air-temperature, wind speed and surface temperature in the same area. Similar studies have been conducted by Toparlar, et al., (2015) to investigate UHI at the Bergpolder region in Rotterdam during a summertime heatwave in 2006. The simulated surface temperature was validated with experimental data from high-resolution thermal infrared satellite imagery, which confirmed the reliability of the CFD model to identify the area with extreme heat. However, due to high computational costs associated with the number of mesh elements required to capture a large geometry such as a city, CFD modelling with high detail can only be conducted for a short period of time or for a small portion of urban topography. As such challenges occur when the analysis of larger urban areas or longer periods or time are desired to study the effects of UHI on a city.

To study the indoor climate and assess the building overheating, whole building evaluation with a building energy model is the most widely used approach, since the contribution of the whole building system, such as material properties, mechanical system, building utilities, and the occupants' schedule, can be considered comprehensively with reasonable computational cost. Moreover, it can be easily used for different climate conditions to consider the impact of urban effects and climate change scenarios on buildings, while the generation of weather files and selecting proper weather files for overheating assessment (Ji et al., 2022) would be crucial for such studies. Girgis, et al., (2016) explored the effect of anthropogenic heat on pedestrian thermal comfort in a historical square of Cairo, Egypt. The impacts of a buildings air conditioning unit and an idling bus on outdoor temperature was evaluated through CFD simulation and the pedestrian's thermal comfort was evaluated by the PMV index calculated by ENVI-met. Subsequently, Katal, et al., (2019) provided an example for integrating the urban-scale CFD and building models by coupling the urban scale building energy model, City-BEM, with the CFD model, City-FFD, to simulate the resilience of buildings under extreme weather conditions.

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. For example, Berardi, et al., (2020) selected two vulnerable locations from the Greater Toronto Area (GTA), and the results from the WRF simulation were used as inputs for a microclimate model, ENVI-met, to test the effectiveness of greenery scenarios. They found that by increasing the tree canopy in the local area, the temperature can be reduced by 0.5°C and 1.4°C at the two locations, respectively. Similarly, to study a period of extreme heat in San Jose, California, McRae, et al., (2020) also integrated WRF results with ENVI-met simulations to measure the cooling effects of vegetation.

There are also attempts to incorporate the climate data from the regional climate model or CFD simulation into whole building simulations. Wong, et al., (2021) developed a multiscale simulation framework to couple WRF, OpenFOAM and EnergyPlus to evaluate the microclimate and the building energy performance of the campus of the National University of Singapore. The method has been verified to estimate the energy saving of the buildings with the urban heat island measures applied in the microscale model. Shu, et al., (2022) proposed using high resolution convection-permitting climate data for city-scale overheating assessment. Where convection-permitting climate data refers to data that has been simulated by a high-resolution climate model that "permits" convection processes, which only occurs on the scale of a few kilometers, which differentiates it from other regional climate models on the scale of approximately 10km. The data was inputted to a building energy model, EnergyPlus, to perform the indoor overheating assessment. It was found that the conventional regional climate model (RCM) in a coarse resolution at 25km may highly underestimate the indoor and outdoor overheating in cities of Ottawa and Montreal.

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 and 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 (Wyszogrodzki, Miao, & Chen, 2012). For example, Tumini & Rubio-Bellido, (2016) evaluated the climate change effect on the microclimate of a park square and its surrounding buildings in Concepcion, Chile. The future climate was obtained through a "morphing" method (Belcher, Hacker, & Powell, 2005; Jentsch, James, Bourikas, & Bahaj, 2013) with reference to the GCM scenario of A2 'medium-high' Greenhouse Gas (GHG) emissions. The microclimate simulation was conducted in ENVI-met, and an increase in the average temperature of 1.02°C, 1.60°C, and 2.70°C was found for 2020, 2050, and 2080, respectively. However, statistical downscaling approaches such as that implemented by Tumini & Rubio-Bellido, (2016) 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 (Thorsson, Lindberg, Björklund, Holmer, & Rayner, 2011). Consequently, to generate data necessary to study UHI and climate change, Conry, et al., (2014) used WRF to dynamically downscale climate projections in Chicago produced by the Community Climate System Model. Subsequently, from a spatial resolution of 0.333km, the data was used to drive an ENVI-met model with a grid resolution of 2 m to study the pedestrian level thermal comfort. The added benefit of dynamically downscaling to such a degree provides a robust source of spatially averaged initial conditions for the microscale CFD model.

Undoubtedly, climate change will significantly impact the urban environment, affect building energy consumption for heating and cooling (Radhi, 2009), air pollution and human health and well-being. For instance, San José R. , et al., (2016) analyzed the change in building energy use due to climate change under two potential global warming scenarios. By gradually dynamically downscaling GCM climate data to a regional scale, and finally to a neighborhood scale through CFD models, climate data that is suitable for building simulations can be produced. Subsequently, this data is then inputted to EnergyPlus to calculate heating and cooling loads for buildings in

Madrid, Milan, and London, where results indicated a relative decrease in heating energy demand while a significant increase in cooling should be expected. A similar procedure was used by San José R. , et al., (2018) to generate climate data to study the effects of climate change on air pollution and human health in London, England. Additionally, the downscaled microscale data was validated against the data obtained from existing air quality stations in the city, where good agreement was found between the model and observed data. Subsequent analyses showed that concentrations of atmospheric pollutants would not change significantly in the future. However, the rise in temperatures will be a larger cause for concern in terms of human morbidity.

2.4 Current challenges in generating urban climate forecasts

The discussion presented in this section highlights that the majority of the studies that assess the impact of urban form or NBS on urban climate have been performed over extreme weather events, or a summer season. The period of high spatial resolution (<4 km) simulations is much shorter compared to recommended timeframes for climate change impact assessments (20-30 years long). This is because, undertaking regional climate simulations at high-spatial resolutions is computationally expensive despite rapid advances in high-performance computing and climate modelling techniques.

As such, conducting multi-decadal urban climate simulations 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 NBS 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 NBS (Le Roy, Lemonsu, & Schoetter, 2021; Duchêne, et al., 2020).

There is also a need to encompass climatic uncertainty that can be used in buildings overheating context. Nik (2017) describes a useful method to select typical and extreme climate files out of a large ensemble of climate simulations for buildings performance assessment studies. The method has been widely used to assess the energy performance of buildings. Some of our recent work (Gaur & Lacasse, 2022) has evaluated the applicability of the method in buildings overheating context and found its performance is acceptable in three Canadian cities. Similarly, (Shu, et al., 2021) has used the method to select representative climate projections and urban sub-regions for detailed future overheating assessment in the Ottawa and Montreal cities of Canada. Such methods need to be further developed and used to reduce the computational requirements of detailed overheating assessments in cities.

3 Effects of Urban Heat Island (UHI) on buildings and urban inhabitants

There are several ways to report the UHI effect; however, the two most commonly reported UHI metrics are surface temperatures and air temperatures (Health Canada, 2020). Surface UHIs refer to elevated temperatures recorded on urban surfaces such as roads, sidewalks, and building envelops. Urban surfaces tend to have elevated temperatures as a result of their dark colours and higher heat capacity compared to natural materials in surrounding areas. Air temperature UHIs refer to the elevated ambient temperatures found within the urban environment, and such temperature elevation is caused by the release of thermal energy from urban surfaces and anthropogenic sources (e.g., human activities, transportation, etc.). The UHI effect is most pronounced during the evening when thermal energy (absorbed solar radiation) is released from urban surfaces, and urban areas remain at elevated temperatures compared to surrounding rural areas.

When analyzing the effects of increased urban temperatures on humans, two frames of reference are generally used. One frame of reference is analyzing how evaluated temperatures impact the energy balance of a building and occupant thermal comfort, while the second is analyzing the perceived environmental temperature experienced by pedestrians within the city. The following sections of the report present an overview of how UHI affects buildings and building occupants as well as pedestrians within the city.

3.1 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 as the periods when elevated indoor temperatures trigger a physiological response and action of building occupants to restore thermal comfort (Laouadi, Bartko, Gaur, & Lacasse, 2021). 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 highly influenced by the outdoor conditions.

Persisting warm or hot indoor conditions over several days may strain the human physiological system and therefore lead to serious health issues or even death, particularly for occupants who are vulnerable to heat. The vulnerable populations may include the elderly, sick and children (Health Canada, 2020). To reduce such effect 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 buildings will have a better chance of maintaining occupants' thermal comfort compared to existing buildings which may not have up-to-date insulation levels or air conditioning systems (Laouadi, Bartko, & Lacasse, 2020). As such, work should firstly focus on finding solutions to maintain occupants' thermal comfort within existing building stock in order to protect any vulnerable populations that may reside in these buildings. Secondly, the load capacity of a structure and the insulation level used within its construction will affect which UHI mitigation strategies can be supported by the structure and how effective the mitigation strategies might be at improving the thermal comfort of the building occupants (Malys, Musy, & Inard, 2016).

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 energy efficiency should be the main objectives of building design. In order to achieve these objectives, designers should make use of design best practices for sustainable building design as much as possible before adding additional cooling design solutions. Aksamija & Perkins+Will, (2013) put together the guidelines for designing sustainable facades, where they outlined passive design strategies that can be used in different climates. A summary of these basic passive design strategies can be seen in Table 1.

Table 1: Best practices for sustainable building design based on climate (Aksamija & Perkins+Will, 2013)

Climate type	Design strategies
Heating-dominated	• Orientation for solar collection for passive heating. • Using thermal mass for heat storage in the wall. • Improved insulation levels. • Use of natural lighting.
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 natural lighting.
Cooling-dominated	• Protecting the façade from direct solar radiation for passive cooling. • Use of natural ventilation where possible. • Use of natural lighting, while using shading devices and light shelves. • Make use of well-insulated opaque façade elements.

From a building performance perspective, the main objective will always be the improving thermal comfort of the building occupant and increasing building energy efficiency. The UHI reduction strategies that can also meet these requirements should be selected since they can bring additional benefits to the urban environment. For example, if it was determined that a vegetated roof would have the same performance benefits as a manufactured material, the selection process should be made on secondary benefits, which could include, habitat generation, pollution reduction, mental health, carbon sequestration as well as altering pedestrian thermal comfort and changing the environment within the local area.

3.2 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 (Laouadi, Bartko, Gaur, & Lacasse, 2021). In order to combat these events, design strategies within urban environments need to be put in place to modify the thermal load acting on pedestrians.

The main causes of elevated ambient temperatures in Canada include, large amounts of surface area with low albedo and high absorptivity, insufficient vegetation and permeable surfaces, urban form with large Height-to-Width ratios creating urban canyons that modify wind speeds and large amounts of heat-generating sources such as transportation and HVAC systems (Wang, Berardi, & Akbari, 2016).

When analyzing the current urban environment, different functions and forms can be identified. Urban function considers how the urban space is used, i.e., residential, commercial and industrial, and the form is the shape and quality of the structures. The function of a specific area will bring a unique occupancy level, occupancy schedule and energy use requirement, which would benefit from unique cooling strategies, whereas the urban form is defined by Height-to-Width ratios of structures, building densities, and the related Sky View Factor (SVF). Height-to-Width ratio of a structure is a dimensionless value that relates a buildings height to it width, and building density describes the maximum floor space per land unit. The size and dimensions of a structure can limit where and how UHI mitigation solutions could be applied, for example, the height of a structure limits the area that vegetation growing from the ground can cover and the slope of a roof limits the implementation of green roofs. The weight of the plants should also be considered, as existing buildings may not have the load capacity for a heavy plant system, such as the intensive green roof or heavy green wall.

Selecting UHI mitigation strategies that will combat rising urban temperatures requires consideration of both the form and function of the urban area. Considerations can include, planning for open space within a city and taking the SVF into consideration. The inclusion of open space 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 cooling at night, but warmer temperatures during the day, therefore, areas with high daytime occupancy may wish lower SVF's to create urban canyons and lower street level temperatures during the day but warmer temperatures at night. Height-to-Width ratios of 0.5 with building density of around 0.3 are being suggested as a mean of best design practice for urban environments to reduce UHI effects (Wang, Berardi, & Akbari, 2016). When considering which UHI mitigation solution needs to be analyzed firstly in each urban form, the following characteristics, as presented in Table 2, should be considered.

Table 2: Characteristics to consider in different urban forms

Building Type	Characteristics
Residential detached	• Single detached or townhome • Some property and space surrounding home • Wider range of roof angles • Primarily occupancy at night
Midrise Urban	• Potential for wider range of occupancy hours • More exposed wall surface compared to residential
High-rise Urban	• Potential for wider range of occupancy hours • More exposed wall surface area compared to roof area • Potential for deep urban canyons and low SVF

When selecting which UHI mitigation strategies to implement in the urban area, there are many factors to consider, including the benefits and trade-off's that result from whether you are observing the changes from inside or outside a building. In order to help city planners, determine which NBS can address multiple urban challenges, a tool developed by Croeser, et al., (2021) can be used which allows a multi-criterial decision analysis to be performed. Their tool was created and evaluated using the feedback from seven cities in the European Union participating in the Urban GreenUP project (Urban GreenUP, 2021). The tool considers several ecosystem benefits including improving air quality, reducing the risk of flooding, reducing the effects of UHI, increasing urban renewal, providing open green space, supporting biodiversity, and improving public health and wellbeing. In order to select the correct ecosystem service, the tool uses a questionnaire to gather information on the city's institutional capacity to implement the NBS. Combining these to parameters the tool selects the NBS that would most likely succeed in meeting the city's ecological needs based on the current policies and political support. Tools such as this provide a starting point for urban planners and policy makers; however, a detailed analysis is required to ensure that these strategies would work within Canada.

In a report by Health Canada, three strategies in which public health professionals in Canada can support the advancement of UHI-reduction actions were identified. These strategies include, building the understanding and capacity of design professionals, providing input to municipal planning and development process and by implementing direct or indirect measures to reduce UHI (Health Canada, 2020). In order to move forward in combating rising urban temperatures, persuasive evidence-based arguments for how UHI reduction strategies may protect public health are required, where access to quantitative and qualitative evidence is key for municipalities to make informed land-use planning decisions in order to improve public health (Health Canada, 2020). The development of guidelines on the design, construction, and use of various green infrastructure projects would help to increase the uptake of these technologies within municipalities (De Carolis, 2012). Dare, (2020) conducted a review of the UHI mitigation policies presented in the planning policy documents of 20 municipalities located within the United States and Canada. Their review showed that municipalities are aware of the UHI effect and its consequences. It was noted, however, that these policies do not always present a local understanding of the potential impacts of the UHI effect, or provide solutions on how to address the issue. The author found that nearly 86 percent of the reviewed UHI mitigation policies focus on increasing latent heat flux, shade, and the albedo of surfaces. It was also found that the most commonly implemented approach was increasing urban vegetation and cooling through latent heat flux. It was speculated that this approach was favored because urban greening strategies have components that are immediately visible upon installation, which shows or suggests improvements are being made. Dare, (2020) Suggests that increasing the public's awareness of both the pros and cons of all strategies is needed in order to increase the appropriate uptake of UHI strategies. This is especially true when considering the fact that some urban vegetation strategies, such as planting trees, can take up to 30 years to achieve their full cooling potential (Health Canada, 2020).

In order to effectively compare different UHI mitigation strategies, comparisons must be made using the same metric and/or frame of reference, especially considering the fact that many mitigation strategies have the potential to reduce both surface and air temperature UHI effects. One frame of reference that can be used to compare the effectiveness of UHI mitigation strategies is their impacts on the energy balance between a building and the surrounding environment which can affect occupants' thermal comfort, while another could be the comparing improvements made to the perceived environmental temperature experienced by pedestrians within the city.

Mitigation strategies that modify the boundary conditions (convective and radiative loads) which act upon a structure or an individual are said to have "direct effects", whereas strategies that modify the ambient conditions surrounding a structure or an individual (such as temperature) which in turn effects the energy that is transferred to a building or individual is said to have "indirect effects" (Malys, Musy, & Inard, 2016). The following section of this report presents the direct and indirect effects that ISG and ISR have on the energy storage of urban agglomerations, the energy transfer to buildings and their occupants, and the resulting effects on the outdoor environment and pedestrian thermal comfort.

4 Approaches to mitigating UHI effects

Buildings account for 28% of global energy-related GHG emissions, and this share is even greater in large cities. Urban heat island (UHI) effects can increase building cooling loads by 19-25% depending on the climate, and in regions where the difference in temperature between urban and rural areas exceeds 10°C, cooling loads may double. Increased temperatures not only increase the cooling energy consumption and peak electricity need but also affect the population, from the loss of urban environmental quality to the increased risk of heat-related mortality and morbidity. Leveraging synergies of nature and the built environment, Nature Based Solutions (NBS), is an approach that Canadian municipalities can take as climate mitigation and adaptation strategies. NBS as defined by Raymond, et al., (2017) are "solutions to societal challenges that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience". NBS may contain design elements that mimic, enhance, conserve or support nature in order to achieve one or more desired ecosystem services (Health Canada, 2020; Croeser et al., 2021). NBS can take the form of Urban Green Infrastructure (UGI) including green roofs, urban forests and vegetated vertical surfaces implemented on and around buildings or Reflective or Cool Infrastructure. UGI and Reflective/ Cool infrastructure can reduce building energy consumption and carbon emissions, moderate the microclimate, and therefor reduce extreme heat events, while UGI can also sequester CO_2. Canada lacks knowledge of how NBS effect surface and air temperatures at the neighbourhood or municipal scale, and how NBS could be prioritised based on cooling performance and co-benefits. To quantify the contribution that NBS could achieve towards carbon-neutral and climate resilient buildings/communities, new knowledge is needed to understand and quantify the effects of Increased Surface Greenery/Vegetation (ISV) and Increased Surface Reflectivity (ISR) has on: urban micro-climate, buildings and communities, and urban dwellers.

Urban planners and policy makers have the challenge of selecting appropriate NBS 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 by NBS, avoiding heuristics when selecting strategies to implement, and obtaining the skills required to design, build and maintain the selected strategy (Croeser et al., 2021). It is therefore suggested that the best NBS be selected for each urban agglomeration in order to address as many of their unique needs and increase their chance of success. As such, if NBS 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, comprehensive analysis of their contributions is needed. Canadian-specific knowledge of how NBS functions with existing and planned buildings and at various scales is lacking. Specifically, methods to quantify and evaluate NBS performance and tools for effective implementation are required.

To fill these knowledge gaps, advanced models will need to be developed to enable generating multi-scale urban microclimates with integrated estimation of carbon emissions and sequestration from urban communities in response to current and future climates. Measurements has to be carried out in community-scale projects for model validation and performance evaluation. Validated models could be used to assess the performance of UGIs designed for archetype buildings & communities that are adaptive and effective to their physical, social and economic environment over their life cycle to optimize NBS. Best practices, policy guidelines & web-based decision-making tools will need to 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.

An integrated engineering approach which includes field measurements, model development and validation, as well as simulations and optimization should be used. A common framework will be established and applied to selected Canadian cities considering differences in current and projected future climates, as well as building and NBS practice and policy. To select NBS for carbon neutral buildings and communities, quantification of carbon sequestration and emissions will need to be carried out at the building, community, and city scale, including:

- Estimating energy use & carbon emissions from buildings;
- Estimating carbon sequestration of different UGIs;
- Carbon balance: CO2 captured by UGIs and CO2 emissions from buildings over their life cycle.

To carry out carbon balance analysis, an advanced urban-scale aerodynamic model will be used, and such model is capable of modeling UGIs and their effect on the urban micro-climate (MC) together with a new process-based urban carbon cycle model which is capable of integrating assessment of various UGIs carbon sequestration schemes. These models will be developed, validated, and used for evaluating and optimizing NBS designed for various scenarios under current and projected future climates.

However, before these analyses can begin, an understanding as to which characteristics of each NBS are the most important to be captured in these models, along with an understanding as to which NBS strategies may function best within Canada is required. As such the following section provides a detailed literature review on Urban Surface Greenery/Vegetation and Reflective/Cool Surfaces.

4.1 Increased Surface Greenery/Vegetation

Urban surface and air temperatures can be lowered by increasing the green infrastructure within the urban environment. In general, the shading from vegetation provides the main cooling effect achieved by urban greenery, where solar radiation that would be incident on urban surfaces can be blocked from hitting the surface below (Dardir & Berardi, 2021). Additional cooling can be achieved as absorbed radiation is dissipated through transpiration from the leaves and/or evaporation from the growing medium, where the cooling achieved from evapotranspiration is usually less than that achieved from shading. Despite a smaller surface cooling effect achieved through evapotranspiration, the process is effective at reducing ambient air temperatures at a larger scale (Koch, Ysebaert, Denys, & Samson, 2020). Urban vegetation can also alter the convective boundary condition by creating a wind barrier next to a surface.

Additional co-benefits that can be achieved from urban vegetation include seasonal shading, management of storm water and storm water runoff, production of oxygen, carbon sequestration, and the filtration of air particulates (Koch, Ysebaert, Denys, & Samson, 2020). Besides building performance, additional co-benefits include improvements to the mental and physical wellbeing of urban inhabitants achieved from green infrastructure. In a study conducted by Elsadek, et al., (2019), subjects who were exposed to a green façade for a period of time reported an increase in comfort and relaxation as well as an improvement in mood compared to their time spent next to an exposed concrete wall. Table 3 summarizes the interactions of the greenery enhancement in the urban canopy.

Many surfaces within the urban environment could benefit from added vegetation; however, the urban environment can be harsh place for plants to grow and survive. In order to increase the likelihood that vegetation will thrive within the urban environment, the use of native and or adapted plant species is suggested Giguère, (2009), as they are likely tolerant to local precipitation levels and climatic events. The use of native plants can also provide co-benefits, including habitat and food for local species. The following section will provide information on green infrastructure and how it is used within the urban environment to mitigate UHI effects and thus reduce indoor air temperatures.

Table 3: Summary of interactions to consider from the use of green infrastructure

Interaction with	Interactions to consider
Buildings	Thermal energy balance and temperature of the building • Reflection of incoming solar • Shading from incoming solar • Dissipation of absorbed radiation by evapotranspiration • Wind barrier altering convective coefficients
Urban environment	Thermal energy balance and temperature of urban surfaces • Reflection of incoming solar • Shading from incoming solar • Dissipation of absorbed radiation by evapotranspiration • Wind barrier altering convective coefficients Moisture control • Water retention and storage • Humidity levels Air quality • Oxygen creation and Carbon capture • Particulate filtration
Society	Inhabitants • Increased biodiversity • Physical and mental wellbeing

4.1.1 Roofs

Green roofs, often referred to as vegetated roofs, eco-roofs (due to ecological benefits), and roof gardens or living roofs, are a system of vegetation planted within a growth medium (substrate). Green roofs bring multiple social, economic and environmental benefits to the top of buildings. A typical green roof is presented in Figure 2. The green roofs are also called vegetation roofing assembly (VRA). The selection and configuration of each component within a green roof will determine both the characteristics of a green roof system and how the system may perform under different climate conditions. Where the thickness of, and materials used within the layers will dictate how a system responds to local climatic conditions and precipitation events. The construction style of green roofs provides a convenient way to classify the different types of green roofs available.

A study was conducted by Coutts, et al., (2013) to determine the cooling effect that three roof options could provide for a retrofit application. The three roof combinations that were analyzed include reflective steel roof, vegetated green roof and non-vegetated green roof (no plants - just soil), where the results were compared to a conventional non reflective steel roof. The authors found that the species of plant affects both the rate of water loss through transpiration and the amount of shading provided by the plants. The rate of transpiration is also dependent on the amount of water available to the plants. As such vegetated roofs may not be able to provide the desired cooling load during extreme heat events if sufficient levels of water are not present. If heat mitigation is the primary goal, then providing a source of irrigation to the vegetated roof may be required. Shading from leaves provides cooling to the growing substrate, which in turn leads to higher substrate moisture levels. The selection of plant species can help balance the cooling potential from the evaporation of water from the substrate and transpiration from the plants.

The Growth media in the green roof can also enhance the thermal resistance of the roofing system (Coutts, Daly, Beringer, & Tapper, 2013). In addition, the thermal mass of the soil causes a thermal lag between the peak ambient air temperature and the cladding cavity temperature behind the growing medium resulting in a more stable internal roof temperature. As such compared to a conventional or reflective steel roof, the vegetated roof provided the lowest cladding cavity temperature during the day. However, with the increased thermal resistance, the cladding cavity temperature remained higher in the evening than the steel roof options. From their results, the authors suggest that if the steel roofs were well insulated, they might decrease the amount of heat transferred into the building while providing an overall benefit to reducing the UHI effect. However, if green roofs are regularly irrigated and have vegetation with a large leaf area index (LAI) and actively transpiring plants, green roofs could achieve a similar cooling potential as reflective/cool roofs. An area of future work suggested by the authors would be to consider harvesting and storing rainwater from cool roofs in order to use as irrigation for street-level greenery, which may provide greater cooling effects for both outdoor air temperatures and pedestrian thermal comfort compared to green roof away from street level.

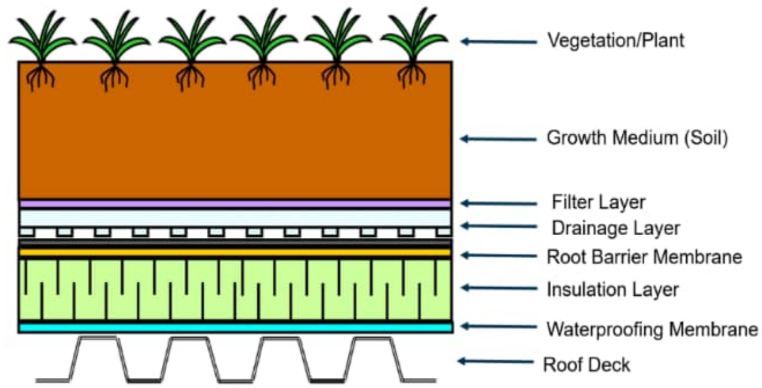

Figure 2: Typical components of a green roof.

The green roofs can be classified into intensive, semi-intensive, and extensive categories, depending on their structural composition and maintenance specifications (see Figure 3). In intensive green roofs, a wide variety of plant species are used, from grasses and small shrubs to trees, where these plants are supported by substrate with a thickness normally greater than 25 cm. Maintenance is required for fertilization, irrigation, and plant accommodation. In comparison, extensive green roofs are characterized by plant species such as herbs, grasses, which are set on a substrate layer of 8–15cm thickness. They require low maintenance and low watering input. 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. They require less maintenance than intensive ones. Of the three types, extensive green roofs are the most common as they are lighter and therefore more easily installed on roofs compared to the other green roof types. In addition, these systems do not require a dedicated irrigation system to be installed and require less capital and maintenance compared to other vegetated roof systems.

Figure 3: Integration of green roof in the built environment

A green roof typically consists of several components, including vegetation, substrate, filter layer, insulation layer, drainage layer, root barrier and water proofing membranes, (Figure 2). A brief explanation of each component is presented in the following.

Vegetation Selection: As urban rooftops are not a natural space for plant growth, there are many factors that are unfavorable for plant growth including elevated ambient temperature, humidity, wind speeds, sun exposure and precipitation levels. The success of any green roof is dependent on the health of the vegetation, which in turn is dependent on the adaptability of the plants to the local climate. The level of plant coverage is important, as it both shades the roof and protects the structure from the winds. Plants with short and soft roots are preferred as this can help prevent the roots from inserting themselves into the roof deck. With the supply of water often being limited in a rooftop environment, the drought tolerance of a plant is often considered. After considering all these restricting conditions on the rooftops, the optimum characteristics for the vegetation/plants used on extensive green roofs include: drought-tolerant, readily available, cost-effective, low growth height, low maintenance, and soft roots.

Growth Medium: The growth medium affects the performance of the green roof system as providing a place for plants to anchor their roots However, building load restrictions are usually the limiting factor for soil media depth. The growth medium should be light-weight with a high ratio of organic minerals in order to help with plant growth. The typical practice is to combine the different components in the growth substrate. Green roofs growth media should have a low bulk density because a high bulk density can collapse the structure, especially in old buildings due to load restriction. Hence the weight of the green roof should be kept as low as possible. Lower density inorganic materials can provide a lower weight of the growing medium. Using 80% of inorganic materials will reduce the green roof growing medium. Growing media should also have a high sorption capacity and less leaching for better performance.

The substrate of the green roof should have high water holding capacity to reduce the peak rainfall and manage storm water events. An optimum substrate supports the wide ranges of the plant/vegetation and helps plants to withstand extreme climatic conditions. Growing media should have several properties including: high stability under different conditions, locally available, cost-effective, containing a minimum organic content and have high water capacity, light weight, high hydraulic conductivity, less leaching, and high sorption capacity, good aeration, and flow properties, and contribute to enhancing the water quality. Despite the thermal resistance of the growing medium used within green roofs or walls, soil is not a substitute for conventional insulation (Koch, Ysebaert, Denys, & Samson, 2020).

Filter Layer: A filter layer separates the growth medium from the drainage layer, preventing smaller particles such as soil fines and plant debris from entering and clogging the drainage layer. This is also called geotextiles and is used to provide a better flow for water in the drainage layer. Filter fabric has high tensile strengths and acts as a root barrier membrane for plants.

Insulation Layer: An insulation layer below the growth medium helps control the amount of thermal energy into and out of the structure. Depending on the design and age of roof some level of insulation is required to help control the dew point within the façade and protect the membrane from any physical damage.

Drainage Layer: A drainage layer helps with the removal of excess water and thus reduces the moisture load on the building structure. The drainage layer protects the waterproof membrane and improves the energy efficiency of the building. There are two commonly used types of drainage layers: 1) drainage modular panels that have holes and 2) drainage granular materials with large pore spaces to store more water.

Waterproofing Membrane: The waterproofing avoids the leakage of water on the roofs. Waterproofing membranes include; modified-bitumen sheets, liquid-applied membranes, polymer cement systems single-ply sheet membranes and thermoplastic membranes. The selection of the optimum waterproofing layer enhances the lifespan of green roofs.

Root Barrier: Root barrier protects the structure of the green roofs from the roots of the plants. The compatibility of the root barrier needs to be checked with the waterproofing membrane to perform well under different climate conditions.

Green roofs can manage storm water, reduce urban heat island, increase urban plant, wildlife habitat and roof life, enhance the air and water quality, decrease the energy consumptions of the building, decrease the noise pollution, procreate recreational activities and increase the green areas and aesthetic value in urban environments. As a result of water quality enhancement, green roofs decrease the burden of the water treatment facilities in an area. The peak cooling effect of green roofs is observed after maximum solar insolation due to evapotranspiration correlating with the peak in air temperature (Sailor, 1994). The load capacity of a roof is a determining factor when considering the installation of a green roof in a retrofit application (Giguère, 2009).

To mitigate the urban flooding, beside the green roofs, another strategy has attracted municipalities and policy makers, known as blue roof or rain detention assembly (Figure 4). In blue roof system, storm-water is temporarily held in roof storage areas or structures until it evaporates, enters a rainwater harvesting system, or flows downstream, at a controlled rate, through the use of flow control devices or structures.

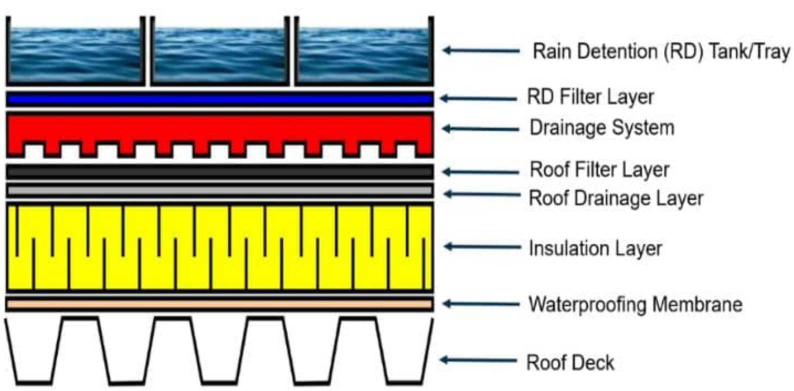

Figure 4: Blue roof components.

Blue roofs have the potential to provide multiple benefits related to storm-water management, including I) reducing peak flow by retaining or detaining storm-water on rooftops during intense storms; II) decreasing runoff volume by reusing storm-water or allowing it to evaporate from a rooftop; III) using storm-water for non-potable purposes, e.g., flushing toilets, irrigating lawns and gardens; IV) mitigating urban heat islanding effects by evaporation processes from water stored on a rooftop, thus reducing the cooling energy demands in the summer time; and V) applying in retrofit scenarios to utilize space in underserviced, crowded urban areas, especially legacy Industrial, commercial and institutional zones which lack adequate storm-water infrastructure. The recent research shows that the combination of the so-called “blue roof” and “green roof” known as “Purple Roof” attracts more attention and is under development and processes to mitigate urban flooding.

4.1.2 Facades

Depending on the urban form, vegetated façades can provide a greater cooling potential compared to roofs. In cases where buildings have large areas of exposed façade, vegetation can provide cooling solutions to multiple floors, while vegetated roofing strategies may only affect those directly below the highest floors (Arenghi, Perra, & Caffi, 2021).

There are many different greenery systems available for vertical surfaces, and each system has its pros and cons. Vertical Greenery Systems (VGS) can be classified into three categories based on their construction and cooling benefits (Arenghi, et al., 2021). The three categories include Green Barrier Systems (GBS), Green Coating Systems (GCS) and Green Walls (GW), (see Table 4), a visual representation of these categories can be seen in Figure 5. As the three categories have different constructions, their effects on building energy use, occupant thermal comfort, or UHI reduction are different. The following sections will provide more detail into the construction and cooling potential of each of the VGS categories presented in Figure 5.

Table 4: Description of vertical greenery system (Arenghi, et al., 2021).

Category	Description
Green Barrier System	A freestanding system not attached to the building.
Green Coating System	A system of plants that grow directly on the façade or from a support system.
Green Walls	A system in which both plants and growing medium are supported by the façade.

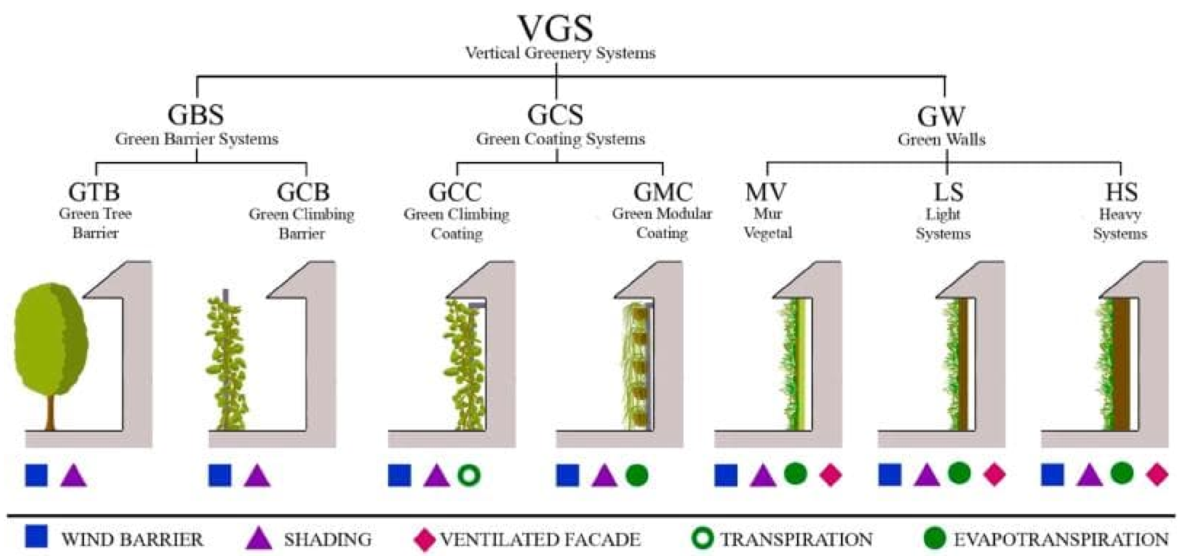

Figure 5: Vertical greenery system classification as defined by (Arenghi, et al., 2021) image licensed under CC BY 4.0.

4.1.2.1 Green Coating Systems

The Green Coating Systems (GCS) can be classified into Green Climbing Coating (GCC) systems where plants grow up from the ground and Green Modular Coating (GMC) systems in which the plants grow from containers attached to the façade (Arenghi, et al., 2021). Typically, GCS alter the thermal performance of a building by shading incoming solar radiation and creating a wind barrier that alters the exterior convective coefficients. GCC systems can be further defined as direct climbing systems (dGCC) where the vegetation attaches itself to the surface or indirect climbing systems (idGCC) where vegetation climbs a lightweight support structure attached to the structure. As GCS requires little to no support structure, these vegetated systems can be implemented with little capital compared to other vertical greenery systems in new construction and retrofit applications. An added benefit of GCS is that the vegetation can provide greater shading coverage at a faster rate compared to trees which may take between 10 – 30 years to reach their cooling potential (Giguère, 2009). However, several years of growth may be required in order to reach sufficient levels of coverage (Koch, Ysebaert, Denys, & Samson, 2020). GMC systems provide planters with growing medium which can be arraigned across a façade for plats to climb up or hang on the façade. With increased root placement options, GMC systems can increase the coverage of vegetation across a façade, compared to GCC systems where the plants growing from the ground may not be able to reach a full height of the structure.

A study conducted by Li, et al., (2019), calculated the cooling load reductions that could be achieved from the application of different VGS to the facades of all the buildings within a city block. The authors noted that cooling of the ambient air and building surface temperatures contributed to the reduction of indoor air temperatures. In their study it was calculated that GCC could reduce indoor air temperature by 1.5 °C (the equivalent of 1 Hp air conditioner), whereas GMC could reduce the air temperature by 3.5 °C (the equivalent of 3 Hp air conditioner). A similar pattern between GCC and GMC systems was found by Arenghi, et al., (2021), where exterior wall temperatures behind the two systems were reduced by 5 and 6 °C respectively. The slightly greater reductions in wall temperatures achieved by the GMC system were attributed to the addition of soil to the wall, which released absorbed radiative energy through evaporative cooling. The cooling results calculated from these two studies are dependent on many factors, including but not limited to the simulated climate, construction of the buildings, and parameters of the vegetated systems simulated.

During the heating season, VGS can act as a wind barrier to decrease heating loads, while shading can increase heating loads. During the winter Arenghi, et al., (2021), found that a reduction in air velocity next to the envelope can lead to a 1 °C increase in the exterior surface temperature due to the reduction of convective heat exchange coefficient. Despite shading providing a positive outcome during the cooling season, shade from leaves and stems in the winter can result in an increase in heating loads. Koch, et al., (2020) found that if the plants remained evergreen throughout the winter (i.e., did not drop its leaves), a greater increase in heating loads would be required compared to if the plants were deciduous. In addition, deciduous plants that had thick woody vines required greater heating loads compared to systems that had thinner vines, where it was stated that in select cases, heating loads could be increased by up to 28 percent. In mixed or heating-dominated climates, the selection of deciduous plant species for GBS and GCS could provide benefits in both cooling and heating seasons.

Pros of GCS – Low cost compared to other VGS as the vegetation used is either self-supporting or requires minimal support structure to climb. With minimal and lightweight support structures these VGS can be implemented in both new and retrofit applications. Vines require little to no maintenance compared to other green wall systems. Faster rates of coverage compared to trees.

Cons of GCS – With plants growing from the ground, the vertical coverage of the structure might be limited by the growing characteristics of the plants, however GMC systems can be used in this instance. They may require a number of years before a sufficient level of coverage is reached (faster than trees, slower than living walls). In addition, some vine species are not adaptable to high solar exposure or wind loads, which may limit the number of plant species that can be used in a specific climate. The spacing and dimensions of a support structure used for an idGCC can influence the cooling potential of the system.

4.1.2.2 Green Wall Systems

Compared to GBS and GCS, where plants are grown from the ground or within elevated planters, green walls have plants growing from medium suspended in the vertical plane. The growing medium in which the plants are rooted allows for a convenient way to group and classify the different GW systems. The three GW systems presented in Figure 5 include Mur-Vegetal (MV), Light systems (LS), and Heavy systems (HS). The MV system is a style of green wall patented by Patrick Blanc in which plants are rooted, irrigated and fed from an inorganic membrane, where both the LS and HS systems are rooted in and fed from an organic growing medium. The LS and HS differ from one another based on the thickness of the growing medium, where LS systems typically have growing material less than 15 cm thick (Arenghi, et al., 2021).

In order to maintain the health of plants used in vertical greenery systems, irrigation must be provided. In the case of GBS and some GCS, Irrigation can be provided from the ground; however, green walls require irrigation of the entire vertical surface, whereas the drought tolerance of the selected plant species dictates the amount of water required to maintain the health of the plants. Despite the drought tolerance of most plant species, a study conducted by Convertino, et al., (2021) found that in order to achieve the optimum cooling potential from plants within a GW system, a sufficient level of irrigation is required. The study found that as plants become stressed from lack of water, their pores close up and the rate of transpiration decreases. Considering the weight of the plants, the growing medium, support structure, and irrigation systems, green walls can become quite heavy compared to other vertical greenery systems. With their weight, green walls are predominantly integrated into the façade of new construction in order to ensure sufficient structural requirements are met.

In a simulation study by Arenghi, et al., (2021), all of the vertical greenery system as shown in Figure 5, were analyzed to determine how they perform at reducing internal surface temperatures compared to a bare concrete wall of 15 cm thickness. The simulations in the study were performed using EnergyPlus. As the authors provide limited details on their modeling assumptions, the results should be considered for reference only comparing one system to another in the application.

During the cooling season Arenghi, et al., (2021), found that the green wall systems achieved the greatest reduction in exterior surface temperature behind the green wall compared to the other vegetated systems through simulation. In their simulation, green walls were able to achieve a 13 °C reduction in exterior surface temperature. The three green wall systems achieved the greatest reduction in surface temperatures due to the thermal mass of their growing medium, their LAI, and the large amount of evaporative cooling achieved from the water present in the growing medium. Compared to the green wall systems, an exterior surface temperature reduction of 1.5 °C was achieved from shading using a GBS, and a reduction of 6 °C from the evapotranspiration and shading of a Green Coating System (GCS). A summary of the author's findings can be seen in Table 5 for cooling conditions.

In the heating season, Arenghi, et al., (2021), found that the growing medium within a green wall system was able to increase the thermal resistance of the façade. In winter conditions, the Mur Vegetal green wall was able to increase the operative temperature of the studied building the most as a result of having a growing medium with lower thermal conductivity compared to the soil-based medium of the other GW systems. Compared to the green wall systems analyzed, the GBS and GCC systems added little to no thermal resistance to the wall. However, due to the deciduous nature of certain plant species, solar radiation would be able to reach the buildings surface; a point that was not fully addressed (Arenghi, et al., 2021). A summary of the author's findings can be seen in Table 6 for heating conditions.

Table 5: Relative reduction in temperatures achieved by different systems compared to a bare concrete wall under summer conditions as determined by (Arenghi, et al., 2021).

VGS	Reduction in Exterior Surface Temperature (°C)	Reduction in Operative Temperature (°C)
Green Tree Barrier	1.5	4
Green Climbing Barrier	1.5	4
Green Climbing Coating	5	6
Green Modular Coating	6	7.5
Mur Vegetal	10	8
Light System	13	8
Heavy System	13	9

Table 6: Relative increase in temperatures achieved by different systems compared to a bare concrete wall under winter conditions as determined by (Arenghi, et al., 2021).

VGS	Increase in Exterior Surface Temperature (°C)	Increase in Operative Temperature (°C)
Green Tree Barrier	0	0
Green Climbing Barrier	0	0
Green Climbing Coating	1	1
Green Modular Coating	1	1
Mur Vegetal	8	4
Light System	8	1
Heavy System	8	2

Pros of GW – Achieve greater levels of cooling to both building surface and urban climate, due to the increased thermal mass and cooling from evapotranspiration compared to other VGS. Wide choices of eligible plant species that can be used due to the growing medium. Due to their modular design, plants and panels can be replaced after plant death or damage.

Cons of GW – Due to the increased mass of GW systems compared to other VGS, their use is limited to structures that can support the increased load. With the additional infrastructure required to install GW systems, they tend to be more expensive compared to other VGS.

4.1.3 Urban vegetation

As a canopy of leaves can directly shade a surface from incoming solar radiation, the use of trees within the urban environment can provide the cooling potential to both horizontal and vertical surfaces. Urban vegetation can accumulate and store less thermal energy compared to conventional grey surfaces. In addition to providing shade, trees can lower the ambient air temperature through transpiration from their leaves. A statistic from Giguère (2009) suggests that a fully grown tree could lose up to 450 liters of water per day due to evapotranspiration, where the heat released during this process would be approximately equal to the cooling capacity of five air conditioners. Kubilay, et al., (2021) found that with their cooling ability, the addition of urban trees can create an overall cooling effect for pedestrian thermal comfort, despite a reduction in air-speed and an increase in relative humidity. However, the authors suggested that with careful planning of the location of the trees, the ventilation achieved from wind corridors and wind coming off large bodies of water can be maintained. In addition to the cooling benefits, urban greenery can reduce runoff from rainfall events.

Despite the majority of the cooling being achieved from shading during light hours, a portion of the total cooling potential from urban vegetation can be achieved from transpiration after the sun sets, where cooling effects from urban vegetation can be felt up to 20 hours of the day (Giguère, 2009). Many urban environments use trees to provide shading in areas where high levels of daytime occupancy are expected. In the review by Giguère, (2009), air temperatures surrounding a row of trees was calculated to be reduced by approximately 1 °C, and that the creation of an urban park could reduce air temperatures by up to 6 °C. The review also showed that the effects from urban trees could extend beyond the immediate planted area toward the downwind environment. However, without details on how these numbers were recorded, there is no real way of comparing these findings to other strategies and climate locations.

Wang & Akbari, (2016a) evaluated how the cooling potential of trees could be affected by the size and positioning of trees within the urban environment. The size of the trees used in their analysis was determined by analyzing the most common trees found with in Montreal. The data were grouped into three categories of trees based on recorded heights and crown diameter. Two simulations were run for each category of tree, where both spacing and no spacing between the crowns were analyzed. By changing the height, crown diameter, and spacing of the studied trees, the SVF at the street level was varied. By increasing the crown diameter and decreasing the SVF from around 0.47 (reference SVF for the city without added trees) to 0.1 (SVF calculated with 12 m diameter tree with no spacing between canopy), a 4 °C reduction in air temperature at the height of 20 m from the ground was achieved. When analysing the tallest trees in their study, a 2 °C reduction of air temperature at the height of 60 m was found compared to the base case. The results showed that a larger diameter tree canopy with smaller spacing between trees contributed more to the reduction in air temperature compared to solely increasing the height of the trees; however, the authors conclude that a combination of increased crown diameter and tree height would be required to reduce air temperatures at both pedestrian and city levels. As the authors were focused on the ambient air temperatures with the urban environment, the direct cooling potential for indoor air temperatures was not determined within their study.

In another study conducted Wang, Berardi, & Akbari, (2016), the authors sought to determine how the addition of trees to three neighbourhoods in Toronto, Ontario would affect the Mean Radiant Temperature (MRT) experienced by pedestrians. The authors found that the greatest reduction of MRT was achieved in the low-rise area where before the addition of trees, large SVF during the day left pedestrians exposed to direct solar radiation and high MRT. Similar results were found by Akbari & Taha, (1992) who determined that by increasing the vegetative cover by 30 percent and increasing the surface albedo of the houses by 20 percent within Toronto neighborhoods, the cooling and heating energy could be reduced by 40 and 10 percent respectively.

Pros of Urban Vegetation – Achieve greater levels of cooling to both building surface and urban climate due to the increased thermal mass and evaporative cooling compared to other VGS and thus lessening the effects of UHI.

Cons of Urban Vegetation – Trees can take between 10 – 30 years to reach their cooling potential. In addition, the roots of urban trees need to be provided sufficient room to grow through the use of cell structures or vaults (which is an added cost to cities) in order for the trees not to be stunted.

4.1.4 Previous modeling and experimental studies

There have been many studies conducted on the use of vertical greenery systems on buildings, and their ability to reduce the impact of the UHI effect. Two recent reviews of NBS have been conducted by Hunter, et al., (2014) and Koch, et al, (2020). These reviews provided a summary of the currently available vertical greenery systems and highlighted the trends that are being found as vertical greenery systems are being implemented. Both reviews found that vegetated surfaces can provide cooling through shading, evapotranspiration and to a certain extent increase the insulating capacity of the wall by adding vegetation and growing medium. However, both reviews concluded that in order to make definitive conclusions as to how one system would perform better compared to another in a specific climate, more information needs to be provided from current research. Where Hunter, et al., (2014) stated that "the effectiveness of green facades in moderating internal building temperature extremes has not yet been unequivocally established and quantified for specific climates, aspects, building construction types, climbing plant support structures, containerized systems or plant characteristics". Where Koch, et al., (2020) suggested that parameters that influence the performance of the vertical greenery systems are not mentioned or described in sufficient detail to make quantitative conclusions as to how specific strategies would perform under different conditions. Both papers provided a list of parameters they thought could aid in the future analysis of vertical greenery systems, and a combination of these parameters can be found below in Table 7.

Table 7: Parameters to analyze vertical greenery systems

System	Parameters of interest
Vegetation	• Species • Seasonal LAI • Growth requirements (light, soil and water requirements) • Growth characteristics (height, life expectancy, rate of growth)
Structure	• Orientation of the system • Material properties of growing substrate if applicable (thermal conductivity, mass/density, water retention ability) • Description of support structure if applicable • Temperatures (inside wall, outside wall)
Climate during analysis	• Solar radiation, wind speed, air temperature on external surface • Solar radiation, wind speed, air temperature behind vegetated façade if designed with an air cavity • Interior set points for simulations

Hunter, et al., (2014) suggested that of particular interest is the interaction between the physiological characteristics of plants and the buildings' energy balance. The authors pointed out that studies often use various assumptions on the physiological characteristics of plants, not necessarily considering the true growth characteristics or cooling capacity of a plant. For example, studies have assumed that regardless of the size/height of a structure and solar/wind exposure on a façade, green facades would be able to cover the entire surface. The authors suggested that the research conducted by architects and engineers could benefit from collaboration with plant biologists and horticultural scientists to better understand how and where plants can grow and the parameters within an urban environment that could affect or alter their ability to grow.

A study by Pérez, et al., (2022) sought to determine the seasonal variations in wall leaf area index (WLAI) of Bostin ivy (Parthenocissus tricuspidata) grown on a double-screen façade in a Mediterranean continental climate. In the study, the leaf evolution process was divided into the five periods: spring (growth), early summer (full new leaf), late summer (degraded foliage), autumn (fall), and winter (no leaves). The authors calculated the WLAI difference between winter and early summer, and such difference could be up to 430 percent. With the variation in LAI, the average daily building operational energy usage for the five periods was calculated to be approximately 12 percent greater in spring, 54 percent lower in early summer, 30 percent lower in late summer, and just over 5 percent greater for autumn and winter compared to the seasonal baseline. The results show that there were energy savings in the spring and summer and an increase in energy use in the other three seasons. Their findings highlighted the need to evaluate both the seasonal WLAI for different plant species and the seasonal energy balance for a system in a specific climate. Where seasonal shading is a well-known phenomenon and in Quebec it is recommended that the vegetation used to shade structures during the summer must also be deciduous with few branches to maximize solar heat gains in the winter (Giguère, 2009).

In order to simulate the effects that green infrastructure has on the cooling potential of a building and the urban environment; several parameters will need to be included in the simulation. The simulation tool should have plant-specific inputs along with being able to specify the geometry of the vegetated system independently of the façade geometry.

- Specify size and location of façade (cover percentage of the façade, simulate realistic growth heights, analyses system based on cardinal direction and orientation between vertical and horizontal),
- Specify plant characteristics (evapotranspiration rates, albedo, LAI, seasonal LAI, which could include shading from stem during winter),
- Climbing characteristics (direct or indirect to provide cooling from air cavity),
- Material characteristics (mass of the vegetation, mass of growing medium, thermal conductivity of growing medium)

In order to cut down on the number of simulations required, it would be helpful to have realistic input values for plants that are able to grow in North America.

Dahanayake & Chow, (2018), simulated the effects of green roofs and green walls on both low-rise and high-rise building styles. The low-rise building was simulated as a single-story building with a shallow roof. The dimensions used were 2.99 m (L) x 2.35 m (W) x 2.75 m (H) for the low-rise building. When vegetation was simulated on an area covering 4.9 m^2 of the single-story building, the results found that green roofs achieved a greater level of cooling compared to green walls covering the same surface area. In the analysis it was shown that applying vegetation to the façade which receives the highest solar radiation achieved the greatest reduction in cooling loads. When analyzing the case of the multi-story building with dimensions 50.00 m (L) x 50.00 m (W) x 100.00 m (H), having a window to wall ratio of 50 percent, their results indicated that if vegetation could be implemented on 25 percent on one of the West, South or East surfaces, a similar reduction to the annual cooling loads can be achieved compared to implementing 50 percent coverage of vegetation on the roof. In their study, the percentage coverage of the vegetation was simulated starting from the ground surface upward, suggesting that climbing vines were considered. Their work shows that reductions in cooling loads can be achieved with vegetation on lower surfaces. If vegetation could be added to the full height of a building, greater levels of cooling could be obtained.

4.2 Increased Surface Reflectivity (ISR) – Reflective and Cool systems

Typically, urban materials are darker in colour and have higher heat capacity compared to vegetation, and because of this, urban areas tend to absorb and store more incoming solar radiative energy compared to surrounding rural communities, leading to higher urban temperatures. 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 convection and radiation, where Figure 6 shows the schematic of roofing surface subjected to incident solar radiation. By utilizing highly reflective materials, incoming radiative energy can be reflected from the urban environment, and surface temperatures can be reduced.

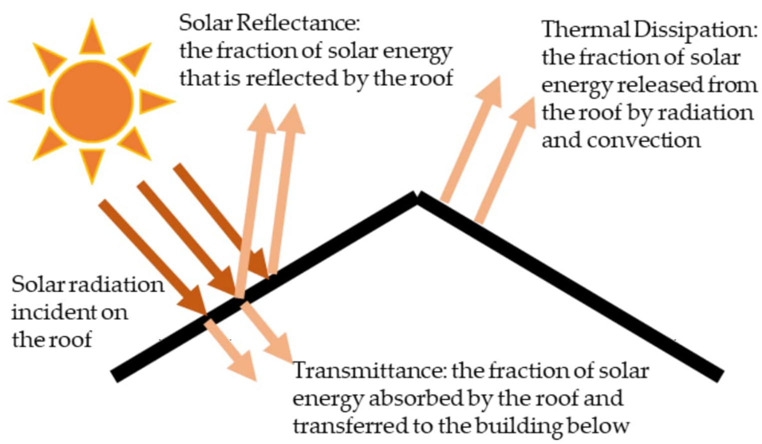

Figure 6: Schematic of roofing surface subjected to incident solar energy.

Hendel (2020) conducted a review of current cool pavers, a subset of materials designed to cool the urban environment, which includes solutions for rooftops, vertical surfaces, and urban floors. In the review, cool solutions were characterized into four categories of reflective, evaporative, high inertia, and energy harvesting, as presented in Table 8. Despite all of these solutions having the potential to reduce urban surface temperatures, not all of these solutions can reduce the effects of UHI. The High Inertia and Energy Harvesting solutions can achieve surface cooling through the day by storing thermal energy, however these strategies will release stored thermal energy at night causing an increase in surface and air temperature in the evening. Solutions that merely shift the timing of when thermal energy is released from the urban surface tend to work best when there is little to no evening occupancy, which is becoming harder to find within diverse urban agglomerations. As such only reflective and evaporative materials will be discussed within this report.

Table 8: Categories of cool solutions (Hendel, 2020)

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.

The urban form plays a role in the overall energy balance of a city, where tall buildings and narrow streets can cause radiative energy to become trapped within the urban form (Wang, Berardi, & Akbari, 2016). During the day, deep urban canyons with low SVF provide more shade at street level compared to open areas and because of this, pedestrians experience fewer periods of heat stress. However, during the night, open areas with high SVF are able to cool at a faster rate compared to deep urban canyons where absorbed radiation remains trapped between buildings causing higher evening temperatures (Erell, Pearlmutter, Boneh, & Kutiel, 2014). In addition, the orientation of urban canyons contributes to how much solar radiation is incident on the canyon surface. Urban canyons orientated along an East-West axis experience a greater period of solar exposure throughout the day compared to canyons orientated with a North-South axis. These findings suggested that when UHI reduction strategies are being selected for use within an existing urban form, both time of occupancy and the urban geometry will need to be taken into consideration. When designing new urban developments, the urban form can be designed to reduce UHI events. Wang, Berardi, & Akbari, (2016) suggested that an urban density of 0.3 and a building Height-to-Width ratio of 0.5 is the optimum urban form to reduce the effects of UHI.

4.2.1 Reflective materials

Compared to conventional urban materials, high albedo materials can reduce surface and air temperatures during the day by reflecting incoming solar radiation away from the surface. Typical urban materials, including asphalt and concrete have albedos in the range of 0.05 – 0.1 and 0.3 – 0.4 respectively, whereas the albedo of reflective surfaces tend to be greater than 0.5. In addition to the material's ability to reflect incoming solar radiation, its ability to store thermal energy, known as specific heat capacity [J kg^{-1} K^{-1}], is important. Specific heat is the measure of energy required to raise the temperature of one kilogram of substance by one decree Kelvin. Materials with a high specific heat can store a greater amount of thermal energy compared to materials with a low specific heat value. In order to ensure the reflectivity of urban materials over time, routine cleaning and maintenance should be conducted (U.S. Green Building Council, 2013). Based on their expected wear and soiling, high-traffic urban surfaces such as walkways or roads will likely require more maintenance to maintain their reflectivity over time.

Wang, Berardi, & Akbari, (2016) analyzed how reflective surfaces might affect the energy balance of structures and the thermal comfort of pedestrians within three urban areas of Toronto Ontario, Canada. Their results showed that the use of high albedo pavers within the analysed mid-rise area would have the greatest impact on street level surface temperatures compared to the low-rise and high-rise areas. It was suggested that these results are due to the lack of tree coverage in the analysed mid-rise areas compared to the low-rise area, and lack of shade compared to the high-ride area. However, the use of high albedo pavers achieved less than a 0.1 °C cooling effect on the ambient air temperature and increased the MRT in all three urban areas during the day, leading to periods of thermal discomfort for pedestrians due to the increase in radiant energy being reflected from the ground. When analyzing the use of cool roof material, the study found that rooftop surface temperatures could be reduced, but the effect of cool roof materials on the ambient air temperatures was again limited. In addition, because of the difference in elevation between roof heights and street level, there was a negligible change to the MRT experienced by pedestrians. In analyzing the use of urban vegetation, the authors found that a reduction of approximately 0.5 °C in air temperatures might be achieved, along with an approximately 6 °C reduction in MRT in all urban environments. In addition, reductions to the ambient air temperature and MRT were calculated into the night. Their results suggested that a combination of strategies is likely required to achieve sufficient cooling across diverse urban agglomerations and that careful consideration of the reflective characteristics, material properties, and implemented locations must be taken in order to achieve the right balance between building performance, pedestrian thermal comfort, and urban climate.

In another study, Erell, et al., (2014), sought to determine if increasing surface albedo had an effect on the thermal comfort of pedestrians. In their review, the aspect ratio, orientation and surface albedo of street canyons were varied to determine if there was any correlation between urban form, increased albedo and thermal stress. Their results showed that an increase in surface albedo would have a positive effect at reducing urban surface temperatures and a minor effect on reducing urban air temperatures in both North-South and East-West orientated urban canyons. However, despite the reduction in canyon surface temperatures, the results determined that the thermal comfort of pedestrians would be negatively affected by the increase in thermal energy acting upon them caused by the reflective surfaces. The results indicated that both urban form and surface albedo contribute to the multiple reflections of solar energy that can be incident on pedestrians.

An aspect that the report by Erell, et al., (2014) did not discuss is the possible positive improvements in thermal comfort that could be achieved after the sun sets depending on the specific heat capacity and thermal conductivity of the reflective materials. With less solar radiation being absorbed by a high albedo surface during the day, a surface with low specific heat capacity will have less thermal energy to release back into the urban environment at night (Yang, Wang, & Kaloush, 2015). The specific heat capacity of reflective surface materials was examined in a report by Wang & Akbari, (2016b) which compared black asphalt to granite pavers. In their study, the granite pavers had a larger albedo and specific heat capacity compared to the asphalt. During the day, the surface temperature and the air temperature above the granite paver was lower than that of the asphalt surface. However, as the sun-set, the surface temperature of the granite paver became greater than that of the asphalt surface due to the greater amount of thermal energy that was stored within the material. In addition to the specific heat capacity, the thermal conductivity [W m^{-1} K^{-1}] of the studied granite was greater than that of the asphalt, where thermal conductivity is a measure of the materials ability to transmit thermal energy. In the study, the high thermal conductivity of the granite pavers would cause the granite pavers to release thermal energy at a faster rate compared to the asphalt, which also contributed to the evening surface temperatures of the granite pavers being greater than that of the asphalt.

As highlighted by previous studies, a drawback of 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 building or pedestrians. The reflected energy can affect the overall energy balance of buildings and pedestrians, leading to periods where overheating and thermal discomfort can occur (Wang, Berardi, & Akbari, 2016). In order to reduce the diffuse scattering of radiation reflected from high albedo surfaces, the use of retro-reflective materials has been proposed. Retro-reflective materials are materials that can reflect radiation back along the incident direction. A review of current retro-reflective materials and their characteristics was completed by Wang, et al., (2021). In the study, retro-reflective materials were categorized into three main categories based on optical mechanism, including glass bead, capsule and prism retro-reflective materials. In regards to their reflective ability, prism retro-reflective materials were found to reflect more incoming radiation compared to bead and capsule retro-reflective materials. However, the prism retro-reflective materials were found to have a critical incident angle for retro-reflection, which limits their effectiveness to periods when incoming radiation within this angle. With their specified incident angle, prism retro-reflective materials can be used strategically to ensure that unwanted glare is not incident on other surfaces. Compared to prism retro-reflective materials, bead and capsule retro-reflective materials have no fixed critical angle, which making them better for vertical urban surfaces where the incident radiation is influenced by the sun's path. In terms of the durability of retro-reflective materials, the authors found that the retro-reflective characteristics of the prism style materials can be retained after cleaning, whereas bead and capsule systems will lose some of their reflectance over time due to surface degradation.

4.2.1.1 Cool roofs

Solar radiation striking a roof surface can have a significant effect on how much thermal energy a building absorbs. The use of roofing material that reflects short-wave radiation back to the atmosphere, results in lowering the roof surface temperature, and subsequent heat flux into the underlying structure. Reflective roofing material can be silicone-based and painted or sprayed onto a structure, or a membrane material that is attached to the roof via adhesive. The effectiveness of reflective roofing material is measured by Solar Reflectance Index (SRI) rating. Figure 7 shows the examples of cool-colored roofing materials in the market, where R is the reported solar reflectance.

Figure 7: Examples of cool-colored roofing materials in the market. R is solar reflectance. Image created by (author/NRC), informed by: Heat Island Group, Lawrence Berkeley National Laboratory, Berkeley, California, USA. (U.S. DOE, 2010)

Cool roofs maintain surface temperatures lower than those found on black roofs because of their low short-wave solar absorption coefficient. However, the energy savings potential and risk of condensation formation must be taken into consideration when designing a reflective roofing system. The moisture-related problems caused by reflective/cool roofing materials can lead to deterioration of roofing system, mold growth, and affecting the thermal performance by reducing the overall thermal resistance and service life of roofing systems. Several studies have investigated the moisture-related problems in commercial buildings. The focus was on single-ply roofing systems with highly reflective materials, white TPO/PVC, and black membranes, where the product is attached mechanically to a low slope roof. In their research (Saber, et al., 2012), conducted hygrothermal simulations for a one-year period on those roofing systems for Boston, Albany, Chicago, Cleveland, and Detroit. Two cases were studied: (1) 10% short-wave solar reflectivity for black roofs, and (2) 70% short-wave solar reflectivity for white roofs. Since those systems were mechanically attached to the metal deck and to account for the leakage due to the attachment, the vapour permeability of metal was considered 0.75 perms. The results showed that even though condensation was found below the membrane TPO/PVC in the winter, all roofs dried out in the summer.

Three roofing systems cases, dark, bright and shaded flat roofs, have been studied for their hygrothermal performance with initial construction moisture. In the summer, the results showed that the bright roofs have the lowest surface temperatures with a smaller drying potential than the other roofing systems. The highest surface temperature and humidity fluctuations were found in the dark roofs with high heat fluxes. In cases where roofs were shaded, lower surface temperatures and drying potential were found. Hygrothermal simulations on white and black Modified-Bitumen (MOD-BIT) roofing systems have been conducted to evaluate their energy and moisture accumulation for different climate zones in North America based on their Heating-Degree-Days (HDD) (Toronto (ON), Montreal (QC), St. John's (NL), Saskatoon (SK), Seattle (WA), Wilmington (AZ), and Phoenix (AZ)). In the cities of St. John's and Saskatoon, the white roofs showed the highest moisture accumulation over time compared to black surfaces, which could lead to moisture damage. On the contrary, there is no risk for the black roofs. The simulation results for Toronto, Montreal, Seattle, Wilmington, and Phoenix, showed that the white roofs have a low risk of experiencing moisture damage. The yearly heating loads of the white roof were slightly higher than that of the black roof. Conversely, the yearly cooling loads of the black roof were more important than the white roof. Thus, buildings with white roofs in these locations are predicted to result in net yearly energy savings compared to buildings with black roofs.

A second potential drawback of utilizing highly reflective materials on the roof 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 (U.S. DOE, 2010). However, there are natural factors that have already minimized the amount of solar energy that would be incident on building roofs during the winter. In the winter the sun follows a lower trajectory across the sky, leading to lower periods of solar exposure hitting the roof. In addition, when snow accumulates on the roof, the underlying surface reflectance becomes irrelevant and according to (U.S. DOE, 2010), in most cases, the winter heating penalty is less than the cooling energy savings.

A review conducted by Yang, et al., (2015) analyzed the environmental impacts of large-scale deployment of reflective materials in the urban environment. The authors found that when reflective roofs and pavements were simulated at a large scale across an urban environment, urban air temperatures became more stable. However, the change in local air temperatures altered the regional air-flow patterns and subsequently increased rural air temperatures due to the changing wind flow. As pointed out by Liu K., (2006) thorough energy and socioeconomic analysis will need to be conducted for diverse Canadian cities and where and how reflective materials are used within an urban environment will require special consideration.

4.2.2 Evaporative surfaces

Evaporative surfaces release absorbed solar heat 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 release of energy and cooler surface temperatures, a sufficient supply of water needs to be present. Vegetated surfaces store water within the plants and within the growing medium, while porous pavers retain water within the material. Permeable paving materials are materials that allow water to drain through to a sublayer below and rely on the sublayer to supply water for the cooling process. To a certain degree, these surfaces can be used to absorb and sequester rainwater, helping to reduce water runoff from otherwise impermeable urban surfaces. Like reflective surfaces, these surfaces require upkeep. In the case of the porous and permeable materials, cleaning involves the removal of debris from the pores, while the plants on the vegetated surfaces require nutrients and care. While vegetated surfaces may work well for open parks, porous materials may be a solution for areas that experience high rates of traffic.

In the review by Hendel (2020), the authors found that systems which store or retain water close to their surface could cool their surface temperatures between 5 and 15 °C lower than materials that did not have a mechanism for water retention. The authors also noted that porous pavers were able to maintain their cooling potential for longer compared to permeable materials that showed cooling rates immediately after wetting events. Vegetated pavers have the ability to achieve cooling levels greater than porous and pervious materials, however, due to their inability to resist mechanical stresses such as traffic and snow plowing, they are not suitable for all street level applications.

Through computer simulation, Kubilay, et al., (2021) found that an improvement to pedestrian thermal comfort could be achieved by irrigating porous pavers during a heat wave. In their study, the porous pavers were artificially wetted during the morning. The improvement to pedestrian thermal comfort was achieved through evaporative cooling of the pavement throughout the day, which in turn decreased the mean radiant temperature that the pedestrians were exposed to. The authors found that the cooling potential of the porous pavers was less than that achieved through the addition of urban trees within their studied area. However, it was recommended that a combination of strategies be used based on the fact that not every surface can sustain vegetation and that vegetated pavers have poor resistance to mechanical stress. In the report they analyzed evaporative surface relied on the manual wetting on a daily basis. This meant that in the event that the surface was not irrigated, no cooling would be achieved. A drawback to porous surfaces is that when the material is dry, the air with the voids acts like a thermal insulator and can result in an increased surface temperature during the summer (Hendel, 2020). This is less of a concern though during winter months when it could be seen as a positive outcome.

Another concern with permeable and porous surfaces is their ability to withstand winter freeze-thaw conditions. In certain cases, trapped water within a material can result in materials failure, due to expansions and contractions caused by the freezing and melting process. In a study conducted by Roseen, et al., (2012) the durability of permeable asphalt pavement installed in the heating-dominated climate of New Hampshire was analyzed. The authors determined that degradation due to winter freeze-thaw cycling could be avoided by varying the components of the aggregate. By varying the components of the aggregate mix, the size and number of pours within a mixture could be controlled, and with that, the correct balance between absorption, storage and dissipation of water could be found. The authors suggested that specific asphalt mixes would be required for each city based on the climate and traffic loads expected.

4.2.3 High inertia paving

High inertial paving works by increasing the thermal mass or storage capacity of a surface. Typically, high inertia paving materials make use of a phase change material, which store thermal energy in the phase change process. The transition of a solid to liquid phase change material occurs at a constant temperature and pressure while absorbing thermal energy. The exact same amount of thermal energy that was gained is then released when the process is reversed and the phase change material transitions from liquid to solid. During the day, pavements utilizing PCM will absorb and store incoming solar radiation while heating up slower and maintaining cooler surface temperatures compared to conventional pavements. However, during the night, the energy that was stored within the material will be released slower than conventional pavements, maintaining higher surface temperatures in the evening.

Despite high inertia paving being able to reduce daytime surface temperatures, the release of energy at night will only shift the UHI effects into the evening hours. When considering the total energy balance of an urban agglomeration, a net reduction in stored thermal energy is desired during the cooling season, which cannot be provided by only using PCMs.

5 Conclusions and implications to landscape and building design

Canada is warming at double the global average rate caused in part by a fast-growing population and extensive land transformations, with urban surfaces contributing to the urban heat island (UHI) phenomenon. The federal government released a strengthened climate plan in 2020, which emphasizes using Nature Based Solutions (NBS) to combat the effects of the UHI phenomenon.

This report provides a snapshot of the current understanding regarding the benefits and drawbacks when implementing NBS to buildings located in Canada. Specifically, this review focuses on how increasing surface greenery/vegetation (ISG) and increasing surface reflectivity (ISR) could affect the balance of thermal energy into and out of urban agglomerations, buildings (and resulting occupant thermal comfort), and outdoor environment (and resulting pedestrian thermal comfort), through a review of current literature, previous modeling, and experimental studies. Following the introduction (1), the report covered reviews on: (2) the changing and warming climate within Canada and how that may affect urban agglomerations; (3) the urban heat island effect and the thermal comfort of pedestrians and building occupants; and (4) approaches to mitigate the UHI effect.

Section two outlines the factors that are leading to increased urban temperatures and the risks associated with rising temperatures. With many strategies being proposed to mitigate the UHI effect, it is imperative to quantify how effective any one cooling strategy could be in any location under a warming climate. As such, both reginal and neighbourhood scale simulations will be required along with high-resolution climate data in both time and space.

Section three explains the effects that rising temperatures have on both buildings and urban inhabitants. With rising urban temperatures, and extreme heat events becoming more prevalent, the likelihood of overheating events occurring within buildings increases. These overheating occurrences put the health and wellbeing of vulnerable populations at risk, and as such finding ways to reduce the severity and frequency of these events is paramount.

Section four highlights the approaches that could be used to mitigate the UHI effects. However, when analysing the approaches, it became evident that there are both pros and cons associated with each UHI mitigation strategy and that there is not a singular solution for any application. While many studies have attempted to quantify the UHI reduction capabilities of different UHI mitigation strategies, more information is required to determine how these mitigation solutions would perform in urban environments across Canada. As such, section four provides an overview as to what parameters of each UHI mitigation strategy should be taken into consideration when evaluating their performance within a Canadian climate.

Both reflective/cool surfaces and urban vegetation have been shown to create a reduction in the UHI effect to some scale. Despite the review being able to provide a list of pros and cons of these strategies and a list of parameters that should be considered when analyzing their cooling potential, this literature review is not able to provide quantitative evidence,

- To show how a specific strategy would perform across Canada at reducing urban temperatures, operative temperatures, and conditioning loads of different building types,
- To recommend how much of and location(s) within a city of a strategy or combination of strategies should be used,
- To show that any of these strategies or combination of strategies would be sufficient at maintaining occupant thermal comfort in a warming climate.

In order to provide answers to these questions, computer simulations analyzing both changing climate and cooling strategies will need to be conducted. Considering the work that is required to achieve these answers, further suggestions can be made to streamline the investigations.

6 Proposed topics for Future work

The primary knowledge gaps in NBS – UHI are: I) the lack of scientific approaches and reliable/verifiable data to investigate the capability and adaptability of NBS in various climatic conditions; II) the lack of consistent guidelines to implement the NBS strategies. There is no coherent and consistent procedure to design, construct and maintain the ISR and ISG techniques on buildings' envelopes to mitigate UHI effects. The NBS scenarios should be tailored for each Canadian climatic zone to meet their specific requirements.

There is a 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. Bridging these knowledge gaps will help create best management practices and specifications to implement the NBS – UHI techniques in urban agglomerations across Canada. Accordingly, the Climate Resilience for Built Environment initiative in the National Research Council of Canada approved funding to address all the details and ramifications that require consideration for the NBS–UHI implementations. It is anticipated that this R&D project will provide a comprehensive guideline to promote the implementation of efficient solutions to mitigate the UHI effects. The road map as presented in Figure 8 consists of;

I) Providing approaches to lessen the UHI influences with respect to the implications of warming/changing climate, urban canopy/landscape characteristics and building design;
II) Development of the best management practices for NBS – UHI for Canadian communities;
III) Development of the guideline for the design of NBS–UHI solutions to mitigate UHI in accordance with Canadian design climatic load.

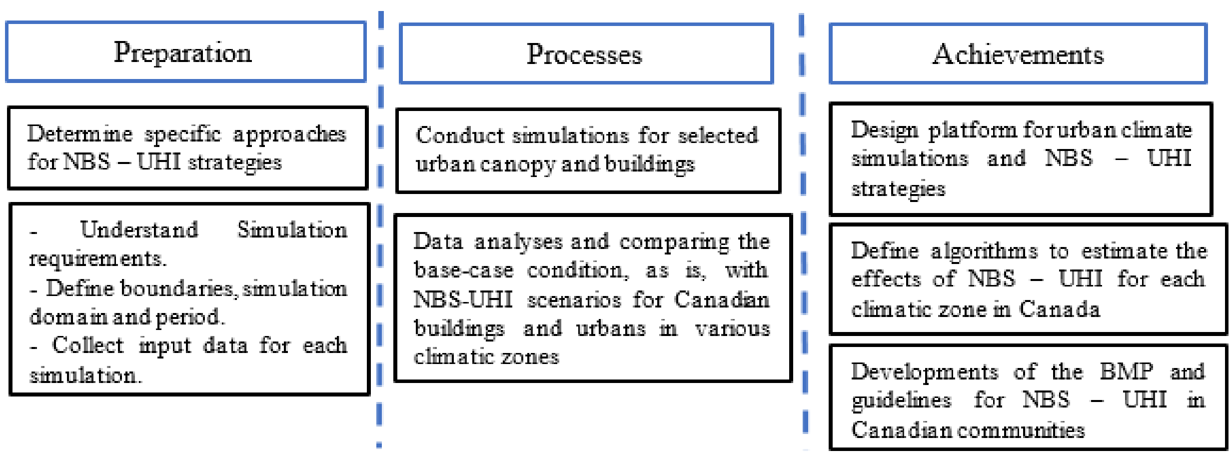

Figure 8: Future steps and road map toward goals of NBS – UHI strategies

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Appendix A - Definitions

Table 9: Special terms used within this literature review are defined as below.

Term	Definition
Thermal stress	Changes in human body (core and skin) temperatures due to the imposed environmental conditions, potentially leading to thermal discomfort, health problems, organ injuries, or death. (Laouadi, Bartko, Gaur, & Lacasse, 2021)
Albedo	The fraction of the incident radiation/solar energy that is reflected by a surface as an outgoing longwave radiation back into the space.
Anthropogenic Sources	Sources of heat originating from human activities including transportation and industry.
Sky View Factor (SVF)	The amount of sky that can be seen when looking upwards compared to the amount of unobstructed sky that would otherwise be available in a scale from 0 – 1, where 0 is no sky visible and 1 is an unobstructed open area with clear 360° view of the sky.
Leaf Area Index (LAI)	The amount of vegetation surface area per ground area [m^2 m^{-2}], LAI can range from 0.001 to 5 (Dahanayake & Chow, 2018)
Wall Leaf Area Index (WLAI)	The amount of vegetation surface area per vertical wall area [m^2 m^{-2}]
Evapotranspiration	Consists of the two processes of transpiration and evaporation.
Transpiration	Where water is released by living plants as a result of opening the stomata for CO_2 uptake, during the photosynthesis process. Transpiration is mainly driven by solar radiation, however it can be stimulated by ambient air temperatures, where transpiration during the night is limited compared to the day. Dependant on plant species, WLAI, air temperature, air humidity, wind speed and substrate water availability (Koch, Ysebaert, Denys, & Samson, 2020).
Evaporation	The transfer of water to the air from the soil or from standing water. Water can be stored in the growing substrate, or on the surface of the plant such as dew.
Physiological Equivalent Temperature (PET)	Defined as the air temperature at which the human energy budget is maintained by the skin temperature, core temperature, and sweat rate equal to those under the conditions to be assessed, considered for outdoor thermal comfort. (Wang, Berardi, & Akbari, 2016)