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URBAN HEAT ISLAND MITIGATION STRATEGIES: 2021 UPDATE

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SYNTHESIS OF KNOWLEDGE

Québec

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FOREWORD

In November 2007, the Ministère de la Santé et des Services sociaux gave the Institut national de santé publique du Québec a mandate to manage the health section of Initiative 21 of *The Action Plan on Climate Change*. In the context of its deliberations, in 2009 the INSPQ published a literature review focusing on measures to mitigate urban heat islands. It was produced mainly for the municipalities and non-profit organizations that work in the field to mitigate urban heat islands and promote the preventive adaptation of programs and infrastructure to climate change. This literature review has become a reference to implement local preventive demonstration projects to deal with the phenomenon.

Given the proliferation over the past 10 years of new scientific studies devoted to measures to mitigate urban heat islands, it seemed not only timely to update the information and references presented in the review but also to review the overall data, especially those available for the hottest years recorded in Québec, climate projections, the impact on morbidity and mortality of urban heat islands, and so on. Moreover, numerous promising projects to mitigate urban heat islands have been implemented since 2009, especially in the context of the Québec government's climate change action plans.

This literature review cannot replace the recommendations of experts in fields such as architecture, urban planning, transportation, and engineering concerned by the fight against urban heat islands. It affords a comprehensive view of existing measures and reports on certain studies that have tested their efficacy in terms of cooling. The literature review was submitted to 11 revisers, seven of them external, who are specialists in the fields of expertise that the control measures listed cover. The necessary corrections were made in the wake of their comments. The authors assume sole responsibility for errors or omissions in the text.

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GLOSSARY

To facilitate the reader's understanding, specialized technical terms used in this literature review have been defined. Accordingly, terms in bold face when they appear for the first time in the text are defined in the glossary.

Adaptation

The process of adjusting to the current or anticipated climate and its consequences. In the case of human systems, this implies mitigating the detrimental impacts and harnessing the beneficial effects. In the case of natural systems, human intervention can facilitate adaptation to the anticipated climate and its consequences.[1]

Albedo

The fraction of incident solar radiation reflected by a surface or object.[2]

Chimney effect

The upward movement in the air inside a building or a duct because the air is hot and thus lighter than the outside air. This movement draws fresh air into the bottom of the building or duct and expels hot air upward to the exterior.[3]

Convection

The process by which heat is transferred between a fluid in movement and a solid surface in contact with the fluid.[4]

Glare

The measurement of an occupant's physical discomfort caused by a light or excessive contrast in the field of vision.[5]

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2 Gago, E. J., Roldan, J., Pacheco-Torres, R., and Ordóñez, J. (2013). The city and urban heat islands : A review of strategies to mitigate adverse effects. *Renewable and Sustainable Energy Reviews*, *25*, 749-758. https://doi.org/10.1016/j.rser.2013.05.057

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5 Jakubiec, J., and Reinhart, C. (2012). The 'adaptive zone' – A concept for assessing discomfort glare throughout daylit spaces. *Lighting Research and Technology*, *44*(2), 149–170. https://doi.org/10.1177/1477153511420097

Green infrastructure

The entire array of natural and semi-natural systems, from trees to green belts, that make services essential to individual and community well-being, from the fight against urban heat islands to the control of runoff and the enhancement of air and water quality.[6]

Heat capacity

The amount of heat to be supplied to a unit mass of material to produce a unit change in its temperature.[7]

Sky view factor

The measurement of the opening to the sky in an urban fabric that affects climatological phenomena such as urban heat islands, natural lighting, and heat absorption.[8]

Solar radiation

All the rays that the sun emits. Light is the visible part of the radiation and corresponds to the range of wavelengths comprised between 380 and 780 nanometres, which extends from blue to red and including green and yellow. Ultraviolet is the shortest wavelength of solar radiation, partially intercepted by the ozone layer in the upper atmosphere. Beyond the visible spectrum, solar radiation of greater wavelength is called “infrared” (heat), partly absorbed by water vapour in the atmosphere.[9]

Transit-oriented development

An approach geared to structuring urban transit and mass transit. It proposes the establishment of communities in which the inhabitants can readily access on foot, i.e., within a radius of roughly 600 m, a core of services and stores and a mass transit station.[10]

Urban morphology

The urban forms over time of cities, towns, and villages. Their spatial models on different scales and physical features reveal the appropriate urban initiatives to promote sustainable urban development.[11]

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6 Rayfield, B., Dupras, J., Francoeur, X., Dumitru, M., Dagenais, D., Vachon, J., Paquette, A., Lechowicz, M., Messier, C., and Gonzalez, A. (2016). *Les infrastructures vertes : un outil d'adaptation aux changements climatiques pour le Grand Montréal*. Fondation David Suzuki. https://www.deslibris.ca/ID/248812

7 Li, Y., et Ren, S. (dir.). (2011). 2-Basic properties of building decorative materials. Dans *Building Decorative Materials* (p. 10-24). Woodhead Publishing. https://doi.org/10.1533/9780857092588.10

8 Nikolopoulou, M. (2004). *Concevoir des espaces extérieurs en environnement urbain : une approche bioclimatique*. Center for Renewable Energy Sources.

9 Salomon, T., and Aubert, C. (2003) *Fraîcheur sans clim'*. Terre Vivante.

10 Vivre en Ville. (2014). *Retisser la ville, [ré] articuler urbanisation, densification et transport en commun*.

11 Chen, F. (2014). Urban Morphology and Citizens' Life. In A. C. Michalos (dir.), *Encyclopedia of Quality of Life and Well-Being Research* (p. 6850-6855). Springer Netherlands. https://doi.org/10.1007/978-94-007-0753-5_4080

INITIALISMS AND ACRONYMS

ADEME	Agency for Environment and Energy Management
GHG	Greenhouse gases
INSPQ	Institut national de santé publique du Québec
IPCC	Intergovernmental Panel on Climate Change
MAMROT	Ministère des Affaires municipales, des Régions et de l'Occupation du territoire
MDDEFP	Ministère du Développement durable, de l'Environnement, de la Faune et des Parcs
MELCC	Ministère de l'Environnement et de la Lutte contre les changements climatiques
Mt CO_2 eq.	Millions of tonnes of carbon dioxide equivalent
UHI	Urban heat island
U.S. EPA	United States Environmental Protection Agency
UV	Ultraviolet
WHO	World Health Organization

HIGHLIGHTS

- This literature review covers measures to mitigate urban heat islands that decision-makers and public and private property managers, municipal stakeholders, non-profit organizations, and other project designers can implement in Québec to ensure healthy, comfortable living environments.
- Urban spread, the loss of crown cover, soil sealing, the use of heat-retaining materials, heat and greenhouse gas emissions stemming from human activities, and urban morphology with dense neighbourhoods and narrow streets are causal factors in urban heat islands. Rising temperatures and more frequent heat waves against a backdrop of climate change are likely to exacerbate their impact.
- Urban heat islands can have detrimental environmental impacts such as the deterioration of air quality and adversely affect human health and well-being. Certain factors for increased vulnerability to heat such as age and chronic diseases warrant paying particular attention to certain populations when adaptation measures are implemented. Urban heat islands, which are often situated in underprivileged neighbourhoods, are also contributing to social inequalities in health.
- Permeable materials facilitate district cooling by fostering water infiltration in the soil and evaporation, whereas high-albedo materials promote the cooling of cities by preventing the absorption of solar radiation.
- Greening measures engender high cooling gains in urban settings. When vegetation is used on the roofs or walls of buildings, it improves their insulation by keeping them cool in the summer and limiting heat loss in the winter. However, climate change is affecting plants (heat, insects). It is, therefore, important to plant more trees but also to carefully choose them to limit deleterious impacts on health and the risk of canopy loss stemming from different meteorological hazards.
- Existing and new buildings must be adapted to climate change. Recourse to air conditioning alone must not be considered to cool homes. Complementary solutions must be explored. Challenges that urban heat poses are to be considered in building architecture, e.g., bioclimatic architecture, and in urban planning, e.g., urban morphology.
- Blue spaces such as lakes and ponds can alternately act as a source of heat or cooling in urban environments. Such spaces with large areas are usually more effective from the standpoint of cooling, as is circulating water in rivers or when technologies based on water evaporation such as fountains are used. Reliance on green infrastructure in stormwater management engenders numerous benefits, including the mitigation of urban heat islands, resilience to flooding, and improved water quality.

- In addition to enhancing thermal comfort conditions, the implementation of measures to address urban heat islands engenders numerous human mental and physical health benefits and prevents heat-related morbidity and mortality.
- The combination of several large-scale measures is necessary and helps to reduce heat in cities. Community involvement in projects to mitigate urban heat islands guarantees success, as reported both in the literature and in case studies.

SUMMARY

This literature review briefly examines methods to mitigate urban heat islands. Climate change is already increasing the number of high-heat days, a trend that will continue in the coming years. It is, therefore, important to bolster the resilience to heat of cities and buildings for the benefit of the health of the population.

Context

In 2009, the Institut national de santé publique du Québec published an initial literature review devoted to measures to mitigate urban heat islands. It was intended mainly for on-site responders from non-profit organizations and the municipalities to support the fight against urban heat islands and preventive adaptation to climate change in programs and infrastructure. Given the abundance of scientific literature concerning the efficacy of measures to mitigate urban heat islands over the past 10 years, it is desirable to update the information. Moreover, case studies are documented to illustrate possible means of combating the phenomenon.

Although the review in no way replaces the opinions of experts in the fields of land-use planning, architecture, and engineering, it affords an overview of existing measures to mitigate urban heat islands and reports certain studies that have tested their efficacy in terms of cooling gains.

They are listed according to four main categories, i.e., revegetation measures, measures related to sustainable urban infrastructure, stormwater management and soil permeability measures, and measures to reduce anthropogenic heat, caused by human beings.

THE DEFINITION OF URBAN HEAT ISLANDS

> **The expression “urban heat islands” means the temperature difference observed between urban environments and surrounding rural areas, or between the areas in an intra-urban perimeter. Air temperatures in urban centres can be as much as 12°C higher than in adjoining regions.**

The causes of urban heat islands

In addition to the local climate, affected by meteorological parameters such as temperature, relative humidity, and wind, several human-induced causes are fostering the emergence and intensification of urban heat islands. Such causes are greenhouse gas emissions, the gradual loss of crown cover in urban areas, impermeability, the low albedo and thermal properties of materials, urban morphology and the size of cities, and anthropogenic heat.

Impact

Urban heat islands can adversely affect both the environment and health during heatwaves. They contribute to the deterioration of outdoor and indoor air quality and to higher demand for energy and water.

The health-related direct impacts of heat include dehydration, hyperthermia, heat exhaustion, or heatstroke. Heat can also exacerbate the symptoms of pre-existing chronic diseases such as diabetes, mental health disorders, respiratory failure, and cardiovascular, cerebrovascular, neurological, and renal diseases, sometimes fatally.

Certain individuals are more vulnerable to heat, such as those suffering from chronic diseases, persons living alone or experiencing a loss of autonomy, children under 4 years of age, pregnant women and their foetuses, or individuals who work in hot environments or engage in intense exercise. Lastly, the elderly, individuals with mental health disorders, and the economically disadvantaged are groups at greater risk during extreme heat events.

Thermal comfort and air conditioning

To reduce individual vulnerability and promote well-being, ambient temperatures must neither be too low nor too high. While thermal comfort is specific to each individual, the acceptable temperature range for most people inside buildings appears to fall between 20°C and 24°C in the winter and between 24°C and 26.5° C in the summer.

Unlike central air conditioners, it has been observed that mobile or window air-conditioning units are less effective in reducing health hazards, except in the case of small volumes of air, e.g., dwelling units with one to three rooms. The size of dwelling units thus appears to affect the efficacy of certain types of air conditioners. In light of the consequences of reliance on large-scale air conditioning, especially on urban heat islands, it is important to contemplate more sustainable solutions both for the environment and the health of current and future generations. Such solutions must focus on considerations that will affect both the causes of climate change and adaptation to such change.

Measures to mitigate Urban Heat Islands

Increased albedo in cities through the use of pale materials in infrastructure and buildings promotes cooling by reflecting large amounts of solar radiation. Reflective surfaces thus have a lower temperature than that of conventional coverings such as asphalt and tar and release less heat at night. The impact of high albedo on surface temperature reduction is more significant on sunny days than on cloudy days.

Urban greening actively moderates temperatures through the evapotranspiration process and passively with the shading of surfaces. The highest distance and intensity of the cooling impact concern major urban parks. The sound growth of trees is essential for them to provide cooling and may depend on soil quality, the availability of water, and sufficient space for the optimum spreading of the root system. Vegetation has an average cooling effect of 1°C to 4.7°C extending from 100 m to 1 000 m in urban areas but is heavily dependent on the amount of water available to plants or trees. The enhanced resilience of urban forests subject to various meteorological hazards can be assured through the functional diversity approach, which consists in selecting species with diversified biological traits to limit the risk of canopy loss. The diversification and increasing complexity of green spaces, especially grassy areas, can be effective in improving their ecological performance from the standpoint of temperature regulation. The revegetation of parking lots creates shade on asphalted surfaces and protects the coverings from major thermal shifts and prolongs their useful life.

It is also possible to lower the indoor temperature of buildings by means of the insulation that plant walls, green roofs, or vegetation planted on the periphery of buildings provide, which keeps heat outside in the summer and inside in the winter. Against a backdrop of growing urbanization, plant walls and green roofs are deemed a promising approach to green cities where green spaces are rare and space on the ground is limited. Similarly, they protect buildings from ultraviolet rays and significant temperature fluctuations. All urban greening measures afford additional benefits, i.e., improved air and water quality, enhanced urban biodiversity, reduced energy consumption, carbon sequestration, reduced noise, better stormwater management, physical and mental health benefits, and aesthetic and, in certain cases, recreational functions.

Blue spaces refer to outdoor urban surfaces mainly dominated by water, e.g., lakes, rivers, ponds, and fountains. Urban blue spaces can simultaneously act as a source of cooling, through evaporation, or a source of heat because of thermal inertia and produce water vapour, thereby creating thermal discomfort in some instances. The cooling effect of blue spaces varies according to the time of day and the season. Accordingly, urban blue spaces do not necessarily act as a cooling agent throughout the day since their surface can reach higher temperatures than their urban environment at night or early in the morning, thereby producing a warming effect. The influence of the geometry and the diversity of urban blue spaces requires more extensive research. Relatively strong winds above the water surface increase evaporation and accentuate the cooling effect. While circulating water such as a river has a more significant cooling effect than stagnant water, the technologies based on water evaporation such as those of a fountain afford the greatest cooling effect. Urban blue spaces can generate between 1°C and 3°C of cooling effect within a perimeter of roughly 30 m.

Limiting soil sealing enhances stormwater management from both a qualitative and a quantitative standpoint. Sustainable stormwater management is an approach that offers numerous benefits that extend beyond the simple mitigation of flooding and water quality. It must be deemed a means of combating climate change and phenomena such as urban heat islands that climate change exacerbates. By reducing runoff, the water that infiltrates soil can cool the ambient air through evaporation. It is also essential to consider challenges related to urban heat in architecture and urban planning on a scale ranging from individual buildings to entire cities, especially by initiating reflection aimed at transforming urban areas to make them denser and enable residents to opt for public and active transportation.

Measures to mitigate urban heat islands are more effective in combination. Such measures are numerous and concern areas of expertise such as urban planning, engineering, architecture, landscape architecture, natural resource management, and transportation. They have a positive impact on local and global climate. In addition to fostering cooling in urban areas, the measures engender numerous co-benefits, especially reduced energy demand, the reduction at the source of water and air pollution, including reduced greenhouse gas emissions, better stormwater management, and increased urban biodiversity.

This literature review briefly examines the measures to mitigate urban heat islands. Climate change is already increasing the number of intensive and extreme heat days, a trend that will continue in the coming years. It is, therefore, important to bolster the resilience to heat of cities and buildings for the benefit of the health and comfort of the population. While this literature review in no way replaces the opinions of experts in different fields of land-use planning, architecture, and engineering, it does review the key thermal management tools. The review describes the measures and discusses their effectiveness from the standpoint of cooling gains. Case studies have also been elaborated to illustrate the different possibilities (see Section **Erreur ! Source du renvoi introuvable.**).

1 INTRODUCTION

Context

According to the World Meteorological Organization, the years 2015 to 2019 were the hottest years ever recorded around the world (World Meteorological Organization, 2020). From 1948 to 2016, the mean annual temperature increased by 1.7°C for Canada as a whole, double the figure for the rest of the world (Environment and Climate Change Canada, 2019). In Québec, 9 of the 10 hottest years have been observed since 1998 (Ministère de l'Environnement et de la Lutte contre les changements climatiques [MELCC], 2021a), a phenomenon attributable to increased atmospheric greenhouse gases (GHG).

Two factors can affect rising temperatures in urban environments, i.e., climate change, and local conditions specific to the city (Dong *et al.*, 2017). According to the projections of the Intergovernmental Panel on Climate Change (IPCC), it is very likely that numerous cities in the world will experience an increase in the frequency and duration of heatwaves (IPCC, 2015). According to the high emissions scenario (RCP 8.5), it is anticipated that the annual number of days on which the maximum temperature exceeds 30°C will triple between 2041 and 2070 in most Québec cities compared with the reference period from 1981 to 2010. In Montréal, the figure would rise from 12.3 days to 42.8 days, an increase of more than 30 days (Ouranos, 2020).

This constant increase in the observed and projected temperature exacerbates a known problem, the urban heat island (UHI) effect. This phenomenon is characterized by higher summer temperatures in urban areas than in the surrounding rural areas and also between the zones in an intra-urban perimeter, e.g., between a parking lot and an adjacent park. This temperature difference stems mainly from the built urban environment. UHI can refer to differences in the air temperature or at ground level, where it is possible to establish urban areas with the hottest surfaces (see Section 2.1). According to observations, the average air temperature in medium-sized to large cities in North America is usually from 1°C to 3°C hotter than that in surrounding rural areas and can reach up to 12°C higher in certain places, which is particularly threatening for urban populations (Oke, 1997, cited in Oke *et al.*, 2017). Such differences can be even greater when the surface temperatures of an intra-urban UHI are compared: a 17°C difference was recorded between a park and a nearby parking lot in the borough of Saint-Laurent (Cavayas and Baudouin, 2008).

The heatwaves in Québec in the summer of 2010 were especially intense and led to 3 400 emergency department admissions and 280 additional deaths[12] (Bustinza *et al.*, 2013). The summer of 2018 was the hottest recorded in 146 years of meteorological observations in southern Québec. While excess mortality was lower than in 2010, 86 additional deaths[13]

[12] Significant excess deaths possibly linked to heat in 2010, compared with 2008 and 2009.

[13] Significant excess deaths possibly linked to heat in 2018, compared with the period 2013 to 2017.

occurred. More targeted, effective **adaptation** measures, in particular, may explain such differences. The fact remains that repercussions on the healthcare system from the standpoint of hospitalizations, ambulance transportation, and emergency department admissions are significant (Lebel *et al.*, 2019).

Many cities have adopted measures to mitigate UHI. Such initiatives protect the public by enhancing adaptability to such phenomena. The World Health Organization (WHO) emphasizes that in the absence of a high level of adaptation, the heat-related morbidity burden will increase against a backdrop of climate change and highlights the need to broaden efforts related to health action plans to combat heat (WHO, 2021). The WHO recommends that all levels of government adopt measures to protect populations against extreme heat (McGregor *et al.*, 2015).

Objectives

This publication updates a literature review focusing on measures to mitigate urban heat islands produced in 2009. Its broad objective is to update the literature review on the measures to mitigate UHI to share current information and present case studies that illustrate the measures. More specifically, the update seeks to:

- compile a list of the key means to mitigate UHI in the scientific literature and grey literature between 2009 and 2020;
- list the measures to mitigate UHI according to the four main categories in Giguère's review (2009), i.e., revegetation measures, measures related to sustainable urban infrastructure, stormwater management and soil permeability measures, **anthropogenic** (human-induced) heat reduction measures, and other categories if need be, depending on changing scientific knowledge;
- provide an overview of measures to mitigate UHI potentially applicable in Québec;
- document, by means of case studies, promising examples of achievements to mitigate UHI in the Québec health and social services network and other organizations.

This review is mainly aimed at public health branch professionals, property managers in the health and social services network and the government, and on-site responders in non-profit organizations and the municipal sector. It seeks to inform them of the most recent measures to mitigate urban heat islands potentially applicable in Québec and the measures that foster cooling in urban environments, and to equip them to make decisions and intervene with the populations most vulnerable to heat.

This literature review first defines an urban heat island and presents its main causes (Section 2) and impacts (Section 3). The areas subject to UHI in Québec are also examined (Section 4). The review then lists the measures to mitigate UHI adapted to Québec cities according to four categories (Section 5): (1) greening measures; (2) measures pertaining to sustainable urban infrastructure; (3) sustainable stormwater management measures; and (4) anthropogenic heat reduction measures. Section 5.6 presents a summary of the measures to mitigate UHI. Lastly, several applications of such measures carried out in Québec cities are proposed as case studies (Section 6).

Appendix 1 describes the methodology used to locate the scientific articles and publications from the grey literature. Appendix 2 indicates the evaluation process of different literature reviews selected in the context of this review.

2 URBAN HEAT ISLANDS: DEFINITION AND CAUSES

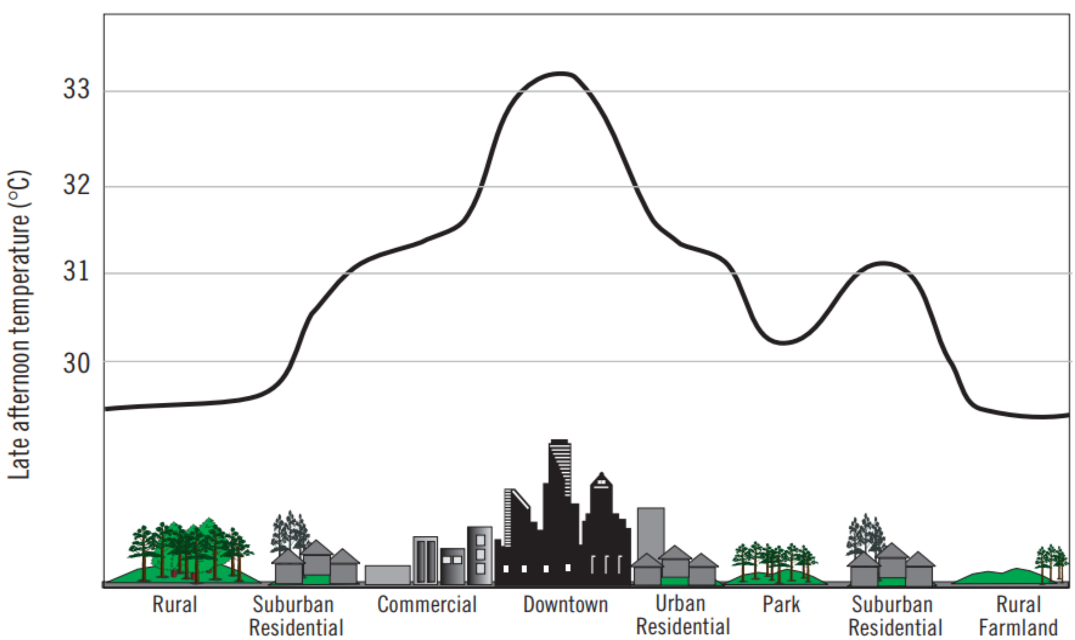
Several studies in recent years have shown that rising temperatures in cities accentuated by UHI engender significant adverse impacts on the social, environmental, and economic dimensions of cities (Akbari *et al.*, 2015). Consequently, it is essential to explore the causes and impacts of UHI and the sustainable strategies aimed at mitigating them and adapting to them (see Section 2.2).

2.1 Definition

The city as a whole modifies weather and environmental conditions, which engenders differences between the city and the surrounding rural area, especially from the standpoint of cloud cover, precipitation, air temperature, wind speed, and so on. The geometry, spacing, and orientation of buildings and outdoor space affects the city's weather and environmental conditions, which can vary considerably over a distance of several metres. The UHI effect is one of the best known impacts of the influence of the urban environment on such conditions (Kleerekoper *et al.*, 2012).

The expression "urban heat islands" means the temperature difference observed between urban areas and the surrounding rural areas. Observations have shown that the air temperature in urban centres can be up to 12°C higher than in neighbouring regions (see Figure 1) (Oke, 1997, cited in Oke *et al.*, 2017).

Figure 1 Profile of an urban heat island



Source: Natural Resources Canada (2004)

The literature distinguishes three types of UHI.

- Ground level heat islands: it is possible to detect the location of the hottest surfaces in a city by means of readings of the infrared rays emitted and reflected by surfaces.
- Urban canopy heat islands encompass the layer of air between the ground and the treetops or the roofs of buildings, where most human activity takes place.
- Urban boundary layer heat islands are situated above the canopy layer.

Urban canopy and urban boundary layer heat islands refer to the air temperature (Oke, 1982; Voogt, 2002).

The intensity of UHI changes on a daily and a seasonal basis according to the meteorological and anthropogenic parameters presented in Section 2.2. The intensity of urban canopy heat islands is usually higher at night than during the day (Pigeon *et al.*, 2008; Oke, 2009; Oke *et al.*, 2017; Filho *et al.*, 2017).

2.2 Causes

In addition to the local climate, affected by meteorological parameters such as temperature, relative humidity, and wind, several human-induced causes are fostering the emergence and intensification of UHI. Such causes are greenhouse gas emissions, the gradual loss of crown and vegetation cover in urban areas, impermeability and the low **albedos** of materials, the thermal properties of materials, **urban morphology** and the size of cities, and anthropogenic heat.

2.2.1 Greenhouse gas emissions

GHG retain solar energy in the atmosphere and thus contribute to heating it. According to the IPCC, if GHG emissions continue, they will cause additional heating and a lasting change in all components of the climate system, which will probably increase the likelihood of serious, widespread, irreversible consequences for populations and ecosystems. It adds that it is very likely that the frequency and duration of heatwaves will increase and that extreme precipitation will become more intense and more frequent in many regions (GIEC, 2015). According to Ouranos' climate projections, Québec is one such region (Ouranos, 2020). In 2018 in Québec total GHG emissions produced by human activity corresponded to 80.6 Mt of carbon dioxide equivalent (Mt CO_2 eq.), equivalent to 11.1% of Canadian emissions, which stood at 729.3 Mt CO_2 eq. For the same year, Québec had the lowest per capita GHG emission rates of the Canadian provinces and territories and hydroelectricity accounted for 93.3% of total electricity generation. The main sources of GHG in urban areas in Québec are vehicles, industrial processes, industrial combustion, and building heating using fossil fuels (Delisle *et al.*, 2020). GHG contribute to global warming. A lower GHG emission rate for the province does not mean that UHI are less important in Québec.

2.2.2 Crown cover in urban areas

Faced with the gradual loss of urban forests, cities have adopted reforestation plans. Policies pertaining to trees have proliferated in Québec municipalities and local commitments to planting abound. However, such initiatives do not immediately produce results and urban sprawl is simultaneously continuing at an accelerating rate. In particular, urban sprawl in the Montréal and Québec City census metropolitan areas has increased rapidly and more drastically over the past 25 years (Nazarnia *et al.*, 2016). Consequently, a slight decrease was observed between 2017 and 2019 in the Montréal metropolitan canopy index (Communauté métropolitaine de Montréal, 2020). The canopy index for Greater Montréal decreased from 26.2% to 26% during this period, a 764-ha reduction (Communauté métropolitaine de Montréal, 2021).

The loss of crown cover in urban environments is largely attributable to urban sprawl stemming from residential, commercial, or industrial development and the absence of adequate protection for vegetation cover. Urban planted species, especially dominant species, often share the same characteristics or functional traits, which reduces the resilience of the urban forest since the species are sensitive to the same types of stress (Paquette, 2016). In Québec, as elsewhere, insects and disease have also decimated certain tree populations, especially ash and elm. The emerald ash borer, an insect that indiscriminately attacks all species of ash and decimates them in only a few years, has led to the disappearance of a number of ash trees on streets, in parks, and on private land in urban centres (Communauté métropolitaine de Montréal, 2020). According to an American study conducted in 15 states under observation over a period of five years, the emerald ash borer caused the loss of 100 million trees and was responsible for 6 113 additional deaths attributable to respiratory diseases and 15 080 deaths related to cardiovascular disease (Donovan *et al.*, 2013). Climate change is also engendering additional stress on trees in urban areas already subject to ongoing stress through soil compacting and lack of space and are likely to adversely affect the ecosystem services that trees render, especially the myriad benefits that they offer for the quality of life of residents (Paquette, 2016).

This loss of vegetation implies a loss of cooling in urban settings. Indeed, vegetation plays an essential role in protecting against heat through the phenomenon of evapotranspiration and shading of soil and buildings. During the natural process of the evapotranspiration of water vapour, the ambient air cools by releasing part of its heat to allow for evaporation. Vegetation also contributes to sound stormwater management and enhanced air quality in cities (Bolund and Hunhammar, 1999; Akbari *et al.*, 2001; English *et al.*, 2007; Cavayas and Baudouin, 2008; Gago *et al.*, 2013).

2.2.3 The impermeability of soils

The intensification in recent decades of urbanization has also modified the types of soil coverings. Natural soils have been replaced by impermeable materials such as asphalt and building construction materials that do not allow for water filtration and absorption modify the natural path of stormwater (Rushton, 2001; Mailhot and Duchesne, 2005; Coutts *et al.*, 2010; Ministère du Développement durable, de l'Environnement, de la Faune et des Parcs [MDDEFP] and Ministère des Affaires municipales, des Régions et de l'Occupation du territoire [MAMROT], undated; Dagenais *et al.*, 2014). Indeed, in a high-density neighbourhood, the runoff rate can reach up to 55% while in a natural environment it is roughly 1% to 10% (Puget Sound Action Team and Washington State University Pierce County Extension, 2012, Federal Interagency Stream Restoration Working Group, 2001, cited in David, 2017).

Natural cooling processes such as water evaporation in soils and the evapotranspiration of vegetation are also restricted and cannot offset urban warming (Brattebo and Booth, 2003, UCAR, 2011, cited in Filho *et al.*, 2017). What is more, impermeable surfacing contributes to the contamination of receiving watercourses through:

- runoff that carries numerous pollutants such as hydrocarbons and pollutants;
- overflowing sewers caused by heavy rains;
- riverbank erosion stemming from the high speed of runoff (Dagenais *et al.*, 2014).

According to the climate scenarios, such detrimental effects risk increasing in southern Québec, where cities will experience heavier rainfall events (Ouranos, 2020).

2.2.4 The thermal properties of surfacing materials

Concrete and asphalt, the materials commonly used to build roads and roofs, have thermal properties, including **heat capacity** and thermal conductivity, and surface radiative properties (albedo and emissivity) that differ significantly from ambient rural areas (Aflaki *et al.*, 2017). Impermeable surfacings and building materials affect the microclimate and thermal comfort conditions since they absorb a great deal of heat during the day and release it into the atmosphere at night, thereby contributing to the UHI effect (Asaeda *et al.*, 1996; Fernández *et al.*, 2015). Certain low-albedo materials can reach temperatures of 80°C in the summer (Liébard and De Herde, 2005; Li *et al.*, 2013). The use in cityscapes of heat-retaining materials combined with the lack of evapotranspiration, for example, because of limited vegetated areas, thus contributes to the appearance of UHI (Chen *et al.*, 2009, O'Malley *et al.*, 2015, Schrijvers *et al.*, 2015, Smith and Levermore, 2008, cited in Aflaki *et al.*, 2017).

2.2.5 The morphology and size of cities

Urban morphology, which refers to three-dimensional forms, orientation, and the spacing of buildings in a city, also plays a role in the formation of UHI (United States Environmental Protection Agency [U.S. EPA], 2008b; Touchaei and Wang, 2015; Aflaki *et al.*, 2017; Valladares-Rendón *et al.*, 2017). The presence in major cities of tall buildings can offer numerous surfaces for the reflection and absorption of solar radiation and is likely to accentuate heat in urban areas (Fernández *et al.*, 2015). The amplitude of the UHI is closely linked to the size of the city (Imhoff *et al.*, 2010). Furthermore, densely built neighbourhoods and narrow streets reduce air flow and impact of natural cooling by retaining and preventing heat from rising skyward (UCAR, 2011, cited in Filho *et al.*, 2017; Lai *et al.*, 2019). Urban morphology is usually quantified by the following parameters: the **sky view factor** for irregular, complex spaces, or the ratio of building height to street width and the orientation of street canyons (Lai *et al.*, 2017). The sky view factor is a scale-free number ranging from 0 to 1 that represents the amount of visible sky from a given point (Oke, 1988, cited in Lai *et al.*, 2019). A low sky view factor indicates greater obstruction of the sky by urban elements such as buildings and trees, which limits the entry of **solar radiation** and promotes the retention of the long-wavelength radiation[14] that urban surfaces emit (Lai *et al.*, 2019).

2.2.6 Heat generated by human activities

Heat generated by human activities such as heat emitted by vehicles, air conditioners, and industrial activity, is another factor that contributes to the UHI effect (U.S. EPA, 2008b; Yang *et al.*, 2016; UCAR, 2011, cited in Filho *et al.*, 2017). This additional heat stemming from human energy consumption is commonly called “anthropogenic heat” (Dong *et al.*, 2017). Rising temperatures resulting from anthropogenic heat emissions could lead to growing energy demand for cooling, especially through air conditioning, which in turn leads to increased anthropogenic heat emissions (Crutzen, 2004, cited in Dong *et al.*, 2017). It has been revealed that anthropogenic heat from the transportation and building sectors depends on population density (Flanner, 2009, Allen *et al.*, 2011, cited in Dong *et al.*, 2017).

[14] The solar radiation that Earth receives comprises short-wavelength electromagnetic waves, roughly 30% of which are reflected into space. Non-reflected radiation (roughly 70%) is partly absorbed by the atmosphere (23%) and partly by the Earth’s surface (47%), which is thus heated. The energy that surfaces absorb is re-emitted in the form of long-wavelength electromagnetic waves, i.e., in thermal infrared (*Termium Plus*, 2021).

3 THE IMPACTS OF URBAN HEAT ISLANDS

Urban heat islands can adversely affect the environment and health during heatwaves.

3.1 Environmental impacts

3.1.1 The deterioration of outdoor air quality

UHI contribute to the formation of summer smog. Smog is mixture of fine particles and ground-level ozone, which is formed by the reaction of pollutants (nitrogen oxides) and volatile organic compounds in the presence of sunlight and heat. Indeed, a greater quantity of pollutants is released in the presence of heat, thereby accentuating smog formation. Air pollution and heatwaves act upon each other (Reeves, 2011). According to a study by Akbari (2005) from the Heat Island Group, 20% of smog concentration in urban areas appears to be attributable to the UHI effect. The resulting increase in air temperature can adversely affect microclimates in cities in relation to rural areas (O'Malley *et al.*, 2015; Radhi *et al.*, 2015), especially through the formation of ground-level ozone (Kleerekoper *et al.*, 2012) and changing local microclimates and macroclimates, i.e., wind models, changes in humidity, storms, flooding, and changes in local ecosystems that it can engender (O'Malley *et al.*, 2015). By reducing urban temperatures, all the UHI mitigation strategies can directly affect outdoor urban air quality. For example, a lower air temperature can slow the photochemical production of pollutants such as ozone (Taha, 1997, cited in Aflaki *et al.*, 2017).

3.1.2 The deterioration of indoor air quality

Against a backdrop of climate change, increased heat and high humidity can affect indoor air quality. Indeed, persistent high temperatures and humidity can result in the degasification of volatile organic compounds such as formaldehyde or cause a proliferation of undesirable organisms such as mould and mites. Uncontrolled, such conditions can also cause significant thermal discomfort (see section 3.2.1) (Poulin *et al.*, 2016).

3.1.3 Higher energy demand

Indoor air cooling and refrigeration needs can engender higher energy demand that leads to GHG emissions depending on the energy source employed (Voogt, 2002). A 2°C increase caused by UHI can increase energy consumption by 5% (Anquez and Herlem, 2011).

3.1.4 Higher demand for drinking water

Because of UHI, demand is likely to be higher for drinking water for cooling off in swimming pools and water-based activities or to water vegetated layouts (Balling *et al.*, 2008). Moreover, Québec City mentions that during heatwaves drinking water consumption can increase by 40% (Ville de Québec, 2021). Such increased demand for drinking water can, in particular, exert pressure on infrastructure, make drinking water sources vulnerable, and restrict groundwater recharge.

3.2 Health impacts

Sweltering heat exacerbated by UHI could increase the number of diseases and deaths attributable to it. In Québec, as elsewhere in Canada and several countries, underprivileged areas tend to be subject to higher average temperatures than comfortably off neighbourhoods since they are often situated in intra-urban heat islands where green spaces are inadequate (Bélanger *et al.*, 2015). Similarly, individuals living in micro-urban heat islands and who are more likely to be exposed to higher temperatures are at more significant risk of mortality during hot summer days (Smargiassi *et al.*, 2009). Researchers have estimated the increase in deaths related to heat spells in Canada between 2031 and 2080 compared with the period 1971 to 2020, which appears to vary from 45% to 455% according to different scenarios that consider GHG emission rates, population growth, and the implementation of adaptation measures (Guo *et al.*, 2018, cited in Health Canada, 2020).

UHI can aggravate the effects of soaring temperatures, which can cause direct health-related impacts such dehydration, hyperthermia, heat exhaustion, or heatstroke. Indirect effects can also aggravate underlying diseases such as diabetes, chronic debilitating pathologies, respiratory failure, and cardiovascular, cerebrovascular, neurological, and renal diseases, to the point of death (Health Canada, 2012; Bélanger *et al.*, 2019). Increased morbidity-mortality linked to UHI is generally estimated at 20% to 25% (Smargiassi *et al.*, 2009; Bélanger *et al.*, 2015).

The scope and seriousness of adverse health impacts linked to extreme heat events especially affect vulnerable populations, the most disadvantaged of which live in urban environments. Low-quality housing often situated in areas exposed to heat, a lack of infrastructure such as parks and swimming pools, and essential services such as medical services exacerbate the risks. In Québec, disadvantaged areas are often associated with smaller green spaces and greater distances between homes and such cooler spaces. Factors that affect indoor temperatures such as the quality of thermal insulation to contend with summer temperatures must also be considered since temperatures vary significantly between housing units in hot weather. Such discrepancies between dwelling units generally appears to be more significant than those stemming from the impact of UHI (Bélanger *et al.*, 2015).

Individuals who are more vulnerable to heat include those suffering from chronic diseases such as respiratory and cardiovascular diseases and diabetes, persons living alone or experiencing a loss of autonomy, individuals in poor physical condition or who are overweight, those with limited access to cool or air-conditioned sites, infants and young children up to 4 years of age, individuals who engage in intense physical activities, workers in high-temperature environments, pregnant women and their fœtuses, individuals who take medications such as diuretics and immunosuppressive drugs, and individuals with alcohol or drug consumption problems (Bustinza and Demers-Bouffard, 2021). Lastly, the elderly, who will account for one-third of Québec's population by 2056 (Institut de la statistique du Québec, 2019) are at greater risk during extreme heat events. The same applies to individuals with mental health disorders, those with a low socio-economic background, or who do not have the financial means to adopt adaptation measures such as air conditioning (Health Canada, 2012; Bélanger *et al.*, 2019; Rebetez *et al.*, 2009, cited in Leal Filho *et al.*, 2018). What is more, one study has shown that the body's ability to dissipate heat diminishes starting at the age of 40 (Larose *et al.*, 2013). Accordingly, the combination of high exposure and several prior vulnerabilities is a factor that exacerbates the risk of experiencing adverse heat-related impacts.

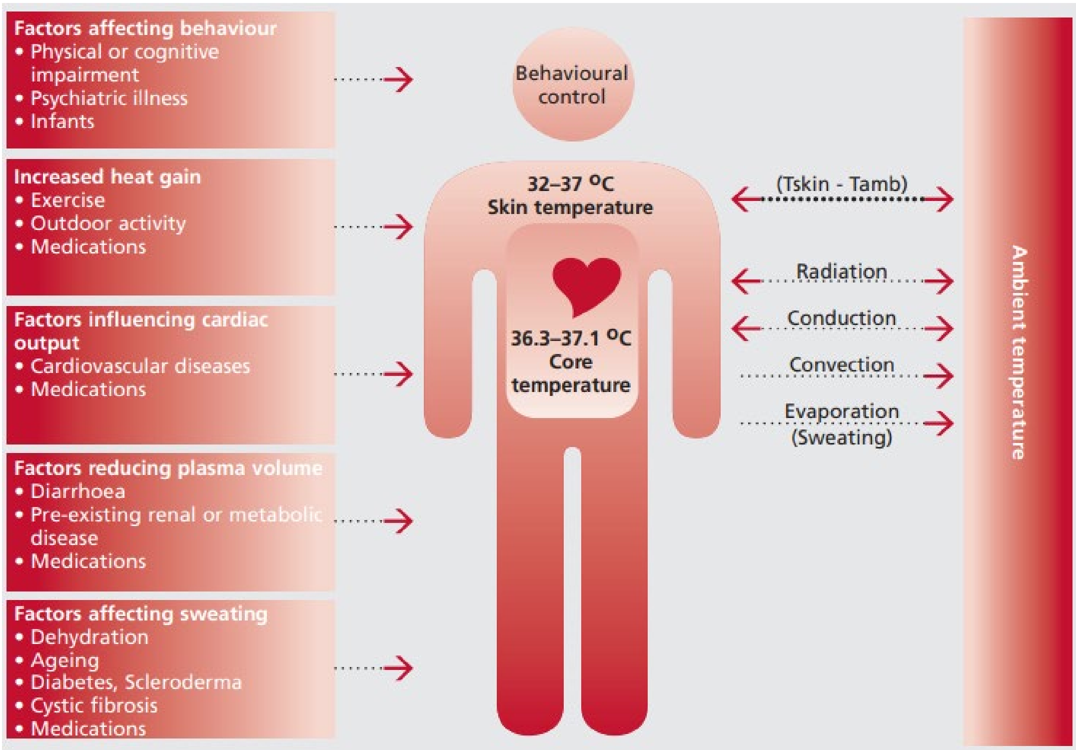
To combat such health impacts, health agencies the world over, including in Québec, on the recommendation of the WHO, have implemented programs to combat the impacts of sweltering heat and to prevent UHI (see Section 6.2).

3.2.1 Thermal comfort

The increased intensity of UHI can adversely affect individual well-being in various ways (see Figure 2), especially by altering the thermoregulatory system (Kleerekoper *et al.*, 2012; Rydin *et al.*, 2012). To reduce individual vulnerability and ensure satisfaction with the thermal environment, ambient temperatures must be neither too low nor too high. Body temperature at around 37°C is maintained through the calories from food and heat exchanges with the immediate environment. Four distinct phenomena promote heat loss into the environment:

- radiation, through electromagnetic energy transfer in the form of infrared rays;
- **convection**, through the contact of air or water with the skin;
- conduction, through direct contact by the skin with a colder object;
- evaporation, through sweating. (Bélanger *et al.*, 2019)

Figure 2 Factors that hamper human thermoregulation and contribute to disease



Source: WHO (2008). Heat-health action plans. World health Organization, 45 p.

Thermal comfort is specific to each individual. However, it is possible to specify a temperature range that is acceptable to a high percentage of people. Consequently, for 90% of people the range appears to lie between 20°C and 23.5°C (Levasseur and Leclerc, 2017). The maximum indoor summer temperature in buildings should fall between 24°C and 26.5°C and between 20°C and 24°C in the winter. Relative humidity between 30% and 50% should be maintained but could vary depending on the time of year (Levasseur *et al.*, 2020).

Extreme heat threshold values have been defined for Québec's health regions (see Table 1). The thresholds correspond to a higher (≥ 50%) mortality risk compared with the historical 30-year average. A heatwave corresponds to a period of at least three consecutive days during which the maximum and minimum average temperatures observed reach the defined sweltering heat threshold values. A very hot period can still be called a heatwave even if it does not reach the extreme thresholds since the latter are used to manage emergency plans.

Table 1 Heatwave threshold values and reference meteorological stations by health region

Health region	Heatwave threshold values		Reference meteorological station
	Max. temp. (°C)	Min. temp. (°C)	
1. 01 Bas-Saint-Laurent	31	16	Amqui
2. 02 Saguenay–Lac-Saint-Jean	31	18	Bagotville
3. 03 Capitale-Nationale	31	18	Jean-Lesage
4. 04 Mauricie-et-Centre-du-Québec	31	18	Nicolet
5. 05 Estrie	31	18	Lennoxville
6. 06 Montréal	33	20	Montréal-Trudeau
7. 07 Outaouais	31	18	Ottawa
8. 08 Abitibi-Témiscamingue	31	18	Val-d'Or
9. 09 Côte-Nord	31	16	Baie-Comeau
10. 10 Nord-du-Québec	31	16	Matagami
11. 11 Gaspésie–Îles-de-la-Madeleine	31	16	Gaspé
12. 12 Chaudière-Appalaches	31	18	Beauceville
13. 13 Laval	33	20	Montréal-Trudeau
14. 14 Lanaudière	33	20	L'Assomption
15. 15 Laurentides	33	20	Lachute
16. 16 Montérégie	33	20	Saint-Hubert
17. 17 Nunavik	31	16	Kuujjuak
18. 18 Cree Territory of James Bay	31	16	Matagami

Source: Environment and Climate Change Canada, cited in Lebel *et al.*, 2019.

3.2.2 Beyond air conditioning

Air conditioning, by cooling the air, also reduces the humidity of indoor air and thus enhances the occupants' thermal comfort (Gervais *et al.*, 2016). To ensure summertime thermal comfort, air conditioning can be employed in various indoor environments such as homes, public spaces, workplaces, and vehicles.

However, this solution does not solely afford benefits and should not be the only solution considered. Indeed, in addition to the higher energy demand that it engenders, more extensive, widespread air conditioning in urban environments can cause impacts that exacerbate UHI. Generally speaking, large-scale air conditioning can cause:

- high energy demand, especially peak demand, which runs counter to the principles of energy efficiency (Déoux and Déoux, 2004). Indeed, in 2017 more than half (56%) of Québec households owned home air-conditioning units of all types (Statistics Canada, 2019);

- the production of anthropogenic heat through the extraction of hot air from the inside of the building outside. Furthermore, the air conditioning process (compression and condensation) emits heat (Gervais *et al.*, 2016);
- GHG emissions (hydridochloridofluoridocarbons [HCFC], hydridofluoridocarbons [HFC]) caused by the use of harmful refrigerants to operate air-conditioning units (United Nations Environment Programme and International Energy Agency, 2020). To reduce the contribution of halocarbons to the GHG balance, a new regulation was adopted aimed at gradually limiting the use of HFC in Québec (MELCC, 2021b);
- the potential deterioration of air quality and its health impacts, mainly because of the risk of the dissemination of *Legionella* bacteria associated above all with industrial air-conditioning units and water-cooling towers used, in particular, to air condition buildings (Déoux and Déoux, 2004; Gervais *et al.*, 2016; American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2010);
- noise pollution created by certain air-conditioning systems such as portable or window units. Air-conditioning units are one of the sources of noise that most disturb Quebecers 15 years of age or over (Camirand *et al.*, 2016);
- reduced ability to adapt to heat (Gervais *et al.*, 2016);
- the introduction of insects through cracks (Natural Resources Canada, 2020).

To date, air conditioning often seems to be contemplated as the ideal solution. According to a study prepared by the Observatoire québécois de l'adaptation aux changements climatiques, individuals over 60 years of age compared with those 18 to 59 years of age are less inclined to recognize the adoption of one or more behaviours to adapt to heat as a means of reducing the adverse impacts of heat on their physical and mental health (Valois *et al.*, 2018). On this account, air conditioning seems useful and essential, above all for vulnerable individuals such as the elderly or people with chronic diseases whose ability to adapt to heat is very limited (Jacques and Kosatsky, 2005).

It has been observed that mobile or window air-conditioning units are less effective than central air conditioners in reducing health hazards, except in the case of small volumes of air, e.g., dwelling units with one to three rooms. The size of dwelling units thus appears to affect the efficacy of certain types of air conditioners (Rogo *et al.*, 1992, Shah, 2014, cited in Gervais *et al.*, 2016). In light of the consequences of reliance on large-scale air conditioning, some of which were reported earlier, it is important to contemplate more sustainable solutions both for the environment and the health of current and future generations. Such solutions must focus on considerations that will affect both the causes of climate change and adaptation to such change (McEvoy *et al.*, 2006; Gervais *et al.*, 2016).

4 URBAN HEAT ISLANDS IN QUÉBEC

4.1 Areas subject to urban heat islands

The geographical area that the problem of UHI concerns is the southern portion of Québec subject to summertime tropicalization (Bourque and Simonet, 2008). Indeed, the cities situated in this region of Québec have a humid continental summer climate. UHI can be detected through satellite surface temperature measurements to map the areas on a small scale (Bureau de normalisation du Québec, 2013). To accurately determine the location of surface UHI, the Centre d'enseignement et de recherche en foresterie de Sainte-Foy has developed a mapping tool. The tool, to be updated in 2022, locates UHI zones in Québec in sectors with a minimum density of 400 inhabitants per square kilometre (Bureau de normalisation du Québec, 2013). It is also possible to detect UHI by means of air temperature calculation methods at a height of 2 m instead of on the surface, although this requires vast computing power (Gachon *et al.*, 2016).

Climate change will considerably alter climatic normals. The average annual temperature and the frequency of hot days will increase in many regions in the province (see Table 2). The problem of UHI in Québec is a reality for many Québec cities.

Table 2 Average annual temperatures and annual number of days with temperatures over 30°C for three different periods according to two climatic scenarios

	City	Period 1981-2010	Period 2041-2070		Period 2071-2100	
			Moderate emissions scenario (RCP 4.5)	High emissions scenario (RCP 8.5)	Moderate emissions scenario (RCP 4.5)	High emissions scenario (RCP 8.5)
Average annual temperature (°C)	Montréal	7.17	9.61	10.32	10.31	12.92
	Québec City	5.1	7.5	8.3	8.4	11.0
	Trois-Rivières	5.3	7.8	8.5	8.5	11.2
	Drummondville	6.0	8.44	9.14	9.19	11.81
	Rimouski	4.0	6.2	7.1	7.1	9.9
Number of days over 30°C	Montréal	12.3	32.4	42.8	38.1	76.4
	Québec City	5.2	18.5	27.2	23.2	54.6
	Trois-Rivières	5.9	20.8	28.9	25.1	61.9
	Drummondville	8.2	23.1	33.1	28.3	64.4
	Rimouski	1.5	5.9	9.7	8.0	25.9

Source: Ouranos (2020).

5 MEASURES TO MITIGATE URBAN HEAT ISLANDS

5.1 General remarks

The measures to mitigate UHI are numerous and their implementation concerns areas of expertise such as urban planning, engineering, architecture, landscape architecture, natural resource management, and transportation. They have a positive impact both on the local climate and the global climate. In addition to targeting cooling in urban areas, the measures engender numerous environmental co-benefits, especially reduced energy demand, the reduction at the source of water and air pollution, including reduced GHG gas emissions, better stormwater management, and increased urban biodiversity. The health co-benefits have also been extensively studied and reported, along with spin-off in the realms of social mobilization, environment-related education (Beaudoin *et al.*, 2017), or social belonging (Beaudoin and Gosselin, 2016).

The following sections present the measures to mitigate UHI and their efficacy in terms of cooling in urban environments when reported in the literature. The measures have been grouped into five categories to directly link them to the causes of UHI mentioned earlier:

- revegetation and cooling measures;
- measures linked to sustainable urban infrastructure (architecture and land-use planning);
- sustainable stormwater management measures;
- anthropogenic heat reduction measures.

It should be noted that UHI mitigation measures are more effective when combined (Mohajerani *et al.*, 2017). Similarly, there is no universal solution to mitigate UHI. The choice of a particular measure must satisfy the community’s needs and consider the economic, social, and environmental aspects.

5.2 Greening measures

Several studies note the paramount importance of revegetation and the preservation of existing green spaces and wooded areas to mitigate UHI in the context of growing urbanization (Heisler *et al.*, 1994; Taha *et al.*, 1996; Mcpherson *et al.*, 2005; Solecki *et al.*, 2005; Aflaki *et al.*, 2017; Besir and Cuce, 2018; Aram *et al.*, 2019). Indeed, vegetation creates cooling through the following processes:

- seasonal shade of infrastructure;
- evapotranspiration;
- the minimization of temperature differences on the ground.

Vegetation also offers other worthwhile, additional benefits in urban environments, including:

- enhanced air quality through the production of oxygen, CO_2 capture, the filtration of suspended particulates, and reduced energy demand related to air conditioning;
- enhanced water quality through the retention and filtration of rainwater in the ground and the control of soil erosion;
- the absorption of local noise pollution;
- the maintenance of biodiversity in cities;
- the enhancement of the aesthetic appearance of cities;
- health benefits for the population, including protection from ultraviolet (UV) radiation, reduced heat-related stress, and enhanced psychological well-being because of the presence of vegetation and the availability of places in which to engage in physical activity (Beaudoin *et al.*, 2017).

In Québec, the vegetation chosen to protect buildings from summer solar radiation must have deciduous foliage, i.e., lose its foliage during part of the year, but limited branches to reduce shade to a minimum in the other seasons, when solar gain is desired (Écohabitation, 2020a). Indeed, the impact of tree shade on winter heating demand can be significant in the case of trees with non-deciduous foliage (McPherson, 1994, cited in Kleerekoper *et al.*, 2012). The species used in urban revegetation must be chosen judiciously to ensure sound foliage density, which will enable the mature tree to filter at least 60% of solar radiation. Ideally, a distance of between one-and-a-half times to twice the height of mature trees is ideal between building façades and the trees. If the trees are situated farther away, their shade will not cover the dwelling in the summer, and they will not protect it from the wind in the winter (Écohabitation, 2020a). Coniferous trees provide less significant cooling in the summer because their foliage less extensively covers the ground and limits the penetration of sunlight in the winter. However, they can limit the wind chill factor in the winter if properly laid out. In short, no greening measures is in itself perfect, but their complementarity will facilitate enhanced adaptation. Each measure must be evaluated in light of the planting site, the presence of public service facilities (Gendron-Bouchard, 2013) and climatic (resistance to climate change) and anthropogenic (maintenance conditions) disturbances (Paquette and Cameron, undated; Messier, 2020). Large-growing trees must also be preferred (Paquette, 2016).

Consequently, trees must be chosen judiciously. Species such as poplars, oaks, and willow trees, which emit volatile organic compounds that are a component of smog, should be avoided (Nowak and Van den Bosch, 2019). Additionally, certain species display allergenicity that can affect human health. According to Laaidi *et al.* (2011), air pollution and, in particular, high ozone concentrations, potentiate the action of allergens. Indeed, plants in urban areas are more stressed and pollinate more extensively, which leads to the fastening of certain pollutants to pollen particles and increases allergenic potential. To date, the allergenic potential of the most popular tree species in cities and the cross-reactivity of most species are largely unknown or are based on non-documented methods. According to current knowledge, only a few tree species such as birch and alder produce pollen with high allergenic potential (Sousa-Silva *et al.*, 2020, 2021). A recent study conducted in five cities, including Montréal, with urban forests and differing population densities reveals that the risk of exposure to pollen varies from 1% to 74% for trees deemed highly allergenic in a given city. Such striking variations in allergenic risk in urban areas stems from a limited knowledge of the allergenic potential of tree pollen (Sousa-Silva *et al.*, 2021). Given that global warming risks extending the pollen season, it is essential to gain a better understanding of tree species with allergenic potential and their distribution in urban spaces to support urban greening (Sousa-Silva *et al.*, 2020). In the meantime, diversified urban forests offer a potentially more reliable strategy to dilute the sources of allergenic pollen in cities (Sousa-Silva *et al.*, 2021).

What is more, it is essential to adapt the choice of species to the space available. Hydro-Québec is proposing an online tool to select the right trees and shrubs according to the distance from electric power transmission lines. It is also preferable to choose indigenous species that tolerate Québec's climatic variations and urban pollution (https://can-plant.ca/).

To maintain the services that urban forests render, the development of efficient tree management practices aimed at minimizing the mortality risk is thus becoming increasingly important. In particular, it is necessary to introduce broader biodiversity in the cities to avoid crown cover loss when climate change phenomena such as flooding, drought, and high winds weaken species. The species planted in North America are biologically very similar. A diversity of biological traits such as rapid growth and resistance to shade, drought, and flooding must be preferred to ensure broader functional diversity (see Table 3) and better resistance to different meteorological hazards, in addition to limiting the risk of canopy loss. Vertical diversity must also be adopted by integrating herbaceous plants and shrubs into tree planting as well as genetic diversity by avoiding the same cultivars in a species (Paquette, 2016; Paquette *et al.*, 2021).

Urban environments are constantly changing and there are numerous opportunities to integrate vegetation into urban restructuring, development, or improvement plans. Different applications, presented in the sections that follow, are accessible to municipalities, entrepreneurs, and individuals to mitigate UHI.

GREEN INFRASTRUCTURE

Green infrastructure can be defined as an interconnected network of natural or developed green spaces dispersed throughout an urban territory. They maintain the benefits that residents derive from ecosystems, especially from the standpoint of stormwater management, support for biodiversity, air purification, the reduction of CO_2 emissions, and the regulation of urban temperatures. The development of green belts is thus relevant. The ILEAU project (see Section 6.2.2) is a Québec example of the establishment of vegetated links in Montréal (Rayfield *et al.*, 2016).

Table 3 Interpretation grid of functional groups

Group	Functional type	Representative species
1A	• Softwoods • Generally tolerate shade but not drought or flooding • EcM mycorrhization • Seeds dispersed by the wind	Spruce trees, fir trees, white cedar, eastern white pine
1B	• Heliophilus conifers • Drought tolerant (pines) • EcM mycorrhization • Seeds dispersed above all by the wind	Pines, larch, junipers, ginkgos
2A	• Climacics • Shade tolerant • Broad, thin leaves, average growth • Mixed mycorrhization • Seeds dispersed above all by the wind	Most maple trees, linden trees, magnolias, beech trees, ironwood, and several other small trees
2B	• Resemble 2A except for very heavy sees dispersed by gravity • Exclusive AM mycorrhization	Chestnut trees
2C	• Big trees • Flood tolerant • AM mycorrhization • Seeds dispersed above all by the wind	Most elms, ash, hackberry trees, red, silver, and Manitoba maples
3A	• Small trees • Drought tolerant • Heavy wood, thick leaves, low growth • AM mycorrhization • Seeds dispersed above all by the wind	Rosaceous plants (sorb trees, pear trees, hawthorn, and serviceberries), lilacs
3B	• Medium trees • Flood intolerant • AM mycorrhization • Seeds dispersed above all by animals	Big rosaceous plants (cherry trees, apple trees), catalpas, maackias, other varied species
4A	• Big trees • Several are drought tolerant • Heavy seeds and wood • Above all EcM mycorrhization • Seeds dispersed by animals	Oak, walnut, and hickory trees
4B	• Big trees • Drought tolerant and shade and flood intolerant • Heavy seeds, abundant leaves • Above all AM mycorrhization • Seeds dispersed by animals	Legumes (honey locusts, Kentucky coffee trees, locusts, Judas trees)

Table 3 Interpretation grid of functional groups (continued)

Group	Functional type	Representative species
5	• Pioneer species with very small seeds • Flood tolerant • Rapid growth, light wood • Mixed (often double) mycorrhization • Seeds dispersed by the wind	Poplars, common willows, alders, birches (except yellow)

Source: adapted from Paquette and Cameron (undated).

5.2.1 The development of urban green spaces

The objective of an urban revegetation strategy is to increase a city's overall vegetation index. To do so, vegetation can be arranged or densified in numerous spaces, for example:

- along transportation routes, e.g., borders on streets, alleyways, rail lines, and highways[15];
- on public lands, e.g., parks, municipal and government lands, schoolyards, and childcare centre yards;
- on private lands, e.g., around residential, commercial, and industrial buildings, and in alleyways (Conseil régional de l'environnement de Montréal, 2010).

Whether plantations are uniformly distributed in parallel or concentric rows, it is possible to place the species that best tolerate de-icing salt on the periphery and less tolerant species in the centre. This principle allows for the use of more varied species or functional groups (Conseil régional de l'environnement de Montréal, 2019).

The cooling that vegetation provides can ensure that residents visit certain spaces (Scotland, 2008). According to Shashua-Bar and Hoffman (2000), the combined effect of evapotranspiration and shade in parks and green spaces significantly reduces the temperature and even creates what are called cool areas in the city (cited in Gago *et al.*, 2013).

While municipalities are mainly responsible for greening public spaces, it is recommended to involve residents to promote the social acceptability of such initiatives (Greenspace, 2005, cited in Kleerekoper *et al.*, 2012). The promotion of greening in private spaces is also relevant in cities since the municipality does not own most of the surfaces exposed to solar radiation. In this instance, initiatives such as the one that Paris has adopted to promote green façades and terraces (Mairie de Paris, 2009, cited in Kleerekoper *et al.*, 2012), or the green roof subsidy program in Rotterdam, define the future trend of adaptation strategies (Waterplan Rotterdam, 2008, cited in Kleerekoper *et al.*, 2012).

[15] Consult the Guide pour des plantations résilientes dans les emprises autoroutières.

COOLING GAINS AND OTHER BENEFITS RELATED TO URBAN GREEN SPACES

According to Dimoudi and Nikolopoulou (2003), vegetation in sparsely vegetated urban environments significantly enhances cooling. For example, a row of trees reduces the temperature of the ambient air by 1°C, while the creation of a downtown park to replace buildings would generate a drop in temperature of the ambient air of 2°C to more than 6°C. According to Liébard and De Herde (2005), an average temperature difference of 3.5°C would also be observable between a sparsely vegetated downtown and neighbourhoods bordering a strip of vegetation between 50 m and 100 m deep. According to the findings of the comparative analysis of Aflaki *et al.* (2017), urban greening could considerably mitigate the intensity of UHI, leading to a reduction in the overall air temperature and the mean radiant temperature to 4°C and 4.5°C, respectively.

Vegetation has an average cooling effect of 1°C to 4.7°C that extends from 100 m to 1 000 m in urban areas but is heavily dependent upon the amount of water available to the plant or tree (Schmidt, 2006, cited in *et al.*, 2012). Other researchers have studied this temperature variation not only in green spaces but also in the surrounding commercial zones. Accordingly, Yu and Hien (2006) observed that in Singapore, urban green spaces had a significant cooling effect not only in parks but also in nearby urban areas. The findings reveal that vegetation could lead to energy savings and reduce demand for cooling in buildings by up to 10% (cited in Gago *et al.*, 2013). A green space does not need to be especially big to generate a cooling effect. According to a study conducted in Tel Aviv, a park covering only 0.15 ha produced an average cooling effect of 1.5°C, and 3°C at noon (Shashua-Bar and Hoffman, 2000, cited in Kleerekoper *et al.*, 2012). In their study, Shashua-Bar and Hoffman (2000) emphasized that urban vegetation islands 60-m wide would generate a sensation of coolness within a 100-m radius. They also reported that the range of the cooling varied exponentially according to the dimensions of the vegetated spaces.

As Lachance *et al.* (2006) observed, in the borough of Mercier–Hochelaga-Maisonneuve in Montréal in the summer, an area bordering a vegetated zone displayed a surface temperature that was 6°C cooler than an area bordering a vegetation-free industrial area, i.e., 29°C and 35°C, respectively.

COOLING GAINS AND OTHER BENEFITS RELATED TO URBAN GREEN SPACES (CONTINUED)

According to Charoenkit and Yiemwattana (2016), trees with high canopy density or mixed tree species in clusters to create multilayered cover should be preferred. The findings of the study by Stojanovic *et al.* (2019) confirm that green species with a higher proportion of broad, dark leaves such as sycamore maple, Constantinople hazel, littleleaf linden, and horse chestnut reduce air temperature over a wider area.

Other factors can help disseminate the coolness that vegetation creates, especially the wind: a big park situated above an urban centre in the direction of the prevailing winds can have a more significant cooling effect (Ca *et al.*, 1998; Honjo and Takakura, 1990). The spatial configuration and type of vegetation in green spaces appears to jointly affect the efficacy of the cooling effect (Sodoudi *et al.*, 2018).

A study conducted in Tokyo by Ca *et al.* (1998) has shown that the air temperature 1.2 m above the ground of a planted surface in a park was 2°C lower at noon compared with the temperature measured in the parking lot of nearby shopping centre. The temperature was 19°C lower at ground level.

Generally, while the size of urban parks is positively linked to the cooling effect, this relationship is not, however, linear and can even be exponential, especially because of the time of day when the temperature is recorded (Chang *et al.*, 2007; Hathway and Sharples, 2012; Hayden *et al.*, 2016, cited in Yu *et al.*, 2020). Indeed, the authors mention that the cooling distance varies from 100 m to 200 m at the end of the day and can extend up to 860 m in the morning. The distances and intensity of the cooling effect that large urban parks provide are highest when the parks have an area of more than 10 ha. Natural elements, the qualities of the urban green spaces, and climatic characteristics also significantly affect cooling (Aram *et al.*, 2019).

A study conducted in a medium-sized city in the Upper Midwest in the United States revealed an average daytime air temperature variability of 3.5°C (1.1°C – 5.7°C) in the urban landscape. The temperature decreased in a non-linear manner with an increase in plant cover. Cooling was more significant when the plant cover exceeded 40% (Ziter *et al.*, 2019).

COOLING GAINS AND OTHER BENEFITS RELATED TO URBAN GREEN SPACES (CONTINUED)

While grass is preferable to mineralized surfaces, a Montréal study has shown that the diversification and increasing complexity of green spaces, especially grassy areas, can be effective in improving their ecological performance from the standpoint of temperature regulation. By comparing mowed grassy areas to three other types of low vegetation, i.e., unmaintained herbaceous fields, unmaintained shrubland, and poorly maintained shrubby hedges, it was observed that varied gradients of complexity mitigated the impact of UHI. Indeed, the other types of installation displayed an average surface temperature 5°C lower in relation to mowed grassy areas on a sunny, wind-free day. Similarly, the maximum surface temperature displayed for shrubland was roughly 20°C lower than that of the mowed grassy area. The increasing complexity of green spaces in terms of plant species and the height of vegetation can be achieved at low cost by reducing the intensity and frequency of maintenance (Francoeur *et al.*, 2018).

5.2.2 One-off planting of trees and vegetation

The sound growth of trees is essential for them to provide cooling and may depend on soil quality, the availability of water, and sufficient space for optimum root development. A tree that occupies limited space in the soil will not attain its maximum size and its lifespan will be shortened (McPherson, 1994). A deep-rooted tree will probably have access to more abundant water, which will support water absorption. Correspondingly, a deep-rooted tree will transpire more and provide better cooling (Peters *et al.*, 2010).

The optimum growth of trees planted along streets is possible through "cellular" arrangements. There are two types of such plantations. Since they are often confused, the following designations are usually used to distinguish them: planting by ecological grouping (companion planting) and containerized planting or planting in closed trenches.

Planting by ecological group is often used to renaturalize or preserve natural environments. This entails identifying the natural companions of the tree or shrub and planting them in the same perimeter. For example, brambles (black raspberries), also called the "cradle of the oak tree" or "the mother of the beech tree or American basswood," are the best companions of sugar maples. However, it should be noted that this type of companion planting is harder to achieve in urban environments, especially because of the surface available, the client's willingness to include this type of planting, habits (single trees or aligned without shrubs and other companions prevail), and the trouble that its implementation causes.

As for planting in containers, it is very widespread for plant production. Although producers cover their plants to protect them from freezing, losses nonetheless occur. In Québec, the borough of Ahuntsic-Cartierville is testing the cellular technique in the Chabanel district, which is creating a temporary green zone, although its long-term survival is questionable. Cellular landscape planting is rarer because of the risk of frost, the need to insulate the containers, wind-related risks, horticultural obligations that are often deemed excessive, and high mortality. This type of planting is mainly found near public spaces where installations do not allow for planting on open ground, in indoor locations such as shopping centres, or bordering staircases or paths to improve rendering. Containerized planting cannot under any circumstances be deemed greening since it is not a lasting solution. Indeed, monitoring of the plants is not guaranteed since they can be moved, and it thus becomes harder to find them in a given territory.

As for planting in closed trenches, it is often used in engineering to green while protecting underground facilities (Bassil, personal communication, July 16, 2021).

COOLING GAINS AND OTHER BENEFITS RELATED TO THE ONE-OFF PLANTING OF TREES AND VEGETATION

Mature trees promote coolness through their evapotranspiration capacity and the area of shade created. A mature tree that transpires 450 l of water allows for estimated cooling equivalent to five air conditioners operating for 20 hours a day (Johnston and Newton, 2004). Similarly, a study conducted in Manchester revealed that mature trees significantly affect the surface temperature of the roadway. The findings of the simulation showed that the addition of 5% mature trees in terms of density would reduce the surface temperature by 1°C (Skelhorn *et al.*, 2014). Nowak and Crane (2002) estimated the carbon sequestration in the trees in urban parks and along streets at roughly 700 Mt in the United States, with annual average sequestration of 22.8 Mt of carbon (cited in Charlesworth, 2010).

Street trees may seem to have limited impact on the intra-urban temperature since they are dispersed but given their significant number they actually have considerable impact. Irrigation can provide additional cooling. Broadbent *et al.* (2018a) studied the cooling potential of irrigation managed in a targeted manner and observed a reduction in the average daytime temperature. However, the authors have shown that additional cooling was negligible when the irrigation rate exceeded 20 l/m^2/day.

COOLING GAINS AND OTHER BENEFITS RELATED TO THE ONE-OFF PLANTING OF TREES AND VEGETATION (CONTINUED)

Tree species with dark green leaves and species such as oak, black locust, ash, sweet chestnut, and elm whose wood is more porous appear to offer better cooling benefits (Rahman et al., 2020). Solar absorption by the leaves of plants also apparently strongly depends on their water content, hair, and the thickness of the leaves. Thick, waxy leaves, such as conifer needles, absorb up to 88% of solar rays (Jones, 1992; cited in Charoenkit and Yiemwattana, 2016). A high leaf surface index is represented by dense leaves with a greater capacity to block solar radiation (Lai *et al.*, 2019).

Sunlight can be further reduced by planting trees with broader crowns. Different shapes of tree crowns have been studied. Based on the findings of their simulation, Milošević et al. (2017) have shown that cylindrical tree crowns more effectively reduce heat stress than spherical or conical crowns of the same height and diameter.

5.2.3 Revegetation of parking lots

Parking lots built with asphalt, a low-albedo material, contribute to the formation of UHI (Rosenzweig *et al.*, 2005). To reduce the heat that asphalted surfaces store, it is advisable to install vegetation on the periphery (vegetated areas) and inside (vegetated islands; see Figure 3) parking spaces. The objective is to create shade on asphalted surfaces. Tree shading will also protect coverings from large temperature variations and prolong their useful life (McPherson et Muchnick, 2005). The Guide de mise en œuvre d'un stationnement écoresponsable, based on the BNQ 3019-190 Guidelines, suggests practical ways to build parking lots so as to limit the formation of UHI.

Figure 3 Vegetated islands - The "Place fraîcheur à l'école Calixa-Lavallée" project in Montréal

Photo credit: Daniela Kowu.

To reduce the surface temperature of parking lots, it is also possible to entirely vegetate surfaces by means of modular coverings composed of concrete, recycled plastic, or other materials that allow plants to grow (see Figure 4). The modules are installed on filtering soils, which promote the natural percolation of rainwater in soil. Vegetated coverings allow for the parking of light-duty vehicles. They can be implemented readily using modular slabs placed directly on natural ground, which are subsequently filled using soil amendment and grass seed. It should be noted that this type of covering is not recommended on steeply sloped surfaces (Grand Lyon communauté urbaine, 2010). It is also inadvisable to park vehicles there that will not move for several days. Likewise, to ensure the long-term survival of vegetated parking lots, load-bearing, draining fertile foundations should be provided for to enable grass to become deeply rooted (O2D Environnement, 2017).

Figure 4 Slabs that allow for plant growth

Photo credit: Les Dalles Vertes.

5.2.4 Revegetation in the periphery of buildings

To achieve optimum coolness, the outfitting of a building's periphery must protect it from solar rays. Indeed, the texture and nature of the soil surrounding a building partly determine the indoor and outdoor temperature. Vegetation keeps soil cooler and avoids direct, reflected, and diffuse solar radiation that can affect a building's coolness (see Figure 5) (Akbari *et al.*, 2001).

To maximize shade on a building, trees must be arranged on the eastern, southeastern, southwestern, and western sides of a house and, ideally, be big enough to shade the roof partly or wholly. It is also possible to install trellises, pergolas, plant walls and green roofs, which, juxtaposed with buildings, ensure cooler indoor temperatures (Courgey and Oliva, 2012). Tree roots seek moisture and they do not survive in concreted environments such as building foundations. However, they could penetrate leaking or cracked water mains or foundations (Société internationale d'arboriculture Québec, undated).

COOLING GAINS AND OTHER BENEFITS RELATED TO THE REVEGETATION OF THE PERIPHERY OF BUILDINGS

Morakinyo *et al.* (2013) assessed the impact of tree shading on thermal conditions in two similar urban buildings on a university campus in Nigeria. Trees on the southeastern side shaded one of the buildings and the other building was unshaded. Air temperature and the temperatures of the inner and outer walls of the buildings were measured. Air temperatures were higher inside the unshaded building. Differences between indoor and outdoor temperatures reached a peak of 5.4°C in the unshaded building while the temperature did not exceed 2.4°C in the shaded building. The findings reveal that tree shading provides an excellent passive building cooling system that potentially enhances thermal control and energy conservation in buildings.

Figure 5 Revegetation in the periphery of buildings – The "Effet de terre aux habitations Jeanne-Mance" project in Montréal

Photo credit: Mathilde Botella.

5.2.5 The installation of plant walls

Against a backdrop of growing urbanization, plant walls and green roofs (see Section 5.2.6) are deemed a promising approach to greening cities where green spaces are rare and space on the ground is limited (Charoenkit and Yiemwattana, 2016). Vertical greenery plays a crucial role in reducing the impacts of UHI, especially in metropolitan cities (Aflaki *et al.*, 2017), where they create a microclimate that significantly reduces the temperature of the building envelope and enhances its energy economy (Dunnett and Kingsbury, 2008; Ekren, 2017; Vox *et al.*, 2018; Besir and Cuce, 2018). Plant walls shade buildings and promote evapotranspiration in the summer and enhance thermal insulation in the winter (Vox *et al.*, 2018).

Such plant installations also offer other benefits:

- they protect the building envelope from bad weather, capture airborne particles, prevent graffiti, provide noise insulation and aesthetic enhancement, broaden biodiversity, and make a positive contribution to mental health (Ekren, 2017; Vox *et al.*, 2018);
- the possibility of establishing the installations on all types of buildings, fences, telephone poles, and streetlamps, and worthwhile greening potential on imposing building façades (Dunnett and Kingsbury, 2008);
- carbon sequestration (Charoenkit and Yiemwattana, 2016; Zaid *et al.*, 2018).

Significant plant variety will promote biodiversity. However, it must be remembered that different plant species require different habitat conditions. Accordingly, plant species must be chosen carefully (Ekren, 2017).

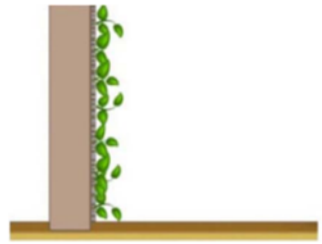
Precautions must be taken as regards the host structure that has to support the vegetation and the type of vegetation selected and its potential colonisers (Dunnett and Kingsbury, 2008). Similarly, while it is simple to maintain the vegetation by means of trimming, weeding, and inspection of the support (Courgey and Oliva, 2012), it is harder to carry out maintenance on vertical surfaces (Ekren, 2017). Constant maintenance must be carried out and high costs and problems related to the irrigation system may arise, especially during winter freeze-ups (Ekren, 2017). In Québec, the irrigation system must be drained in the fall with the first frost to completely remove water. The wall then enters a period of winter dormancy (Bernier, 2011). It is also essential to consider that the plant wall applied to the southern façade of a building needs more water than when applied to the northern façade because of evaporation (Ekren, 2017). The environmental and economic sustainability of the systems marketed are, nevertheless, still called into question since they are highly variable and related to the complexity of the systems, which hampers their widespread use in cities. To enhance the attractiveness of plant walls, technical changes that incorporate environmental and economic sustainability seem indispensable (cited in Lagurgue *et al.*, 2019). Regular maintenance and the appropriate financial support will eliminate such risks (Ekren, 2017).

There are two types of plant walls (see Figure 6): façade plant walls and living walls. First, the façade plant wall is a wall covered with climbing plants rooted in the ground or in pots at different heights on the façade that can climb up to 30 m. A minimum space of 15 cm x 15 cm is required on the ground to place the plant there. Certain plants can climb directly on the surface of the wall by means of their morphological characteristics such as aerial roots, leaf tendrils, and adhesive pads (see Figure 7). Second, the living wall, a more complex installation, comprises plants rooted in a medium attached to the wall. The main types of living walls are classified as continuous or modular, the main difference being the growing medium (Besir and Cuce, 2018). The presence of a space, usually from 3 cm to 15 cm, between the building wall and the revegetation system acts as a thermal buffer, thereby enhancing the building's thermal insulation (Dunnett and Kingsbury, 2008; Vox *et al.*, 2018).

On the one hand, in relation to façade plant walls, living walls require certain essential materials such as supports for the cultivation of the substratum and irrigation systems to maintain various plants. Maintenance costs are, therefore, especially high (Perini and Rosasco, 2013). On the other hand, living walls usually perform better because of precultivated plants and the possibility of transferring them (Raji *et al.*, 2015). Living walls are also subject to fewer limitations concerning the application to the upper floors of very tall buildings (Charoenkit and Yiemwattana, 2016). While the installation of living walls is still limited and at an experimental stage in Québec, mainly because of cost and maintenance, they are nonetheless adapted to external use (N. Zepeda, personal communication, February 10, 2021).

According to popular belief, the installation of climbing plants might damage wall surfaces. To the contrary, most climbing plants cling by means of their extremities that resemble suction cups and prolong the useful life of bricks, stone, paint, dyes, and other materials by protecting them from bad weather such as temperature changes, wind, rain, and UV rays (Bernier, 2011). The attachments to the wall can be solid and they must, however, be removed delicately from the wall to avoid damaging it (Écohabitation, 2021). A multi-year study was conducted in Berlin to evaluate, in particular, the condition of stucco following the installation of climbing plants. Most of the walls in question were covered with Boston ivy, Virginia creeper, and English ivy, plants that are adapted to Québec's climate. The study's findings revealed that 83% of the walls were intact, 16% were slightly damaged, and 1% displayed severe damage in the case of clinging climbing plants and climbing plants with crampon roots. The damaged walls were very old or covered with shoddy stucco. The aerial roots of plants with crampon roots can in point of fact penetrate and widen existing cracks in shoddy or decrepit stucco (cited in Dunnett and Kingsbury, 2007).

Figure 6 The types of plant walls

Green facade	Living wall
	
In green facade, plants are rooted on the ground in soil and climb on facade and covers elevation	Living walls are pre-vegetated sheets that are attached to a structural wall or frame

Source: cited in Besir and Cuce (2018).

Figure 7 Façade plant walls – The “Mature vines for walls” project in Montréal

Photo credit: Mathilde Botella.

COOLING GAINS AND OTHER BENEFITS RELATED TO PLANT WALLS

The maximum temperature of plant walls is 30°C, while the temperature of traditional walls can reach 60°C depending on the type of cladding (Dunnett and Kingsbury, 2008). In California, Sandifer and Givoni (2002) assessed the cooling effect of Virginia creeper on a wall. They observed maximum daily surface temperature reductions of up to 20°C compared with an unshaded wall.

The modular systems with vertical vegetated panels appear to surpass the living wall based on planters in temperate and Mediterranean climates. It was observed that the average surface temperature of living walls with vertical panels was roughly 8°C to 9°C lower than that of a reference wall, i.e., a temperature reduction 2°C to 3°C higher than that of a plant wall based on planters (Ottelé, 2011). Luxmoore *et al.* (2005) modeled the cooling gains generated by the use of vegetation on buildings that form street canyons in the city. They concluded that the hotter and drier the city's climate, the greater the cooling gains. That being the case, cities with hot, humid climates can also benefit from plant walls to lower by several degrees the temperature in street canyons.

In Italy, research conducted by Perini *et al.* (2017) revealed that the average energy conservation of plant walls was roughly 26.5% in relation to traditional walls. Under temperate, hot climatic conditions in Oxford in the United Kingdom, Sternberg *et al.* (2011) observed a 9.15°C temperature reduction of the wall generated by a 45-cm thick covering of English ivy on a wall with a south-facing wall.

A correlation was observed between the thickness of the foliage and the temperature reductions. Similarly, a 13% to 54% increase in the percentage of foliage appears to reduce the temperature of the outer surface of the wall by 3.7°C to 11.3°C (Koyama *et al.*, 2013). The density and coverage of foliage affect, in particular, shade performance on the building's façade (Besir and Cuce, 2018). The substratum is the most important component of living walls, especially for the modular system. Its moisture content and thickness are deemed significant factors that affect the thermal performance of living walls (Charoenkit and Yiemwattana, 2016).

COOLING GAINS AND OTHER BENEFITS RELATED TO PLANT WALLS (CONTINUED)

> **The findings of a study of deciduous-leaf vegetation cover by Ip *et al.* (2010) in the United Kingdom showed the seasonal benefits stemming from shade in the summer leading to a 4°C to 6°C temperature reduction inside the building. When the leaves fell in the fall, all incidental sunlight could penetrate through the windows and heat the inside of the building.**

5.2.6 Green roof design

Roofs account for 20% to 25% of the total urban surface. Consequently, the greening of roofs has considerable potential to affect temperatures in buildings and the urban environment (Raji *et al.*, 2015; Charoenkit and Yiemwattana, 2016; Susca, 2019). Traditional building roofs are dark, waterproof surfaces that contribute to the UHI effect in cities and increase flooding problems. Green roofs are solutions for multi-storey buildings, single-family dwellings, commercial buildings, and other constructions. They enhance the energy performance of buildings and environmental conditions (Gago *et al.*, 2013). They simultaneously provide active cooling through evaporation and passive cooling through insulation (Aflaki *et al.*, 2017).

Benefits linked to energy conservation, thermal insulation, shade, and evapotranspiration highlight the key role that green roofs play in the overall thermal performance of buildings (Besir and Cuce, 2018). Traditional roofs are made of asphalt, metal cladding, rubber materials, or typical clay tiles, which considerably increase the surface temperature and readily transfer heat inside the building (Enríquez *et al.*, 2017). Green roofs reduce the amount of heat transferred from the roof inside the building through evapotranspiration and the shade that plants create. What is more, they cool the outside ambient air (McPherson, 1994) while contributing to:

- enhanced thermal insulation both in winter and in summer through the thermal inertia of the plant cover and the water in the earth or the humidifying cladding;
- the aesthetic integration of buildings into the landscape;
- potential for urban agriculture;
- improved air quality, since the plants on planted roofs trap dust and airborne pollutants;
- improved water quality, since vegetation on roofs compensates surface sealing and vegetation cover loss stemming from the ground coverage of buildings (see Section 5.4);
- reduced stormwater discharges in sewer systems;
- extending the lifespan of the roof because the green roof affords protection against bad weather, exposure to UV rays, and significant temperature variations, all factors that degrade the roof (Déoux and Déoux, 2004; Oberndorfer *et al.*, 2007; Besir and Cuce, 2018);

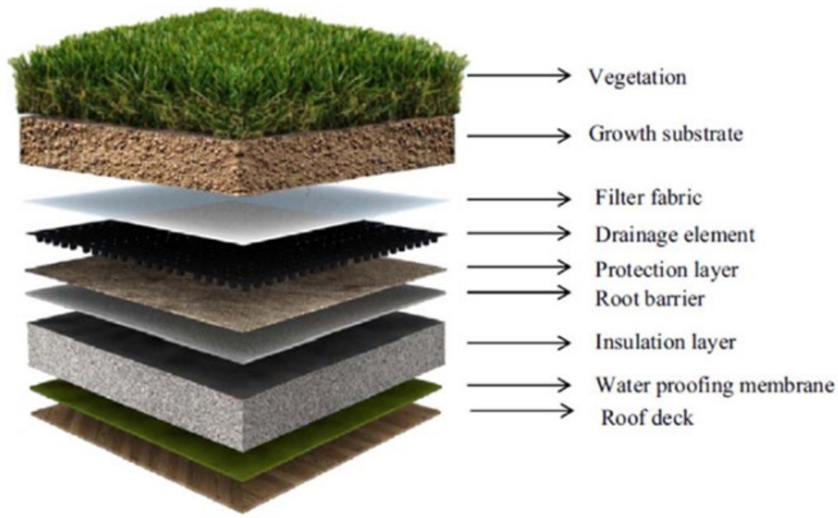
- enhanced ecological habitat for urban life and wildlife;
- carbon sequestration (Charoenkit and Yiemwattana, 2018);
- the absorption of local noise pollution in urban areas.

In certain cities in the world and increasingly in Québec green roofs are now used as a measure in urban planning strategies. It is essential for urban planners and political decision-makers to be aware of their benefits in relation to traditional roofs (Francis and Jensen, 2017). There is enormous potential to install new green roofs on tens of billions of square feet of roofs in North America (Green Roofs for Healthy Cities, 2019) and growing interest in all types of organizations, especially cooperatives and community-based housing units, which, however, have limited means to carry out such work (N. Zepeda, personal communication, February 10, 2021). A number of major cities, especially in Europe and North America, are acting by implementing regulatory and economic incentives (Écohabitation, 2017b). In Québec, the adoption of incentive policies like those implemented in Toronto and Vancouver could promote the use of green roofs in urban environments (Ouranos, 2015). Otherwise, businesses and institutions may perceive social responsibility and their image as worthwhile inducements to establish green roofs (N. Zepeda, personal communication, February 10, 2021).

Green roofs are best suited to flat roofs or roofs that slope less than 20% (Déoux, 2004, Peck and Kuhn, 2001, cited in MDDEFP and MAMROT, undated), although they are appropriate for all types of roofs provided that their structures can bear the weight. Where appropriate, the installation of planted roofs can require significant renovations (Fischetti, 2008) and engender substantial costs for existing buildings (N. Zepeda, personal communication, February 10, 2021). Regulations that require greater roof bearing capacity for new buildings would facilitate the implementation of green roofs with a minimum increase in construction costs (Écohabitation, 2017b).

A standard green roof comprises several components, mainly a load-bearing structure, a waterproof pour coat, a barrier coat (if the roof is not ventilated), a root-repelling membrane, a drainage and filtering section, a geomembrane to retain the soil, a growth medium, and a plant layer or a substrate layer (Besir and Cuce, 2018). Figure 8 presents the main components of a green roof.

Figure 8 Components of a standard green roof



Source: cited in Besir and Cuce (2018).

An analysis of the life cycle of extensive green roofs was conducted to assess the potential environmental impacts related to their introduction and maintenance. It was observed that extensive green roofs engendered significantly fewer adverse environmental impacts than asphalt or gravel roofs (Centre international de référence sur le cycle de vie des produits, procédés et services, 2011). Figure 9 shows examples of extensive green roofs.

As Table 4 illustrates (Pisello *et al.*, 2015), there are three categories of green roofs: extensive, semi-intensive, and intensive, according to the weight, the substrate layer, maintenance, cost, the plant species introduced, and irrigation. Intensive roofs are the heaviest and are more expensive than the other types of roofs. Furthermore, they require a higher level of maintenance. Extensive roofs do not have additional weight because of the shallower growth medium and their maintenance costs are particularly low (Coma *et al.*, 2016).

Figure 9 Extensive green roofs – Maison du développement durable in Montréal and the “Relocalisation du siège social de l’Office municipal d’habitation de Trois-Rivières” project

Photo credit: Maison du développement durable Laetitia Laronze.

Photo credit: Mathilde Botella.

Table 4 Classification of types of green roof

	Extensive green roof	Semi-intensive green roof	Intensive green roof
			
Maintenance	Low	Periodic	Regular
Irrigation	None	Periodic	Regular
Type of vegetation	Moss, sedum, herbs, and grasses	Lawn, herbs, and shrubs	Lawn, hardy perennials, shrubs, and trees
Cost	Low	Average	High
Weight	60 kg/m^2 -150 kg/m^2	120 kg/m^2 - 200 kg/m^2	180 kg/m^2 - 500 kg/m^2
Use	Ecological protective layer	Green roof	Park-style garden
Thickness of the system	60 mm - 200 mm	120 mm - 250 mm	150 mm - 400 mm

Source: adapted from Besir and Cuce (2018).

Lastly, several studies have examined the types of plants adapted to extensive green roofs. They reveal that sedum, grasses, and very rustic hardy perennials appear to be highly successful on extensive roofs, which require plants resistant to the Québec climate's temperature and humidity variations (Monterusso *et al.*, 2005). While green roof irrigation systems are necessary in hot, arid regions, they are unnecessary in humid, temperature climates (Besir and Cuce, 2018).

Based on the studies conducted, it has been concluded that an appropriate growing environment should mainly comprise high-porosity, low-density inorganic matter and only 0% to 20% organic matter to increase water retention capacity and promote nutrient recycling. A mixture of several organic materials such as soil, clay, and green waste composted in a green roof substratum appears to promote plant growth and contribute to increased carbon sequestration in green roof systems (Charoenkit and Yiemwattana, 2016). Humidity and temperature variations should also be considered when plants are chosen for green roofs.

In recent years, some developed countries such as the United States, Canada, Australia, Singapore, and Japan have put forward new standards aimed at the profitable, economical modernization of energy use in existing buildings and new applications built with green systems. A standard has been adopted in Canada to ensure that green systems cover between 20% and 60% of the roof surface when the building's floor area exceeds 2 000 m^2 (Besir and Cuce, 2018).

COOLING GAINS AND OTHER BENEFITS RELATED TO GREEN ROOFS

The interior temperature of buildings under green roofs is likely to be cooler, which reduces the need for air conditioning and, therefore, energy consumption and carbon emissions (Charlesworth, 2010). The annual carbon capture of green roofs is on the order of 0.375 kg/m^2 to 30.12 kg/m^2, while it falls between 0.14 kg/m^2 and 0.99 kg/m^2 for vertical green systems (Besir and Cuce, 2018).

Of all the types of roof covering (traditional, reflective coating, plant), the green roof achieves the most cooling. A dark roof exposed to the sun can reach 80°C, a white roof, 45°C, and a green roof, 29°C (Liu and Bass, 2005; Fischetti, 2008; Perrin, 2020).

Niachou *et al.* (2001) analyzed the thermal properties of green roofs and concluded that, during the summer, they maintained low indoor daytime air temperatures and higher nighttime temperatures, compared with a conventional roof. However, they observed that night ventilation maintained lower temperatures day and night. Accordingly, energy consumption in buildings equipped with green roofs was lower than consumption for non-green roofs and could even be enhanced through natural ventilation during the summer (cited in Gago *et al.*, 2013). Buildings equipped with green roofs appear to consume 2.2% to 16.7% less energy in the summer than those equipped with conventional roofs. A similar trend has been observed in the winter according to regional and climatic conditions (Besir and Cuce, 2018). Annual energy demand appears to be lower for intensive green surfaces (8.2 kWh/m^2) compared with semi-intensive (12.3 kWh/m^2) or extensive (23.6 kWh/m^2) green surfaces. The temperature difference between conventional roofs in the winter appears to be roughly 4°C, compared with roughly 12°C in the summer (Silva *et al.*, 2016).

It has been observed in several studies in the literature review that the characteristics of green roofs affected the thermal and energy performance of buildings. Moreover, such performance is greater when the substratum is thick (Permpituck and Namprakai, 2012, Liu and Minor, 2005, cited in Besir and Cuce, 2018) and the water content is high in the summer and low in the winter (Lazzarin *et al.*, 2005, cited in Besir and Cuce, 2018). It should be noted that it is advisable to use a moist substratum in the summer and dry soil in the winter. Indeed, dry soil is used to increase heat storage and

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thermal insulation in the winter (Besir and Cuce, 2018). A study based on four North American cities showed that thicker soil achieved greater energy savings in all the cities, including Toronto and Vancouver (Mahmoodzadeh *et al.*, 2020).

The cooling that green roofs engender is not negligible. In Chicago, an intensive roof installed on a city hall had an average annual temperature 7°C lower than the surrounding conventional roofs, a difference that could reach 30°C during the hottest periods of the summer (Daley, 2008). In Ottawa, Liu (2002) drew similar conclusions: the same roof half covered by vegetation cover and half covered with conventional asphalt covering displayed a temperature difference of 45°C on a 35°C sunny day. Similarly, were Detroit to green all of its nearly 15 000 ha of roofs, 55 252 tonnes of carbon could potentially be sequestered (Getter and Rowe, 2009, cited in Charlesworth, 2010).

According to the literature, based on 17 studies that provide original data on the reduction of UHI, the maximum cooling of green roofs at street level appears to vary between 0.03°C and 3°C. The study that presents the smallest cooling effect (0.03°C) is noteworthy since it considers the coverage of only 25% of the green roof instead of 100% as do most of the other studies (Gromke *et al.*, 2015). On a pedestrian scale, intensive green roofs could engender double the cooling effect in terms of the heat felt compared with extensive green roofs (Berardi, 2016). According to their study conducted in Singapore, Wong *et al.* (2003) indicated that the installation of green roofs on buildings less than 10 m tall would engender a cooling effect at street level. Similar findings were observed in France (Berardi, 2016) and Toronto (Ouldboukhitine *et al.*, 2014, cited in Lai *et al.*, 2019). The street-level cooling effect for green roofs installed on medium-height (roughly 30 m) and tall (roughly 60 m) buildings would, however, be negligible *(Lai et al.*, 2019).

Sookhan *et al.* (2018) studied the thermoregulation services that extensive green roofs provide during hot and cold seasons in Toronto. They observed that sedum surpassed a mixture of perennial grasses and indigenous herbaceous flowers during the overall interannual investigation period. The

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flowering prairie appears to depend more on additional irrigation compared with the sedum and is apparently more sensitive to interannual climate variability. The findings emphasize the durability of sedum as a plant for the extensive cooling of green roofs and the importance of plant selection and the determination of the traits that correspond not only to summertime microclimatic conditions but also to wintertime conditions.

Susca *et al.* (2011) studied during daily rush hour in New York the surface temperature of a 10-cm thick green roof encompassing 1 000 m^2 of sedum with an albedo of roughly 0.2. It was between 1°C and 8°C lower than the temperature of the white membrane (albedo 0.6), while the reflecting membrane was 1°C to 5°C cooler than the green roof during the night. The findings also revealed that the installation of a green roof instead of a reflecting roof led to energy savings ranging from 40% to 110% and the UHI mitigation potential was greater.

While cooling effects are higher in cities with dry climates, the building's characteristics also define the possible contribution of green roofs (Santamouris, 2014). Summertime air conditioning needs can be reduced by means of a green roof, especially for roofs that were originally less well insulated. In fact, energy use can be relatively stable up to a certain temperature. Beyond this critical threshold, a 2°C increase due to UHI can increase energy consumption by 5% (Bass et al., 2003). Research conducted in southern Italy revealed that uninsulated green roofs were roughly 12°C cooler than traditional roofs according to average summertime temperature measurements. Likewise, the wintertime temperature difference between traditional roofs and green roofs was nearly 4°C (Bevilacqua et al., 2017). Numerous researchers have studied both experimentally and digitally the potential energy savings stemming from green systems in buildings. The observations reveal that green roofs reduced summertime and wintertime heat loss from the roofs by roughly 70% to 90% and 10% to 30%, respectively (Besir and Cuce, 2018).

5.3 Measures related to sustainable urban infrastructure

Different types of surfaces that absorb solar rays and then reflect them at night characterize urban areas. Airborne particles and combustion gases retain the radiation. Daylight harvesting, sun-shading devices, and urban design are significant energy conservation strategies that reduce the UHI effect (Tsangrassoulis *et al.*, 1999, Ferrante and Cascella, 2001, cited in Gago *et al.*, 2013). UHI results from the heat that the surfaces that dominate the urban environment absorb, then radiate. Reflective materials are used to increase the albedo of cities. Instead of absorbing sunlight, the surfaces reflect most of it, thereby reducing the local heat effect. Methods such as surface painting aimed at increasing the albedo are relatively simple and inexpensive to implement (Yang *et al.*, 2015, cited in Leal Filho *et al.*, 2018; Qin, 2015).

5.3.1 Buildings

The materials used in building façades significantly affect urban heat balance. The solar rays that construction materials absorb are dissipated through convective, radiative transfer into the atmosphere and consequently raise the temperature of the ambient air. The appropriate selection of materials can thus reduce energy consumption and enhance the comfort of buildings and urban spaces (Santamouris *et al.*, 2011).

Buildings that integrate protection against heat usually have openings equipped with sun-shading devices, reflective materials, and, occasionally, clever natural cooling systems.

5.3.1.1 Choice of reflective materials

The higher the reflectivity (albedo) and emissivity of a material, the lower the risk of storing heat and diffusing it in the atmosphere or inside a building through the walls and the roof (Paroli and Gallagher, 2008; Synnefa *et al.*, 2007).

The reflectivity of surfaces refers to their capacity to reflect solar radiation, a property called albedo. Albedo is represented on a scale of 0 to 1. A high albedo, which approaches 1, means that the surface reflects a great deal of solar radiation. Accordingly, the more reflective a surface is, the higher its albedo (see Table 5). Clear, shiny surfaces have higher albedo values than darker, more opaque ones (Gago *et al.*, 2013).

Emissivity is the property of a material to disseminate the energy that it accumulates. Energy that is not diffused contributes to surface heating. The emissivity coefficient of a material depends on its surface condition and, for a metal, its degree of oxidation. The coefficient is also expressed as a value falling between 0 and 1. A material displaying lower emissivity is a better thermal insulating material (Liébard and De Herde, 2005).

Table 5 Albedo of different materials

Albedo	Material
~0.93	Plaster
~0.85	Polished aluminum
~0.82	White paint
~0.56	White marble
~0.36	Dull copper
~0.32	Red brick
~0.20	Dirty concrete
~0.15	Dark wood

Source: Liébard and De Herde (2005).

The modification of the thermal property of urban surface materials is the cheapest way to reduce the UHI effect. Even though the impacts of this strategy are inferior to those obtained through revegetation, its cost and technical feasibility facilitate the coverage of larger surfaces and the attainment of better results (Rosenzweig *et al.*, 2006, cited in Kleerekoper *et al.*, 2012). The potential of reflective materials depends on an array of factors, including, by way of an example, the building's characteristics, the urban environment, and weather patterns and geographic conditions (Yang *et al.*, 2015). In the same way, it has been observed that the impact of high albedo on surface temperature reduction is more significant on sunny days than on cloudy days (Rosso *et al.*, 2016).

Roofs can be painted white to increase their albedo. The paints now on the market can reflect up to 90% of solar rays (Perrin, 2020). The roofing materials industry has recently developed high-performance roofing materials such as elastomeric or polyurea membranes, pale tiles and gravel, whose albedos are all higher than those of traditional materials (Akbari *et al.*, 2006; Perrin, 2020). The use of such materials is recommended solely for flat roofs in regions subject to UHI since they can create **dazzling** when installed on sloping roofs (Nikolopoulou, 2004; Perrin, 2020).

Fourth-generation reflective materials based on nanotechnological additives such as thermochromic paints and tiles (Ma *et al.*, 2001, 2002; Karlessi *et al.*, 2009) or phase-change materials (PCM) (Karlessi *et al.*, 2011; Zhang *et al.*, 2007; Pasupathy *et al.*, 2008; Cabeza *et al.*, 2007) have been developed and will probably be used for future applications for reflective roofs (cited in Santamouris, 2014). Over time, all reflective materials lose some of their reflective efficiency because of the dirt that settles on the covering (U.S. EPA, 2012). It has been shown that because of the effects of alteration, the potential of reflective materials is reduced by at least 25% during the first year following their installation (Lontorfos *et al.*, 2018). The alteration of reflective materials stemming from accumulated dust, soot particles, and biomass, exposure to UV rays, microbial growth, the penetration of humidity and condensation considerably reduced their initial solar reflectivity (Berdahl *et al.*, 2002, Levinson *et al.*, 2005, cited in Lontorfos *et al.*, 2018).

5.3.1.2 The choice of coloured roof coverings with high solar reflectivity

To increase the albedo of sloping roofs, the Lawrence Berkeley National Laboratory, in collaboration with the Oak Ridge National Laboratory, conducted research on the properties of different colour pigments. The studies revealed that they can reflect a high rate of near-infrared radiation, which constitutes half of solar energy (Akbari *et al.*, 2006). The colours of coverings made up of these pigments are visually similar to those of conventional roofs, but their reflectivity capacity is appreciably higher (Levinson *et al.*, 2005).

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Generally speaking, when the albedo increases by 0.1, the ambient temperature on hot days can be reduced by roughly 1°C (Santamouris, 2014). A simulation focusing on Montréal showed that an increase in albedo from 0.2 to 0.85 would reduce annual temperatures by 0.2°C and up to 4°C on hot days (Touchaei and Akbari, 2015). A dark, low-albedo roof covering can reach a temperature of 50°C higher than that of the ambient air while, according to Akbari *et al.* (2001), a high-albedo roof will reach a maximum temperature of 10°C higher than that of the ambient air. This surface can contribute greatly to the reduction of air conditioning needs (Écohabitation, 2020c). American studies have shown that the reduction in air conditioning needs might reach between 13% and 40% depending on the cities (Konopacki *et al.*, 1998). In the same way, a California study established that the addition of high-albedo colour pigments when roof coverings are manufactured could reduce air conditioning needs by 10%, ambient heat by 1°C to 1.5°C, and smog by roughly 5% (Akbari *et al.*, 2006). The use of low-emissivity reflective materials appears to generate more cooling in urban environments and thereby enhance air quality by minimizing smog formation (Taha, 1997a).

A study conducted for the Greater Toronto Area estimated air conditioning costs could be reduced by some $11 million (150 GW) if the city installed white roofs and adopted a greening strategy (Akbari and Konopacki, 2004). Snow also reduces heating demand for a reflective roof, thus contributing to higher overall annual savings on energy expenditures (Hosseini and Akbari, 2016). A simulation study showed that with a 100% increase in local albedo (0.15 to 0.30), a reduction in the ambient temperature was almost negligible, while when the local albedo stood at 0.45 (a 200% increase), the peak

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ambient temperature in the city fell by 2.5°C (Zhou and Shepherd, 2010).

Scherba *et al.* (2011) reported in their study conducted for several American cities using simulation techniques that the nighttime temperature of green roofs was nearly 1.5°C to 2.0°C higher than that of reflective roofs (albedo of 0.7). Conversely, during the daily peak period, the corresponding surface temperatures were almost equal. The reflective roof's lower nighttime surface temperatures and the relatively higher surface temperature of the plant-covered roof are attributed to radiative cooling and the storage capacity of the soil, respectively.

An experiment was conducted in London to measure the temperature difference on two walls that both received the same rate of solar radiation situated in the same urban canyon. A high-albedo material (0.50) covered one of the walls and a low-albedo dark material (0.03) covered the other wall. Different measurements were recorded on a sunny afternoon and the temperature of the reflective surface was 6°C to 10°C cooler during this period. To conclude, if all surfaces had good reflective capacity, the temperature in the canyon could have been reduced by 3°C to 4°C at the hottest time of the day (Watkins *et al.*, 2007).

5.3.2 Bioclimatic architecture

The principles of bioclimatic architecture protect buildings from summertime overheating since they consider climatic and environmental conditions. From envelope design to building orientation, bioclimatic architecture makes every effort to ensure the occupants' thermal comfort, thereby protecting the most vulnerable individuals from heat (Liébard and De Herde, 2005; Agence de l'environnement et de la maîtrise de l'énergie, 2012). This approach is based on multidisciplinary research, which ensures the development of sound buildings that are comfortable for their occupants, do not disturb the environment, and contribute to biodiversity (Widera, 2015).

5.3.2.1 Insulation and air tightness of buildings

While insulation and air tightness are parameters associated with cold climates, they are also indispensable to control coolness inside buildings. They prevent cold or heat from penetrating buildings through the walls, the roof, the ground, or windows, and thus mitigate the occupants' thermal discomfort (Déoux et Déoux, 2004).

Sound building insulation conserves heat in the winter and avoids overheating in the summer. It is assured, in particular, by installing thicker insulation on the building envelope and installing double- or triple-glazed windows (Écohabitation, 2020a). Building insulation is especially effective when the envelope displays few or no thermal bridges. Thermal bridges usually stem from design or construction flaws in the insulating envelope that allow air to enter the building in the winter and do not keep it cool in the summer. They engender thermal discomfort and over-consumption of energy for heating and air conditioning. They can lead to condensation zones and, consequently, the development of mould (Liébard and De Herde, 2005).

Improved air tightness can also reduce air flows between the outside and the inside of a building. It also controls humidity, which can cause health problems and thermal discomfort. To limit the transfer of heat and humidity on either side of building envelopes, specific construction, insulation, and sealing processes are applied to new buildings (Poulin *et al.*, 2016). In the same way, better sealing must be combined with a properly maintained, appropriate ventilation system that ensures healthy indoor air quality and cools the ambient air at night if possible (Déoux and Déoux, 2004).

When they are concomitantly, optimally applied, such techniques that affect building envelopes offer a passive, energy-efficient solution to deal with heatwaves and protect vulnerable populations from their effects (Santamouris *et al.*, 2010, cited in Poulin *et al.*, 2016). Several building certification systems are available in Québec, some of them recognized the world over, such as the LEED and ENERGY STAR programs. Similarly, the Novoclimat 2.0 program[16], which also specifies technical requirements to ensure better energy performance, greater comfort, and improved indoor air quality (Ministère de l'Énergie et des Ressources naturelles, 2016), is offered for new building or major renovation projects carried out in Québec south of the 51st parallel (cited in Poulin *et al.*, 2016).

5.3.2.2 Maximization of thermal inertia

The thermal inertia of a building is its capacity to store then diffusely release heat. The higher the building's inertia, the slower it heats up and cools down (Écohabitation, 2012b).

High-inertia materials allow for excess heat accumulation and storage, which avoids heat in the ambient air and improves thermal comfort. The heat that high-inertia materials contain will be diffused between six and 10 hours after the materials start to accumulate the heat, i.e., toward the end of the day when it will be possible to let cooler air enter the home (Hollmuller *et al.*, 2005; Agence de l'environnement et de la maîtrise de l'énergie, 2012). Stone, concrete, bricks, and raw earth are examples of materials with good thermal inertia.

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16 Novoclimat – Critères d'admissibilité : https://transitionenergetique.gouv.qc.ca/residentiel/programmes/novoclimat-professionnels-construction/novoclimat-petit-batiment-multilogement#c4809.

To maximize the cooling potential that high-inertia materials afford inside buildings, it would be ideal to place high-inertia walls in sunny locations and ensure that at least 50% of the room walls are high inertia (Courgey et Oliva, 2012; Agence de l'environnement et de la maîtrise de l'énergie, 2012). High thermal inertia avoids overheating by conserving cool nighttime air throughout the day, while maintaining coolness in the building through sound insulation and air tightness.

5.3.2.3 The use of high-performance glazing

Glazing is a weak point in a building's thermal insulation both in summer and in winter (Armstrong *et al.*, 2008). However, it is possible to enhance the performance of thermal insulation, in particular by choosing:

- smart anti-emissive glazing, which reduces sunlight inside a building. Such glazing adapts according to the seasons and the angle of inclination of the incident rays: they allow wintertime light to pass when the sun is lower and limit summertime solar radiation when it is higher (Armstrong *et al.*, 2008);
- double- or triple-glazing with gas space or inert gas, which minimize heat exchanges through conduction and convection. Air acts as insulation and double- or triple-glazing that encloses a 16-mm to 20-mm air space increases the insulating capacity. The insufflation of non-flammable, non-toxic argon or krypton gas to replace air affords better insulation in such glazing. Sealed double glazing with a low-emissivity coating, an insulating-glass spacer, and argon produces performance similar to that of triple glazing at optimum cost effectiveness without the potentially harmful weight of the latter glazing when the window is opened and the loss of light entry through triple glazing (CAA-Québec, 2021; Écohabitation, 2018);
- self-adhesive plastic film that blocks 99.5% of UV radiation and 86% of solar energy (Filmpourvitre.com, 2021a, 2021b).

Frank (2005) specifies that one simpe way to bolster the thermal inertia of the building envelope is to limit the extent of glazed surfaces (cited in Poulin *et al.*, 2016). In the same way, at least 60% south-facing glazing is to be preferred to optimally recover heat from sunlight. North- and west-facing openings are to be minimized since they display poor energy balance (Écohabitation, 2018).

Low-solar-gain glazing also exists and could solve the problem of summertime overheating. However, its use would lead to a wintertime loss of solar heat gain and thus to higher energy demand. Researchers at the National Research Council of Canada in Ottawa conducted a study to compare the year-round energy performance of two types of low-emissivity glazing, i.e., high-solar-gain glazing and low-solar-gain glazing. It showed that the use of high-solar-gain glazing should be advocated in cities in which are recorded more than 3 000 Celsius degree-days, i.e., most Québec cities. The use of high-solar-gain glazing also appears to engender a reduction of 13% to 17% in combined heating and cooling costs, while the use of low-solar-gain glazing appears to engender savings of 8% to 10% (Natural Resources Canada, 2014).

Skylights integrated into roofs also warrant attention. Unless they can be covered outside, it is highly inadvisable to incorporate them into the building to avoid the attendant greenhouse effect that can require energy-intensive air conditioning (Courgey and Oliva, 2012; Écohabitation, 2020a). Compared with conventional skylights, tubular skylights appear to be better adapted to Québec's climate, especially because of enhanced air tightness, greater luminosity, and a reduced greenhouse effect in the summer (Écohabitation, 2020a).

As for old windows, a complete change is necessary only if the frame is damaged, the insulation has deteriorated, or there are numerous leaks. Otherwise, it is relatively simple and inexpensive to change the glazing. It is also possible to add additional glazing to the existing window or to apply a surface film (Écohabitation, 2018). Under Québec's climatic conditions, the ideal situation is to take advantage of winter sunshine and rely on sun-shading devices to protect against it in the summer.

5.3.2.4 The addition of sun-shading devices

In addition to vegetation, which, as noted earlier, is an excellent means of protecting the building envelope from direct sunlight, glazing and building sun-shading devices are other solutions to limit the contribution of heat from solar rays. Unlike interior protection, sun-shading devices are installed outside around the windows or on them to block summertime solar rays while allowing light to enter. Table 6 presents different types of sun-shading devices.

Recourse to fixed solar masks requires precise proportioning to avoid losing the benefits of wintertime sunlight (avoid installing an overly long sunshade that will block wintertime entry of sunlight when the sun is lower) (Courgey and Oliva, 2012). While interior sun-shading devices such as opaque shades or blinds are much less effective in protecting the building interior from summertime overheating, they must be clear and cover the entire surface of the window (Courgey and Oliva, 2012). A Canadian study conducted by the National Research Council of Canada showed that half-closed revolving shutters installed on the windows of a typical North American house could reduce air conditioning needs by 67% during the hottest weeks of the summer (Écohabitation, 2020b).

Table 6 Different types of exterior sun-shading devices

Fixed sun protection systems			
Awnings Opaque, horizontal sun-shading devices included in the building structure 	**Louvred shutters** A series of fixed or mobile exterior slats arranged on the façade 	**Shade screens** Made up of slats arranged on a frame 	**Eaves and upper-floor balconies** Equally protect the windows and part of the building from solar rays 

Mobile sun protection systems		
Horizontal sunshades Protect the windows, façades, or part of the sidewalks from solar rays 	**Shutters** Protect the windows from summertime solar rays and can be removed in the winter 	**Retractable awnings** Protect the windows from summertime solar rays and can be removed in the winter 

Source: Liébard and De Herde (2005).

5.3.3 Road infrastructure

5.3.3.1 Choice of high-albedo pavement

It has been estimated that dark surfaces might represent more than 40% of a city's area. As noted earlier, large paved urban areas such as schoolyards, roads, and parking lots are often covered with asphalt or concrete. Such surfacings have a very low albedo. This results in a higher ambient temperatures, typical of the UHI effect, which can reach 80°C under the summer sun (U.S. Department of Transportation Federal Highway Administration, 2019).

Typical albedo values range from 0.04 to 0.16 for asphalt roadways and from 0.18 to 0.35 for concrete roadways (Pomerantz *et al.*, 2003), although the albedo of new concrete can reach 0.69 (Marceau and VanGeem 2007, cited in U.S. Department of Transportation Federal Highway Administration, 2019). Since the thickness of the pavement affects its ability to store heat, thinner surfaces are to be preferred for low albedos, which absorb heat (Golden and Kaloush, 2006). The albedo of an asphalt surface is higher in the winter than in the summer since in the winter the asphalt surface can be covered with ice or snow so that the colour of the asphalt is lighter, which leads to an increase in reflected radiation. Changes in albedo of 0.2, in the summer, to 0.3 or 0.35, in the winter, have thus been observed (Hermansson, 2004, cited in Bobes-Jesus *et al.*, 2013). In the same way, it should be noted that the albedo of roadways changes over time. The albedo of concrete roadways decreases and that of asphalt roadways increases as they age (EPA, 2008, cited in U.S. Department of Transportation Federal Highway Administration, 2019).

To minimize heat accumulation in pavement, the following techniques can be used to increase its albedo.

- **Inverted pavement:** existing asphalted roads comprise roughly 85% mineral aggregate covered with 15% bitumen. One way to increase the albedo of asphalt is to invert the manner in which the pavement is manufactured, i.e., by spreading a thin layer of bitumen on which high-albedo aggregate is placed, e.g., 0.60. The aggregate thus exposed increases the reflectivity rate of the surfacing, which reduces the temperature of the pavement. However, these types of pavement are inadvisable for high-speed roads since the pieces of aggregate can unstick and break windshields and affect user safety.
- **Coloured asphalt and concrete:** the addition to asphalt and concrete of reflective pigments increases their reflectivity.
- **A thin layer of concrete:** a layer of concrete is added to the surface of asphalt pavement in good condition (Lai *et al.*, 2019). Concrete has a higher albedo (from 0,30 to 0.40 when new), which maintains a cooler surface temperature. This method appears to be very effective and allow for the circulation of all types of vehicles (Winkelman, 2005; Synnefa *et al.*, 2007).

With specific reference to bituminous pavement, most losses of reflectivity occur during the first month of use, which is attributable to the significant deposit by automobile traffic of rubber on roadway surfaces. The loss of reflectivity observed for concrete pavement is fairly gradual over time and stems mainly from significant dust deposits on its surface (Lontorfos *et al.*, 2018).

As is true of buildings or pavement, paints with high solar reflectivity rates are available for vehicles and businesses should recommend their use. Such paints are made up of special pigments that increase by 17.5% on average their albedo (Ihara, 2006).

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A study conducted by the Heat Island Group estimated that the installation of high-albedo pavement combined with a revegetation strategy could reduce by 0.6°C the ambient temperature in Los Angeles (Rosenfeld *et al.*, 1998). According to a comparative study of the state of pavement in several American cities, the heat in the city appears to affect the rate of deterioration of the composites of asphalt. Lighter paving thus appears to have a better useful life (Heat Island Group, 2021).

5.3.4 Urban planning

5.3.4.1 Recommendation of well spaced out urban morphology

The distribution of urban structures and buildings in a city affects the formation of UHI since it can determine the absorption of solar energy and formation of wind currents. The performance of an urban area as regards solar radiation and airflow between buildings also plays a role in the dispersal of airborne particles and pollutant gases. The urban response to solar radiation and airflow can be controlled through urban design (Ratti *et al.*, 2003, cited in Gago *et al.*, 2013).

Kristl and Krainer (2001) have conducted an energy assessment of the urban structure and the proportioning of parcels of land. They observed that a north-south orientation was more logical for low buildings (6 m high). Conversely, no orientation was preferred for average-sized (12 m) and tall (36 m) buildings. An increase in the width of buildings appears to reduce the impact of the orientation in the case of low buildings (cited in Gago *et al.*, 2013). In the same way, a more random arrangement of tall buildings can reduce the UHI effect (Cheng *et al.*, 2006, cited in Gago *et al.*, 2013).

Urban morphology can, in particular, generate urban canyons that confine heat and airborne pollutants (Gago *et al.*, 2013). According to Ratti *et al.* (2006), maximum turbulence is necessary to disperse pollutants (cited in Gago *et al.*, 2013). The consideration of wind in urban planning processes can lead to effective cooling of buildings in urban areas (Kleerekoper *et al.*, 2012).

Simulations conducted by Wang and Akbari (2014) in four typical urban neighbourhoods in Montréal revealed that an increase in the sky view factor led to a daytime temperature reduction of the air. At night, in the absence of direct sunlight, open spaces allowed for greater heat loss skyward through long-wave radiation, which lowered the air temperature.

There exists a correlation between morphological indicators such as rugosity, built density, surface albedo, and urban geometry, and heat in urban areas. Research has established this relationship between urban morphology and microclimates (Fouad, 2007; Pinho *et al.*, 2003; Nikolopoulou, 2004; Gago *et al.*, 2013).

UHI effects are relatively weak and can become negative, thereby creating a cool island, in the parts of the city where tall buildings create extensive shade and the high thermal capacities of construction materials slow heating (Oke *et al.*, 2017). Johanson (2006) showed that even if a shallow canyon is uncomfortable in the summer, wintertime sunlight makes it more comfortable than a deep canyon (cited in Lai *et al.*, 2019). A compromise between summer and winter must be contemplated when urban morphology is designed for outdoor thermal comfort, especially in temperate regions (Lai *et al.*, 2019). Wind flow is channeled in the canyon if the street is oriented in a direction parallel to that of the wind. In coastal cities, an effective ventilation strategy consists in orienting streets parallel to the sea breeze. Ng (2009) suggested limiting the angle between a street and the orientation of wind flow to less than 30 degrees to obtain good ventilation in high-density cities (cited in Lai *et al.*, 2019).

Urban planners can foster residents' thermal comfort by focusing on the following concerns in the urban planning process:

- land-use planning that targets good summertime wind circulation, which is very useful in cities with a high degree of humidity. Combined with this development strategy, vegetation and water (jets, falls, and fountains) can create additional coolness;
- the development, sound distribution, and preservation of green spaces. Urban green spaces should be properly distributed to facilitate access to them, i.e., less than a 20-minute walk from any dwelling. Ideally, they must create green corridors that pedestrians can easily use. Large green spaces situated upstream from the city in line with the prevailing winds can also contribute to cooling the air;
- mixed uses that allow for the development of continuous trips intended for active transportation and that promote access to recreational and social areas and to essential services such as food stores, near dwelling places;
- the promotion of mass transit, the limitation of the use of privately-owned motor vehicles, and urban development inspired by **transit-oriented development** (see section 0) (U.S. EPA, 2008b); *Coutts et al.*, 2010; Nikolopoulou, 2004; Vivre en Ville, undated).

5.3.4.2 The development of blue spaces

The term "blue spaces" refers to outdoor urban surfaces that are mainly dominated by water, such as lakes, rivers, ponds, and fountains. Static lakes and ponds and dynamic rivers and streams have the potential to lower the surface temperature through constant evaporation, especially on sunny days (Yang *et al.*, 2020). However, evaporation appears to increase humidity around water bodies, which appears to reduce thermal comfort (Yu *et al.*, 2015). On the one hand, the flow characteristics of dynamic water bodies can play a significant role in the spatial distribution of heat release since rivers can move the stored energy downstream (Hathway and Sharples, 2012; Kleerekoper *et al.*, 2012). On the other hand, given the limited movement of water in static water bodies, the latter tend to be more sensitive to heat transfers between the water and the air (Ampatzidis and Kershaw, 2020).

The cooling intensity of water is apparently generally stronger in low-altitude cities than in high-altitude cities (Yu *et al.*, 2020). In the same way, the cooling effect appears to depend on seasonal and diurnal variations (Ellison *et al.*, 2017). When a water body is integrated into the city core, an oasis effect can be observed during the day (Ampatzidis and Kershaw, 2020). Relatively strong winds above the water surface increase evaporation and accentuate the cooling effect, while higher water vapour content limits heat loss through evaporation and can reduce the cooling effect (Webb and Zhang, 1999, Stathopoulos, 2006, cited in Ampatzidis and Kershaw, 2020). Because of their high thermal capacity, water bodies can, however, have a warming effect if the surrounding urban areas cool more rapidly (Broadbent *et al.*, 2018b).

The capacity of a water body to cool the surrounding urban environment depends chiefly on local environmental and meteorological conditions such as ambient temperature, humidity, wind speed and direction, and the inherent properties of water (Ampatzidis and Kershaw, 2020). The cooling effect of water on sunny days is more significant than on cloudy days since the higher solar radiation on sunny days provides additional energy for the evaporation of water and the reduction of the air temperature (Lai *et al.*, 2019).

Small installations or expanses of water such as ponds, fountains, and water jets act as thermal buffers since they moderate temperature fluctuations, thereby creating microclimates. It should be noted that large water bodies increase the spreading of sound and should be avoided in very noisy urban areas (Déoux and Déoux, 2004).

From a strategic standpoint, high cost makes difficult the promotion of the use of blue spaces to take advantage of the evapotranspiration effect. The installation of fountains can be deemed a sound cost-benefit option in specific, high-use spaces such as streets and business premises. With intelligent design, it is possible to use the same space for other purposes in the winter (Kleerekoper *et al.*, 2012).

Different facilities can be offered to the public, such as aquatic areas, ponds, and mist makers. More recently, reflecting pools (a thin film of water spread over slabs) are also enabling residents to cool off. Spraying or misting processes promote evapotranspiration by maximizing the contact surface between air and water and thus accentuate the cooling of the ambient air. It should be noted that the efficacy of evaporation due to fogging or spraying is more significant than natural evaporation but consumes much more water (Agence de l'environnement et de la maîtrise de l'énergie, 2012).

Access to and the proximity of aquatic areas are also essential to enable residents to cool off both in natural environments and in developed public areas (see Figure 10). Other facilities such as ponds and mist makers also provide cooling and can be installed in parks and recreation centres (Raymond *et al.*, 2006). The ambient air provides the water with the energy to evaporate, and the evaporation process thus cools the ambient air.

Figure 10 Fountains and a swimming pool

Photo credit: Ville de Québec.

5.3.4.3 Installation of cooling areas

Access to cooling areas such as shopping centres, schools, cultural centres, or any other air conditioned public building open to the public is sometimes essential to alleviate the detrimental effects on residents of sweltering heat. It is also important to provide for assistance for individuals unable to move about alone to access such sites (English *et al.*, 2007; Widerynski *et al.*, 2017). Rest areas such as shelters or airconditioned centres must also be available for outside workers. Data show that individuals at low risk go more often to cooling centres than high-risk individuals, which highlights the need to encourage those most at risk to visit cool zones (Kovats *et al.*, 2006, cited in Widerynski *et al.*, 2017). According to Kosatsky *et al.* (2009), in Montréal 25% of 238 elderly patients suffering from chronic diseases stated that they would refuse to seek shelter in a cooling facility in the event of a prolonged heatwave because of concerns related to sleeping in a dormitory or not deeming themselves sufficiently ill to need such a facility (cited in Widerynski *et al.*, 2017).

COOLING GAINS AND OTHER BENEFITS RELATED TO BLUE SPACES AND COOLING FACILITIES

Blue spaces can engender a cooling effect of 1°C to 3°C within roughly 30 m (Kleerekoper *et al.*, 2012). However, there is little information on the broader impact of blue spaces on UHI at the city level. Several researchers have suggested that the establishment of numerous smaller blue spaces in the urban environment may provide more dispersed cooling in relation to a single larger water body, which, on the other hand, may afford more

COOLING GAINS AND OTHER BENEFITS RELATED TO BLUE SPACES AND COOLING FACILITIES (CONTINUED)

significant but localized cooling. The size and shape of blue spaces are important variables as regards the cooling obtained in urban environments, but there is no consensus in the literature because of the different sites and climates where the studies were conducted (Ampatzidis and Kershaw, 2020).

Blue spaces are usually more effective when they have large areas or when the water flows or disperses, such as from a fountain (Kleerekoper *et al.*, 2012). By focusing mainly on the studies that involve technologies based on water evaporation, such as sprinklers, water curtains, or fountains installed in public spaces to mitigate heat stress, it has been observed that, on average, water-based techniques afford an average cooling effect of 1.9°C and that the higher the temperature of the air, the higher the cooling potential is (Santamouris *et al.*, 2017).

Völker *et al.* (2013) conducted a meta-analysis that compiles the empirical findings drawn from static and dynamic water bodies that evaluate the impacts of blue spaces on the temperature in relation to a reference urban area. The median temperature difference was 2.5°C, which indicates a high cooling effect. The meta-analysis of Gunawardena *et al.* (2017) revealed that blue spaces can engender nocturnal warming, which more extensively affects thermal comfort and human health. In Brazil, Targino *et al.* (2019) observed that Lake Igapó was warmer than the neighbouring green park throughout the day but relatively cooler than the urban environment. It should be noted that the measurements were made in late fall. Indeed, warming is usually more apparent at the end of the summer when the water temperature reaches its maximum because of the accumulated heat (Gunawardena *et al.*, 2017). Li and Yu, 2014, cited in Ampatzidis and Kershaw (2020), also mention the higher cooling potential of green parks. The studies have shown that the expansion of green spaces appears to offer more extensive benefits than the expansion of water bodies. Green spaces appear to be more likely to provide constant daytime and nighttime thermal effects in relation to blue spaces (Sun *et al.*, 2018). Hathway and Sharples (2012) observed that in Sheffield in the United Kingdom the cooling effect of water bodies only occurred during the day and varied from 0.25°C to 1.82°C (cited in Yu *et al.*, 2020).

COOLING GAINS AND OTHER BENEFITS RELATED TO BLUE SPACES AND COOLING FACILITIES (CONTINUED)

As is true of green spaces, the cooling efficiency (scope and distribution) of blue spaces is affected, by way of an example, by the size and distribution of such spaces, and the distances between them (Gunawardena *et al.*, 2017). The findings of a study conducted in China revealed that as the air temperature fell, the cooling effect of a lake became weaker and weaker, reaching the lowest value of 0.3°C in October. In the same way, the shores of lakes with heavy vegetation play a more important role in cooling the air temperature than the shores of lakes made up of permeable or impermeable materials (Yang *et al.*, 2020). According to their study conducted in Bucharest, Romania, Robitu *et al.* (2004) observed that a 4-m x 4-m pond could also cool an urban environment in the summer by displaying a cooling effect of roughly 1°C at a height of 1 m, measured at a distance of 30 m (cited in Kleerekoper *et al.*, 2012). Other studies corroborate the efficacy of ponds from the standpoint of urban cooling: one of the first studies to measure the cooling effect of an urban pond was conducted in Fukuoka, Japan, by Ishii *et al.* (1991), who observed a 3°C reduction in the air temperature. Nishimura *et al.* (1998) subsequently conducted a similar study in Osaka, Japan, on two consecutive typical summer days under clear skies during the day. The findings revealed a temperature reduction of up to 2°C on the lee side of the pond.

In the same way, observations stemming from a study conducted in Tel Aviv, Israel, show a nearly 1°C reduction in the ambient temperature for a small pond (40 000 m^2) during the day, which indicates that even small blue spaces can provide cooling effects. Syaffi *et al.* (2016) used an experimental model reduced to the scale of an urban island in Saitama, Japan, to study the thermal effects of a pond. Despite a cooling effect of nearly 2.5°C during the hottest part of the day, they also observed that during the night the pond could be warmer than its urban environment. Using the same model, Syaffi *et al.* (2017) studied the effect of different sizes and configurations of ponds on urban thermal regulation capacity. The findings showed that the bigger the pond, the greater the cooling effect in the surrounding area. As for orientation, ponds parallel to the prevailing wind direction seemed more effective with an average decrease in air temperature of roughly 1.5°C at a height of 30 cm above the water, corresponding to the reduced pedestrian

COOLING GAINS AND OTHER BENEFITS RELATED TO BLUE SPACES AND COOLING FACILITIES (CONTINUED)

level. Lastly, Syafii *et al.* (2017) also emphasized the possible negative impact of higher humidity that might hamper thermal comfort (cited in Ampatzidis and Kershaw, 2020).

Ampatzidis and Kershaw (2020) conducted a meta-analysis to examine the thermal effects of static blue spaces on the urban climate. While studies that rely on remote sensing to study UHI in Europe are relatively fewer in number, they suggest that water bodies can mitigate urban air temperatures from 1°C to 10°C. Similarly, it was observed that blue spaces were the key cooling mechanism in an urban area in Toronto, Canada.

Water micronization techniques such as spraying micrometer-sized airborne water droplets promote the cooling of ambient air. Their effect is maximized in a hot, dry climate but also allows for cooling gains in environments where the relative humidity is higher, especially when cooling by air movement is possible (Liébard and De Herde, 2005). In the wake of a heatwave that struck Europe in 2003, French researchers conducted a study focusing on the use of a fogger in a gerontology centre in Marseille. The device's use in the living room where caregivers and residents mingle led to a 3°C indoor temperature reduction (Bonin-Guillaume, 2005).

5.3.4.4 The use of sun-shading devices in public areas

Direct sunlight raises the temperature that individuals feel and has an appreciable impact on their thermal comfort (Watkins *et al.*, 2007). As is true of buildings or infrastructure, shade partly protects individuals from direct sunlight and the UV rays that cause skin cancer. An array of options ranging from "natural shade" to "built shade" can provide shade. The first option relies on trees, big shrubs, vines, and ground cover to block direct UV rays and absorb indirect UV rays. The second option is designed and configured to satisfy specific needs and relies on manufactured components (Toronto Cancer Prevention Coalition, 2010). To this end, pergolas, awnings, or parasols, for example, can be installed in places of public use to protect residents from sunlight.

5.3.4.5 The choice of materials in parks

It should be noted that that the materials used in artificial surfaces absorb and store heat, thereby considerably increasing the surface and air temperatures and amplifying the UHI phenomenon (Macfarlane *et al.*, 2015). Several studies have showed that the temperature of artificial turf could exceed surrounding temperatures by 10°C (De Carolis, 2012; Government of

Western Australia, 2011; McNitt *et al.*, 2007). Another study, conducted in Montréal, attempted to compare the surface temperatures of artificial, natural, and maintained grass. The average daytime surface temperature of synthetic turf was 17.4°C higher than maintained grass and 10.3°C higher than natural grass. However, this temperature difference was less pronounced at night (the temperature was 2°C higher compared with natural grass and 0.6°C lower compared with maintained grass) (Canuel Ouellet, 2017).

5.4 Sustainable stormwater management measures

Climate change is likely to affect southern Québec's rainfall regime especially through the rising intensity of annual maximums and more intense, frequent rainfall. Combined with growing urbanization, such changes may engender increased volumes and peak urban runoff flows, thereby leading to greater risks of flooding, overflowing sewers, and the degradation of water quality in receiving water bodies (Dagenais *et al.*, 2014).

Sustainable stormwater management is an approach that offers numerous benefits that extend beyond the simple mitigation of flooding and water quality. It must be deemed a means of combating climate change and phenomena such as urban heat islands that climate change exacerbates. By promoting infiltration, evaporation, and evapotranspiration by means of vegetated structures, the literature widely mentions the attendant benefits both from a hydrological (a reduction of volumes and peak flows), aesthetic (a contribution to the urban landscape), or environmental (reduced UHI, broader biodiversity, and enhanced air and water quality) standpoint (Dagenais *et al.*, 2014; Flanagan *et al.*, 2017).

Several studies establish a correlation between the soil moisture level and UHI mitigation. Indeed, through evaporation, moist soils have cooling capacities similar to those of vegetation and their surface temperatures are cooler than those of dry soils (Lakshmi *et al.*, 2000; Sun et Pinker, 2004). Accordingly, a moist substratum allows for better heat dissipation and minimizes summertime cooling demand (Castleton *et al.*, 2010; Raji *et al.*, 2015). To promote the humidity of soil in urban areas and ensure the availability of water for plants, there are several sustainable stormwater management and water pollution control practices. They reflect the low-impact development approach that calls for broader management that considers various scales, ranging from the drainage basin to the private lot, as well as development interventions. This approach seeks to imitate natural or pre-development hydrology by limiting disturbances in natural environments during development to reduce runoff at the source and control pollutant concentrations (Credit Valley Conservation and Toronto and Region Conservation, 2010; Dagenais *et al.*, 2014).

To ensure the efficiency and safety of small-scale developments, the sites where they are established must be subject to preliminary studies. The proximity of a water table, the granulometry of the soil, and pollution risks are all factors to consider when measures are introduced that target the infiltration of stormwater in the soil. In the case of sites such as parking lots and industrial sites where sediments and pollutants are present, rigorous follow-up and maintenance must be carried out (MDDEFP and MAMROT, undated; Dagenais *et al.*, 2014).

Stormwater management practices can be divided into three categories: (1) practices focusing on pre-treatment such as filter belts; (2) practices related to the transportation of runoff such as valley gutters; and (3) practices geared to infiltration or retention at the source such as green roofs and bioretention zones, or at the conclusion of the treatment process, such as filter marshes. Given the difficulty of introducing valley gutters and filter belts in existing built environments because of the space they require, the practices presented in this section are related to infiltration or retention at the source. Similarly, related to the low-impact development approach that targets control at the source and because of the lengthy period of retention of the water (≥ 24-48 hours) that can be conducive to the proliferation of mosquitos, end-of-treatment practices are not examined in detail (Dagenais *et al.*, 2014).

5.4.1 Planting trees and installing green roofs

The promotion of greening must go hand in hand with that of enhanced stormwater management (Kleerekoper *et al.*, 2012). The root system of trees greatly maximizes water seepage. Plants with thicker roots appear to be especially effective in creating pores of significant dimensions that promote stormwater infiltration. Interception rates vary according to age, type of bark, the extent of foliage and thus the season, the architecture (the size and arrangement of small branches), the density of forest stand, and the species present. Other factors also affect the interception of rain, such as the intensity and duration of the rain and wind speed. Generally speaking, trees intercept the most rain, followed by shrubs, bushes, and grasses (Dagenais *et al.*, 2014).

It is acknowledged that the revegetation of urban areas and the installation of planted roofs enhance air and water quality, lower the ambient temperature, and reduce energy demand related to air conditioning (Niachou *et al.*, 2001; Missios *et al.*, 2005; Charlesworth, 2010; Gago *et al.*, 2013). Vegetated installations can also capture large amounts of stormwater (Gill *et al.*, 2007; DeNardo *et al.*, 2005; Charlesworth, 2010; Gago *et al.*, 2013; Besir and Cuce, 2018), which offsets the loss of vegetation cover stemming from the presence of buildings on the ground (Agence de l'environnement et de la maîtrise de l'énergie, 2012). The characteristics of green roofs affect their water retention capacity, including the depth of the substratum, the slope of the roof, the type of plants, and the intensity of precipitation (Oberndorfer *et al.*, 2007). To avoid increasing the content of phosphorous and other pollutants in water following movement through green roofs, it is important to carefully select the growth medium and adjust the fertilization accordingly. Lastly, plants also appear to be useful to limit clogging of the surfaces of stormwater infiltration systems (Dagenais *et al.*, 2014).

RETENTION BY TREES AND GREEN ROOFS OF RAINWATER

> **An extrapolation of the potential of public trees in Montréal to intercept precipitation shows that the trees now capture roughly 2.2% of rainwater (Vergriete and Labrecque, 2007). Another study concluded that the rainwater retention capacity of a 10-cm thick green roof was roughly 60% (Moran *et al.*, 2005). Rainwater retention appears to vary from 25% to 50% for thinner substrata. The literature indicates that extensive roofs could retain a maximum of 45% of water while intensive roofs appear to retain up to 75% (Carter and Keeler, 2008). A modelling study showed that if 10% of roofs in Brussels were green roofs, total runoff would be reduced by 2.7% (Mentens *et al.*, 2006).**

5.4.2 The choice of permeable coverings

The porous surface of permeable coverings captures precipitation and surface runoff that allows the water to slowly infiltrate the soil (Selbig and Buer, 2018).

Such coverings engender benefits from the standpoint of reduced rainfall runoff, the protection of soils through water infiltration, or a reduction in urban heat through hydrothermal exchange. Soils covered with gravel have been used for a long time as permeable coverings. They allow for sound water seepage in the soil when the latter is not too compact but are not valued in urban environments (Gilbert and Clausen, 2006).

Other types of permeable coverings include:

- impermeable slabs (paving stones) arranged contiguously that allow rainwater to percolate in the permeable joints (see Figure 11). This type of covering can be used if the soil on which it is installed is permeable, on varied sites such as schoolyards, pedestrian streets, alleyways, parks, pedestrian access routes, bicycle paths, and parking lots. It is not suitable for airports or freeways since it is vulnerable to abrupt braking and heavy weights;
- porous concrete slabs or coverings that allow water to flow through small cavities. This type of paving is obtained by eliminating or reducing the finest materials (sand and finer aggregates). Porous concrete usually has 20% voids (pores) in relation to its total volume and can allow water to infiltrate at a speed of 5 m/h to 45 m/h (Pilon *et al.*, 2019). Its maintenance requires cleaning by vacuum cleaner or water jet to remove substances that can plug the cavities. Its use is recommended for pedestrian footpaths since the absence of a joint does not afford the slabs considerable mechanical strength;
- the honeycomb shape of the structures that facilitate sodding allows for the revegetation of the soil and promotes water infiltration in the soil. The structures can also bear the parking of

light-duty vehicles (see **Erreur ! Source du renvoi introuvable.**) (Coste and Noel-Letendre, 2019).

Porous coverings can pose certain challenges since they allow water to infiltrate to the foundation layers, which can affect structural integrity when heavy loads are applied or during freeze-thaw cycles. The design of materials and the foundation must also consider both structural capacity and permeability. Similarly, they require regular maintenance and specific practices to avoid the contamination of the water table and clogging. Spreading sand in the winter is not appropriate since it can accelerate clogging in the covering (MDDEFP and MAMROT, undated).

WATER INFILTRATION CAPACITY RELATED TO PERMEABLE COVERINGS

According to the Milwaukee Metropolitan Sewerage District (2020), permeable, porous pavers appear to facilitate the infiltration of 70% to 80% of annual rainfall. What is more, a study that compared three types of parking lot coverings, i.e., asphalt, permeable pavers, and rock dust, showed that permeable pavers foster greater filtration of pollutants and better runoff water purification (Gilbert and Clausen, 2006).

Vaillancourt (2018) characterized the infiltration capacity of five permeable paving sites in Greater Montréal. The author observed very high infiltration capacity on the sites. Rainfall data were analyzed on one of the sites and the findings revealed a reduction of between 6 mm and 12 mm in the volume of runoff per rain event and up to a three hours time-lag in the peak flow.

Pilon *et al.* (2019) conducted a study in Tennessee, in the United States, focusing on a water quality assessment on a site comprising both impermeable asphalt and permeable concrete parking lots. The findings showed that the use of permeable concrete produced a statistically significant reduction in pollutants such as total suspended solids, nitrite, and hydrocarbons in relation to runoff from the asphalt.

Figure 11 Impermeable slabs with permeable joints – The "Le Vieux Beloeil prend le frais" and "Place St-Martin" projects and pedestrian areas that allow for water percolation

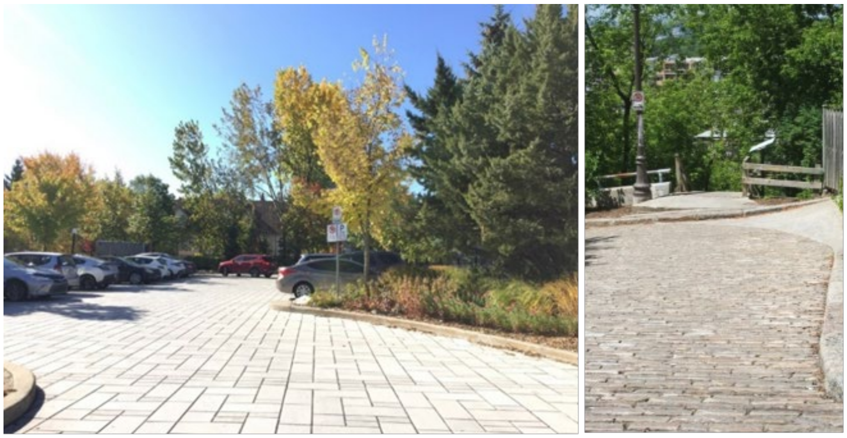

Photo credit: Mathilde Botella, Daniela Kowu and Mélissa Giguère.

5.4.3 The development of rain gardens

A rain garden can be developed at low cost to channel rainwater flowing from the roof, impermeable surfaces of the building, and its periphery to the stormwater drainage network. Such an installation is very attractive and fairly easy to implement in small and medium-sized residential buildings. Rain gardens afford a means of reducing runoff and increasing the degree of humidification of soils and the percolation of water to regenerate water tables (Frazer, 2005; U.S. EPA, 2007).

According to the Canada Mortgage and Housing Corporation (2011), a rain garden is a bed of plants or stones designed expressly to catch rainwater and allow the soil to slowly absorb it through infiltration. The dimensions of rain gardens will depend on the amount of runoff water captured and the speed at which it is absorbed. In general, the depth of the depression should range from 7.5 cm to 15 cm depending on the soil's absorption capacity, from the most clayey to the sandiest. They must be longilineal (at least 1.5 times longer than they are wide) and their length lie perpendicular to the depression. The installation will usually comprise a mixture of hardy perennials, ornamental pasture, and deep-rooted woody shrubs that are adapted to both wet and dry conditions. It is essential to ensure that the soil is permeable up to a depth of 0.6 m to 1.2 m under the rain garden (Canada Mortgage and Housing Corporation, 2011). When a rain garden is well designed, all stagnant water should disappear after 24 to 48 hours (Franti and Rodie, 2013).

It is advisable to situate the rain garden at least 3 m but not more than 9 m from the house, install it on a gentle slope of less than 12% and far from cabling, gas mains, buried pipes, and septic tanks. It is also advisable to consider runoff from neighbouring land that can flow toward the site of the rain garden. To ensure the durability of rain gardens, the addition of a layer of organic mulch retains moisture in the soil during periods of drought. Similarly, the selection of plants that do not require frequent pruning and fertilization minimizes rain garden maintenance (Franti and Rodie, 2013).

Private gardens can be used as rain gardens, thereby promoting slow water infiltration. The Royal Horticultural Society (2005) notes that the capacity of an average suburban garden is 10 l/min of water, equivalent to 10% of the incident precipitation absorbed. Cumulatively this could represent thousands of litres of water that might be diverted from a city's sewer system (cited in Charlesworth, 2010).

WATER INFILTRATION CAPACITY RELATED TO RAIN GARDENS

The impact on runoff following the installation of experimental rain gardens in a residential district was compared with that of a similar district without a rain garden. It was noted that the volume of runoff in the district with rain gardens was 90% lower than that in the reference district (Richards, 2009, cited in Boucher, 2010).

5.4.4 Retention pond design

A retention pond is an installation of the same type as a rain garden but of a bigger dimension in which the slope of the land creates a depression. The depression collects the water than runs into it and lets it infiltrate the soil (U.S. EPA, 1997). There are two types of retention ponds, i.e., permanently contained water pools that permanently preserve stagnant water, and dry lagoons, designed to collect certain types of flow and that empty fairly quickly and stay dry in the absence of precipitation. Among dry lagoons, those with prolonged containment retain water for frequent events lasting from 24 to 48 hours, thereby enhancing water treatment. This type of installation also affords other benefits such as the creation of plantscapes, indeed of play areas and recreational areas (dry lagoons) in urban environments. It can be equipped with means to prevent environmental pollution such as a debris basin or filtering aquatic plants, especially on parking lots and industrial sites (MDDEFP and MAMROT, undated). Settling is the main mechanism that allows for the removal of pollutants from the water and is completed, to a lesser extent, by certain biological and chemical processes in the case of lagoons with permanent containment (Moisan, 2013). Installations of this type have been carried out in Boucherville, where retention ponds integrated into the green and blue belt create connectivity between the ecosystems. Ponds with an ecological function have also been established in highly urbanized districts in Québec City, i.e., the pond in the Parc de la Montagne-des-Roches (see Figure 12) and the Ruisseau Rouge pond. The settling includes an upstream settling pond that allows for water purification and a waterfall comprising three levels that oxygenates the water. It is also equipped with a sedimentation chamber where the water is purified through the action of aquatic plants, and a final downstream settling pond situated just before the water is discharged into the stream (Boucher, 2010, cited in Moisan, 2013). Special attention must be paid to the design of control structures at the outlet of the retention ponds since they are crucial elements to ensure quantitative and qualitative control.

Figure 12 The Parc de la Montagne-des-Roches retention pond

Photo credit: Organisme des bassins versants de la Capitale

5.4.5 The installation of inception trenches

Runoff can also be collected in linear, shallow 1-m inception trenches, covered with a permeable surfacing, pebbles, or lawn. They can also serve as access routes for automobiles or pedestrians. This type of installation integrates well into the urban landscape since it occupies little space. Regular maintenance is important to avoid sedimentation in the inception trench and prolong its useful life. Water can be channelled on the surface or through a pipe. This type of installation is not appropriate for industrial or commercial sites likely to generate significant amounts of sediments and pollutants (City of Portland, 2020; MDDEFP and MAMROT, undated).

5.4.6 The installation of infiltration wells

Infiltration wells collect runoff and allow it to infiltrate the soil. They are used, in particular, to collect runoff that is relatively free of pollutants, such as runoff from roofs. They therefore require little maintenance. The filter must be cleaned annually, preferably in the fall after the leaves have fallen (MDDEFP and MAMROT, undated).

OTHER BENEFITS RELATED TO STORMWATER MANAGEMENT

Several laboratory studies and pilot projects have revealed the efficacy of sustainable stormwater management in temperate climates. In colder climates, such as the Scandinavian countries, while hydraulic performance may be reduced during the winter period, treatment capacity from the standpoint of the reduction of pollutant concentrations nonetheless appears to maintain itself (Dagenais *et al.*, 2014).

Simulations focusing on the implementation of stormwater management practices centred on green roofs and bioretention and bioretention alone that were to represent 10% of the impermeable surfaces on sites in the borough of Beauport were conducted to determine the reductions in the volumes and peak flows of rainwater. Effective control of the volumes of runoff (95% or more for 26-mm of rainfall lasting six hours) and peak flows (98% or more) of rainwater were observed for 90% of annual rains, even in a future climate (2041-2070) (93% and 89%, respectively, of the reduction or more) *(Dagenais et al.*, 2014).

5.5 Anthropogenic heat reduction measures

Anthropogenic heat sources stemming from human activities are numerous, including electric household appliances, computers, air conditioners, and cars, and are related to our way of life. According to an analysis by Taha (1997b), anthropogenic heat may be responsible for an increase of 2°C to 3°C in urban centres. Improved energy management, the proximity and mixture of uses, and the replacement of cars with active and collective transportation reduce anthropogenic heat emissions (Écohabitation, 2014a).

5.5.1 Buildings

Most anthropogenic heat emission models consider emissions from vehicles, buildings, and human metabolism. It has been observed that heat emissions from buildings made the biggest contribution to the total (Allen *et al.*, 2011, Iamarino *et al.*, 2011, cited in Dong *et al.*, 2017). Heat produced inside a building contributes to its overheating in the summer period, especially when added to direct sunlight or poor thermal insulation in the building. Electric household appliances, lamps, and computers, for example, transform the energy that they consume into heat. Such internal heat gains are not simultaneous and instead represent a diffuse source of heat in buildings.

5.5.1.1 The appropriate use of artificial light and the optimization of natural light

Lighting contributes to internal heat gains. Halogen and incandescent lamps produce a great deal of heat, which, through radiation or convection, is absorbed by walls and surrounding materials. When the walls and materials reach their heat storage capacities, the heat is rediffused in the ambient air. The use of low-energy compact fluorescent lamps contributes to reducing the amount of heat dissipated. This type of lamp consumes one-fifth the amount of energy and lasts 10 times longer than an incandescent lamp and provides the same level of lighting. However, caution must be exercised when such lamps are discarded since they contain mercury. They must be returned to a retailer that offers a recovery service (Association provinciale des constructeurs d'habitations du Québec, 2008). Unlike incandescent light bulbs, which use only 5% of the electricity that they consume to produce light and dissipate the remainder in the form of heat, light emitting diode (LED) light bulbs use energy efficiently, with energy savings of 70% to 90% in relation to incandescent light products (Hydro-Québec, 2021a).

Another way to control the heat generated by artificial light is to regulate its use. There are several ways to do so:

- control the luminous flux by continuously adjusting artificial light according to the natural light coming from outside;
- ensure hourly control by means of clocks of the illumination on sites such as commercial enterprises, office buildings, and schools where lighting needs are fixed;
- use timers to briefly light sites that are intermittently visited;
- use motion detectors to only light a site when it is occupied;
- use lighting cells, devices placed in a room or on the building that measure the natural lighting and adjust artificial light needs solely when required (Liébard and De Herde, 2005).

It is also worthwhile for certain buildings such as hospitals and schools to maximize the use of natural light, except on premises such as laboratories where the lighting must be constant. However, natural light entries must be equipped with sun-shading devices to protect the occupants from direct solar rays (Liébard and De Herde, 2005).

What is more, when new buildings are erected, natural light gains should be optimized to reduce dependency on artificial light. To this end, a study of the site's seasonal lighting capacity must be conducted at the outset of the construction project (Salomon and Aubert, 2007).

5.5.1.2 The proper use of electronic and electric devices

All electronic and electric devices emit heat, even in sleep mode. The use of computer and electric equipment with high energy efficiency is therefore strongly recommended. Moreover, to minimize heat gain, it is important to turn off and unplug the devices when they are not in use or are fully charged. Indeed, simply plugging in a cell phone charger or an external power adapter for a laptop uses energy even if it is not connected to the device that it is powering, or the device is fully charged. Electronic devices certified ENERGY STAR limit the amount of energy that is consumed in sleep mode, i.e., a 40% to 50% reduction in energy consumption for a television set, and 70% for a computer, compared with conventional devices (Transition énergétique Québec, 2021a).

Indoor heat gains quickly warm the ambient air, above all if the buildings are constructed with low-inertia materials that cannot absorb a lot of heat. On hot days, it is appropriate to limit the use of electric household appliances such as dishwashers, washers, and dryers, and run them only when they are full and in economy mode. For example, washing garments in cold water saves more than 50 l of hot water per load. Likewise, it is inadvisable to place a refrigerator directly beside a stove, dishwasher, or sunny window, since it will run longer to reach the desired temperature (Transition énergétique Québec, 2021b; Agence de l’environnement et de la maîtrise de l’énergie, 2021).

Household appliances and electronic devices are very energy intensive and account for one-fifth of the total energy consumed in a home (Transition énergétique Québec, 2021b). It is recommended to use a switched power bar since it allows for several devices to be plugged in and shut off at the same time (Agence de l’environnement et de la maîtrise de l’énergie, 2021). UHI have an impact on demand for energy, especially because of air conditioning and refrigeration. Higher demand may be such that it causes an overload that overwhelms the electrical power grid. To avoid such a situation, the choice of ecoenergetic certified devices is recommended (Association provinciale des constructeurs d’habitations du Québec, 2008).

5.5.2 Reduction of the vehicle fleet in urban environments

Automobiles and other vehicles emit heat and GHG. In Québec, in 2018, the road transport sector accounted for 35.6% of total GHG emissions (Delisle *et al.*, 2020). The total heat that vehicles emit can be trapped in poorly ventilated urban canyons, thereby reducing the thermal comfort of residents. Vehicle emissions also contribute to the formation of urban smog and global warming (Watkins *et al.*, 2007; Younger *et al.*, 2008; Ouranos, 2010). Between 1990 and 2017, when Québec’s population rose by only 25%, the fleet of passenger vehicles for personal use increased by 64%. Similarly, from 2000 to 2017, the number of light trucks, which includes SUVs, pickup trucks, and vans for personal use, increased by 128% in Québec, i.e., an increase from 24% 39% in the proportion of light trucks in the total passenger vehicle fleet during this period (Laviolette, 2020). Given that electric vehicles emit much less heat than conventional vehicles for a given kilometrage, their replacement can mitigate the UHI effect by reducing the energy consumption of air conditioners (Li *et al.*, 2015). Sound transportation planning, including active and public transportation, is thus essential to minimize heat gains in urban areas (Coutts *et al.*, 2010).

5.5.2.1 The densification of urban centres and the limitation of urban sprawl

The densification of urban centres reduces reliance on automobiles and, incidentally, air pollution and heat generation, since it shortens automobile trips, offers more choices of modes of transportation, and reduces the need to own a vehicle (Coutts *et al.*, 2010).

The concept of transit-oriented development can serve as a guide to urban development that encourages general use of mass transit. It seeks to satisfy certain core principles:

- urban growth that hinges on structuring, structured mass transit networks by means of a network of varied, quality public venues that emphasize human-scale architecture;
- the development of dense, multi-purpose districts that offer a mixture of activities and greater proximity to services that promotes recourse to public and active travel;
- consideration of the overall life environment, i.e., the district's location, its relationship to the existing city, and its vocation and boundaries (Vivre en Ville, 2013).

Furthermore, it has been observed that greater urban density may lead to a corresponding reduction in energy consumption (Mindali *et al.*, 2004, Liu *et al.*, 2012, cited in *Gago et al.*, 2013).

5.5.2.2 Encouraging mixed uses

Several studies have showed that mixed uses in the vicinity promotes accessibility and thereby reduces automobile traffic. In residential areas, road traffic is lighter in districts where commercial enterprises are accessible on foot than in districts without such enterprises, where car travel is inevitable (Rancourt, 2019; Robitaille *et al.*, 2017; Vivre en Ville, undated). In addition to encouraging active travel and making services more accessible to residents, mixed uses also promote the establishment of neighbourhood life. Indicators can help to establish the definition of respectable proximity, such as the number of dwellings situated less than a certain distance on foot from commercial enterprises, the number of jobs within a determined radius, or the presence of social, cultural, and educational services (Écohabitation, 2017a).

5.5.2.3 Development centred on active and public transportation

Automobiles are currently the main means of transportation for 80% of Quebecers (Gravel, 2014). One conceivable solution to ensure greater coolness in urban areas is to limit access to them and vehicle traffic. Some means of achieving this end are:

- the control of traffic flow by means of traffic by-laws on hot days;
- higher parking costs in the city;
- the establishment of tolls to travel in specific areas of the city and the gradual reduction of parking spaces;

- the development near mass transit terminals of eco-friendly park-and-ride lots intended for residents living on the periphery (such parking lots allow motorists to leave their vehicles on the periphery and reduce car traffic in the city);
- the introduction of strategically located bicycle racks and a bicycle-sharing system (Écohabitation, 2014b);
- free access to mass transit during sweltering heat alerts (Déoux and Déoux, 2004; Vivre en Ville, 2004; Cappe, 2003).

Such measures can be combined with enhanced public and active transportation services, including tramways, buses, and rented bicycles (Vivre en Ville, 2004; Vivre en Ville, 2013).

Cars consume twice as much energy per kilometre as trains and four times more than buses. The impacts related to heat and air pollution that broader car use in urban centres where mass transit is insufficiently developed are inevitable. Mass transit services such as metros and buses that satisfy the public's needs and are easy to use, or indeed, free of charge, reduce the adverse impacts of individual transportation. Additionally, the use of more fuel-efficient, low-emission vehicles can improve air quality and contribute to combating UHI (Bennicelli *et al.*, 2019). Unlike cars, public transport modes dictate fairly compact urban development where active travel prevails (Vivre en Ville, 2013).

The development of infrastructure that facilitates cycling or walking is also preferred since active transportation contributes to reducing anthropogenic heat related to motorized transportation while benefiting human health by encouraging physical activity (Scotland, 2008). Indeed, through the enhancement of users' health, savings stemming from healthcare appear to be almost triple the investment needed to develop such infrastructure (Wang *et al.*, 2004).

According to Wendel *et al.* (2008), the design of bicycle lanes and pedestrian precincts warrant special attention. To be safe, they should be adapted, by way of an example, to children, the elderly, mobility-impaired individuals, and low-income earners who do not own a private vehicle. Additionally, such developments are ideal sites on which to introduce trees and sustainable stormwater management measures that contribute to mitigate UHI. The presence of trees along streets encourages greater active mobility, thereby contributing to the creation of a greenway and allowing travel under tree cover (Beaudoin *et al.*, 2017). However, vegetated installations should abide by certain safety regulations, such as ensuring good visibility on-site to avoid creating environments conducive to loitering, vandalism, or crime (Green City Partnerships, 2019). Accordingly, several options are conceivable to promote active transportation:

- create bicycle lanes or tracks;
- propose a bicycle-sharing system;

- enhance the security of pedestrians by means of curb extensions, signage, and crossings;
- create pedestrian corridors;
- widen sidewalks;
- cover spaces with plants to make them pleasanter to walk in;
- offer more extensive street furniture for resting;
- install bicycle racks in strategic places, near commercial enterprises (Écohabitation, 2014b).

5.5.3 Passive air conditioning

In 2017, more than half of Québec households (56%) said that they owned an air conditioner of all types (Statistics Canada, 2019). In the census metropolitan areas, Gatineau, Montréal, and Trois-Rivières accounted for the highest proportion of households with different types of air conditioners, i.e., 75%, 70%, and 65%, respectively, while this proportion did not exceed 41% in the other census metropolitan areas (Bustinza, 2021). According to a study conducted among more than 3 000 respondents from Québec and Ontario, air-conditioning unit ownership appears to be associated with property status with property owners being more likely to own one (76%) than tenants (57%) (Laliberté *et al.*, 2016). In Canada, between 1990 and 2015, energy consumption attributable to space cooling in the commercial and institutional sector increased from 30.3 PJ to 55.3 PJ (Natural Resources Canada, undated). Air conditioning in homes and vehicles is rising and has almost become the norm in certain regions. Less energy-consuming, more sustainable replacement solutions exist to cool indoor air in buildings. Indeed, it is possible to resort to different passive air conditioning techniques to cool a building that was not designed to protect itself from very high temperatures.

5.5.3.1 The use of natural ventilation

Natural ventilation occurs through air introduction (the movement of outdoor air indoors) and air exfiltration (the movement of indoor air outdoors) (Leclerc *et al.*, 2006). It occurs through openings and cracks such as windows, doors, ducts, joints, chimneys, and electrical outlets in the building envelope (Panzhauser *et al.*, 1993, cited in Poulin *et al.*, 2016).

There are two types of natural ventilation, i.e., cross ventilation, and natural draft ventilation or night ventilation. Cross ventilation occurs when windows and doors situated on opposite walls are opened, which allows air currents to circulate in the rooms. The greater the temperature difference between the outside and inside air, the greater the optimization of cooling capacity (Leclerc *et al.*, 2006). Wind and wind direction also affect the cooling achieved (Health Canada, 2018). During the heatwave in Europe in 2003, it was observed that excess mortality was higher in apartments with a single orientation that did not allow for cross ventilation (Déoux and Déoux, 2004).

The natural draft ventilation technique requires fresh, cooler air to enter through openings preferably situated at the bottom of the north façade of the building and allowing hot air to exit through an opening situated at the top the building. This temperature differential creates a **chimney effect** and allows for vertical ventilation and faster air exchanges. In addition to the temperature differential or local effect, the chimney effect is also related to the difference in atmospheric pressure between the bottom and the top (Health Canada, 2018). Such night ventilation offers cooling gains solely in places where the outside air is cooler than the inside air during the night. This technique can thus reduce the indoor air temperature by several degrees (Salomon and Aubert, 2007).

Natural ventilation can make it harder to manage summertime and wintertime relative humidity (Health Canada, 2018). Likewise, in the summer when it is very hot during the day, opening windows is not indicated except at night when the temperature has fallen. Relying on natural ventilation at night can also limit the introduction into the building of external contaminants, which are less concentrated during this period (Poulin *et al.*, 2016).

To promote natural ventilation in a new building, the architect must study the local prevailing wind regime. A building situated at a 45° angle to the wind will allow for optimum high pressure and low pressure that promote ventilation. Devices such as deflectors can also be added to the building to alter the impact of the wind and facilitate ventilation (Liébard and De Herde, 2005). Increasing the air tightness of buildings can limit the possibility of passive natural ventilation that is not controlled by the occupants. Similarly, the efficacy of voluntary natural ventilation, which individuals control, for example by opening windows, is heavily dependent on the weather patterns and climatic conditions and is thus hard to control. Given natural ventilation's uncertain nature, it is suggested that it be combined with mechanical ventilation to obtain acceptable air flows year round (Leclerc *et al.*, 2006).

5.5.3.2 The use of mechanical ventilation

The growing air tightness of current dwellings limits natural infiltration of fresh air because of an insufficient air change rate, especially during heat spells. Strategies that consider mechanical ventilation appear to ensure a more uniform ventilation rate compared with natural ventilation alone (Leclerc *et al.*, 2006). Mechanical ventilation requires a system that uses one or more fans to regularly remove foul indoor air from rooms and dilute the contaminants found there by introducing outside air (Anctil *et al.*, 2021). Experts in the field must conduct the preliminary assessment of the buildings from the standpoint of the elements to be implemented to ensure optimized ventilation, especially according to the building's use and mode of occupation (Anctil *et al.*, 2021). The mechanical ventilation system can limit the introduction of external contaminants when required by running the recirculation mode and keeping windows closed (Sherman and Matson, 2013, Ilacqua *et al.*, 2015, cited in Gervais *et al.*, 2016). To ensure the efficacy of these mechanical ventilation systems, they must be properly designed and installed. Likewise, it is essential to use them suitably and adequately maintain them (Anctil *et al.*, 2021).

Exhaust-only systems

Exhaust-only systems are among the most widely used in Canadian dwellings. To ensure the systems' efficacy throughout the home, an air distribution systems must operate in parallel. While central exhaust systems are more complete than separate bathroom or kitchen fans, they are rarely used in single-family dwellings in Canada, especially because they are more complex and costly to install. It should be noted that because of more extensive air movement, central exhaust systems also increase the risk of backflow and can promote the infiltration of underground gases such as radon (Health Canada, 2018).

Supply-only systems

Supply-only systems are only rarely used in Canada and are not recommended in new dwellings, which are more airtight (Health Canada, 2018).

Balanced systems

A balanced system is preferable when air flows on the same order of magnitude must be simultaneously introduced and removed from the dwelling.

Balanced systems without heat recovery are equipped with two fans, one to draw air into the dwelling and the other to vent the air outside.

There are two categories of balanced ventilation systems with heat recovery, i.e., heat-recovery ventilators, and energy-recovery ventilators. Both transfer heat from the exhaust air to the intake air. An exchange of humidity between damper air and drier air is also possible with the energy recovery ventilator (Health Canada, 2018).

Table 7 presents the mechanical ventilation systems used in Canadian dwellings.

Table 7 Mechanical ventilation systems used in Canada

Type of system	Characteristics	Examples
Exhaust-only systems	*Advantages* • Eliminate at the source indoor pollutants in the most contaminated or dampest areas • Easy to install, simple, fairly inexpensive, and low maintenance • Quality devices provide silent ventilation *Drawbacks* • Sporadic use involving short-term ventilation • Ventilation is confined to rooms where exhaust fans are installed • Depressurization in the dwelling that can promote soil gas infiltration or backflow in combustion devices equipped with a smoke duct • Make-up air is introduced through uncontrolled entries such as cracks that can foster the introduction of outdoor pollutants • Excessive wintertime use can engender high heating costs	• Bathroom exhaust fans • Exhaust range hoods • Electric household appliances that can remove a significant volume of air • Linked ventilators or several rooms connected to a single exhaust fan (central exhaust system)
Supply-only systems	*Advantages* • Efficient when a low ventilation rate is required • Require little maintenance and are inexpensive *Drawbacks* • Hot, moist air is expelled that can engender condensation and mould • Generally inadequate ventilation	• An air distribution duct without a motor connected to the return-air duct of the furnace
Balanced systems (combining extraction and supply)	**Without heat recovery:** *Advantages* • Can include a mixing box to transfer heat from the foul air to the fresh air *Drawbacks* • It is hard to determine the volume of air simultaneously introduced and extracted • Subject to freezing and condensation in the winter **With heat recovery:** *Advantages* • Transfers heat from exhaust air to the new air in the winter • Ventilation rates are adjustable • De-icing possible in the winter • Uses ecoenergetic fans that reduce operating costs • The most profitable systems that operate continuously • Low degree of humidity maintained in winter • Flexibility to locate air extraction and inflow • Relatively quiet • Can be used as a heat recovery ventilator in the winter and an energy recovery ventilator in the summer	• Air exchange system • The heat recovery ventilator is connected to the heat generator ducts • The heat recovery ventilator has separate ducts • Energy recovery ventilator

Table 7 Mechanical ventilation systems used in Canada (continued)

Type of system	Characteristics	Examples
Balanced systems (combining extraction and supply)(continued)	*Drawbacks* • Significant depressurization occurs when the de-icing mechanisms block the operation of the fan blower • Requires an air distribution system throughout the dwelling • Higher acquisition and installation costs • Operation can be complex and control panels are less intuitive • Requires more maintenance	

Source: Health Canada (2018).

Exhaust-only systems are among the most widely used in Canadian dwellings. While central exhaust systems are more complete than separate bathroom or kitchen fans, they are rarely used in single-family dwellings in Canada, especially because they are more complex and costly to install (Health Canada, 2018).

A balanced system is preferable if air must be simultaneously introduced into and removed from the dwelling (Health Canada, 2018).

5.5.3.3 The use of electric fans

Electric fans can enhance the occupants' thermal comfort since they accelerate the movement of the air and heat loss from the skin through convection and evaporation. However, it should be noted that beyond a high temperature (> 35°C), where the air temperature exceeds that of the skin, the efficacy of electric fans appears to be limited and might instead increase the thermal load of individuals. The use of electric fans and electric air conditioners should be combined with passive heat mitigation measures such as blinds and sunshades to promote more effective cooling and possibly reduce air conditioning needs (Potvin and Leclerc, 2021).

5.5.3.4 The installation of geothermal systems

Geothermal systems can be used to heat and air condition buildings. The systems hinge on the principle that at a depth of between 6 m and 10 m, the earth's temperature remains relatively constant between 8°C and 10°C since it is not affected by temperature variations on the earth's surface. This means that the earth's subsurface is warmer than the wintertime air temperature and cooler than the summertime air temperature. Geoexchange systems comprise an underground heat exchanger, a heat pump, and a heat distribution system. The consumption by the pump of 1 kW would produce on average between 3 kW and 5 kW of energy. Indeed, using the earth as the source and discharge point of heat results in high coefficients of performance, i.e., the ratio of the energy produced, and the electric power consumed (Écohabitation, 2012a). The system is costly, ranging from $20 000 to $40 000 for an average-sized home, and it may be necessary to adapt the heat distribution or cooling system in an existing dwelling. Similarly, the cost of installing the underground loop can vary depending on the nature of the soil (Hydro-Québec, 2021b).

COOLING GAINS AND OTHER BENEFITS RELATED TO PASSIVE AIR CONDITIONING

Generally speaking, when the temperatures inside a building fall within the comfort zone (see Section 3.2.1), no minimum air movement is necessary to ensure thermal comfort (Charbonneau and Douville, 2004). Air currents directed toward the head and the legs, e.g., the ankles and feet, can cause discomfort. It is, therefore, preferable for the occupant to control the direction of the wind (Canadian Centre for Occupational Health and Safety, 2021). In general, the higher the air velocity, the greater the cooling effect is. It should be noted that when the air velocity exceeds 0.2 m/s, the temperature can be increased up to 3°C above the comfort zone. Air velocity should not, therefore, exceed 0.8 m/s (Charbonneau and Douville, 2004).

5.6 Summary

Table 8 presents the key measures to mitigate UHI in this literature review and identifies the main advantages and drawbacks in a non-exhaustive manner.

Table 8 Summary table of the measures to mitigate UHI

Measures	Heat reduction zone	Additional advantages	Drawbacks
Greening			
Common to all greening measures	N/A	• Improved air quality • Improved water quality and water retention • Encourages leisure activities • Biodiversity conservation • Enhanced aestheticism • Reduced energy consumption • Health benefits • Noise reduction • Carbon sequestration	• Allergenic potential
The development of urban green spaces	City	• N/A	• Requires sufficient space for roots to spread
One-off planting of trees and vegetation	Building, city	• N/A	• Requires sufficient space for roots to spread

Table 8 Summary table of the measures to mitigate UHI (continued)

Measures	Heat reduction zone	Additional advantages	Drawbacks
Greening (continued)			
Revegetation of parking lots	City	• N/A	• Requires sufficient space for roots to spread
Revegetation in the periphery of buildings	Building, city	• N/A	• Requires sufficient space for roots to spread
The installation of plant walls	Building, city	• Protects building envelopes	• The maintenance of vertical surfaces is more complex • Living walls have high maintenance costs (irrigation system, weight-bearing elements for plants and the substratum)
Sustainable urban infrastructure			
The choice of coloured roof coverings with high solar reflectivity	Building, city	• Lower air conditioning costs	• N/A
Insulation and air tightness of buildings	Building	• Humidity control • Reduced energy consumption	• Reduced natural ventilation (not subject to human control)
Maximization of thermal inertia	Building	• Reduced energy consumption	• N/A
The use of high-performance glazing	Building	• Reduced energy consumption	• N/A
The addition of sun-shading devices such as shutters, awnings, and sunshades	Building	• Reduced energy consumption	• N/A
Choice of high-albedo paving stones	City	• N/A	• Gradual loss of reflectivity
Recommendation of well spaced out urban morphology	City	• Improved air quality • Encourages active transportation • Encourages leisure activities	• N/A
The development of blue spaces	Population, city	• Encourages leisure activities • Enhanced aestheticism	• Increases sound propagation (large blue spaces)

Table 8 Summary table of the measures to mitigate UHI (continued)

Measures	Heat reduction zone	Additional advantages	Drawbacks
Sustainable urban infrastructure (continued)			
Installation of cooling areas	Population	• Encourages leisure activities	• Awareness-raising among vulnerable populations to be planned to encourage their use
The use of sun-shading devices in public areas	Population	• Protection against UV rays	• N/A
The choice of materials in parks	City	• Improved air and water quality • Water retention • Encourages leisure activities • Biodiversity conservation • Enhanced aestheticism	• Certain materials such as synthetic turf accumulate heat
Sustainable stormwater management measures			
Planting trees and installing green roofs	• Refer to the greening section		
The choice of permeable coverings	Building, city	• Reduced runoff •	• Certain types are unsuited to heavy-duty vehicle traffic, spreading sand in the winter, or freeze-thaw cycles • Maintenance is required
The development of rain gardens	Building, city	• Improved water quality and water retention • Biodiversity conservation • Enhanced aestheticism • Low cost • Minimal maintenance is required when well designed	• The choice of a site that considers runoff from neighbouring land
Retention pond design	City	• Improved water quality and water retention • Encourages leisure activities • Biodiversity conservation • Enhanced aestheticism	• N/A
The installation of inception trenches	City	• Improved water quality and water retention • Occupies little space	• Regular maintenance required • Hardly appropriate for certain industrial and commercial sites
The installation of infiltration wells	City	• Improved water quality and water retention • Minimal maintenance	• N/A

Table 8 Summary table of the measures to mitigate UHI (continued)

Measures	Heat reduction zone	Additional advantages	Drawbacks
Anthropogenic heat reduction			
The appropriate use of artificial light and the optimization of natural light	Building	• Reduced energy consumption	• Provision of a deposit location because of mercury content (compact fluorescent lamps only) • The use of sun-shading devices to protect the occupants from direct sunlight (natural light)
The proper use of electronic and electric devices	Building	• Reduced energy consumption	• N/A
The densification of urban centres and the limitation of urban sprawl Encouraging mixed uses Development centred on active and public transportation	City	• Improved air quality • Encourages leisure activities • Reduced GHG emissions • Reduced energy consumption • Offers health benefits	• N/A
The use of natural ventilation	Building	• Improved indoor air quality (nighttime ventilation) • Reduced energy consumption	• Effective only when the outdoor air is cooler than the indoor air • Effective only when the dwellings do not have a single direction of orientation (cross-ventilation) • Relative humidity is hard to control • Efficacy may be reduced because of increased building air tightness (natural passive ventilation that the occupants do not control) • Use depends strongly on weather patterns (voluntary human-controlled natural ventilation)

Table 8 Summary table of the measures to mitigate UHI (continued)

Measures	Heat reduction zone	Additional advantages	Drawbacks
Anthropogenic heat reduction (continued)			
The use of mechanical ventilation	Building	• Improved indoor air quality	Exhaust-only systems: • ventilation is usually short-term and confined to the rooms where the devices are installed • infiltration is possible of soil gas and external pollutants or flowback in combustion devices Supply-only systems: • possible problems with mould • generally inadequate ventilation • Balanced systems without heat recovery: • it is hard to determine the volume of air simultaneously introduced and extracted • subject to freezing and condensation in the winter • Balanced systems with heat recovery: • require an air distribution system throughout the dwelling • complex operation • more demanding maintenance • significant depressurization is possible in some instances
The use of electric fans	Building	• Improved indoor air quality	Limited efficacy when the air temperature exceeds 35°C
The installation of geothermal systems	Building	• Reduced energy consumption	• The system is expensive and drilling costs vary depending on the nature of the soil It is sometimes necessary to adapt the heating-cooling distribution system in existing dwellings

6 CASE STUDIES AND EXPERIENCE UNDER THE *CLIMATE CHANGE ACTION PLAN*

6.1 Case studies

This section presents case studies that describe the implementation of concrete initiatives to reduce UHI carried out in Québec. For each case study, the measures to mitigate UHI used, the context that led to the project, a description of the project, the maintenance required, and the spinoff and co-benefits are described. In most instances, the total cost of the projects is indicated. The case studies also review the factors that facilitated the implementation of the measures and fostered the projects' success. They were documented by means of interviews conducted with the project managers.

6.1.1 The Aréna Rodrigue-Gilbert parking lot in Montréal

THE MEASURES TO MITIGATE UHI ADOPTED

Tree planting, stormwater management, permeable pavers, active transportation (bicycle garage), electric transport (charging stations), pooling of spaces

Context

Photo credit: Rousseau Lefebvre. Source: https://www.rousseau-lefebvre.com/fr/arena-rodrigue-gilbert/.

In 2018, in the wake of work carried out at the Aréna Rodrigue-Gilbert in the borough of Rivière-des-Prairies–Pointe-aux-Trembles in Montréal, Rousseau-Lefebvre and Tetra Tech, in collaboration with a team from the city, were mandated to redevelop the parking lot to make it more ecological. To this end, the project sought to incorporate good stormwater management practices by means of bioretention and permeable coverings, enhance biodiversity, and provide for interpretation elements. Reflection was initiated upstream on its redefinition in the urban fabric, its use outside peak times such as during the day, and facilities that would better combat climate change, especially UHI, and adapt to them.

The project was carried out to satisfy the community's needs. Accordingly, from the outset of the project, the borough encouraged discussions between all the stakeholders to ascertain needs and adjust before the work began.

Description of the project

Several trees were planted and roughly 20% of the parking lot was outfitted with permeable pavers. A planting pit and conventional islands of greenery or in the form of bioretention cells were also installed to enhance stormwater management and optimize biodiversity. Bioretention-based islands of greenery allow rainwater to infiltrate by acting as a bioretention pond and storing surplus water.

To promote alternative modes of travel that do not rely on fossil energy, a bicycle garage and a secure pedestrian path have been installed. Moreover, four parking spaces have been equipped with electric vehicle charging stations.

Maintenance

The city maintains the parking lot. Except for the first year of planting, the plants require little maintenance and were selected for this reason. Occasional pruning is sufficient. The permeable pavers must be maintained to avoid obstructing the pores since the joints between the pavers allow the water to infiltrate. Nevertheless, even if the joint pores are partly blocked, the pavers have a high retention capacity (1 ml/h) and are always effective.

Spin-off and co-benefits

The redevelopment of the Aréna Rodrigue-Gilbert parking lot included enhancements from the standpoint of greening, biodiversity, stormwater management, and active and alternative transportation. While no temperature measurements have been conducted since the conclusion of the work, the site has become pleasanter, and the project has beautified the district and enhanced the quality of the living environment. What is more, the permeable covering on part of the parking lot has improved stormwater management since part of the surface water is directly retained on site, which reduces the water load in city pipes.

The project also includes an educational section centred on the installation in the parking lot of three interpretation panels devoted to stormwater management, biodiversity, and climate change. Furthermore, part of the parking lot can be temporarily transformed for specific public and sports activities to foster creation and social ties.

The Conseil régional de l'environnement de Montréal certified the parking lot eco-friendly in 2018.

➔ Total cost of the project: $1,800,000

To obtain additional information on the project, please visit https://stationnementecoresponsable.com/2018/12/06/arena-rodrigue-gilbert/.

6.1.2 The Collège de Rosemont green roof in Montréal

THE MEASURES TO MITIGATE UHI ADOPTED

Green roof, white roofs

Context

In 2007, the Collège de Rosemont installed 10 000 ft^2 of green roof to mitigate UHI. The project's objectives focused on heat reduction, better stormwater management and improved air quality, biodiversity, and aestheticism.

Description of the project

The Collège de Rosemont's green roof was covered with a precultivated carpet of sedum, a succulent. The plants store water in their leaves and act as a retention pond. They also have considerable adaptability since they are drought-, disease- and parasite-resistant in addition to acting as a filter by trapping urban dust and pollen.

Maintenance

The sedum used in the green roof requires little maintenance. Limited weeding and occasional fertilization suffice. While the plant is drought-resistant, the building's roof is irrigated in periods of sweltering heat to ensure its long-term survival. The college directly performs the maintenance, which, aside from fertilizer purchases, does not engender any additional costs.

Spinoff and co-benefits

The plants on the roof act as a rainwater retention pond. Accordingly, less wastewater is discharged into the city's sewers and the water is cleaner since it is filtered by the plants on the roof. Additionally, the green roof reduces heat outside and inside the building and reduces air conditioning costs at the same time. It also purifies the air by capturing CO_2 and promotes biodiversity. The site chosen for this installation is visible from the college's glass-paned library and it makes the users' living environment pleasanter.

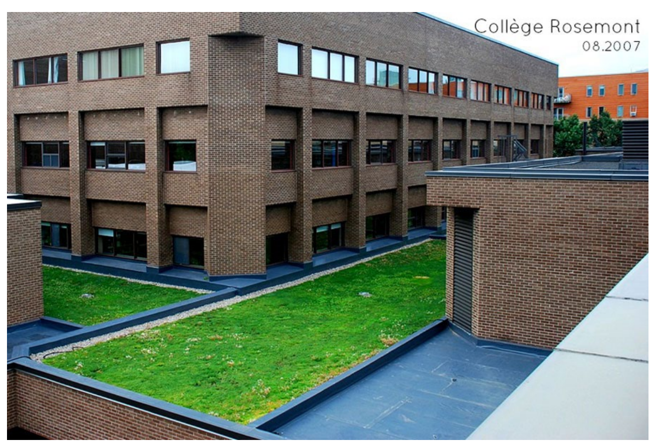

Photo credit: Toits vertige. Source: http://toitsvertige.com/portfolio/institutionnel/.

An educational section was also implemented. Educational panels devoted to green roofs were installed inside the library to heighten students' awareness of the topic.

To obtain additional information on the project, please visit https://www.crosemont.qc.ca/developpement-durable/vert-jusque-sur-les-toits/.

BY-LAWS IN FORCE IN ROSEMONT–LA-PETITE-PATRIE

In 2011, regulatory measures to mitigate UHI were added to the zoning by-law of the borough of Rosemont–La-Petite-Patrie in Montréal. The by-law stipulates that when roofs are rebuilt or new buildings are constructed, if the roof has a slope below 2 units vertically for 12 units horizontally (2:12), it must necessarily be vegetated, white, or covered with a material with a solar reflectance index of at least 78. To comply with the by-law, all the roofs at the Collège de Rosemont that had to be renovated became green roofs (5%) or white roofs (80%). Since then, most boroughs have followed suit by promoting white or plant-covered roofs to mitigate UHI.

To obtain additional information on the new measures, please consult the Règlement d'urbanisme de l'arrondissement Rosemont–La-Petite-Patrie of the City of Montréal and the Mesures visant la réduction de l'effet d'îlot de chaleur urbain dans Rosemont–La Petite-Patrie on the Natural Resources Canada website.

6.1.3 The École Saint-Pierre schoolyard in Alma

THE MEASURES TO MITIGATE UHI ADOPTED

Planting trees and plants, urban agriculture, and removal of asphalt

Context

The schoolyard of the École Saint-Pierre in Alma in the Saguenay–Lac-Saint-Jean region was redeveloped in June 2019. A teacher and a volunteer landscaper, both of whom wished to make the schoolyard a pleasanter environment, instigated the project. Upstream from the project, they observed a problem of surface water capture and the presence of a UHI in the schoolyard. Moreover, a temperature imbalance in the building stemming from the orientation of the premises and central heating caused discomfort for students and staff. Indeed, the south-facing classrooms exposed to the sun could reach more than 30°C starting in March. Opening south-facing windows did not facilitate the maintenance of a comfortable temperature. South-facing classrooms remained too hot and north-facing classrooms, too cold.

A schoolyard development plan was designed by volunteers to create the grass-free school of the future. The school administration and teaching staff approved the project. A crowdfunding campaign with an initial budget of $30 000 was launched to collect cash donations and materials. Residents and local businesses mobilized to support the project, which raised $135 000 and allowed for more extensive plant cover in the initial project and enhanced the quality of the materials. Since the schoolyard cost roughly $100 000, the surplus was placed in a fund devoted to training the students and maintenance, if necessary.

Description of the project

The work began with the removal of 27 000 ft^2 of grass. To avoid using herbicide and make the project as ecological as possible, the grass was removed by using chip wood mulch to smother it. Next, 1 340 trees, shrubs, and hardy perennials were planted to create shade and facilitate better surface water management. Plant-free areas were preserved to allow the children to go sliding in the winter. Lastly, 35% of the vegetation cover is a kitchen garden.

A wooded path has replaced nearly 4 000 ft^2 of asphalt in the centre of the schoolyard, which has been surrounded by plants, mainly lilacs, to create intimacy, provide fragrance, and reduce background noise.

Maintenance

Trees and shrubs are pruned once a year in the spring by Grade 5 and Grade 6 student volunteers who have received gardening training supervised by a landscaper. Starting in the first year, 90 young people participated in the training. Consequently, the maintenance of the plants does not engender additional costs for the school. The training also ensures the continuity of the project and is offered both to students and parents. As well, snow fences are installed in the winter to prevent trampling the plants.

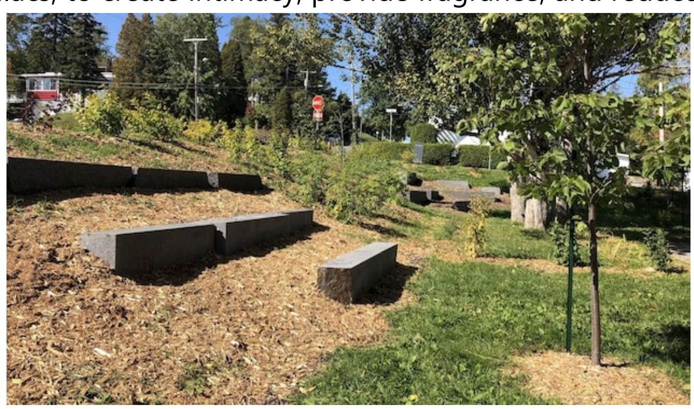

Photo credit: Claude Bouchard, Radio-Canada. Source: https://ici.radio-canada.ca/nouvelle/1306769/projet-verdissement-terrain-etablissement-scolaire.

CAREFULLY CHOSEN TREES

To obtain vegetation cover as quickly as possible, Accolade elms, big, super-fast-growing trees were preferred and planted strategically to help cool the premises. Since the work carried out in June 2019, the positive effects of the shade structures should be felt in the classrooms since these trees grow 1.5 m to 2 m a year.

OTHE CAREFULLY CHOSEN TREES (CONTINUED)

> **Other factors were also considered in the choice of the trees. For example, birch was avoided because of its irritating pollen but also because its bark peels, making it very tempting for children to pull the bark. The height of hazel trees makes them accessible to children and they were avoided because of nut allergies. Consequently, walnut trees and horse chestnut trees, whose fruits are less accessible, were planted. Moreover, to reduce the impact of a possible infestation of a specific species, varied species were chosen.**

Spin-off and co-benefits

Since the project was completed recently, it is not yet possible to observe the impacts on the temperature inside the classrooms and in the schoolyard. However, a drop in temperature is anticipated and would thus affect building air conditioning and heating costs. While the trees are still young, it is already possible to observe an improvement from the standpoint of rainwater management during heavy rains. The water no longer pools in the schoolyard. Lastly, the trees planted capture carbon, purify the air around the school, and beautify the neighbourhood. The removal of the grass has reduced noise engendered by mowing as well as maintenance costs and GHG emissions.

The project also included an educational facet since the grass embankments have been replaced by five outdoor classrooms. Granite, wood, and mulch were provided free of charge to make chairs, benches, and tables.

Tours of the schoolyard with teachers and students were conducted the first year to familiarize them with the tree species planted, the attraction of the wooded path and the outdoor classroom on the embankment, and the schoolyard's future perspective. Today, the students are immersed in their new schoolyard and the school's dynamic has changed. No vandalism or destruction of plants has been observed. The students have reclaimed the schoolyard and formerly deserted places are now occupied. Previously, all the young people flocked together in the same places.

Involving the young people and their families has created a connection with the environment. On the day of the planting, 284 volunteers lent a hand and local businesses were also present to offer lunch and refreshments. What is more, since the conclusion of the project, the schoolyard is much more frequented, thereby created a hub for sharing and exchanges in the community.

The École Saint-Pierre schoolyard is an innovative, unifying project that has enhanced social cohesion in Alma. It is the first grass-free schoolyard in Québec, a source of pride for residents and, above all, the students. The project has enhanced the quality of the living environment and heightened awareness among the students of their environment. The project earned the City of Alma first prize for greening of the Fleurons du Québec in 2019.

THE ADVICE OF THE VOLUNTEER LANDSCAPER

> **"We must proceed on a case-by-case basis according to what we have. Here, the project grew gradually through the entire community's involvement. My advice would be to involve to the utmost residents and local businesses by collaborating with them to recycle their salvaged materials."**

➔ Total cost of the project: $100 000

6.1.4 The construction of Les Habitations Sainte-Germaine-Cousin in Montréal

THE MEASURES TO MITIGATE UHI ADOPTED

> **Green roof, high-albedo roof, tree planting, geothermal energy, ecoenergetic design**

Context

The former Église Sainte-Germaine-Cousin in Montréal was preserved and restored to house a childcare centre and to build a residence comprising rooms and dwelling units for autonomous seniors and seniors experiencing a loss of autonomy. The church was situated in the middle of a UHI in a highly mineralized area of the city with limited tree canopy.

Description of the project

Local and natural materials such as linen and jute were preferred to reduce the project's environmental impact. Contempra concrete was selected instead of Portland cement to limit CO_2 emissions by 10%, thereby achieving a 72-tonne saving of CO_2 for the project overall.

Photo credit: Rayside Labossière. Source: https://www.construireavecleclimat.org/etudes-de-cas/habitations-sainte-germaine-cousin/

A green roof and an accessible green terrace were built on a portion of the roof to limit the UHI phenomenon and optimize the building's stormwater management by retaining part of the rainwater in addition to improving the roof insulation. The other portion of the roof was covered with light paint with a high solar reflectance index. Lastly, vegetated islands were installed in the parking lot and around the building, thereby providing shade and purifying the air.

As for air conditioning, it was deemed essential to ensure health and comfort considering the clientele vulnerable to heat. However, to limit the project's carbon balance and reduce air conditioning costs, only the common areas were air conditioned. Additionally, a geothermal air conditioning system was chosen to limit the UHI phenomenon, which standard air conditioning often accelerates. Accordingly, 28 430-foot-deep wells were installed to supply the forced-air air conditioning and heating system. While the system is fairly costly, it reduces heating and air conditioning costs by 50% to 65%, thereby ensuring a prompt return on investment. The windows were designed to maximize the use of natural light and thereby contribute to reducing electricity costs. Additionally, the building was designed to satisfy the Novoclimat energy performance standards.

The work was completed in 2015.

Maintenance

The maintenance does not engender additional costs for the dwelling. Part of the roof was mowed once in five years.

Spin-off and co-benefits

The tenants have adopted the site and the roof-top terrace and the green spaces situated around the building are used frequently. In addition to creating coolness for the residents, the project allows for mixed uses and multigenerational exchanges since it groups together young and old alike.

The project, which highlights a generational mix and sustainable, ecological components, has enhanced the residents' quality of life and revitalized the neighbourhood. It has thus reduced the residents' vulnerability by making their life environment pleasanter and more varied. The project promotes building recycling.

➔ Total cost of the project: $35 000 000

To obtain additional information on the project, please visit https://www.construireavecleclimat.org/etudes-de-cas/habitations-sainte-germaine-cousin/ or http://www.rayside.qc.ca/?portfolio_page=sainte-germaine-cousin.

6.1.5 The Hôpital de Saint-Eustache parking lot

THE MEASURES TO MITIGATE UHI ADOPTED

Planting of trees and plants, permeable high-albedo surfacing, active transportation (shade, bicycle shelter, secure spaces for pedestrians and cyclists)

Context

In conjunction with remedial work on its parking lot, the Hôpital de Saint-Eustache, in collaboration with the Société québécoise des infrastructures and the Centre de santé et de services sociaux du Lac-des-Deux-Montagnes, implemented adaptation solutions to mitigate the impact of UHI. More specifically, it sought to:

- reduce the impact of UHI by installing shaded areas and islands of greenery;
- foster water retention by means of the integration of stormwater management strategies and reduce runoff in the municipal network;
- promote active transportation by installing facilities to ensure the safety of pedestrians and cyclists.

Description of the project

To meet these objectives, the parking lot was first greened through the addition of trees and the integration of planting strips between certain parking spaces. Next, roughly 10% of the soil was replaced with light permeable pavers, thereby fostering water seepage in the soil and reducing heat accumulation. What is more, an open retention pond was built to store water. Lastly, a partly covered, shaded secure pedestrian path and a bicycle shed connected to the bicycle path were installed. Secure spaces for bicycles and pedestrians were also built, thereby reducing GHG emissions and vehicle use.

Maintenance

To ensure the project’s continuity, tree species and hardy perennials that require little maintenance were preferred. Furthermore, the metal and steel shed is maintenance-free. The cost of maintenance that the hospital carries out has not increased significantly since the design phase.

Spin-off and co-benefits

Surface temperature measurements were recorded before and after the completion of the work. The findings are inconclusive since the measurements were not made in the same weather conditions. Additionally, they were made when the trees were not fully mature, which allowed insufficient time to elapse to estimate the impacts on heat. However, the measures’ long-term impact on shade and heat should be conclusive.

Moreover, before and after the work, patients, visitors, and hospital staff were interviewed. The users were satisfied with the new installations and found the parking lot safer and pleasanter.

This project has thus enhanced the quality of the living environment and, above all, visitor experience by improving users' comfort in the parking lot. It has contributed significantly to increasing the parking lot's permeable surface, thereby allowing more rainwater to filter and evacuate and, consequently, to reduce discharges into the municipal sewer system. What is more, the trees increase the vegetation cover, provide shade, and reduce the temperature in the parking lot, which makes it pleasanter during severe heat. The parking lot is also encouraging sustainable mobility through the installation of secure spaces for bicycles and pedestrians, thus reducing GHG emissions by reducing vehicle use.

Photo credit: Mon climat, ma santé. Source: http://www.monclimatmasante.qc.ca/le-centre-hospitalier-de-saint-eustache.aspx.

➔ Total cost of the project: $3 500 000

6.1.6 The greening of the Institut de réadaptation en déficience physique de Québec in Québec City

THE MEASURES TO MITIGATE UHI ADOPTED

A high-albedo roof, planting trees and plants, revegetation of the periphery of the building

Context

To mitigate UHI, the Centre intégré universitaire de santé et de services sociaux de la Capitale-Nationale, with support from Nature Québec, carried out several greening projects. Because the Institut de réadaptation en déficience physique de Québec is situated close to a very busy urban intersection, greening work was undertaken. A committee comprising representatives of Nature Québec and the Centre intégré universitaire de santé et de services sociaux de la Capitale-Nationale was established to design and carry out the project.

Description of the project

The project began in 2018 with the rebuilding of 25% of the roof. A white, high-reflectance PVC membrane was installed on one of the roofs. A similar covering will replace the other portions of the roofs once they reach their useful life. The option of a plant-covered roof was excluded since the building structure could not support its weight.

Photo credit: Milieux de vie en santé. Source: https://milieuxdevieensante.org/projet/irdpq/.

A landscaped urban meadow with a pedestrian path crossing it was installed. The path will be made wheelchair accessible during a second phase. The landscaped urban meadow comprises grasses and legumes such as flax and clover, which enhance soil quality by increasing its carbon content and attract pollinators. The plants also increase the site's biodiversity.

More than 200 trees, shrubs, and plants were placed on the periphery of the meadow and the building. The plantings mitigate the UHI phenomenon. They also purify the air and reduce traffic-generated noise and dust. The landscaped urban meadow also retains water, which enhances stormwater management. Lastly, it competes with ragweed, an allergenic, invasive plant that poses a health issue in Québec.

Maintenance

The Centre intégré universitaire de santé et de services sociaux cleans the roof every year in the spring and the fall. The company that installed the roof also conducts an annual inspection. If a deficiency is observed during the inspection, the company directly remedies the situation without generating additional costs under a contract with a 10-year guarantee.

No special maintenance is carried out on the landscaped urban meadow and the plantings, except for mowing by a landscaper on the pedestrian path. The maintenance does not engender an additional cost for the Institut de réadaptation en déficience physique de Québec in relation to the preliminary project.

Spin-off and co-benefits

No temperature measurements have been made since the completion of the project. However, the rebuilt roof is better insulated than the old one, reducing in principle wintertime heat losses and maintaining coolness in the summer. Air conditioning and heating costs should, therefore, decrease. Additionally, when they mature, the trees should contribute further to reducing the temperature both outside and inside the buildings. The site is also pleasanter and more conducive to physical activity.

➔ Total cost of the project: roughly $750 000 ($100 000 for the vegetation and $650 000 for the roof)

To obtain additional information on the project, please visit https://milieuxdevieensante.org/projet/irdpq/.

6.2 Experience of the *Climate Change Action Plan*

6.2.1 *2006-2012 Climate Change Action Plan*

From 2010 to 2014, the INSPQ supported projects to mitigate UHI carried out by different partners that reduced the impact of climate change on the health of vulnerable populations. The anticipated projects were to specifically target the implementation of one or a series of measures to promote cooling in urban environments. Generally speaking, the measures included the densification of vegetation and the installation of pedestrian streets, parking lots, recreational areas, schoolyards, public childcare services such as day care centres and childcare centres, public spaces, and buildings frequented by vulnerable populations such as housing cooperatives and seniors' centres. In the wake of three calls for proposals, more than 40 projects were carried out and funded under the Québec government's *Climate Change Action Plan* (2006-2012 CCAP).

Table 9 presents several project-related statistics.

A map summarizing the entire array of projects is available on the Mon climat, ma santé website.

Table 9 Statistics concerning projects to mitigate urban heat islands carried out in the context of the 2006-2012 CCAP

Project	Statistics
Type of project	• 17 schoolyards • 7 green alleyways • 8 cool spots • 10 parking lots • 5 childcare centres • 4 municipal housing bureaus
Plantings	• 3 000 trees • 26 000 shrubs and climbing plants, hardy perennials, and annuals
Roof	• 600 m^2 of green roof (four projects) • 65 000 m^2 of white roof (two projects)
Urban agriculture	• More than 1 500 urban agriculture planters (11 projects)
Removal of asphalt	• 40 000 m^2 of asphalt

Statistics compiled by the Changements climatiques team of the INSPQ.

6.2.2 *2013-2020 Climate Change Action Plan*

In light of experience pursuant to the 2006-2012 CCAP, two projects were announced in 2015 to densify the vegetation in neighbourhoods to mitigate UHI. This led to the *Milieux de vie en santé* program carried out by Nature Québec, and the ILEAU campaign led by the Conseil régional de l'environnement de Montréal. Since 2015, nearly 300 greening projects and more than 30 000 plants have been planted under the two initiatives. Moreover, a major awareness-raising campaign aimed at decision-makers and the public was implemented from the outset of the projects.

Eight new projects were initiated in the spring of 2020 to disseminate the learning in a growing number of Québec cities. The projects will end in December 2022.

Table 10 describes the 10 projects implemented under the 2013-2020 CCAP greening program.

Table 10 Projects to combat urban heat islands and archipelagos under way in the context of the 2013-2020 CCAP

City	Lead organization	Name of the project	Website
Drummondville	Conseil régional for the Centre-du-Québec environment	Coup de fraîcheur	https://crecq.qc.ca/wp-content/uploads/2020/11/Fiche_CoupdeFraicheur_2020.pdf
Gatineau	Conseil régional de l'environnement et du développement durable de l'Outaouais	Vivre en vert	https://www.vivreenvert.ca/
Laval	Canopée, le réseau des bois de Laval	Île en vert	https://www.reseaucanopee.org/fr/ile-en-vert/
Montréal (east)	Conseil régional de l'environnement de Montréal	ILEAU	https://ileau.ca/
Montréal (north-central)	Ville en vert	Vert le nord	https://villeenvert.ca/vert-le-nord/
Montréal (south-central)	Regroupement des éco-quartiers	Verdir le sud	https://www.eco-quartiers.org/verdir-le-sud
Québec City	Nature Québec	Milieux de vie en santé	https://milieuxdevieensante.org/
Repentigny	Comité Écologique du Grand Montréal	Verdir pour l'avenir	https://cegm.ca/projets/verdir-pour-lavenir/
Saguenay	Eurêko	Canopée et biodiversité Saguenay	https://eureko.ca/services/canopee-et-biodiversite-saguenay
Sherbrooke	Conseil régional de l'environnement de l'Estrie	Vent de fraîcheur sur l'est	https://www.environnementestrie.ca/priorites/lurgence-climatique/vent-de-fraicheur-sur-lest/

Compiled by the Changements climatiques team of the INSPQ.

7 LIMITATIONS

The literature

Most of the databases available to conduct research in the scientific literature centred on health-related aspects of UHI. It is, therefore, possible that certain articles of interest as regards measures to mitigate UHI were not picked up.

From the standpoint of the efficacy of measures to mitigate UHI, the absence of an air temperature measurement standard to analyze the UHI mitigation strategies implemented may pose a problem. Indeed, while the air temperature at an elevation 2 m has until now been widely used to measure the intensity of UHI, air temperature measurements taken at different elevations are frequently reported in the literature. Similarly, certain studies report maximum temperature differences while others indicate instead average temperature differences.

The scope of thermal performance in buildings is heavily dependent upon the orientation of the walls, their size, the building’s characteristics, plant species, and the type of substratum. This considerable variation in data collection complicates performance comparisons of measures to mitigate UHI.

The objective of this literature review was not to target the costs related to each of the measures. Since costs vary inordinately from region to region and from year to year, it will be important for readers wishing to implement one or more of the measures described to consult experts in the region.

What is more, the authors are neither architects, landscapers, nor engineers and their interpretation of study findings is their own.

Lastly, the literature review does not broach the legislative and regulatory tools that can provide a framework for the implementation of measures to mitigate UHI, although the authors acknowledge that growing involvement by governments and urban planning officials will facilitate quicker attainment of the benefits that stem from operational implementation.

Case studies

Surface temperature measurements were recorded for only one case study but were not taken according to generally accepted practices. Since the measurements were not necessarily made under the same weather conditions before and after the installations, the findings are inconclusive. Additionally, the measurements were made when the trees were not fully mature, which allowed insufficient time to elapse to estimate the impacts on heat.

8 CONCLUSION

In numerous urban areas in Québec, the concentration of roads, buildings, and any other infrastructure built with materials with high heat absorption capacity lead to a UHI effect. The lack of vegetation exacerbates this effect, thereby creating local microclimates separate from those in the areas in the urban periphery. Impermeable, low-albedo urban materials such as asphalt and certain types of concrete that largely make up cities reduce the possible cooling effect through evaporation and increase the gain from sunlight. Urban morphology, especially through the density of built environments and the narrow streets in them can also increase the phenomenon. Moreover, the release of anthropogenic heat in urban environments contributes to UHI, which in turn exacerbates the impact of heatwaves. Because of rising temperatures stemming from climate change, already significant heat stress will worsen in the coming years. Climate change is threatening urban trees because of unprecedented urban growth and new pests and emerging diseases.

Given that scientific knowledge concerning the best measures to mitigate UHI to be implemented is constantly changing, this update of the 2009 publication provides more current information concerning the practices adopted and potentially applicable in Québec. Several aspects have been enhanced bearing in mind the most recent research. The case studies round out the review by providing concrete examples of the implementation of projects to mitigate UHI to encourage the realization of this type of initiatives and to inspire the stakeholders in the built environment. This literature review is thus a tool to which professionals in public health branches, property managers in the government health and social services network, and on-site interveners from non-profit organizations in the municipal sector can refer to contribute to protecting the health of the most vulnerable populations from the detrimental effects of sweltering heat exacerbated by UHI.

The literature review reveals that different measures reduce the UHI effect and its environmental impacts on the air, water, and energy demand, and health impacts. While, from the standpoint of thermal comfort, air conditioning is one way of reducing the consequences of heat on vulnerable populations, other measures applicable to buildings can be contemplated to better adapt cities to climate change in the long term. What is more, bearing in mind the specific context in which measures to mitigate UHI are implemented, they are acknowledged to be more effective when used in combination to complement each other.

Urban greening actively moderates temperatures through the evapotranspiration process and passively by creating shade areas. Large urban parks rank first in terms of distance and the intensity of the cooling effect. Different types of vegetation can be used in a vegetation densification approach. The benefits that trees afford are combined with those of low vegetation and shrubs. City-wide overall vegetation densification engenders a worthwhile impact on urban coolness. Trees and shrubs can be planted not only on public spaces to create urban cool islands but also bordering streets or building peripheries. What is more, when the building structure allows, both intensive and extensive planted roofs can be installed. In addition to reducing the UHI effect, green roofs facilitate better stormwater management. Sound building walls can also be planted, especially through the addition of climbing plants. Energy saving, thermal electric generation, shade, and evapotranspiration characteristics highlight the key role that green roofs and plant walls play in the overall thermal performance of buildings. Such initiatives lower the indoor temperature of buildings by means of the insulation that vegetation provides, which keeps heat outside in the summer and inside in the winter.

Increased albedo in cities promotes cooling by reflecting large amounts of solar radiation. The surface temperature of reflective surfaces is thus lower than that of conventional coverings and they release less heat at night. Both the roofs and walls of buildings and road infrastructure or ground coverings can be adapted, thereby reducing the surface temperature but also the indoor temperature of dwelling units. This benefit is all the more appreciable in dwelling units situated in central neighbourhoods that are subject to intense heat because of the density of construction. Likewise, the populations living there are often more vulnerable because of reduced adaptability. Dwellings and commercial enterprises can also be adapted with different types of sunshades to limit the entry of sunlight and the accumulation of heat in buildings.

Blue spaces can simultaneously provide cooling due to evaporation or heat because of thermal inertia, in addition to producing water vapour that causes thermal discomfort in some instances. The influence of the geometry and the diversity of urban blue spaces requires more extensive research. While circulating water has a more significant cooling effect than stagnant water, water dispersed as it is by a fountain has the greatest cooling effect. Cooling facilities in cities also provide coolness for residents.

Limiting soil sealing enhances stormwater management from both a qualitative and a quantitative standpoint. By reducing runoff, the water that infiltrates soil can cool the ambient air by evaporation. Various options can be used, such as rain gardens, inception trenches, retention ponds, or infiltration wells. The use of permeable materials and planting vegetation will also contribute to reducing the UHI effect by means of their potential to retain water.

It is also essential to consider challenges related to urban heat in architecture and urban planning on a scale ranging from individual buildings to entire cities, especially by initiating reflection aimed at transforming urban areas to make them denser and enable residents to prefer public and active transportation. Likewise certain changes to consumption habits can be encouraged to emphasize low-heat, low-energy electronic and electric devices, as well as how the devices are used.

In the realm of public health, the UHI effect can be measured in terms of public health impacts. For 20 years, each year has witnessed its share of heat records and projections tend to show that the situation is not improving. Heat waves in recent years have revealed the full impact of UHI on hospitalizations, ambulance transportation, and mortality. The populations that are most vulnerable to heat do not always have the physical, mental, financial or social capacity to adapt to high-heat days. Indeed, while certain characteristics such as age and health status define the strata of the population most sensitive to heat, their exposure, e.g., living in a UHI, and their adaptability, e.g., by living in an air conditioned dwelling unit, also determine their vulnerability in sweltering heat. Accordingly, a 65-year-old whose residence in a green neighbourhood has air conditioning will be much less vulnerable than a 50-year-old living in an overheated dwelling in a highly mineralized central district. This state of affairs emphasizes the need for municipalities to be cognizant of their territory and population to adopt strategies to mitigate UHI in districts where the positive impact on the health of the population will be felt most rapidly. To ensure that the choices made are sustainable and are socially acceptable, they must be made in collaboration with professionals such as architects, engineers, urban planners, and landscapers according to each specific situation, together with community-based organizations and with public support. Reflection must also consider the question of infrastructure maintenance to ensure optimal quality, efficacy, and lifespan.

This review reveals the broad range of measures that can be adopted and the multidisciplinary nature of the fight again UHI. Its authors do not claim that it is exhaustive. To this end, the systematic reviews targeted for each category could be developed, including research on the real costs of implementing these measures in Québec and the economic value of the co-benefits that the initiatives engender. Indeed, the economic question is a factor that warrants more specific research since it is both a lever and a damper as regards the implementation of such measures. This review also leads to reflection on the need to break down existing walls between government organizations and broaden opportunities for exchanges between different professionals to promote the sharing of knowledge and experience. Adapting cities and buildings to curtail the UHI effect is essential from a public health standpoint and engenders numerous health, social, environmental, and economic co-benefits. The transformation of Québec cities can be accelerated through the collaboration of a vast network of stakeholders.

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APPENDIX 1 LITERATURE SEARCH STRATEGY

This literature review sought to compile a list of the main measures to mitigate urban heat islands (UHI) potentially applicable in the Québec context. It comprises publications from the scientific literature and from grey literature. A literature search strategy was devised with the assistance of an INSPQ librarian.

The scientific literature

Six databases were queried on July 6, 2020 as regards the scientific literature: Embase, Global Health (through the Ovid research platform) and Medline, Environment Complete, Health Policy Reference Center (through the EBSCO platform, and ScienceDirect. The search was launched to pinpoint articles written in English or French between 2009 and 2020 focusing on measures to combat UHI applicable in the Québec context. No restriction on geographic scope was applied when the search was launched.

The search terms used to pinpoint the relevant articles referred to the two key concepts of the purpose of the literature search, i.e., UHI (concept 1) and measures to mitigate UHI (concept 2). A list of terms (keywords) was elaborated for each concept both in an uncontrolled vocabulary (natural language) and a controlled vocabulary (descriptors drawn from a thesaurus) et combined using Boolean operators (AND, OR) and proximity operators (ADJn). The keywords were sought in titles, summaries, and keywords determined by the articles' authors. Tables A1 to A6 present the database consultation algorithms.

The 4 487 articles were located following a literature search in the scientific literature. Once duplications (985 articles) were eliminated, 3 502 articles were evaluated in two stages based on inclusion and exclusion criteria.

First, for an article to be selected, the title or the summary had to deal with UHI and minimally mention at least one measure to mitigate UHI. Articles focusing on the effects of UHI on human or animal health were excluded. Following this initial evaluation, 1 003 articles were deemed admissible. Of this number, 35 literature reviews and 968 original articles were selected.

Second, the articles deemed admissible were read in their entirety. Among the 35 literature reviews pinpointed, nine were excluded since they did not mainly focus on measures to mitigate UHI. Seven reviews were not selected because they focused on technological development and did not broach the link or efficacy from the standpoint of reducing UHI. One other review was excluded since it dealt with the elaboration of a protocol to enhance systematic reviews related to greening and human health and did not mention measures to combat UHI. Lastly, one review was excluded because it focused on the health impacts of UHI. Accordingly, 23 literature reviews were selected since they examined UHI and minimally mentioned one measure to mitigate UHI.

Given the significant number of original articles (n = 968) selected following the initial evaluation, it was agreed with an INSPQ librarian to evaluate the 23 literature reviews selected to determine the review deemed to be of the best quality and conduct an additional search through the original articles to round out the missing years according to the review's publication date (see the review evaluation process in Appendix 2). Following the evaluation of the reviews, the original articles published starting in 2017, i.e., the year of the review deemed to be of the best quality, were read in their entirety.

Among the 968 original articles deemed admissible in the wake of the initial evaluation based on the title and the summary, 503 articles corresponded to the period from 2017 to 2020. For the second selection, the articles in respect of which the climate context differed from that of Québec (non-temperate) (n = 180), those that did not focus on measures to mitigate UHI (n = 87), and those focused primarily on the health-related impacts of UHI (n = 10), were excluded. All told, 208 original articles that mainly examined the question of measures to combat UHI applicable in the Québec context were selected for the purposes of the project. Of this number, only the original articles that presented elements not discovered beforehand in the literature reviews were selected (n = 32).

All told, 55 studies (23 literature reviews and 32 original articles) were selected for the project.

The grey literature

The literature search also included grey literature sources, which were used to round out the information concerning the efficacy of the measures to mitigate UHI and update the data overall. The Google and Google Scholar search engines and certain government websites of interest such as the Lawrence Berkeley National Laboratory, the United States Environmental Protection Agency, the Ministère de l'Environnement et de la Lutte contre les changements climatiques were queried. The search terms were essentially the same ones as those used to pinpoint articles from the scientific literature. English and French keywords were associated with these concepts. Quotation marks were applied when the term to be searched was made up of more than one word, e.g., "urban heat." This approach allowed for precise searches for keywords in quotation marks.

Searches were then elaborated in French and in English by applying the codes to refine the search. For example, "intitle" facilitated searches solely in the title of Google search results. To avoid repeatedly consulting the same result, the search terms for a given concept were linked with the Boolean operator "OR." The operator "AND" was represented by a space between the different concepts. Google's advanced parameters were used to refine the search for the period 2009-2021. The consultation of the results for each search launched was halted when the results no longer seemed relevant.

Table A1 Research strategy launched in Embase (Ovid)

#	Concepts	Searches	Results
1	Concept 1	(((island* OR urban) adj3 heat) OR ((urban OR city OR cities OR neighbo#rhood* OR town OR towns) adj3 (fresh OR thermal))).ti,ab,kw.	963
2	Concept 1	(((street OR urban) adj3 canyon*) OR ((urban OR city OR cities OR neighbo#rhood* OR town OR towns) adj3 (climate OR microclimate OR "micro-climate"))).ti,ab,kw.	1399
3	Concept 1	(heat OR solar OR sun OR temperature OR thermal OR UV OR UVR OR ultraviolet OR ultra-violet OR weather).ti,ab,kw.	1,148,333
4	Concept 1	((episode* OR event* OR wave*) adj3 heat).ti,ab,kw.	2,419
5	Concept 1	(urban OR city OR cities OR neighbo#rhood* OR town OR towns).ti,ab,kw.	384,774
6	Liaison concept 1	1 OR (2 AND 3) OR (4 AND 5)	1,574
7	Concept 2a:	**(**adapt* OR fight* OR intervention* OR limit* OR measure* OR mitigat* OR (plan N1 action*) OR policy OR policies OR program OR programs OR programme* OR reduc* OR strateg*).ti,ab,kw.	11,637,185
8	Liaison 1+2	6 adj6 7	402
9	Concept 2: Revegetation measures	("ecosystem service*" OR (green adj3 (area* OR building* OR infrastructure* OR roof* OR space* OR structure* OR wall*)) OR greenroof* OR (living adj (cover* OR wall*)) OR (roof* adj3 (benefit* OR garden* OR vegetation)) OR shadow* OR shading* OR tree OR trees OR (urban adj3 (forest* OR greening OR park OR parks)) OR vegetation*).ti,ab,kw.	206,568
10	Concept 2: SUSTAINABLE URBAN INFRASTRUCTURE	(albedo OR architecture OR bikeabilit* OR ((cool OR reflective OR white) adj roof*) OR ((built OR urban OR design*) adj2 (environment* OR surrounding* OR infrastructure* OR surrounding* OR form)) OR ((climate-proof OR eco OR ecologic* OR resilient OR sustainable OR friendly) adj6 (city OR cities OR neighbo#rhood*)) OR concrete OR cooling OR pedestrian OR "solar reflectance" OR ((urban OR city OR cities OR town OR towns OR municipalit*) adj3 (design* OR development* OR form* OR planning* OR sprawl* OR landscaping OR land-use* OR landuse* OR environment* OR infrastructure* OR sprawl*)) OR (white adj3 (surface OR coating)) OR walkabilit* OR woonerf*).ti,ab,kw.	221,692
11	Concept 2: STORMWATER MANAGEMENT SOIL PERMEABILITY	(asphalt OR demineralization OR ((permeable OR porous) adj pavement*) OR ((stormwater OR rainwater OR water) adj3 (manag* OR infiltrat*)) OR "pluvial garden*").ti,ab,kw.	16,544
12	Concept 2: ANTHROPOGENIC HEAT REDUCTION	("cool car*" OR (energy adj3 (efficiency OR heating OR cooling)) OR (vehicule* adj2 emission adj2 reduc*) OR ((active OR public OR mass OR infrastructure*) adj3 transport*) OR ((anthropogenic OR human-made) adj heat) OR ((natural OR urban) adj ventilation) OR_"transit oriented development").ti,ab,kw.	32,829
13	Liaison 1+2	**6 AND (9 OR 10 OR 11 OR 12)**	754
14	Liaison	**8 OR 13**	917

Table A1 Research strategy launched in Embase (Ovid) (continued)

#	Concepts	Searches	Results
15	Time limit	limit 14 to yr=2009-2020	749
16	Language limit	15 and (French or English).lg.	725
17	Except animal studies	16 not ((animal/ not exp human/) or (arthropod* or avian or bird* or fish or fishes or herbivore* or insect* or mice or mosquito* or mouse or rat or rats or snake* or spider*).ti.)	**698**

Table A2 Research strategy launched in Global Health (Ovid)

#	Concepts	Searches	Results
1	Concept 1	(((island* OR urban) adj3 heat) OR ((urban OR city OR cities OR neighbo#rhood* OR town OR towns) adj3 (fresh OR thermal))).ti,ab,id.	462
2	Concept 1	(((street OR urban) adj3 canyon*) OR ((urban OR city OR cities OR neighbo#rhood* OR town OR towns) adj3 (climate OR microclimate OR "micro-climate"))).ti,ab,id.	393
3	Concept 1	(heat OR solar OR sun OR temperature OR thermal OR UV OR UVR OR ultraviolet OR ultra-violet OR weather).ti,ab,id.	164,025
4	Concept 1	((episode* OR event* OR wave*) adj3 heat).ti,ab,id.	839
5	Concept 1	(urban OR city OR cities OR neighbo#rhood* OR town OR towns).ti,ab,id.	161,705
6	Liaison concept 1	1 OR (2 AND 3) OR (4 AND 5)	787
7	Concept 2a	**(**adapt* OR fight* OR intervention* OR limit* OR measure* OR mitigat* OR (plan N1 action*) OR policy OR policies OR program OR programs OR programme* OR reduc* OR strateg*).ti,ab,id.	1,414,290
8	Liaison 1+2	6 adj6 7	229
9	Concept 2: <u>REVEGETATION MEASURES</u>	("ecosystem service*" OR (green adj3 (area* OR building* OR infrastructure* OR roof* OR space* OR structure* OR wall*)) OR greenroof* OR (living adj (cover* OR wall*)) OR (roof* adj3 (benefit* OR garden* OR vegetation)) OR shadow* OR shading* OR tree OR trees OR (urban adj3 (forest* OR greening OR park OR parks)) OR vegetation*).ti,ab,id.	36,550
10	Concept 2: <u>URBAN INFRASTRUCTURE</u>	(albedo OR architecture OR bikeabilit* OR ((cool OR reflective OR white) adj roof*) OR ((built OR urban OR design*) adj2 (environment* OR surrounding* OR infrastructure* OR surrounding* OR form)) OR ((climate-proof OR eco OR ecologic* OR resilient OR sustainable OR friendly) adj6 (city OR cities OR neighbo#rhood*)) OR concrete OR cooling OR pedestrian OR "solar reflectance" OR ((urban OR city OR cities OR town OR towns OR municipalit*) adj3 (design* OR development* OR form* OR planning* OR sprawl* OR landscaping OR land-use* OR landuse* OR environment* OR infrastructure* OR sprawl*)) OR (white adj3 (surface OR coating)) OR walkabilit* OR woonerf*).ti,ab,id.	23,640
11	Concept 2: <u>STORMWATER MANAGEMENT SOIL PERMEABILITY</u>	(asphalt OR demineralization OR ((permeable OR porous) adj pavement*) OR ((stormwater OR rainwater OR water) adj3 (manag* OR infiltrat*)) OR "pluvial garden*").ti,ab,id.	5,842

Table A2 Research strategy launched in Global Health (Ovid) (continued)

#	Concepts	Searches	Results
12	Concept 2: ANTHROPOGENIC HEAT REDUCTION	("cool car*" OR (energy adj3 (efficiency OR heating OR cooling)) OR (vehicule* adj2 emission adj2 reduc*) OR ((active OR public OR mass OR infrastructure*) adj3 transport*) OR ((anthropogenic OR human-made) adj heat) OR ((natural OR urban) adj ventilation) OR_"transit oriented development").ti,ab,id.	4,233
13	Liaison 1+2	**6 AND (9 OR 10 OR 11 OR 12)**	396
14	Liaison	**8 OR 13**	472
15	Time limit	limit 14 to yr=2009-2020	427
16	Language limit	15 and (French or English).lg.	411
17	Except animal studies	16 not ((animals/ not man/) or (arthropod* or avian or bird* or fish or fishes or herbivore* or insect* or mice or mosquito* or mouse or rat or rats or snake* or spider*).ti.)	**405**

Table A3 Research strategy launched in Medline (EBSCO)

#	Concepts	Searches	Results
1	Concept 1	**TI** (((island* OR urban) N2 heat) OR ((urban OR city OR cities OR neighbo#rhood* OR town OR towns) N2 (fresh OR thermal))) OR **AB** (((island* OR urban) N2 heat) OR ((urban OR city OR cities OR neighbo#rhood* OR town OR towns) N2 (fresh OR thermal)))	731
2	Concept 1	**TI** (((street OR urban) N2 canyon*) OR ((urban OR city OR cities OR neighbo#rhood* OR town OR towns) N2 (climate OR microclimate OR "micro-climate"))) OR **AB** (((street OR urban) N2 canyon*) OR ((urban OR city OR cities OR neighbo#rhood* OR town OR towns) N2 (climate OR microclimate OR "micro-climate")))	887
3	Concept 1	**TI** (heat OR solar OR sun OR temperature OR thermal OR UV OR UVR OR ultraviolet OR ultra-violet OR weather) OR **AB** (heat OR solar OR sun OR temperature OR thermal OR UV OR UVR OR ultraviolet OR ultra-violet OR weather)	1,143,171
4	Concept 1	**TI** ((episode* OR event* OR wave*) N2 heat) OR **AB** ((episode* OR event* OR wave*) N2 heat)	2,227
5	Concept 1	**TI** (urban OR city OR cities OR neighbo#rhood* OR town OR towns) OR **AB** (urban OR city OR cities OR neighbo#rhood* OR town OR towns)	312,279
6	Liaison concept 1	S1 OR (S2 AND S3) OR (S4 AND S5)	1,252
7	Concept 2a	**TI** (adapt* OR fight* OR intervention* OR limit* OR measure* OR mitigat* OR (plan N1 action*) OR policy OR policies OR program OR programs OR programme* OR reduc* OR strateg*) OR **AB** (adapt* OR fight* OR intervention* OR limit* OR measure* OR mitigat* OR (plan N1 action*) OR policy OR policies OR program OR programs OR programme* OR reduc* OR strateg*)	8,991,180
8	Liaison 1+2	S6 N5 S7	329

Table A3 Research strategy launched in Medline (EBSCO) (continued)

#	Concepts	Searches	Results
9	Concept 2: REVEGETATION MEASURES	TI ("ecosystem service*" OR (green N2 (area* OR building* OR infrastructure* OR roof* OR space* OR structure* OR wall*)) OR greenroof* OR (living W1 (cover* OR wall*)) OR (roof* N2 (benefit* OR garden* OR vegetation)) OR shadow* OR shading* OR tree OR trees OR (urban N2 (forest* OR greening OR park OR parks)) OR vegetation*) OR AB ("ecosystem service*" OR (green N2 (area* OR building* OR infrastructure* OR roof* OR space* OR structure* OR wall*)) OR greenroof* OR (living W1 (cover* OR wall*)) OR (roof* N2 (benefit* OR garden* OR vegetation)) OR shadow* OR shading* OR tree OR trees OR (urban N2 (forest* OR greening OR park OR parks)) OR vegetation*)	177,132
10	Concept 2: URBAN INFRASTRUCTURE	TI (albedo OR architecture OR bikeabilit* OR ((cool OR reflective OR white) W1 roof*) OR ((built OR urban OR design*) N1 (environment* OR surrounding* OR infrastructure* OR surrounding* OR form)) OR ((climate-proof OR eco OR ecologic* OR resilient OR sustainable OR friendly) N5 (city OR cities OR neighbo#rhood*)) OR concrete OR cooling OR pedestrian OR "solar reflectance" OR ((urban OR city OR cities OR town OR towns OR municipalit*) N2 (design* OR development* OR form* OR planning* OR sprawl* OR landscaping OR land-use* OR landuse* OR environment* OR infrastructure* OR sprawl*)) OR (white N2 (surface OR coating)) OR walkabilit* OR woonerf*) OR AB (albedo OR architecture OR bikeabilit* OR ((cool OR reflective OR white) W1 roof*) OR ((built OR urban OR design*) N1 (environment* OR surrounding* OR infrastructure* OR surrounding* OR form)) OR ((climate-proof OR eco OR ecologic* OR resilient OR sustainable OR friendly) N5 (city OR cities OR neighbo#rhood*)) OR concrete OR cooling OR pedestrian OR "solar reflectance" OR ((urban OR city OR cities OR town OR towns OR municipalit*) N2 (design* OR development* OR form* OR planning* OR sprawl* OR landscaping OR land-use* OR landuse* OR environment* OR infrastructure* OR sprawl*)) OR (white N2 (surface OR coating)) OR walkabilit* OR woonerf*)	204,545
11	Concept 2: STORMWATER MANAGEMENT SOIL PERMEABILITY	TI (asphalt OR demineralization OR ((permeable OR porous) W1 pavement*) OR ((stormwater OR rainwater OR water) N2 (manag* OR infiltrat*)) OR "pluvial garden*") OR AB (asphalt OR demineralization OR ((permeable OR porous) W1 pavement*) OR ((stormwater OR rainwater OR water) N2 (manag* OR infiltrat*)) OR "pluvial garden*")	13,712
12	Concept 2: ANTHROPOGENIC HEAT REDUCTION	TI ("cool car*" OR (energy N2 (efficiency OR heating OR cooling)) OR (vehicule* N1 emission N1 reduc*) OR ((active OR public OR mass OR infrastructure*) N2 transport*) OR ((anthropogenic OR human-made) W1 heat) OR ((natural OR urban) W1 ventilation) OR_"transit oriented development") OR AB ("cool car*" OR (energy N2 (efficiency OR heating OR cooling)) OR (vehicule* N1 emission N1 reduc*) OR ((active OR public OR mass OR infrastructure*) N2 transport*) OR ((anthropogenic OR human-made) W1 heat) OR ((natural OR urban) W1 ventilation) OR_"transit oriented development")	31,234
13	Liaison 1+2	**S6 AND (S9 OR S10 OR S11 OR S12)**	613

Table A3 Research strategy launched in Medline (EBSCO) (continued)

#	Concepts	Searches	Results
14	Liaison	**S8 OR S13**	733
15	Time limit	S14 AND (DT 2009-2020)	665
16	Language limit	S15 AND LA (English OR French)	642
17	Except animal studies	S16 NOT (MH (animals+ NOT humans+) OR TI (arthropod* OR avian OR bird* OR fish OR fishes OR herbivore* OR insect* OR mice OR mosquito* OR mouse OR rat OR rats OR snake* OR spider*))	**604**

Table A4 Research strategy launched in Environment Complete (EBSCO)

#	Concepts	Searches	Results
1	Concept 1	**TI** (((island* OR urban) N2 heat) OR ((urban OR city OR cities OR neighbo#rhood* OR town OR towns) N2 (fresh OR thermal))) OR **AB** (((island* OR urban) N2 heat) OR ((urban OR city OR cities OR neighbo#rhood* OR town OR towns) N2 (fresh OR thermal))) OR **DE** "URBAN heat islands"	3,037
2	Concept 1	**TI** (((street OR urban) N2 canyon*) OR ((urban OR city OR cities OR neighbo#rhood* OR town OR towns) N2 (climate OR microclimate OR "micro-climate"))) OR **AB** (((street OR urban) N2 canyon*) OR ((urban OR city OR cities OR neighbo#rhood* OR town OR towns) N2 (climate OR microclimate OR "micro-climate")))	2,949
3	Concept 1	**TI** (heat OR solar OR sun OR temperature OR thermal OR UV OR UVR OR ultraviolet OR ultra-violet OR weather) OR **AB** (heat OR solar OR sun OR temperature OR thermal OR UV OR UVR OR ultraviolet OR ultra-violet OR weather)	527,283
4	Concept 1	**TI** ((episode* OR event* OR wave*) N2 heat) OR **AB** ((episode* OR event* OR wave*) N2 heat)	2,400
5	Concept 1	**TI** (urban OR city OR cities OR neighbo#rhood* OR town OR towns) OR **AB** (urban OR city OR cities OR neighbo#rhood* OR town OR towns)	182,051
6	Liaison concept 1	S1 OR (S2 AND S3) OR (S4 AND S5)	4,067
7	Concept 2a	**TI** (adapt* OR fight* OR intervention* OR limit* OR measure* OR mitigat* OR (plan N1 action*) OR policy OR policies OR program OR programs OR programme* OR reduc* OR strateg*) OR **AB** (adapt* OR fight* OR intervention* OR limit* OR measure* OR mitigat* OR (plan N1 action*) OR policy OR policies OR program OR programs OR programme* OR reduc* OR strateg*)	1,584,489
8	Liaison 1+2	S6 N5 S7	2,680
9	Concept 2: <u>REVEGETATION MEASURES</u>	TI ("ecosystem service*" OR (green N2 (area* OR building* OR infrastructure* OR roof* OR space* OR structure* OR wall*)) OR greenroof* OR (living W1 (cover* OR wall*)) OR (roof* N2 (benefit* OR garden* OR vegetation)) OR shadow* OR shading* OR tree OR trees OR (urban N2 (forest* OR greening OR park OR parks)) OR vegetation*) OR AB ("ecosystem service*" OR (green N2 (area* OR building* OR infrastructure* OR roof* OR space* OR structure* OR wall*)) OR greenroof* OR (living W1 (cover* OR wall*)) OR (roof* N2	220,467

Table A4 Research strategy launched in Environment Complete (EBSCO) (continued)

#	Concepts	Searches	Results
9	Concept 2: REVEGETATION MEASURES (continued)	(benefit* OR garden* OR vegetation)) OR shadow* OR shading* OR tree OR trees OR (urban N2 (forest* OR greening OR park OR parks)) OR vegetation*)	
10	Concept 2: URBAN INFRASTRUCTURE	TI (albedo OR architecture OR bikeabilit* OR ((cool OR reflective OR white) W1 roof*) OR ((built OR urban OR design*) N1 (environment* OR surrounding* OR infrastructure* OR surrounding* OR form)) OR ((climate-proof OR eco OR ecologic* OR resilient OR sustainable OR friendly) N5 (city OR cities OR neighbo#rhood*)) OR concrete OR cooling OR pedestrian OR "solar reflectance" OR ((urban OR city OR cities OR town OR towns OR municipalit*) N2 (design* OR development* OR form* OR planning* OR sprawl* OR landscaping OR land-use* OR landuse* OR environment* OR infrastructure* OR sprawl*)) OR (white N2 (surface OR coating)) OR walkabilit* OR woonerf*) OR AB (albedo OR architecture OR bikeabilit* OR ((cool OR reflective OR white) W1 roof*) OR ((built OR urban OR design*) N1 (environment* OR surrounding* OR infrastructure* OR surrounding* OR form)) OR ((climate-proof OR eco OR ecologic* OR resilient OR sustainable OR friendly) N5 (city OR cities OR neighbo#rhood*)) OR concrete OR cooling OR pedestrian OR "solar reflectance" OR ((urban OR city OR cities OR town OR towns OR municipalit*) N2 (design* OR development* OR form* OR planning* OR sprawl* OR landscaping OR land-use* OR landuse* OR environment* OR infrastructure* OR sprawl*)) OR (white N2 (surface OR coating)) OR walkabilit* OR woonerf*)	106,374
11	Concept 2: STORMWATER MANAGEMENT SOIL PERMEABILITY	TI (asphalt OR demineralization OR ((permeable OR porous) W1 pavement*) OR ((stormwater OR rainwater OR water) N2 (manag* OR infiltrat*)) OR "pluvial garden*") OR AB (asphalt OR demineralization OR ((permeable OR porous) W1 pavement*) OR ((stormwater OR rainwater OR water) N2 (manag* OR infiltrat*)) OR "pluvial garden*")	35,355
12	Concept 2: ANTHROPOGENIC HEAT REDUCTION	TI ("cool car*" OR (energy N2 (efficiency OR heating OR cooling)) OR (vehicule* N1 emission N1 reduc*) OR ((active OR public OR mass OR infrastructure*) N2 transport*) OR ((anthropogenic OR human-made) W1 heat) OR ((natural OR urban) W1 ventilation) OR_"transit oriented development") OR AB ("cool car*" OR (energy N2 (efficiency OR heating OR cooling)) OR (vehicule* N1 emission N1 reduc*) OR ((active OR public OR mass OR infrastructure*) N2 transport*) OR ((anthropogenic OR human-made) W1 heat) OR ((natural OR urban) W1 ventilation) OR_"transit oriented development")	30,196
13	Liaison 1+2	**S6 AND (S9 OR S10 OR S11 OR S12)**	2,636
14	Liaison	**S8 OR S13**	3,388
15	Time limit	S14 AND (DT 2009-2020)	2,843
16	Language limit	S15 AND LA (English OR French)	2,817
17	Except animal studies	S16 NOT TI (arthropod* OR avian OR bird* OR fish OR fishes OR herbivore* OR insect* OR mice OR mosquito* OR mouse OR rat OR rats OR snake* OR spider*)	**2,802**

Table A5 Research strategy launched in Health Policy Reference Center (EBSCO)

#	Concepts	Searches	Results
1	Concept 1	**TI** (((island* OR urban) N2 heat) OR ((urban OR city OR cities OR neighbo#rhood* OR town OR towns) N2 (fresh OR thermal))) OR **AB** (((island* OR urban) N2 heat) OR ((urban OR city OR cities OR neighbo#rhood* OR town OR towns) N2 (fresh OR thermal))) OR **DE** "URBAN heat islands"	39
2	Concept 1	**TI** (((street OR urban) N2 canyon*) OR ((urban OR city OR cities OR neighbo#rhood* OR town OR towns) N2 (climate OR microclimate OR "micro-climate"))) OR **AB** (((street OR urban) N2 canyon*) OR ((urban OR city OR cities OR neighbo#rhood* OR town OR towns) N2 (climate OR microclimate OR "micro-climate")))	35
3	Concept 1	**TI** (heat OR solar OR sun OR temperature OR thermal OR UV OR UVR OR ultraviolet OR ultra-violet OR weather) OR **AB** (heat OR solar OR sun OR temperature OR thermal OR UV OR UVR OR ultraviolet OR ultra-violet OR weather)	5,671
4	Concept 1	**TI** ((episode* OR event* OR wave*) N2 heat) OR **AB** ((episode* OR event* OR wave*) N2 heat)	222
5	Concept 1	**TI** (urban OR city OR cities OR neighbo#rhood* OR town OR towns) OR **AB** (urban OR city OR cities OR neighbo#rhood* OR town OR towns)	41,323
6	Liaison concept 1	S1 OR (S2 AND S3) OR (S4 AND S5)	83
7	Concept 2a	**TI** (adapt* OR fight* OR intervention* OR limit* OR measure* OR mitigat* OR (plan N1 action*) OR policy OR policies OR program OR programs OR programme* OR reduc* OR strateg*) OR **AB** (adapt* OR fight* OR intervention* OR limit* OR measure* OR mitigat* OR (plan N1 action*) OR policy OR policies OR program OR programs OR programme* OR reduc* OR strateg*)	357,861
8	Liaison 1+2	S6 N5 S7	52
9	Concept 2: <u>REVEGETATION MEASURES</u>	TI ("ecosystem service*" OR (green N2 (area* OR building* OR infrastructure* OR roof* OR space* OR structure* OR wall*)) OR greenroof* OR (living W1 (cover* OR wall*)) OR (roof* N2 (benefit* OR garden* OR vegetation)) OR shadow* OR shading* OR tree OR trees OR (urban N2 (forest* OR greening OR park OR parks)) OR vegetation*) OR AB ("ecosystem service*" OR (green N2 (area* OR building* OR infrastructure* OR roof* OR space* OR structure* OR wall*)) OR greenroof* OR (living W1 (cover* OR wall*)) OR (roof* N2 (benefit* OR garden* OR vegetation)) OR shadow* OR shading* OR tree OR trees OR (urban N2 (forest* OR greening OR park OR parks)) OR vegetation*)	2,470
10	Concept 2: <u>URBAN INFRASTRUCTURE</u>	TI (albedo OR architecture OR bikeabilit* OR ((cool OR reflective OR white) W1 roof*) OR ((built OR urban OR design*) N1 (environment* OR surrounding* OR infrastructure* OR surrounding* OR form)) OR ((climate-proof OR eco OR ecologic* OR resilient OR sustainable OR friendly) N5 (city OR cities OR neighbo#rhood*)) OR concrete OR cooling OR pedestrian OR "solar reflectance" OR ((urban OR city OR cities OR town OR towns OR municipalit*) N2 (design* OR development* OR form* OR planning* OR sprawl* OR landscaping OR land-use* OR landuse* OR environment* OR infrastructure* OR	5,339

Table A5 Research strategy launched in Health Policy Reference Center (EBSCO) (continued)

#	Concepts	Searches	Results
10	Concept 2: URBAN INFRASTRUCTURE (continued)	sprawl*)) OR (white N2 (surface OR coating)) OR walkabilit* OR woonerf*) OR AB (albedo OR architecture OR bikeabilit* OR ((cool OR reflective OR white) W1 roof*) OR ((built OR urban OR design*) N1 (environment* OR surrounding* OR infrastructure* OR surrounding* OR form)) OR ((climate-proof OR eco OR ecologic* OR resilient OR sustainable OR friendly) N5 (city OR cities OR neighbo#rhood*)) OR concrete OR cooling OR pedestrian OR "solar reflectance" OR ((urban OR city OR cities OR town OR towns OR municipalit*) N2 (design* OR development* OR form* OR planning* OR sprawl* OR landscaping OR land-use* OR landuse* OR environment* OR infrastructure* OR sprawl*)) OR (white N2 (surface OR coating)) OR walkabilit* OR woonerf*)	
11	Concept 2: STORMWATER MANAGEMENT SOIL PERMEABILITY	TI (asphalt OR demineralization OR ((permeable OR porous) W1 pavement*) OR ((stormwater OR rainwater OR water) N2 (manag* OR infiltrat*)) OR "pluvial garden*") OR AB (asphalt OR demineralization OR ((permeable OR porous) W1 pavement*) OR ((stormwater OR rainwater OR water) N2 (manag* OR infiltrat*)) OR "pluvial garden*")	308
12	Concept 2: ANTHROPOGENIC HEAT REDUCTION	TI ("cool car*" OR (energy N2 (efficiency OR heating OR cooling)) OR (vehicule* N1 emission N1 reduc*) OR ((active OR public OR mass OR infrastructure*) N2 transport*) OR ((anthropogenic OR human-made) W1 heat) OR ((natural OR urban) W1 ventilation) OR_"transit oriented development") OR AB ("cool car*" OR (energy N2 (efficiency OR heating OR cooling)) OR (vehicule* N1 emission N1 reduc*) OR ((active OR public OR mass OR infrastructure*) N2 transport*) OR ((anthropogenic OR human-made) W1 heat) OR ((natural OR urban) W1 ventilation) OR_"transit oriented development")	845
13	Liaison 1+2	**S6 AND (S9 OR S10 OR S11 OR S12)**	26
14	Liaison	**S8 OR S13**	59
15	Time limit	S14 AND (DT 2009-2020)	49
16	Language limit	S15 AND LA (English OR French)	49
17	Except animal studies	S16 NOT TI (arthropod* OR avian OR bird* OR fish OR fishes OR herbivore* OR insect* OR mice OR mosquito* OR mouse OR rat OR rats OR snake* OR spider*)	**49**

Table A6 Research strategy launched in ScienceDirect

#	Concepts	Searches	Results
1	Concept 1	Title: heat island	676
2	Concept 2	Title, abstract, keywords: (adapt OR fight OR intervention OR limit OR measure OR mitigation OR policy program OR reduce OR strategy)	2,910,167
3	Liaison	Liaison 1+2	362
4	Time limit	Years: 2009-2020 (drop-down menu)	**329**

APPENDIX 2 EVALUATION OF THE LITERATURE REVIEWS

An evaluation grid was elaborated to ascertain the quality of the literature reviews selected. The grid comprised two sections: (1) the matching of the reviews with the topic under study; and (2) the methodological quality. A librarian approved the grid (see Table B1). The methodological section of the grid draws inspiration from the AMSTAR grid model developed by the Institut national d'excellence en santé et en services sociaux (INESSS). Each of the two sections accounted for 50% of the score attributed to the reviews and encompassed the criteria to which a rating was ascribed:

- a score of 2 was attributed when the review perfectly satisfied the criterion;
- a score of 1 was attributed when the review partially satisfied the criterion;
- a score of 0 was attributed when the review hardly satisfied or did not satisfy the criterion.

The section focusing on the matching of the reviews with the topic hinged on three criteria, i.e., relevance, the completeness of the measures to mitigate UHI, and the geographic area studied. To accord greater weight to certain criteria deemed more important in this section, the 50% was not distributed uniformly.

The section focusing on methodological quality hinged on five criteria, i.e., the number of authors who collaborated on the article, the level of detail of the research plan, the research strategy, the heterogeneity of the findings, and the disclosure of conflicts of interest.

A research professional and a trainee independently assessed the literature reviews. Discussions were held when differences arose concerning the attribution of a score in order to achieve a consensus. Tables B2 to B24 present the entire array of scores stemming from the evaluation of the 23 literature reviews. Three literature reviews obtained a score of 1.4 out of 2, the highest score resulting from the evaluation process of the reviews: Yu *et al.*, 2020 (Table B23), Gago *et al.*, 2013 (Table B11), and Filho *et al.*, 2017 (Table B9). Since Yu *et al.*, 2020 and Gago *et al.*, 2013 dealt mainly with a single measure to mitigate UHI, it was agreed to select the year 2017, which is associated with the review by Filho *et al.* that covered several measures to mitigate UHI.

Table B1 Evaluation grid of the literature reviews

Criteria and weighting (50%)	Description of the criteria	Strong (++) (2 points)	Moderate (+) (1 point)	Weak (-) (0 point)
Matching of the studies with the topic section				
Relevance (20%)	*Relevance in terms of the topic*	Examines measures to mitigate UHI	Partially examines measures to mitigate UHI	Does not examine measures to mitigate UHI **(rejected)**
Completeness of the measures studied (20%)	*Number of measures examined in the review*	Examines more than two measures to mitigate UHI	Examines two measures to mitigate UHI	Examines only one measure to mitigate UHI
Geographic area (10%)	*Applicability to Québec's climatic context of the measures or outcomes*	Québec, Canada, Northeastern United States	Other countries whose measures or outcomes are applicable to the Québec context	Other countries whose measures or outcomes are hardly applicable to the Québec context
Methodological quality section				
Number of authors (10%)	*The multiplicity of collaborators ensures conflict resolution*	Produced by at least three authors	Produced by two authors	Produced by one author
Research plan (10%)	*Establishment of the research plan*	The research question and the inclusion and exclusion criteria are determined prior to beginning the review	The research question or the inclusion and exclusion criteria are determined prior to beginning the review	The research question and the inclusion and exclusion criteria are not determined prior to beginning the review
Research strategy (10%)	*Database searches and identification of keywords*	The search was launched in at least two databases and the keywords are identified	The search was launched in at least one database OU the keywords are identified	The authors did not mention any research strategy, or it was impossible to verify
Heterogeneity of the research findings (10%)	*Presence or absence of differences in the findings of the original studies*	Lack of heterogeneity in the findings	The authors explain the heterogeneity of the research findings	The authors do not explain the heterogeneity of the research findings
Conflicts of interest (10%)	*Presence or absence of conflicts of interest*	The authors do not report any conflict of interest	-	The authors report neither the presence nor the absence of potential conflicts of interest

Table B2 Evaluation - Aflaki *et al.* (2017)

Criteria and weighting	Strong (++)	Moderate (+)	Weak (-)	Total	Comments
Matching of the studies with the topic section					
Relevance (20%)	2			**0,4**	Examines measures to mitigate UHI
Completeness of the research findings (20%)			0	**0**	Examines only one measure to mitigate UHI
Geographic area (10%)			0	**0**	East Asia, humid tropical countries (Malaysia, Singapore) and Hong Kong (humid subtropical climate)
Methodological quality section					
Number of authors (10%)	2			**0,2**	Produced by seven authors
Research plan (10%)			0	**0**	N/A
Research strategy (10%)			0	**0**	N/A
Heterogeneity of the research findings (10%)	2			**0,2**	Lack of heterogeneity in the findings
Conflicts of interest (10%)			0	**0**	The authors report neither the presence nor the absence of potential conflicts of interest
Total (maximum 2 points)				**0.8**	

Reference: Aflaki, A., Mirnezhad, M., Ghaffarianhoseini, A., Ghaffarianhoseini, A., Omrany, H., Wang, Z.-H., and Akbari, H. (2017). Urban heat island mitigation strategies: A state-of-the-art review on Kuala Lumpur, Singapore and Hong Kong. *Cities, 62*, 131-145. https://doi.org/10.1016/j.cities.2016.09.003

Table B3 Evaluation - Ampatzidis and Kershaw (2020)

Criteria and weighting	Strong (++)	Moderate (+)	Weak (-)	Total	Comments
Matching of the studies with the topic section					
Relevance (20%)	2			**0.4**	Examines measures to mitigate UHI
Completeness of the research findings (20%)			0	**0**	Examines only one measure to mitigate UHI
Geographic area (10%)			0	**0**	The great majority of the studies were conducted in humid subtropical climates, mainly in Asia
Methodological quality section					
Number of authors (10%)		1		**0.1**	Produced by two authors
Research plan (10%)			0	**0**	N/A
Research strategy (10%)			0	**0**	N/A
Heterogeneity of the research findings (10%)		1		**0,1**	The authors explain the heterogeneity of the research findings
Conflicts of interest (10%)	2			**0,2**	The authors do not report any conflict of interest
Total (maximum 2 points)				**0,8**	

Reference: Ampatzidis, P. and Kershaw, T. (2020). A review of the impact of blue space on the urban microclimate. *Science of the Total Environment*, *730*, 139068. https://doi.org/10.1016/j.scitotenv.2020.139068

Table B4 Evaluation - Aram *et al.* (2019)

Criteria and weighting	Strong (++)	Moderate (+)	Weak (-)	Total	Comments
Matching of the studies with the topic section					
Relevance (20%)	2			**0,4**	Examines measures to mitigate UHI
Completeness of the research findings (20%)			0	**0**	Examines only one measure to mitigate UHI
Geographic area (10%)		1		**0,1**	The studies were conducted in various countries, including European countries.
Methodological quality section					
Number of authors (10%)	2			**0,2**	Produced by four authors
Research plan (10%)	2			**0,2**	The research question and selection criteria are defined
Research strategy (10%)			0	**0**	N/A
Heterogeneity of the research findings (10%)			0	**0**	The authors do not explain the heterogeneity of the research findings
Conflicts of interest (10%)	2			**0,2**	The authors do not report any conflict of interest
Total (maximum 2 points)				**1.1**	

Reference: Aram, F., Higueras García, E., Solgi, E. and Mansournia, S. (2019). Urban green space cooling effect in cities. *Heliyon*, *5*(4), e01339. https://doi.org/10.1016/j.heliyon.2019.e01339

Table B5 Evaluation - Besir and Cuce (2018)

Criteria and weighting	Strong (++)	Moderate (+)	Weak (-)	Total	Comments
Matching of the studies with the topic section					
Relevance (20%)	2			**0.4**	Examines measures to mitigate UHI
Completeness of the research findings (20%)			0	**0**	Examines only one measure to mitigate UHI
Geographic area (10%)	2			**0.2**	The studies were conducted in various countries, including Canada and the United States
Methodological quality section					
Number of authors (10%)		1		**0.1**	Produced by two authors
Research plan (10%)		1		**0.1**	The research question is described
Research strategy (10%)			0	**0**	N/A
Heterogeneity of the research findings (10%)	2			**0.2**	Lack of heterogeneity in the findings
Conflicts of interest (10%)			0	**0**	The authors report neither the presence nor the absence of potential conflicts of interest
Total (maximum 2 points)				**1**	

Reference: Besir, A. B. and Cuce, E. (2018). Green roofs and facades: A comprehensive review. *Renewable and Sustainable Energy Reviews*, *82* (Part 1), 915-939.

Table B6 Evaluation - Bobes-Jesus *et al.* (2013)

Criteria and weighting	Strong (++)	Moderate (+)	Weak (-)	Total	Comments
Matching of the studies with the topic section					
Relevance (20%)		1		**0.2**	Partially examines measures to mitigate UHI
Completeness of the research findings (20%)			0	**0**	Examines only one measure to mitigate UHI
Geographic area (10%)		1		**0.1**	The studies were conducted in the United States and in Europe
Methodological quality section					
Number of authors (10%)	2			**0.2**	Produced by four authors
Research plan (10%)		1		**0.1**	The research question is described
Research strategy (10%)			0	**0**	N/A
Heterogeneity of the research findings (10%)	2			**0.2**	Lack of heterogeneity in the findings
Conflicts of interest (10%)			0	**0**	The authors report neither the presence nor the absence of potential conflicts of interest
Total (maximum 2 points)				**0.8**	

Reference: Bobes-Jesus, V., Pascual-Muñoz, P., Castro-Fresno, D. and Rodriguez-Hernandez, J. (2013). Asphalt solar collectors: A literature review. *Applied Energy*, *102*, 962-970. https://doi.org/10.1016/j.apenergy.2012.08.050

Table B7 Evaluation - Charlesworth (2010)

Criteria and weighting	Strong (++)	Moderate (+)	Weak (-)	Total	Comments
Matching of the studies with the topic section					
Relevance (20%)		1		**0.2**	Partially examines measures to mitigate UHI
Completeness of the research findings (20%)			0	**0**	Examines only one measure to mitigate UHI
Geographic area (10%)		1		**0.1**	The studies were conducted in various countries, including the United States
Methodological quality section					
Number of authors (10%)			0	**0**	Produced by one author
Research plan (10%)		1		**0.1**	The research question is described
Research strategy (10%)			0	**0**	N/A
Heterogeneity of the research findings (10%)	2			**0.2**	Lack of heterogeneity in the findings
Conflicts of interest (10%)			0	**0**	The authors report neither the presence nor the absence of potential conflicts of interest
Total (maximum 2 points)				**0.6**	

Reference: Charlesworth, S. M. (2010). A review of the adaptation and mitigation of global climate change using sustainable drainage in cities. *Journal of Water and Climate Change*, *1*(3), 165-180. https://doi.org/10.2166/wcc.2010.035

Table B8 Evaluation - Charoenkit and Yiemwattana (2016)

Criteria and weighting	Strong (++)	Moderate (+)	Weak (-)	Total	Comments
Matching of the studies with the topic section					
Relevance (20%)	2			**0.4**	Examines measures to mitigate UHI
Completeness of the research findings (20%)			0	**0**	Examines only one measure to mitigate UHI
Geographic area (10%)		1		**0.1**	The studies were conducted in various countries, some of which have temperate climates
Methodological quality section					
Number of authors (10%)		1		**0.1**	Produced by two authors
Research plan (10%)	2			**0.2**	The research question and the inclusion and exclusion criteria are described
Research strategy (10%)	2			**0.2**	The databases and keywords are described
Heterogeneity of the research findings (10%)	2			**0.2**	Lack of heterogeneity in the findings
Conflicts of interest (10%)			0	**0**	The authors report neither the presence nor the absence of potential conflicts of interest
Total (maximum 2 points)				**1.2**	

Reference: Charoenkit, S. and Yiemwattana, S. (2016). Living walls and their contribution to improved thermal comfort and carbon emission reduction: A review. *Building et Environment*, *105*, 82-94. https://doi.org/10.1016/j.buildenv.2016.05.031

Table B9 Evaluation - Filho *et al.* (2017)

Criteria and weighting	Strong (++)	Moderate (+)	Weak (-)	Total	Comments
Matching of the studies with the topic section					
Relevance (20%)		1		**0.2**	Partially examines measures to mitigate UHI
Completeness of the research findings (20%)	2		0	**0.4**	Examines more than two measures to mitigate UHI
Geographic area (10%)		1		**0.1**	The studies were conducted in various countries, some of which have temperate climates
Methodological quality section					
Number of authors (10%)	2			**0.2**	Produced by four authors
Research plan (10%)		1		**0.1**	The research question is described
Research strategy (10%)			0	**0**	N/A
Heterogeneity of the research findings (10%)	2			**0.2**	Lack of heterogeneity in the findings
Conflicts of interest (10%)	2			**0.2**	The authors report neither the presence nor the absence of potential conflicts of interest
Total (maximum 2 points)				**1.4**	

Reference: Filho, W. L., Icaza, L. E., Emanche, V. O. and Al-Amin, A. Q. (2017). An evidence-based review of impacts, strategies and tools to mitigate urban heat islands. *International Journal of Environmental Research and Public Health*, *14*(12), 1600. https://doi.org/10.3390/ijerph14121600

Table B10 Evaluation - Francis and Jensen (2017)

Criteria and weighting	Strong (++)	Moderate (+)	Weak (-)	Total	Comments
Matching of the studies with the topic section					
Relevance (20%)		1		**0.2**	Partially examines measures to mitigate UHI
Completeness of the research findings (20%)			0	**0**	Examines only one measure to mitigate UHI
Geographic area (10%)		1		**0.1**	The studies were conducted in various countries, including the United States and in Europe
Methodological quality section					
Number of authors (10%)		1		**0.1**	Produced by two authors
Research plan (10%)	2			**0.2**	The research question and the inclusion and exclusion criteria are determined
Research strategy (10%)	2			**0.2**	The search was launched in at least two databases and the keywords are identified
Heterogeneity of the research findings (10%)		1		**0.1**	The authors explain the heterogeneity of the research findings
Conflicts of interest (10%)		1		**0.1**	The authors report neither the presence nor the absence of potential conflicts of interest
Total (maximum 2 points)				**1.0**	

Reference: Francis, L. F. M. and Jensen, M. B. (2017). Benefits of green roofs: A systematic review of the evidence for three ecosystem services. *Urban Forestry et Urban Greening*, *28*, 167-176. https://doi.org/10.1016/j.ufug.2017.10.015

Table B11 Evaluation - Gago *et al.* (2013)

Criteria and weighting	Strong (++)	Moderate (+)	Weak (-)	Total	Comments
Matching of the studies with the topic section					
Relevance (20%)	2			**0.4**	Examines measures to mitigate UHI
Completeness of the research findings (20%)		1		**0.2**	Examines only one measure to mitigate UHI
Geographic area (10%)		1		**0.1**	The studies were conducted in various countries, including the United States and in Europe
Methodological quality section					
Number of authors (10%)	2			**0.2**	Produced by four authors
Research plan (10%)	2			**0.2**	The research question and the inclusion and exclusion criteria are determined
Research strategy (10%)	2			**0.2**	The search was launched in at least two databases and the keywords are identified
Heterogeneity of the research findings (10%)		1		**0.1**	The authors explain the heterogeneity of the research findings
Conflicts of interest (10%)			0	**0**	The authors report neither the presence nor the absence of potential conflicts of interest
Total (maximum 2 points)				**1.4**	

Reference: Gago, E. J., Roldan, J., Pacheco-Torres, R. and Ordóñez, J. (2013). The city and urban heat islands : A review of strategies to mitigate adverse effects. *Renewable and Sustainable Energy Reviews*, *25*, 749- 758. https://doi.org/10.1016/j.rser.2013.05.057

Table B12 Evaluation - Kleerekoper *et al.* (2012)

Criteria and weighting	Strong (++)	Moderate (+)	Weak (-)	Total	Comments
Matching of the studies with the topic section					
Relevance (20%)	2			**0.4**	Examines measures to mitigate UHI
Completeness of the research findings (20%)	2			**0.4**	Examines more than two measures to mitigation UHI
Geographic area (10%)		1		**0.1**	Other countries whose measures or outcomes are applicable to the Québec context (the United States and European countries)
Methodological quality section					
Number of authors (10%)	2			**0.2**	Produced by three authors
Research plan (10%)		1		**0.1**	The research question or the inclusion and exclusion criteria are determined prior to beginning the review
Research strategy (10%)			0	**0**	The authors did not mention any research strategy or it was impossible to verify
Heterogeneity of the research findings (10%)		1		**0.1**	The authors explain the heterogeneity of the research findings
Conflicts of interest (10%)			0	**0**	The authors report neither the presence nor the absence of potential conflicts of interest
Total (maximum 2 points)				**1.3**	

Reference: Kleerekoper, L., van Esch, M. and Salcedo, T. B. (2012). How to make a city climate-proof, addressing the urban heat island effect. *Special Issue: Climate Proofing Cities.*, *64*, 30-38. https://doi.org/10.1016/j.resconrec.2011.06.004

Table B13 Evaluation - Lai *et al.* (2019)

Criteria and weighting	Strong (++)	Moderate (+)	Weak (-)	Total	Comments
Matching of the studies with the topic section					
Relevance (20%)	2			**0.4**	Examines measures to mitigate UHI
Completeness of the research findings (20%)	2			**0.4**	Examines more than two measures to mitigate UHI
Geographic area (10%)		1		**0.1**	Other countries whose measures or outcomes are applicable to the Québec context
Methodological quality section					
Number of authors (10%)	2			**0.2**	Produced by five authors
Research plan (10%)	2			**0.2**	The research question and the inclusion and exclusion criteria are determined prior to beginning the review
Research strategy (10%)			0	**0**	The authors did not mention any research strategy, or it was impossible to verify
Heterogeneity of the research findings (10%)			0	**0**	The authors do not explain the heterogeneity of the research findings
Conflicts of interest (10%)			0	**0**	The authors report neither the presence nor the absence of potential conflicts of interest
Total (maximum 2 points)				**1.3**	

Reference: Lai, D., Liu, W., Gan, T., Liu, K. and Chen, Q. (2019). A review of mitigating strategies to improve the thermal environment and thermal comfort in urban outdoor spaces. *Science of the Total Environment*, *661*, 337-353. https://doi.org/10.1016/j.scitotenv.2019.01.062

Table B14 Evaluation - Leal Filho *et al.* (2018)

Criteria and weighting	Strong (++)	Moderate (+)	Weak (-)	Total	Comments
Matching of the studies with the topic section					
Relevance (20%)		1		**0.2**	Partially examines measures to mitigate UHI
Completeness of the research findings (20%)	2			**0.4**	Examines more than two measures to mitigate UHI
Geographic area (10%)		1		**0.1**	Other countries whose measures or outcomes are applicable to the Québec context
Methodological quality section					
Number of authors (10%)	2			**0.2**	Produced by five authors
Research plan (10%)		1		**0.1**	The research question or the inclusion and exclusion criteria are determined prior to beginning the review
Research strategy (10%)			0	**0**	The authors did not mention any research strategy or it was impossible to verify
Heterogeneity of the research findings (10%)	2			**0.2**	Lack of heterogeneity in the findings
Conflicts of interest (10%)			0	**0**	The authors report neither the presence nor the absence of potential conflicts of interest
Total (maximum 2 points)				**1.2**	

Reference: Leal Filho, W., Echevarria Icaza, L., Neht, A., Klavins, M. and Morgan, E. A. (2018). Coping with the impacts of urban heat islands. A literature based study on understanding urban heat vulnerability and the need for resilience in cities in a global climate change context. *Journal of Cleaner Production*, *171*, 1140-1149.
https://doi.org/10.1016/j.jclepro.2017.10.086

Table B15 Evaluation - Mohajerani *et al.* (2017)

Criteria and weighting	Strong (++)	Moderate (+)	Weak (-)	Total	Comments
Matching of the studies with the topic section					
Relevance (20%)		1		**0.2**	Partially examines measures to mitigate UHI
Completeness of the research findings (20%)	2			**0.4**	Examines only one measure to mitigate UHI
Geographic area (10%)		1		**0.1**	Other countries whose measures or outcomes are applicable to the Québec context
Methodological quality section					
Number of authors (10%)	2			**0.2**	Produced by at least three authors
Research plan (10%)		1		**0.1**	The research question or the inclusion and exclusion criteria are determined prior to beginning the review
Research strategy (10%)			0	**0**	The authors did not mention any research strategy, or it was impossible to verify
Heterogeneity of the research findings (10%)		1		**0.1**	The authors explain the heterogeneity of the research findings
Conflicts of interest (10%)			0	**0**	The authors report neither the presence nor the absence of potential conflicts of interest
Total (maximum 2 points)				**1.1**	

Reference: Mohajerani, A., Bakaric, J. and Jeffrey-Bailey, T. (2017). The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete. *Journal of Cleaner Production*, *197*, 522-538. https://doi.org/10.1016/j.jenvman.2017.03.095

Table B16 Evaluation - Qin (2015)

Criteria and weighting	Strong (++)	Moderate (+)	Weak (-)	Total	Comments
Matching of the studies with the topic section					
Relevance (20%)	2			**0.4**	Examines measures to mitigate UHI
Completeness of the research findings (20%)			0	**0**	Examines only one measure to mitigate UHI
Geographic area (10%)		1		**0.1**	Other countries whose measures or outcomes are applicable to the Québec context
Methodological quality section					
Number of authors (10%)			0	**0**	Produced by one author
Research plan (10%)		1		**0.1**	The research question or the inclusion and exclusion criteria are determined prior to beginning the review
Research strategy (10%)			0	**0**	The authors did not mention any research strategy or it was impossible to verify
Heterogeneity of the research findings (10%)		1		**0.1**	The authors explain the heterogeneity of the research findings
Conflicts of interest (10%)			0	**0**	The authors report neither the presence nor the absence of potential conflicts of interest
Total (maximum 2 points)				**0.7**	

Reference: Qin, Y. (2015). A review on the development of cool pavements to mitigate urban heat island effect. *Renewable and Sustainable Energy Reviews*, *52*, 445- 459. https://doi.org/10.1016/j.rser.2015.07.177

Table B17 Evaluation - Rahman *et al.* (2020)

Criteria and weighting	Strong (++)	Moderate (+)	Weak (-)	Total	Comments
Matching of the studies with the topic section					
Relevance (20%)	2			**0.4**	Examines measures to mitigate UHI
Completeness of the research findings (20%)			0	**0**	Examines only one measure to mitigate UHI
Geographic area (10%)		1		**0.1**	Other countries whose measures or outcomes are applicable to the Québec context
Methodological quality section					
Number of authors (10%)	2			**0.2**	Produced by at least three authors
Research plan (10%)	2			**0.2**	The research question and the inclusion and exclusion criteria are determined prior to beginning the review
Research strategy (10%)	2			**0.2**	The search was launched in at least two databases and the keywords are identified
Heterogeneity of the research findings (10%)		1		**0.1**	The authors explain the heterogeneity of the research findings
Conflicts of interest (10%)			0	**0**	The authors report neither the presence nor the absence of potential conflicts of interest
Total (maximum 2 points)				**1.2**	

Reference: Rahman, M. A., Stratopoulos, L. M. F., Moser-Reischl, A., Zölch, T., Häberle, K.-H., Rötzer, T., Pretzsch, H. and Pauleit, S. (2020). Traits of trees for cooling urban heat islands: A meta-analysis. *Building et Environment*, *170*. https://doi.org/10.1016/j.buildenv.2019.106606

Table B18 Evaluation - Santamouris (2013)

Criteria and weighting	Strong (++)	Moderate (+)	Weak (-)	Total	Comments
Matching of the studies with the topic section					
Relevance (20%)	2			**0.4**	Examines measures to mitigate UHI
Completeness of the research findings (20%)			0	**0**	Examines only one measure to mitigate UHI
Geographic area (10%)		1		**0.1**	Other countries whose measures or outcomes are applicable to the Québec context
Methodological quality section					
Number of authors (10%)			0	**0**	Produced by one author
Research plan (10%)		1		**0.1**	The research question or the inclusion and exclusion criteria are determined prior to beginning the review
Research strategy (10%)			0	**0**	The authors did not mention any research strategy, or it was impossible to verify
Heterogeneity of the research findings (10%)	2			**0.2**	Lack of heterogeneity in the findings
Conflicts of interest (10%)			0	**0**	The authors report neither the presence nor the absence of potential conflicts of interest
Total (maximum 2 points)				**0.8**	

Reference: Santamouris, M. (2013). Using cool pavements as a mitigation strategy to fight urban heat island—A review of the actual developments. *Renewable and Sustainable Energy Reviews*, *26*, 224-240. https://doi.org/10.1016/j.rser.2013.05.047

Table B19 Evaluation - Santamouris (2014)

Criteria and weighting	Strong (++)	Moderate (+)	Weak (-)	Total	Comments
Matching of the studies with the topic section					
Relevance (20%)	2			**0.4**	Examines measures to mitigate UHI
Completeness of the research findings (20%)			0	**0**	Examines only one measure to mitigate UHI
Geographic area (10%)		1		**0.1**	Other countries whose measures or outcomes are applicable to the Québec context
Methodological quality section					
Number of authors (10%)			0	**0**	Produced by one author
Research plan (10%)		1		**0.1**	The research question or the inclusion and exclusion criteria are determined prior to beginning the review
Research strategy (10%)			0	**0**	The authors did not mention any research strategy, or it was impossible to verify
Heterogeneity of the research findings (10%)		1		**0.1**	The authors explain the heterogeneity of the research findings
Conflicts of interest (10%)			0	**0**	The authors report neither the presence nor the absence of potential conflicts of interest
Total (maximum 2 points)				**0.7**	

Reference: Santamouris, M. (2014). Cooling the cities – A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Solar Energy*, *103*, 682-703. https://doi.org/10.1016/j.solener.2012.07.003

Table B20 Evaluation - Susca (2019)

Criteria and weighting	Strong (++)	Moderate (+)	Weak (-)	Total	Comments
Matching of the studies with the topic section					
Relevance (20%)	2			**0.4**	Examines measures to mitigate UHI
Completeness of the research findings (20%)			0	**0**	Examines only one measure to mitigate UHI
Geographic area (10%)		1		**0.1**	Other countries whose measures or outcomes are applicable to the Québec context
Methodological quality section					
Number of authors (10%)			0	**0**	Produced by one author
Research plan (10%)	2			**0.2**	The research question and the inclusion and exclusion criteria are determined prior to beginning the review
Research strategy (10%)		1		**0.1**	The search was launched in at least one database, or the keywords are identified
Heterogeneity of the research findings (10%)		1		**0.1**	The authors explain the heterogeneity of the research findings
Conflicts of interest (10%)			0	**0**	The authors report neither the presence nor the absence of potential conflicts of interest
Total (maximum 2 points)				**0.9**	

Reference: T. Susca (2019). Green roofs to reduce building energy use? A review on key structural factors of green roofs and their effects on urban climate. *Building et Environment*, *162*. https://doi.org/10.1016/j.buildenv.2019.106273

Table B21 Evaluation - Valladares *et al.* (2017)

Criteria and weighting	Strong (++)	Moderate (+)	Weak (-)	Total	Comments
Matching of the studies with the topic section					
Relevance (20%)		1		**0.2**	Partially examines measures to mitigate UHI
Completeness of the research findings (20%)			0	**0**	Examines only one measure to mitigate UHI
Geographic area (10%)		1		**0.1**	Other countries whose measures or outcomes are applicable to the Québec context
Methodological quality section					
Number of authors (10%)	2			**0.2**	Produced by at least three authors
Research plan (10%)		1		**0.1**	The research question or the inclusion and exclusion criteria are determined prior to beginning the review
Research strategy (10%)			0	**0**	The authors did not mention any research strategy, or it was impossible to verify
Heterogeneity of the research findings (10%)		1		**0.1**	The authors explain the heterogeneity of the research findings
Conflicts of interest (10%)			0	**0**	The authors report neither the presence nor the absence of potential conflicts of interest
Total (maximum 2 points)				**0.7**	

Reference: Valladares-Rendón, L. G., Schmid, G. and Lo, S.-L. (2017). Review on energy savings by solar control techniques and optimal building orientation for the strategic placement of façade shading systems. *Energy et Buildings*, *140*, 458-479. https://doi.org/10.1016/j.enbuild.2016.12.073

Table B22 Evaluation - Yang *et al.* (2015)

Criteria and weighting	Strong (++)	Moderate (+)	Weak (-)	Total	Comments
Matching of the studies with the topic section					
Relevance (20%)	2			**0.4**	Examines measures to mitigate UHI
Completeness of the research findings (20%)			0	**0**	Examines only one measure to mitigate UHI
Geographic area (10%)		1		**0.1**	Other countries whose measures or outcomes are applicable to the Québec context
Methodological quality section					
Number of authors (10%)	2			**0.2**	Produced by at least three authors
Research plan (10%)	2			**0.2**	The research question and the inclusion and exclusion criteria are determined prior to beginning the review
Research strategy (10%)			0	**0**	The authors did not mention any research strategy, or it was impossible to verify
Heterogeneity of the research findings (10%)		1		**0.1**	The authors explain the heterogeneity of the research findings
Conflicts of interest (10%)			0	**0**	The authors report neither the presence nor the absence of potential conflicts of interest
Total (maximum 2 points)				**1.0**	

Reference: Yang, J., Wang, Z.-H. and Kaloush, K. E. (2015). Environmental impacts of reflective materials: Is high albedo a 'silver bullet' for mitigating urban heat island? *Renewable and Sustainable Energy Reviews*, *47*, 830-843. https://doi.org/10.1016/j.rser.2015.03.092

Table B23 Evaluation - Yu *et al.* (2020)

Criteria and weighting	Strong (++)	Moderate (+)	Weak (-)	Total	Comments
Matching of the studies with the topic section					
Relevance (20%)	2			**0.4**	Examines measures to mitigate UHI
Completeness of the research findings (20%)			0	**0**	Examines only one measure to mitigate UHI
Geographic area (10%)		1		**0.1**	Other countries whose measures or outcomes are applicable to the Québec context
Methodological quality section					
Number of authors (10%)	2			**0.2**	Produced by at least three authors
Research plan (10%)	2			**0.2**	The research question and the inclusion and exclusion criteria are determined prior to beginning the review
Research strategy (10%)	2			**0.2**	The search was launched in at least two databases and the keywords are identified
Heterogeneity of the research findings (10%)		1		**0.1**	The authors explain the heterogeneity of the research findings
Conflicts of interest (10%)	2			**0.2**	The authors do not report any conflict of interest
Total (maximum 2 points)				**1.4**	

Reference: Yu, Z., Yang, G., Zuo, S., Jørgensen, G., Koga, M. and Vejre, H. (2020). Critical review on the cooling effect of urban blue-green space: A threshold-size perspective. *Urban Forestry et Urban Greening*, *49*. https://doi.org/10.1016/j.ufug.2020.126630

Table B24 Evaluation - Zaid *et al.* (2018)

Criteria and weighting	Strong (++)	Moderate (+)	Weak (-)	Total	Comments
Matching of the studies with the topic section					
Relevance (20%)		1		**0.2**	Partially examines measures to mitigate UHI
Completeness of the research findings (20%)			0	**0**	Examines only one measure to mitigate UHI
Geographic area (10%)			0	**0**	Other countries whose measures or outcomes are hardly applicable to the Québec context
Methodological quality section					
Number of authors (10%)	2			**0.2**	Produced by at least three authors
Research plan (10%)	2			**0.2**	The research question and the inclusion and exclusion criteria are determined prior to beginning the review
Research strategy (10%)	2			**0.2**	The search was launched in at least two databases and the keywords are identified
Heterogeneity of the research findings (10%)	2			**0.2**	Lack of heterogeneity in the findings
Conflicts of interest (10%)			0	**0**	The authors report neither the presence nor the absence of potential conflicts of interest
Total (maximum 2 points)				**1.0**	

Reference: Zaid, S. M., Perisamy, E., Hussein, H., Myeda, N. E. and Zainon, N. (2018). Vertical Greenery System in urban tropical climate and its carbon sequestration potential: A review. *Ecological Indicators*, *91*, 57-70. https://doi.org/10.1016/j.ecolind.2018.03.086

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