THE BENEFITS OF GREEN ROOF RETROFITS AS LOCAL INTERVENTIONS FOR MITIGATING THE URBAN HEAT ISLAND EFFECT IN TORONTO

Abstract
The increasing awareness of the urban heat island (UHI) effect has raised the attention about the outdoor thermal comfort in cities. Several studies in the last decade have revealed how critical the UHI effect can be in Canadian cities too. As a result, in Toronto, one of the cities experiencing the highest rate of building development, UHI mitigation strategies are currently the object of several policies. This paper describes the studies done through the CUR-Ryerson project “Policies for Increasing the Outdoor Thermal Comfort in Toronto”. In particular, the investigation uses a case study building at Ryerson University to assess the benefits of green roofs for the local microclimate and UHI mitigation. The software ENVI-met is used to simulate the microclimate effects of a large green roof retrofit project on a three story building. Results indicate that an extensive green roof would lead to a cooling effect of the air temperature up to 0.4°C during the day at pedestrian level. Increasing the leaf area index (LAI) of the green roof leads to an increased cooling effect at pedestrian-level, although a more significant temperature reduction is attained at the rooftop-level, confirming the potential of green roofs as urban heat island mitigation strategies.

Keywords:
Green roof; Urban Heat Island; Outdoor microclimate; Urban simulation.

1 Introduction
Episodes of extreme heat are becoming common worldwide, including in countries often considered cold, such as Canada. Toronto, like many urban centres, experiences warmer average temperatures than the surrounding countryside, and over the last century, its average air temperature has increased continuously [1]. In 2005, Toronto sustained 41 days with temperatures above 30°C, and 25 nights with minimum temperature above 20°C [2]. Climate models indicate that, due to the expected warming of up to 9°C by the 2080s in the Arctic and the southern and central Prairies, the number of days with average temperatures above 30°C is likely to increase in cities across Canada, and particularly in those located in the Windsor-Quebec corridor. As a consequence, in Toronto, days with temperatures above 30°C are expected to increase from an average of 13 per year in the 1960s and 1970s, and the actual number of 26, to 65 by the end of this century [2].

Some years ago, the Natural Resources Canada used air temperature and surface temperature measurements collected from satellite imagery and 30 stationary temperature stations to characterize the microclimatology across the Greater Toronto Area (GTA). Thermal images of surface temperatures clearly illustrated the UHI effect (Fig. 1). The larger differences of the average temperature coincided the warmer areas along the boundary of Toronto [3]. To improve the understanding of these impacts, the Canada Centre for Remote Sensing (CCRS) undertook several initiatives to create quantitative portrayals
of the urban form over years, such as the Canadian Urban Land Use Survey database [3]. Rinner and Hussai using this database were able to prove average temperatures for commercial and resource/industrial land uses above 29.1 °C, versus a value of 25.1 °C for parks/recreational land use, and of 23.1 °C for water bodies; residential and open area land uses averaged temperatures of 27.5 °C [4]. However, recent studies have clarified the spatial limits and lack of accuracy in satellite analysis of the urban environment.

The UHI effect has already shown many health, environmental, and energy consumption implications. Elevated air temperatures facilitate the chemical reactions that transform atmospheric nitrogen oxides and volatile organic compounds into ozone, one of the main components of urban smog. Health Canada reported that in the seven biggest Canadian cities, when the daily average temperature is higher than 20 °C, the relative mortality increases by 2.3% for each degree increase in the air temperature [1,2]. This means that a UHI intensity of 2-3 °C translates into a 4% to 7% increase in the mortality rate in Canada.

![Figure 1: Satellite observation of the normalized surface effective summer temperature showing the intensification of the UHI in the GTA between 1985 and 2005](image)

The main factors that contribute to UHI are: large surfaces of materials with low albedo and high admittance; reduced vegetation and permeable surfaces, which limit shade and evapotranspiration; tall buildings and narrow streets that modify overall wind speeds, and create urban canyons; concentration of heat-generating activities released from fuel combustion (including cars), HVAC systems, and other anthropogenic processes [4-6]. In particular, the absence of vegetation impacts the UHI in several ways, since vegetation, intercept solar energy, and reduces the temperature of surfaces while increasing the latent heat exchange for the evapotranspiration process [7].

Wang et al. recently investigated the impact of various UHI strategies in Toronto [8]. Microclimate simulations showed that increasing the amount of vegetation had the largest impact on UHI mitigation compared to cool pavements and cool roofs. Combining all these three UHI mitigation strategies, it would be possible to reduce the air temperature by 0.8 °C at mid-day and 0.6 °C at mid-night in the summer.

More urban vegetation is a fundamental aspect of the UHI mitigation policies promoted over the last years in Toronto. As in an urban environment where available ground space is limited, roofs offer a substantial area for the implementation of UHI mitigation strategies. In particular, green roofs offer many environmental benefits including stormwater flow reduction, air
quality improvements, building energy saving, and mitigation of urban heat island (UHI) effects [7,9]. Given their commonly recognized benefits, the city of Toronto has adopted the Green Roof By-law, which requires the construction of vegetated roofs on all new developments with a gross floor area greater than 2,000m² [10]. Given to this policy, from 2010 to 2015, over 196,000m² of green roofs have been constructed in Toronto. The increasing attention towards green roofs is also supported by the Toronto Eco-Roof Program, which guarantees an incentive of $75 per m² for existing buildings and new buildings not subject to the Green Roof By-law [10].

A study by Ryerson University researchers estimated that a roof surface of about 50 million m² is available for green roof applications in Toronto, and that the implementation of these green roofs would have an annual public cost saving of $37 million for the city [9]. The study assumed an additional building energy saving of 4.15kWh/m²/year obtained through to green roofs. In retrofit projects, green roofs are generally built to enhance the energy saving of the buildings [11,12], although the resulting increase in the thermal capacity of green roofs compared to traditional roofs, if not controlled, may not be beneficial to the building cooling and heating loads [13,14].

So far, only a few studies have also looked at the capability of green roof retrofits as a measure to reduce the urban canyon temperatures [15,16]. A recent review by Santamouris found that the UHI mitigation potential of green roofs is highly dependent on the climate, roof U-value, and latent heat loss [6]. Green roofs applied on a city scale were found to reduce the ambient air temperature by 0.3°C to 3°C [7]. Smith and Roeber, performing an equivalent albedo study to model the impact of green roofs indirectly, found that the complete adoption of green roofs in the city of Chicago would reduce the air temperature by up to 3°C from 7pm to 11pm [17]. According to Savio et al. [18], the adoption of green roofs in New York would reduce daily average temperatures by 0.3°C and afternoon temperatures by 0.6°C. In a study conducted in Tokyo by Chen et al. [19], green roofs were found to have a negligible impact at pedestrian level due to the height of the buildings. Similarly, minimal effects were found in Hong Kong by Ng et al. [20]. However, another study in some neighborhoods in Hong Kong found that a cooling from 0.4°C to 0.7°C resulting from extensive green roofs and from 0.5°C to 1.7°C resulting from intensive green roofs could be obtained at pedestrian level [21]. Bass et al. [22] and Krayenhoff et al. [23] examined the impact of green roofs on Toronto’s UHI by using mesoscale models. Those studies integrate an urban surface parameterization to take into account the urban canopy layer into a meteorological model. Results suggested that the effects of a 50% green roof or white roof (albedo increase from 0.15 to 0.60) coverage would be minimal. As said, recent studies have clarified the limited capabilities of satellite analysis and mesoscale assessment for evaluate UHI mitigation interventions, and have suggested a combination of these with more detailed analyses at the scale of single neighborhoods in order to capture specific urban elements.

The present paper represents one of the first examples where microclimate benefits of a green roof retrofit are evaluated at the microscale of a single (large) building block.

2 CASE STUDY BUILDING

Green roofs have received increasing attention in Toronto. Moreover, in recent years, an increasing attention to green roofs has been supported by the rooftop agriculture movement. As an example, the new Ryerson Engineering building, designed with a 1000 m² green roof was recently reconverted in a small farm capable of producing 2 tonnes of food yearly (Fig.2).

A proposal for installing a green roof on the main Ryerson building was discussed recently. This building was completed in 1969 and consists of four wing buildings, forming a square which surrounds the Ryerson Community Park (Fig.3). The roof construction of the building consists of a bitumen foil, variable thickness layer (5 to 10 cm), cork insulation (50 cm), and a structural concrete roof (20 cm).
The design of a green roof is a demanding task which is affected by many parameters, as a green roof is itself a multilayer structure. Green roofs are often classified in intensive or extensive according to the depth of the soil. Obviously, since extensive green roofs have a shallow growing medium and are lighter, considering the structural capacity of the existing building, an extensive green roof was considered as the only option for this retrofit application. In particular, a structural analysis of the existing roof suggested to limit the additional weight of the green roof to 150 kg/m², which corresponds to a regular soil depth of less than 20 cm or to a lighted soil medium up to 25 cm. By changing the plant selection (also expressed in terms of Leaf Area Indices) and soil depth, four green roof systems were analysed, as reported in Table 1. Green roofs C and D were assumed for comparative evaluations about their potential for the building energy saving.
3 METHODOLOGY of the study

Microclimate simulations were performed using ENVI-met 4.0, a three-dimensional computational fluid dynamics non-hydrostatic S.V.A.T. (soil, vegetation, atmosphere, and transfer) model. This program models the surface-plant-air interactions in urban environments, and it has been extensively validated and used over the years [8,11,24]. The program also simulates the flows around buildings, heat and vapor transfer at the urban surfaces, turbulence, exchanges of energy and mass between vegetation and its surroundings, and simple chemical reactions. The main input parameters of ENVI-met simulations include weather conditions, initial soil wetness and temperature profiles, structures and physical properties of urban surfaces, and plants [24]. In ENVI-met, the soil model is organized in layers: heterogeneous surface types are simulated assigning temperature, water vapor pressure, relative humidity, wind velocity, and mean radiant temperature of each grid cell a different thermodynamic and hydraulic conductivity, and albedo value. Vegetation is modelled for its evapotranspiration processes, shadow, and drag effects. ENVI-met carries out calculation in regards to both shortwave and long-wave radiation fluxes with respect to shading, reflection, and re-radiation from buildings and vegetation. The temperatures of the ground and building surfaces are finally calculated from an energy balance of differential equations solved using the finite difference method.

The model was simulated in the warmest day of the last year, using the data reported in Table 2 as initial boundary conditions. Only summer time was considered as a prior study showed negligible effect of the vegetation on the winter outdoor microclimate in Toronto [8].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Input value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start time</td>
<td>August 15th, 4:00 am</td>
</tr>
<tr>
<td>Simulation time</td>
<td>24 hours</td>
</tr>
<tr>
<td>Wind direction</td>
<td>South-West (225°)</td>
</tr>
<tr>
<td>Wind speed (10m)</td>
<td>1.39 m/s</td>
</tr>
<tr>
<td>Specific humidity (2500m)</td>
<td>7.0 g/kgda</td>
</tr>
<tr>
<td>Relative humidity (2m)</td>
<td>68.6%</td>
</tr>
</tbody>
</table>

ENVI-met requires an area input file with a 3-dimensional geometry. In this study, the geometrical model had dimensions of 220.5(x) x 217(y) x 60(z) m (with z being the vertical axis), with cell grids of 49x62x30 (Fig.4). The total height of the model was significantly higher that the building height. Moreover, three nesting grids were implemented into the model in order to increase the accuracy around the borders. The ENVI-met model included the near buildings in order to calibrate the as-it-is model using local weather stations [11].

For the placement of the vegetation into the model, the Ryerson Park-trees database was used. This database provides information on the tree species, location, and attributes, such as tree height or crown radius. One of the important aspects while modelling green roofs is that plants have not the same characteristics over time. For example, the foliage density and the height of the plants are higher in summer compared to winter while the water content, and hence the thermal conductivity, changes frequently. This analysis was not considered in the present paper as the single warmest day was simulated only.
Fig. 4: ENVI-met microclimate model.

4 MICROCLIMATE RESULTS

First of all, the ENVI-met model was validated using the measured data from local rooftop weather stations. The simulated air temperature was compared to the air temperature data. The difference between simulation data and measured ones resulted on average below 0.5°C, and could be explained by inaccuracies in the input parameters for the simulation. A full discussion of these discrepancies is reported in [14].
Looking at simulation results in Fig. 5, at noon the maximum cooling effect is 0.2°C and 0.4°C for green roofs A and B respectively compared to the as is case. At midnight the cooling increases with maximum differences of 0.7°C and 1.1°C for green roofs A and B respectively. The decrease in air temperature is due to the evapotranspiration of the vegetation and the increase in albedo of the roof. In Fig 5, it is evident that the increase in LAI has a significant impact on the cooling effect at pedestrian level. Air temperature cooling predominantly occurs north-east of the building (Fig. 5).

The MRT proved to be less impacted by the addition of the green roofs (Fig. 6). At noon, there is no significant decrease in MRT for green roof A and a maximum decrease of only 0.2°C for green roof B. At midnight, the impact on MRT increases to a maximum decrease of 0.1°C for green roof A and 0.3°C for green roof B.

After having evaluated the effect at pedestrian level, the study also looked at the impact over the roof. The rooftop microclimate may play several roles in outdoor comfort and may also improve HVAC performance due to its free cooling effects, and their resulting lower outdoor air temperatures. The difference in air temperature at the rooftop level for green roof retrofits A (LAI=1) and B (LAI=2), compared to the as is the case showed that while at noon there is minimal...
difference (green roof retrofit B shows a maximum cooling of 0.4°C), at midnight the cooling is increased with a maximum reduction of 1.6°C and 2.6°C for green roofs A and B respectively. As expected, the impact of the green roof retrofits on the air temperature is more pronounced at the rooftop level. This also agrees with previous studies [19,20].

![Image of MRT difference between green roof A (LAI 1) or case green roof B (LAI 2) and as is case at pedestrian-level (1.8m above ground) at 12pm (on the left) and at 12am (on the right).]

5 DISCUSSION and CONCLUSIONS

The study has demonstrated that the application of a green roof retrofit on a building in Toronto may decrease the surrounding air temperature by up to 0.4°C during the day and 0.8°C at night. The cooling effect on the urban microclimate with green roof retrofits increased with the increase of the LAI. At pedestrian level the cooling pattern followed the wind prevalent directions. An average reduction in peak temperature up to 0.4°C and 0.7°C for green roofs with a LAI of 1 or 2 respectively was found, although no appreciable effect was obtained for the MRT at pedestrian level. Reversely, at the rooftop level, the cooling effects were larger. Peak air temperature reductions of 0.4°C and 0.8°C during the day and of 1.1°C and 2.0°C at night were found. These results are comparable to those found in other studies. For example, in New York City afternoon temperatures were found to be reduced by up to 0.6°C with the adoption of green roofs [18], while in Hong Kong, air temperatures were reduced by up to 0.7°C at 2pm with green roof applications [21]. These studies showed slightly larger reductions in air temperatures during the day than the present study, however, they also implemented green roofs on the larger scale of an entire neighbourhood.

In conclusion, this paper has shown that a green roof retrofit could have an appreciable impact on the outdoor microclimate while resulting in energy savings too. However, in this study, two different models were created for the different simulations. The hope is that in the near future, energy modelling will allow to interact with urban modelling more closely,
as this last seems to attract an increasing attention, not only for architects and designers, but also for city planners, policy makers and for the large community of building citizenships.

6 ACKNOWLEDGEMENTS

This research was funded by the Centre for Urban Research (CUR) of Ryerson University through the project “Policy Guidelines for Increasing Outdoor Thermal Comfort in Toronto: An Analysis of the Urban Microclimate”. The author expresses his gratitude to Melissa Furukawa for the ENVI-met simulations developed for her Master thesis.

7 References


