WORKING PAPER SERIES **GREENBELT FOUNDATION**

Cooling Corridors: The Role of Green Infrastructure in Building Resilience to Extreme Heat

BeTop Lab at Ryerson University

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Possibility grows here.

Greenbelt Foundation
661 Yonge Street, Suite 500
Toronto, Ontario
M4Y 1Z9
Canada

Tel (416) 960-0001
Fax (416) 960-0030
info@greenbelt.ca
www.greenbelt.ca

Research for this report was prepared by Prof. Umberto Berardi, Dr. Zahra Jandaghian and Jonathan Graham at Ryerson University's BeTop Lab.

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The Greenbelt Foundation's Working Paper series provides an avenue to disseminate research findings and information on particular topics. It is intended to encourage discussion and the exchange of ideas among Greenbelt stakeholders and the public.

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1. Executive Summary

Extreme heat is a human health risk that can be increased by urban development and climate change. Forested areas in communities like the Greenbelt's urban river valleys and urban tree cover can provide cooling benefits and build resilience in Ontario's Greater Golden Horseshoe communities to the increasing risks associated with extreme heat. This report provides evidence of those impacts, based on novel local research on the role of urban river valleys in providing localized cooling. It also demonstrates the potential cooling benefit of increased urban tree cover in two neighbourhoods in the Region of Peel.

For two heat vulnerable neighbourhoods in the Region of Peel, two potential greening scenarios were modeled, one a 50% increase in tree cover and one that represents an 80% increase. These scenarios were modeled during a July 2018 extreme heat event at two scales. A regional model was used for the entire neighbourhood and a local model was used in part of each neighbourhood to better understand the impact trees have on personal comfort levels.

Findings show significant potential benefit of urban river valleys and increased urban tree cover in reducing exposure to extreme heat. Both neighbourhoods had evident urban heat island effects, where human structures absorb heat and increase surrounding air temperatures. At the regional scale, 50% greening resulted in average daily ambient temperature decreases of 0.8 to 1.3 ^{o}C. 80% greening showed even more promise, decreasing the average air temperature by 1.5 to 2 ^{o}C.

Individual modeled trees also showed an impressive impact on perceived temperature, at a 3 ^{o}C change in the urban thermal comfort index (UTCI) in the evening. The benefits of full reforestation were even greater, leading to perceived temperature decreases as great as 11 ^{o}C. The cooling benefits of trees extended beyond their immediate locations as well. Depending on wind conditions and the arrangement of buildings, this cooling effect expanded as far as 150 m to 250 m downwind.

Overall, increasing tree cover in these neighbourhoods was enough to decrease human thermal heat stress from "strong" to "moderate". These findings suggest that increasing the number of mature trees in these neighbourhoods could be an effective public health measure toward reducing vulnerability to extreme heat and that where and how trees are planted can affect the cooling services they provide.

Recommendations for Follow- up by Decision Makers

Local governments, public health advocates, and individuals in the Greater Golden Horseshoe may benefit from this research. High-level recommendations for decision makers are as follows:

- Provide public access to areas with high/dense tree canopy, including those in urban river valleys, to provide the public with natural cooling benefits.
- Extend forest cover around URVs to increase their “cooling shadow”.
- Prioritize reforestation over more spaced-out landscape trees to provide a greater cooling benefit.
- School grounds present opportunities for tree canopy increases and are areas that could benefit populations that are more vulnerable. While it was not explored in this report, this may also be true of other public lands with vulnerable populations like long-term care, other seniors' care facilities and hospitals.
- Plant trees to allow cooling effects to circulate freely downwind to beneficiaries.
- Increase tree cover in parking lots to reduce “hot spots”.
- Maintain trees so that they reach maturity to maximize their benefits. The more mature trees, the better for cooling.

2. Introduction

Extreme heat is a human health risk increased by urban development and climate change impacts. Green infrastructure like the Greenbelt's urban river valleys and urban tree canopy can provide cooling benefits and build the resilience of communities in Ontario's Greater Golden Horseshoe to these increasing risks associated with extreme heat. This report provides evidence based on novel local research on the role that the Greenbelt's urban river valleys play in providing local cooling benefits. It also demonstrates that increased urban tree canopy cover (UTC) has the potential to reduce neighbourhood-level vulnerability to extreme heat events through climate modeling of tree canopy cover scenarios in two case study neighbourhoods adjacent to urban river valleys in the Region of Peel.

HEAT WARNINGS

Environment and Climate Change Canada (ECCC) monitors weather forecasts and notifies public health staff 2-4 days in advance, if their climate modelling predicts weather that meets the criteria for a health warning or an extended heat warning. Not all predictions result in a heat or extended heat warning being issued. As the heat event approaches, ECCC continues to advise public health authorities until it is confirmed that the event will meet the criteria.

There are three heat warning regions in Ontario – extreme Southwest Ontario, Southern Ontario and Northern Ontario. The Region of Peel is in Southern Ontario.

All warning levels are based on forecasted conditions. Health Canada and Public Health Ontario developed the following triggers for heat/extended heat warnings when forecasted daytime temperatures are expected to be at least 31^{o}C and overnight temperatures are 20^{o}C or above OR Humidex is at least 40:

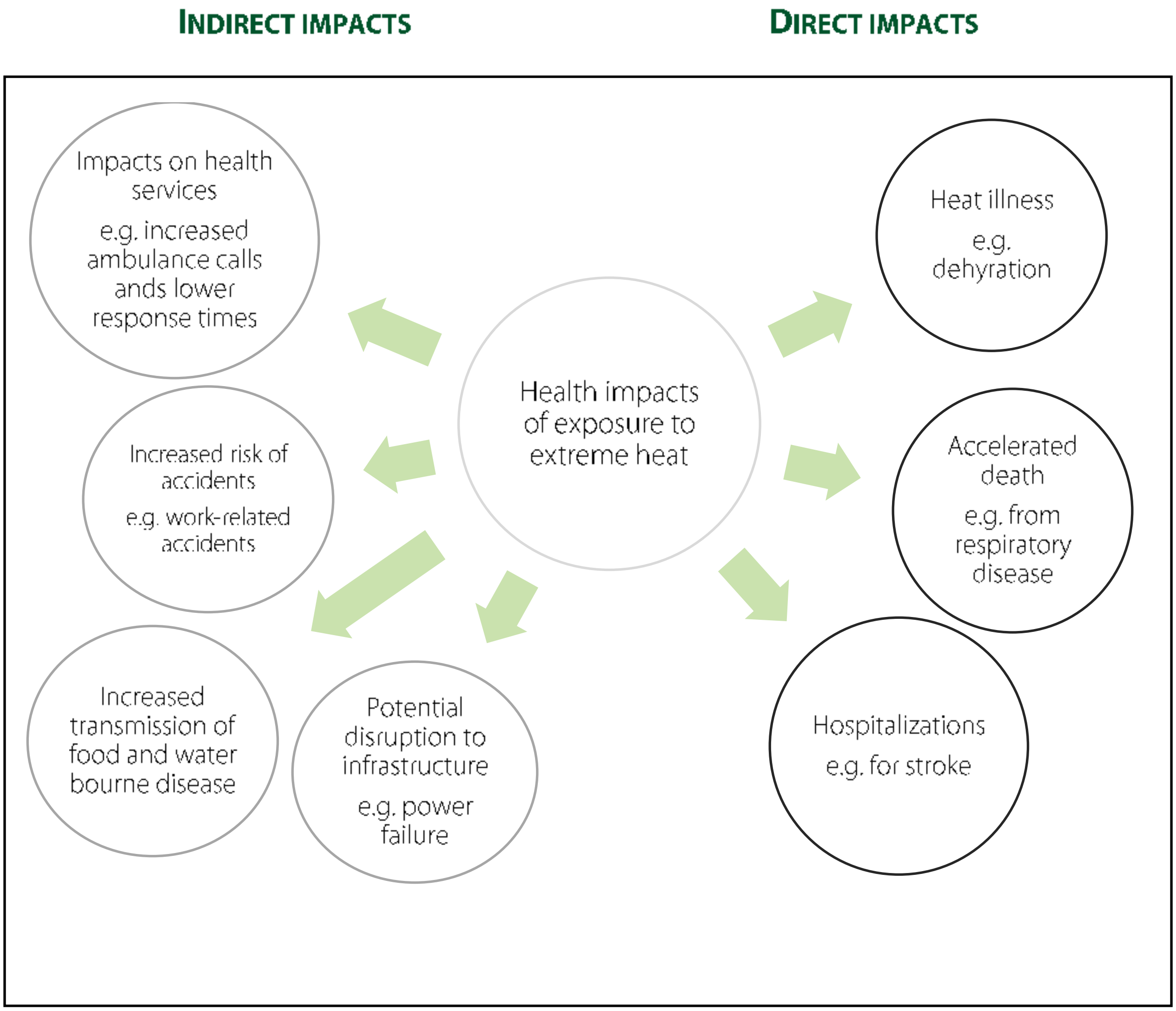
1) Heat warnings are issued when forecasted conditions meet this trigger **for 2 days.**
2) Extended heat warnings are issued when forecasted conditions meet this trigger **for 3+ days.**

Extreme Heat

Extreme heat events are expected to increase in frequency and intensity in the Greater Golden Horseshoe in the coming decades. Single heat events have been attributed to tens of thousands of excess deaths, as seen in Europe in 2003 (World Health Organization, 2018). In Quebec, 86 excess deaths in 2018 and 280 excess deaths in 2010 were attributed to individual extreme heat events (Climatedata.ca, 2020). In addition to increased mortality, there are a number of direct and indirect impacts of extreme heat on our communities (Figure 1).

Extreme heat affects everyone, but vulnerability to extreme heat is not equal across all populations. A community's vulnerability to extreme heat is a combination of exposure (e.g. exposure to high ambient temperature), sensitivity (demographic factors like age that play a role in how people respond to extreme heat events) and adaptation (or community infrastructure like cooling facilities). While some sensitivity factors, like the social determinants of health, can be addressed through policy interventions (e.g. poverty reduction initiatives), many, like the proportion of seniors, cannot. In the Greater Golden Horseshoe, seniors are expected to comprise over 25% of the population by 2041 (Hemson Consulting Ltd., 2013). Policy interventions that help communities adapt to extreme heat events through heat warning systems, public education and cooling centres are common and often successful public health strategies for preparing for extreme heat. Interventions also exist to help limit exposure to extreme heat events. Exposure to extreme heat is caused by a combination of environmental factors including the built environment and local weather, which is affected by climate change.

Figure 1: Direct and Indirect Impacts of Exposure to Extreme Heat. Adapted from: https://www.who.int/globalchange/publications/heat-and-health/en/



Climate Change

Global temperatures are rising. The last decade has been the hottest on record globally (NOAA, 2020). Mean annual daily temperatures in southern Ontario have increased by 0.5°C to 1.5°C over a 61-year period (1950–2010). While warming has increased more in the winter season, the occurrence of warm nights and heatwaves that cause human health impacts is likely to increase in cities around the Great Lakes because of climate change and the locally humid climate in our region (Casati, 2013). As described by the International Panel on Climate Change (IPCC) in their 2018 summary for policymakers, limiting global warming through policy mechanisms is necessary to reduce the risk of extreme heat events in the Greater Golden Horseshoe and around the world (IPCC, 2018). In addition to global efforts to reduce exposure to extreme heat events, local climate can be adapted by changing the built form to reduce vulnerability of our communities. In fact, evidence in southern Ontario shows that, even without accounting for climate change, vulnerability to extreme heat is on the rise because of the aging population and increased urban development and sprawl (Smoyer, Rainham , & Hewko , 2000). Interventions that address land cover are therefore needed for changes in climate and in land use.

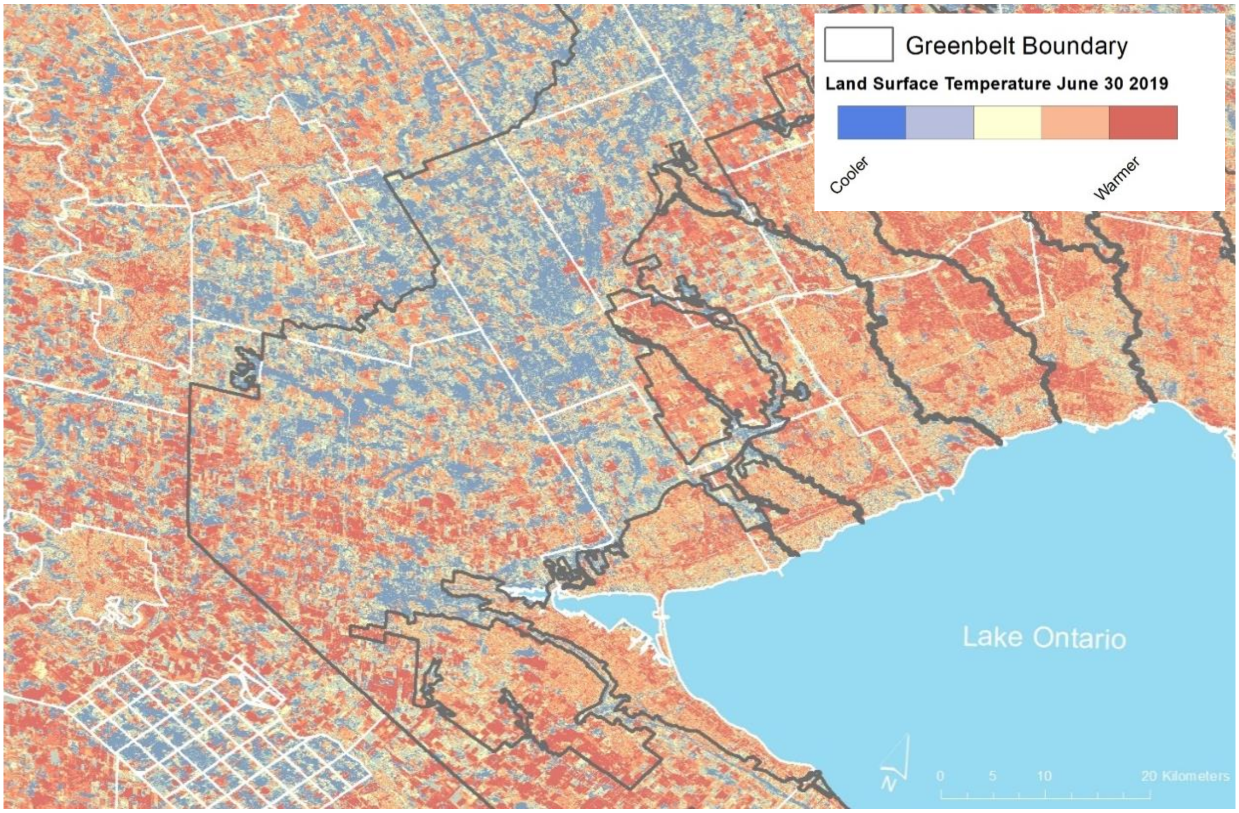
Urban Heat Island

Like all densely populated areas, the Greater Golden Horseshoe has a large proportion of "built up area" with modified land cover surfaces, particularly in urban settlements, but also in smaller towns. Modified surfaces like asphalt and concrete absorb energy from the sun and readily release it as heat. In addition, reduced vegetation and heat generated from human activities all contribute to a phenomenon called the urban heat island (UHI) effect, where cities are warmer than surrounding natural and rural areas. The tall, narrow buildings in cities can trap heat. In addition, heat waste from factories, air conditioners and cars can all further intensify the UHI effect. Healthy soil and vegetation shade these surfaces and provide local cooling through evapotranspiration, making urban vegetation an opportunity for reducing the urban heat island effect (Figure 2).

Figure 2: Urban surfaces have higher albedo (reflectivity) and emissivity (ability to release transfer heat to the air) leading to higher temperatures in urban areas, known as the urban heat island effect (left). Urban vegetation can reduce this effect (right)

The urban heat island is visible in urban areas around the Greenbelt in the Greater Golden Horseshoe. In Figure 3, the Greenbelt area appears cooler from space than surrounding urban settlements.

Figure 3: Thermal image of land surface on June 30 2019. Landsat-7 image courtesy of the U.S. Geological Survey.



Urban River Valleys and Green Infrastructure

The Greenbelt provides opportunity for residents in the Greater Golden Horseshoe to spend time in nature and find relief from the heat during heat events. The Greenbelt's 21 Urban River Valleys (URVs), which run along major urban rivers like the Humber and Bronte Creek, are particularly important to urban residents because of the proximate cooling opportunity they provide in the densest urban areas in the country (Figure 4). In addition to improving access to these URVs,

Figure 4: Urban River Valleys in Ontario's Greenbelt

increasing urban vegetation like urban tree canopy in neighbourhoods can act as a form of green infrastructure to provide cooling services.

While there is a large body of evidence showing the cooling impact of natural areas and green infrastructure, this is the first effort to quantify the impact of the Greenbelt Urban River Valleys. Furthermore, this report takes a unique approach by modeling the before and after impact of urban tree canopy scenarios in case study neighbourhoods.

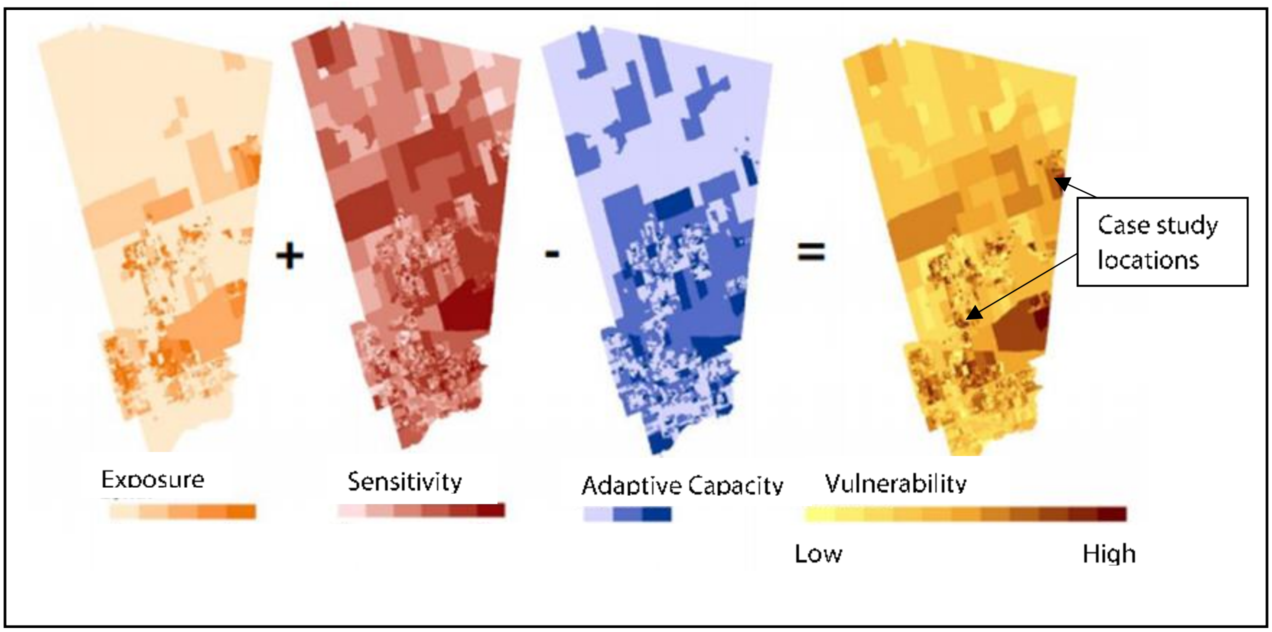
3. Methods

This study uses climate models to assess the cooling benefit of the Greenbelt's URVs and quantifies the impact of increased urban tree canopy on local climate by comparing existing conditions to greening scenarios in two case study neighbourhoods.

Study Area

The case study locations were selected based on their vulnerability to extreme heat and were provided by the Peel Climate Change Partnership (PCCP) (Figure 5). Two priority neighbourhoods adjacent to URVs were selected, one in the City of Brampton and one in the Town of Caledon. Priority neighbourhoods were identified by PCCP through a heat vulnerability index developed by Toronto and Region Conservation Authority that accounted for neighbourhood-level exposure, sensitivity and adaptive capacity to cope with extreme heat events. This is based on the research of Dr. Chris Buse for Peel Public Health, as summarized in the Report on Health Vulnerability to Climate Change (Internal document, the Region of Peel).

Figure 5: Heat vulnerability index factors developed by Toronto and Region Conservation Authority for the Region of Peel using exposure, sensitivity and adaptive capacity factors.



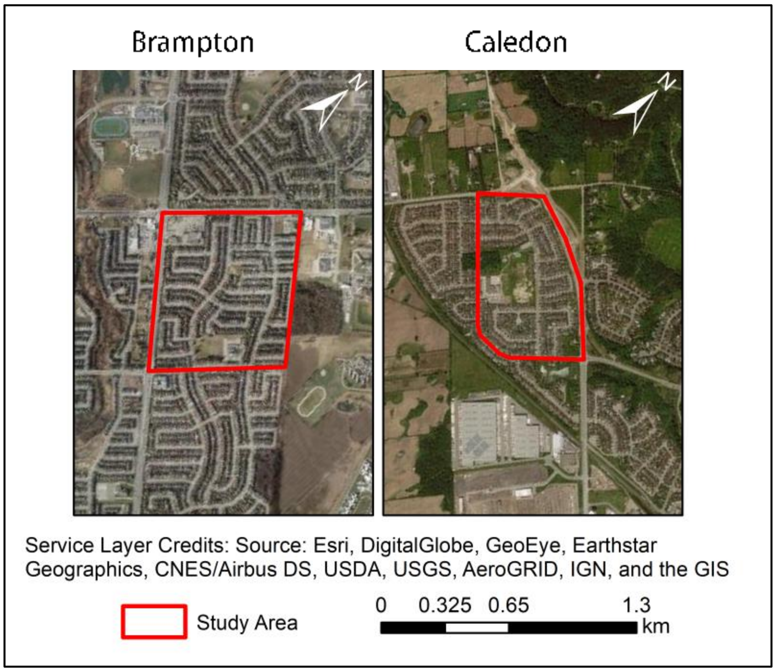
Climate Models

To understand the role of URVs as well as finer-scale impacts of increased tree canopy, climate models at two scales were used. Both models relied on information on surface properties, land use/land cover, topography, and water/land distributions. This information was obtained from the United States Geological Survey (USGS), remotely sensed information and aerial photographs. The performance of both models was evaluated by comparing simulated air temperatures and wind speeds to observations recorded at local weather stations. The models had a very good fit to observations, particularly in urban areas and at mid-day. Slight differences observed in the evenings may owe to the accumulation of anthropogenic heat during rush hours and to heat emitted by from urban surfaces. See Appendix A for the full results of the model evaluations.

A higher level (mesoscale) model was prepared and used to assess the larger impacts of increased urban tree canopy in the two neighbourhoods. At this scale, the Weather Research and Forecasting (WRF) model with the multi-layer Urban Canopy Model (UCM) was used to model a four consecutive day period starting on July 2, 2018 (three of which are presented in the results, see Appendix A for more details). The mesoscale simulations cover the Greater Toronto Area (GTA) with a horizontal grid resolution of 333 m. This model simulates ambient air temperature and wind speed.

A more local (microscale) model looked at the impact of adding trees within a small portion of the neighbourhoods (0.55 km2 of the Brampton neighbourhood and 0.39 km2 in Caledon, see Figure 6). The specific locations for this modeling were selected based on their homogeneity and significant potential for greening. A homogenous landscape ensures the simulation results are less likely to be influenced by unique features. In this case, undesirable unique features that were avoided include ponds, rapid changes in elevation, condominium towers, etc. By avoiding these features, the results are more representative of all low-rise residential neighborhoods in the Greater Golden Horseshoe. The ENVI-met model was used to simulate the 13-hour period of July 5, 2018, from 8 a.m. to 9 p.m. This local model is able to compute human thermal comfort indices (HTCIs), which yield “feels like” temperatures composed of several meteorological parameters in addition to ambient temperature (e.g. wind speed, solar radiation, humidity). This report uses the HTCI called the Universal Thermal Climate Index (UTCI) assessment scale, developed by Błażejczyk, et al. (2010).

Figure 6: Extents of the Brampton and Caledon neighbourhoods selected for microclimate analysis.

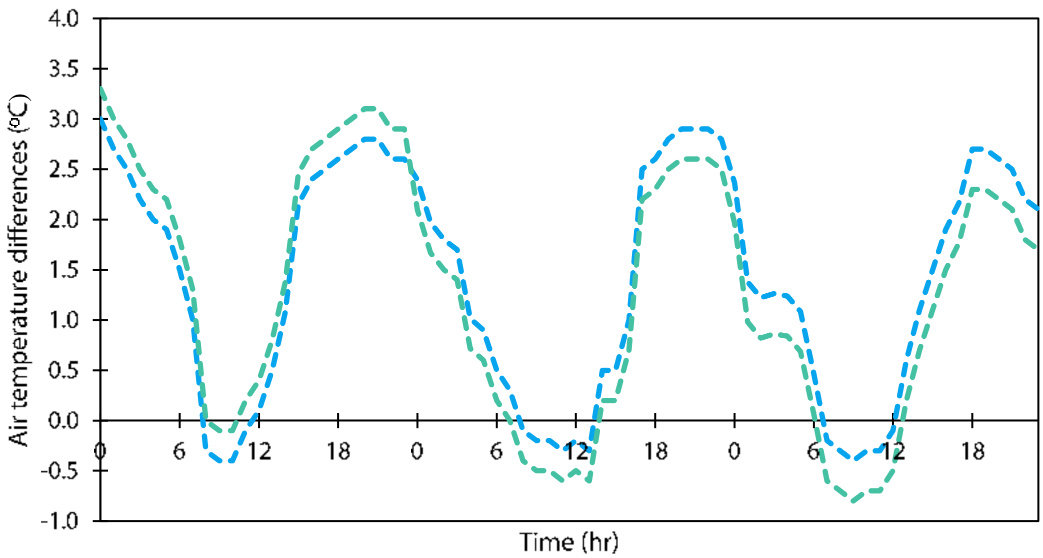


Baseline Condition

Mesoscale

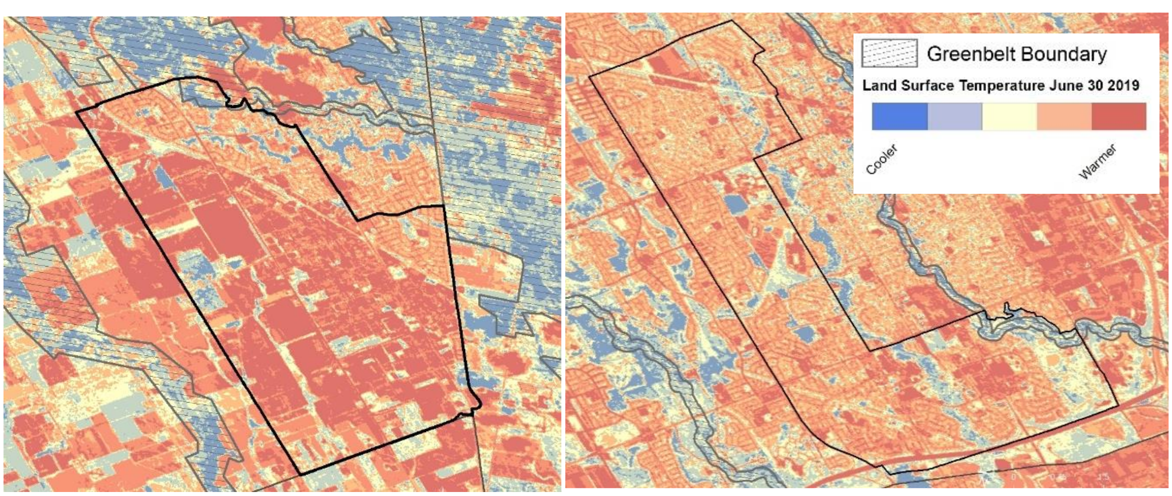
Recorded air temperatures at Pearson International Airport over the three-day modeled period ranged from a low of 19 to a high of 33 °C (Environment and Climate Change Canada, 2020). An urban heat island effect, showing warmer conditions in these neighbourhoods compared to surrounding rural lands and the URVs, can be seen in both neighbourhoods during this period (Figure 7). The average daily urban heat island intensity (UHII) for this period (in both neighbourhoods) is around 1.2 to 1.5 °C. It is more significant during nighttime, at 2 to 3 °C cooler in natural/rural areas like the URVs.

Figure 7: Temporal variation of 2-m air temperature (°C) differences between built-up structure and rural parts of the URVs during 2018 heat wave period (3rd-5th of July) in Brampton (dashed green line) and Caledon (dashed blue line) during the 2018 heat



Like the rest of the Greenbelt area, surface temperature in the URVs appears cooler than much of the surrounding urban neighbourhoods (Figure 8, note this imagery is from June 2019 and was not used in the climate models). This thermal map illustrates that URVs already provide cooling opportunities that nearby communities should have access to during extreme heat events.

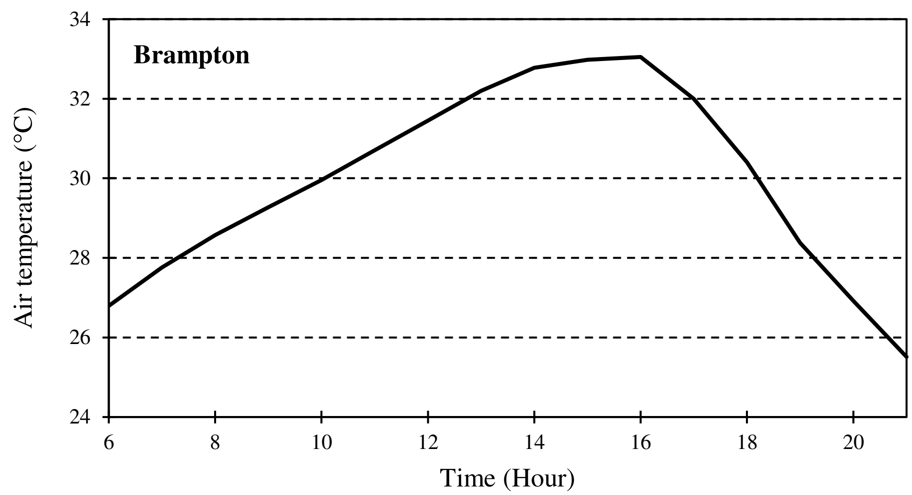
Figure 8: Thermal image of land surface on June 30 2019 in the Caledon neighbourhood (left) and the Brampton neighbourhood (right). Landsat-7 image courtesy of the U.S. Geological Survey



Microscale

In the smaller portion of the neighbourhoods modeled at the microscale during the 13-hr period, pedestrian-height air temperature increased steadily until 1 pm, tapered off and then began to decline at 4 pm. The maximum temperature was 33.2°C, which occurred at 4 pm. The mean temperature was 30.3°C (Figure 9). Deviation from observed weather station data is greatest in the evening, suggesting there is an urban heat island effect within these smaller study areas as well.

Figure 9: Average air temperature at 1.5 height in the Baseline Brampton simulation



In this baseline, portions of the neighbourhood are warmer than others. For example, the large unshaded swaths of asphalt around the elementary school and in the commercial plaza in the Brampton neighbourhood are hot spots. Asphalt areas where wind speeds are reduced because of surrounding buildings are even warmer.

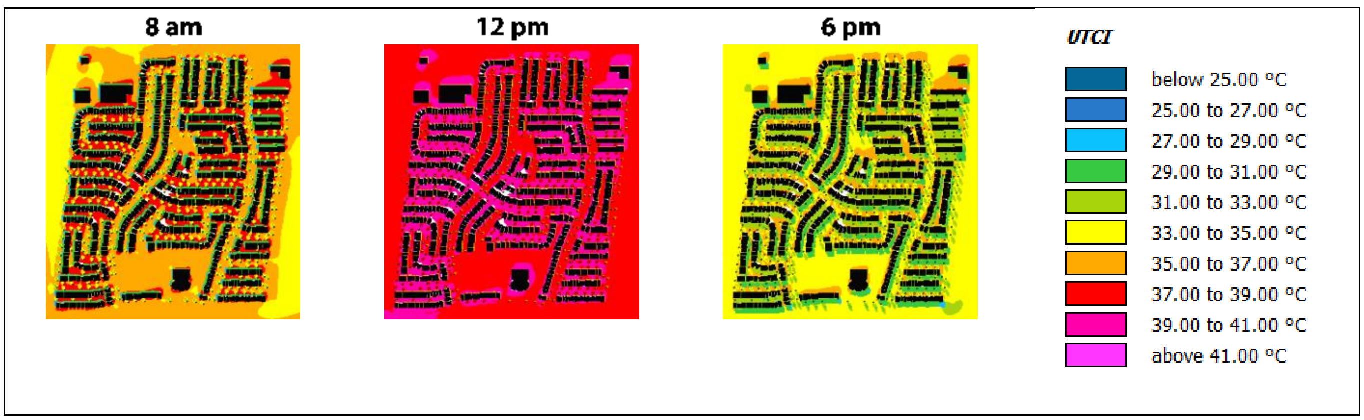
Large open areas have higher wind speeds. Compared to the effects of solid buildings, wind-dampening effects of the trees are negligible. Wind speed varies between the four sample locations in the model. Among these locations, the maximum, mean, and minimum wind speed are 2.0 m/s, 1.2 m/s, 0.2 m/s for the whole day, respectively.

In terms of human thermal comfort, baseline UTCI for the 13-hr event shows that when solar radiation is considered, the human-perceived temperature is higher than the air temperature (Figure 11). Throughout most of the day, UTCI is greater than 32°C, a threshold above which strong heat stress is possible (Figure 10). Wind suppressing impacts of buildings can be seen at noon and moderate cooling from existing trees on the landscape can be seen at 6 pm (Figure 11). The UTCI in the baseline shows that a person can feel much warmer than the air temperature would suggest. For example, at 3 p.m., the UTCI reached as high as 40°C in Caledon, which corresponds to the very strong heat stress category. On average, the baseline UTCI simulations peaked at ~36°C UTCI.

Figure 10: Assessment scale which links the Universal Thermal Climate Index to human physiological responses. Values between 9 and 26 correspond to no thermal stress (comfortable conditions). (Błażejczyk, Bröde, Fiala, & Havenith, 2010)

UTCI (°C)	Stress category
> 46	Extreme heat stress
38 to 46	Very strong heat stress
32 to 38	Strong heat stress
26 to 32	Moderate heat stress
9 to 26	No thermal stress

Figure 11: UTCI equivalent temperature at 1.5m height in the Brampton neighbourhood



Greening (UTC) Scenarios

The scenario modeling relies on information provided by greening scenarios developed by the PCCP. These greening scenarios were produced based on the potential to increase urban tree canopy in the two priority neighbourhoods without any modification to hardscapes (roads, sidewalks). Two scenarios were developed for both neighbourhoods, one where mature trees are placed in all potential locations resulting in an 80% urban tree canopy increase from the baseline and one where approximately half of those potential locations are filled, resulting in a 50% urban tree canopy increase. These increases in % urban tree canopy were input into the mesoscale model as changes in vegetative fraction and were further refined as individual trees in the microscale model.

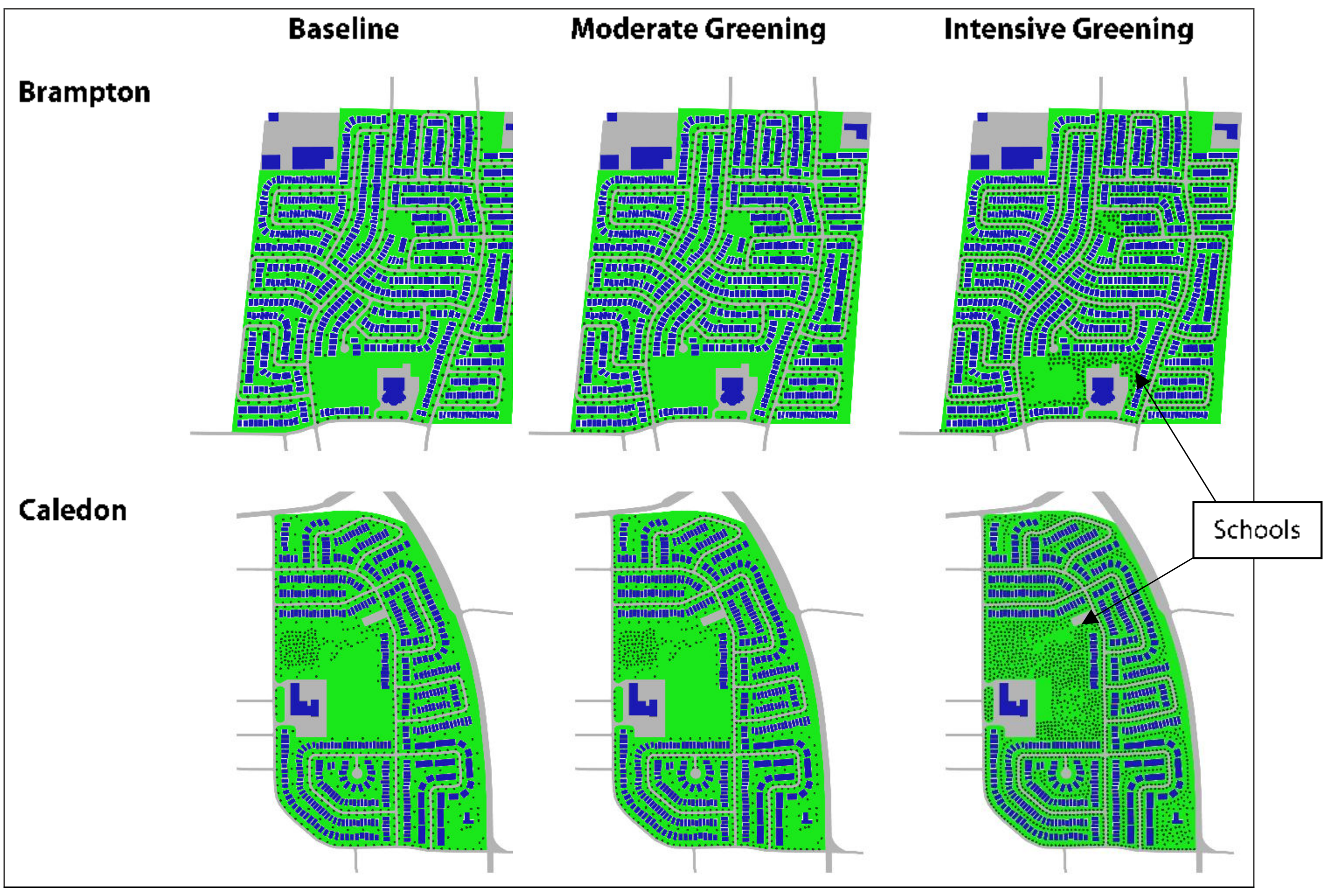
For the microscale model, individual trees were placed across the study area to develop a moderate and intensive greening scenario. All trees were assumed to be medium-sized trees, 10m in height and 7m in crown width, approximating the size of a dense maple tree (Stadt &

Lieffers, 2000) (Table 1). In both neighbourhoods, the intensive greening scenarios result in a large increase in the number of trees near schools. More trees exist in the Caledon neighbourhood at baseline and more new trees are added to the Caledon neighbourhood in both the moderate (8 more trees) and intensive greening scenarios (237 more trees).

Table 1: Summary of microscale scenarios modeled

	Number of trees		
	Baseline	**Moderate Greening**	**Intensive Greening**
Brampton	445	585	1064
Caledon	469	617	1325

Figure 12: The three scenarios as modeled. Each dark green dot represents a tree canopy, light green is grass, silver is asphalt, and buildings are in blue.



4. Findings

Mesoscale

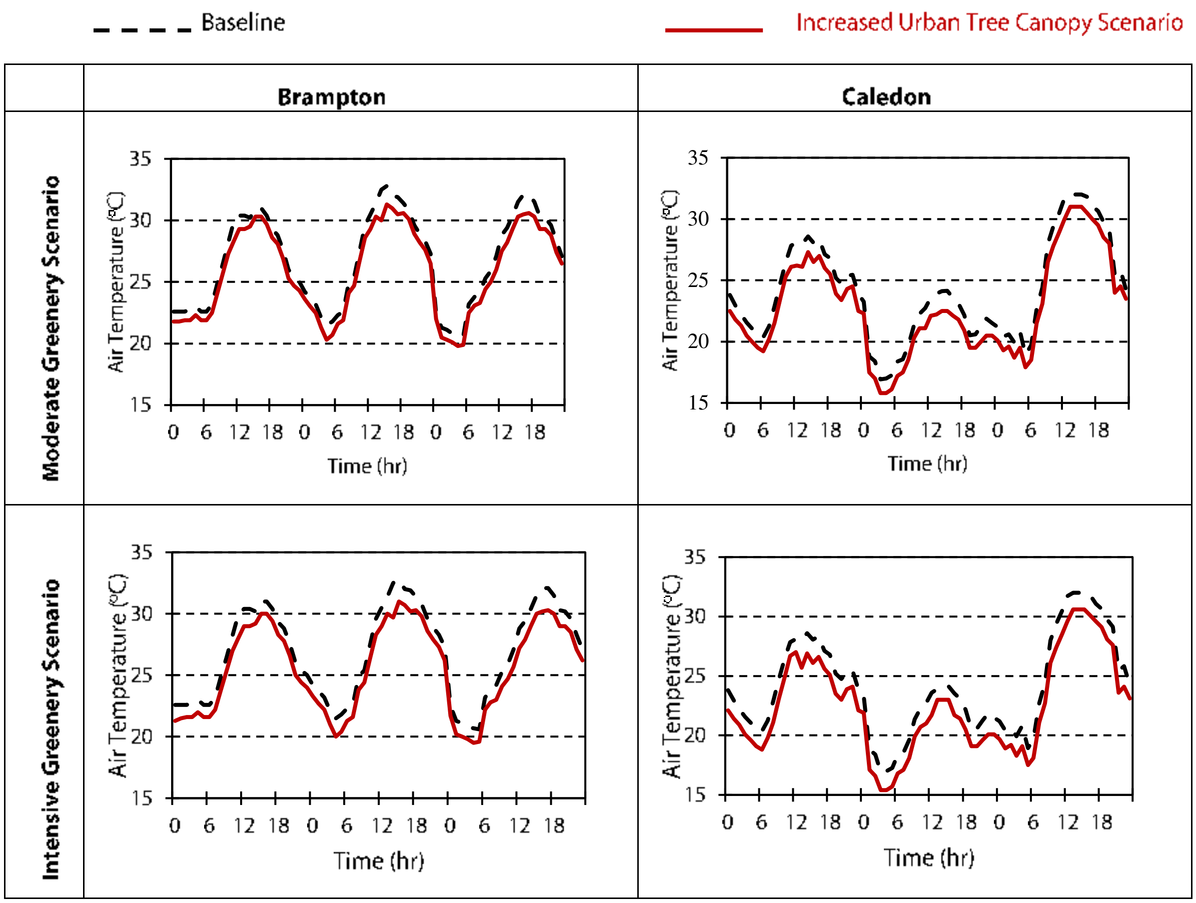
Increasing urban tree cover resulted in reduced temperatures in both neighbourhoods at the mesoscale. Averaged across both neighbourhoods, a moderate tree cover increase of 50% resulted in average daily ambient temperature decreases of 0.8 to 1.3^{o}C over the three days, with slightly increased wind speeds, and relative humidity increases of nearly 7%. Increasing the tree canopy cover by 80% shows even more promising results, decreasing the average air temperature by nearly 20%, or 1.5 to 2^{o}C below the baseline (Table 2). Increasing urban tree canopy reduces wind speed slightly and increases relative humidity which can also have an impact on perceived temperate. While perceived temperature was not modeled at the mesoscale, observed temperature reductions likely make up for any humidity increases caused by the increased vegetation.

Table 2: Changes in temp, wind speed and humidity during the 2018 heatwave period for the moderate greening scenario (50% more tree cover) and the intensive greening scenario (80% more tree cover)

Change from baseline	Brampton neighbourhood		Caledon neighbourhood	
	Moderate Greening	Intensive Greening	Moderate Greening	Intensive Greening
Δ air temperature (°C)	-0.88	-1.48	-1.26	-1.82
Δ wind speed (m/s)	-0.22	-0.38	-0.31	-0.46
Δ relative humidity (%)	6.38	7.46	7.10	8.73

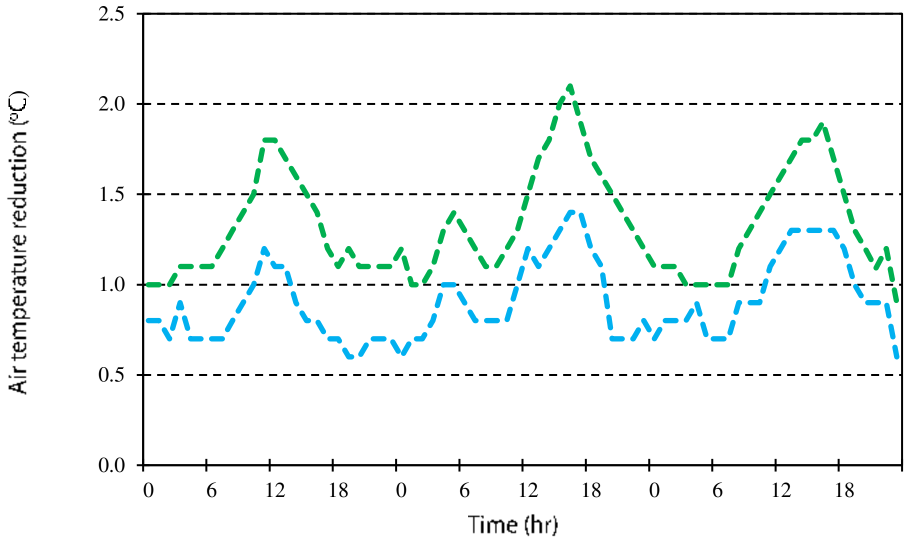
The cooling effect of increased urban tree canopy varied throughout the day, with a greater difference from the baseline in the evenings. This is a similar pattern to the UHI effect in the baseline conditions, suggesting the greatest cooling benefit of trees occurs around the time urban heat islands are evident. Figure 13 shows the hourly changes in the 2-m air temperature in moderate and intensive greening scenarios. The greening scenarios show similar benefits in both neighbourhoods, suggesting these results would be applicable to other similar neighbourhoods throughout the Greater Golden Horseshoe.

Figure 13: The changes in hourly 2-m air temperature (°C) by GREEN (red solid line) and baseline (black dashed red) scenarios in Brampton and Caledon during the 2018 heatwave period (3rd to 5th July).



Across both neighbourhoods, the intensive greening scenario shows greater cooling impact than the moderate scenario at all times during the heat event (Figure 14) cooling benefit urban tree canopy provides does not plateau in these neighbourhoods between a 50% and 80% increase, suggesting that the more trees the better for reducing heat, at least up to the modeled 80% increases.

Figure 14: The averaged hourly 2-m air temperature reduction (oC) in Moderate Green Scenario (blue dashed line) and Intensive Green Scenario (green dashed line) in Brampton and Caledon during the 2018 heatwave period (3rd to 5th July).



Microscale

The results of the microscale simulations show significant cooling potential in the study areas of Brampton and Caledon. Maximum air temperature reductions were between 0.4 and 0.6°C for the moderate greening scenario and 1.3 to 1.5°C for the intensive greening scenario (Table 3). The added trees in the intensive scenario were particularly effective at 5 p.m. when the spatially averaged cooling was ~0.1°C for in the moderate scenario and 0.4 to 0.6°C in the intensive scenario. Figure 15 shows the results spatially. Overall, spatially averaged cooling at 5 pm was greatest in the Caledon neighbourhood with the intensive greening.

Table 3: Average and maximum air temperature reductions in Moderate Green Scenario (MGS) and Intensive Green Scenario (IGS).

Green Scenarios	Brampton		Caledon	
	Spatially averaged cooling at 5 pm (°C)	Max cooling (°C)	Spatially averaged cooling at 5 pm (°C)	Max cooling (°C)
Moderate	0.11	0.39	0.1	0.59
Intensive	0.46	1.51	0.56	1.29

Figure 15: Air temperature at 5 p.m. in Moderate Green Scenario (MGS) and Intensive Green Scenario (IGS).

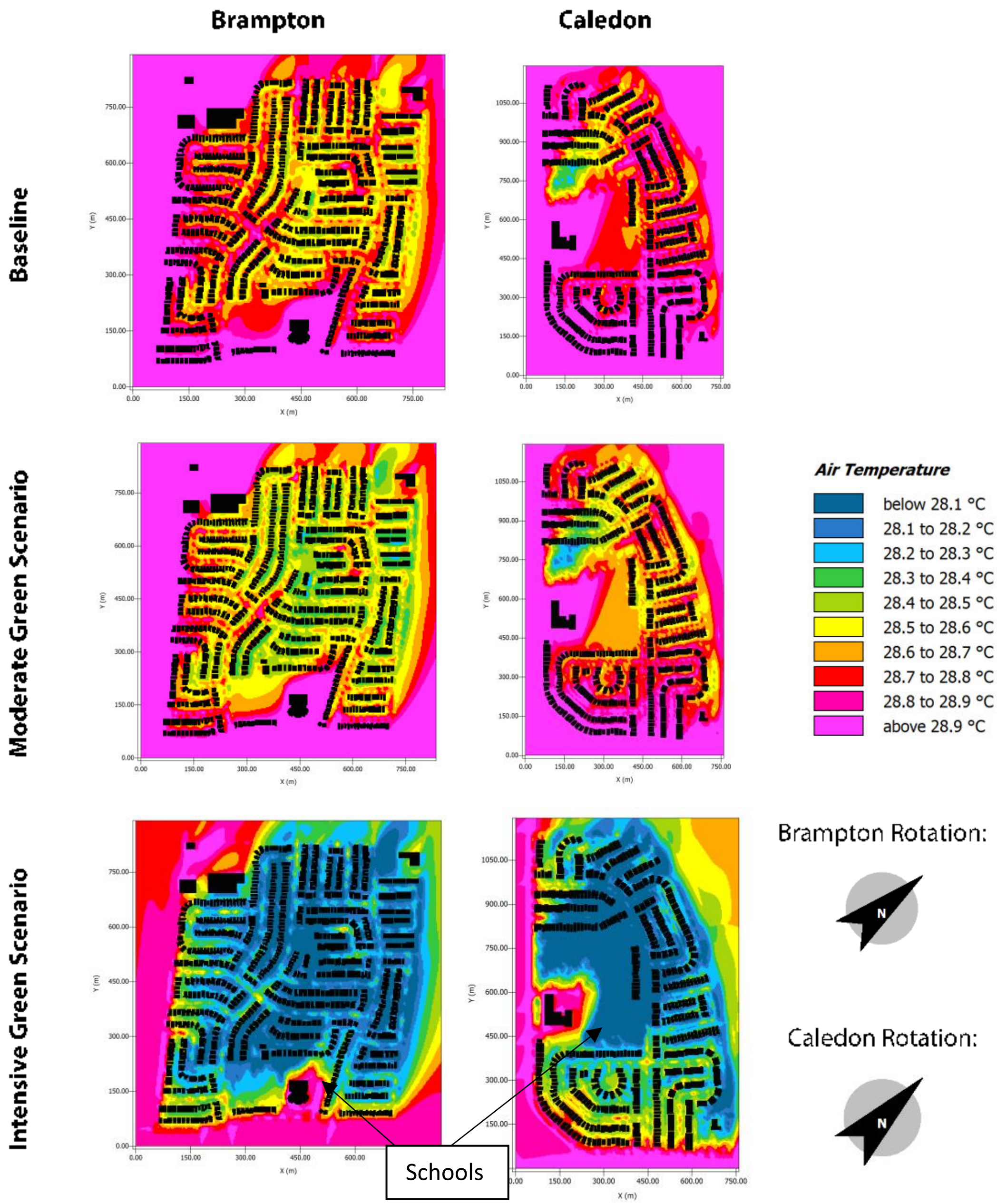
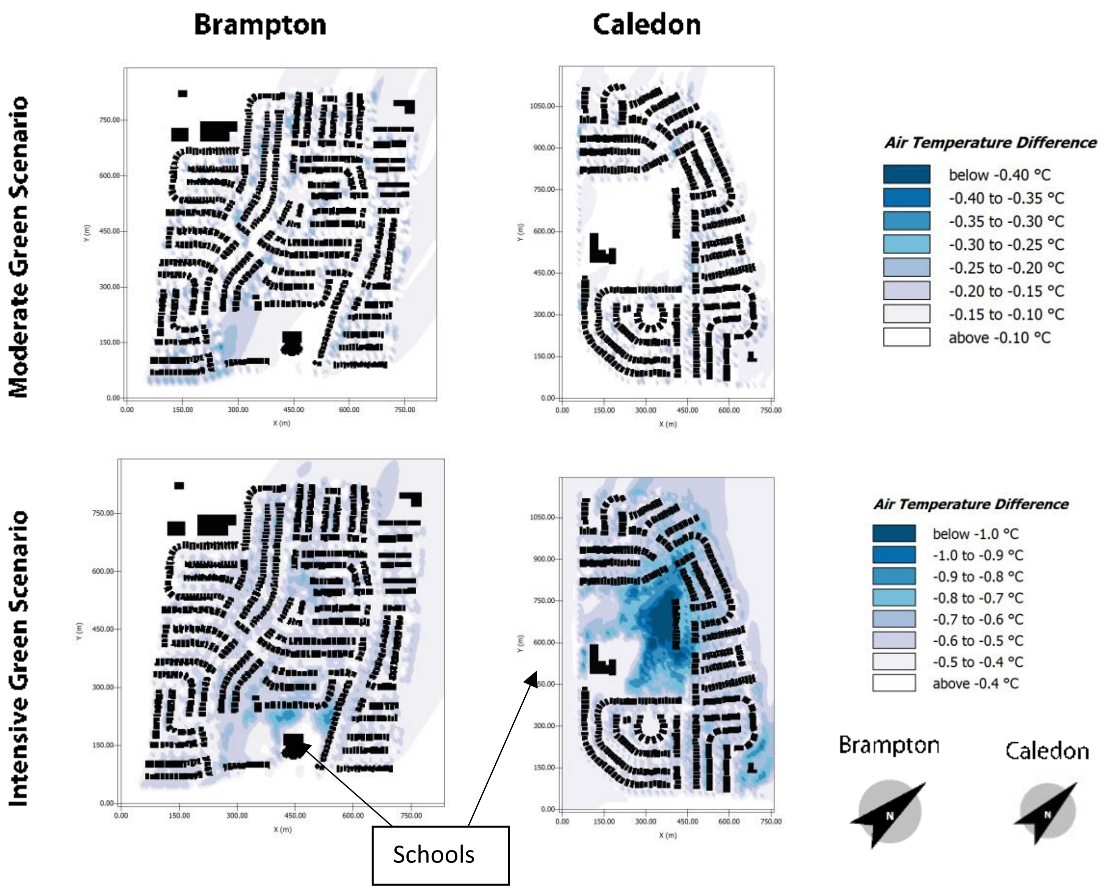


Figure 16 presents air temperature difference relative to the baseline simulation at 5 p.m. It is evident that cooling is not uniform across the neighbourhood and there seems to be greater temperature reductions in areas where more trees were added, suggesting cumulative cooling impacts in areas where the new trees have essentially reforested the area around the schools. The intensive scenario provides a greater spatial extent of cooling throughout both neighbourhoods.

Within both study areas, the cooling shadow of added trees was most visible downwind (North) of the trees and inside the newly forested natural areas (Figure 16). In the intensive green scenario, the 0.5°C cooling is visible at 150m – 250m downwind of the newly forested area in Caledon. For smaller patches of trees, 0.5°C cooling is visible ~75m downwind. Streets orientated perpendicular to the wind direction received less of a cooling benefit.

Figure 16: Air temperature difference relative to the baseline simulation, at 5 p.m. in Moderate Green Scenario (MGS) and Intensive Green Scenario (IGS). Negative values indicate cooling was achieved.



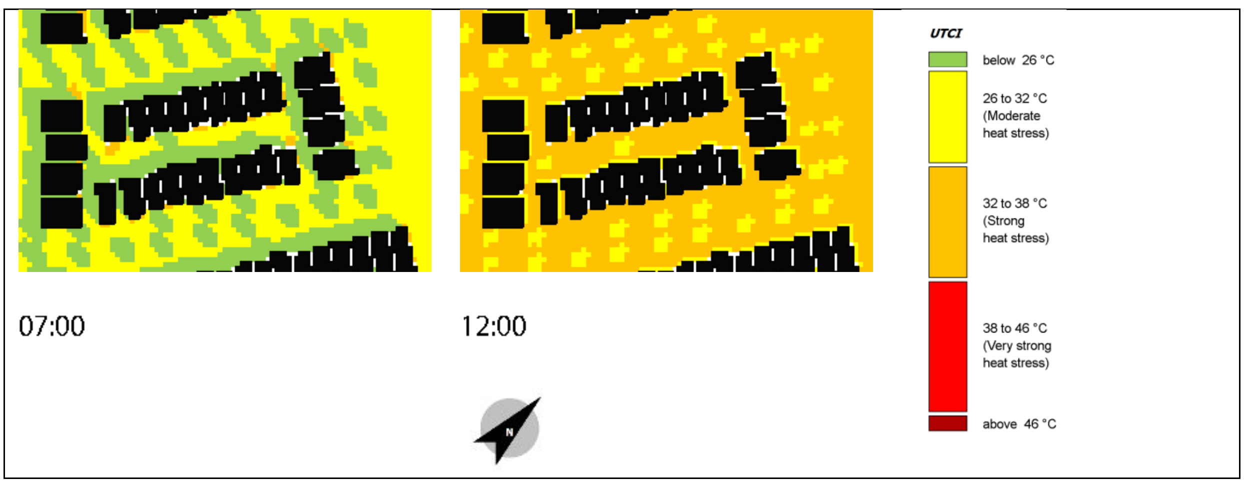
Both scenarios of increased urban tree canopy improve perceived temperature, measured as UTCI, noticeably. At 5 p.m., the spatially averaged UTCI reductions were between 0.3°C for the moderate greening scenario and 1.2°C for the intensive greening scenario (Table 4). The maximum reductions in perceived temperature were around 11°C for the moderate greening scenario and 10°C for the intensive greening scenario. Note that these maximum values represent a single location at a single point in time during the simulations period. Hence, the moderate scenario was cooler at that location and that point in time, but on average over the whole neighbourhood, the intensive greening provided greater perceived temperature reductions at 5 pm.

Table 4: Average and maximum perceived temperature reductions at Moderate Green Scenario (MGS) and Intensive Green Scenario (IGS)

GREEN Scenarios	Brampton		Caledon	
	Spatially averaged cooling at 5 pm (°C)	Maximum cooling (°C)	Spatially averaged cooling at 5 pm (°C)	Maximum cooling (°C)
Moderate	0.28	11.06	0.2	11.19
Intensive	1.12	9.7	1.17	10.33

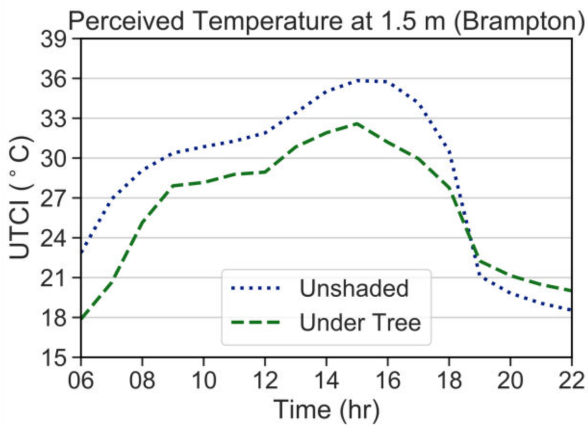
Perceived cooling occurred mainly in the shadow cast by the additional trees (see example in Figure 17). The magnitude of cooling caused by a single tree was not very evident prior to noon but was nominally around 3°C UTCI for both study areas (Figure 8). During the hottest times of day, this was enough to reduce the UTCI thermal stress classification from “strong heat stress” to “moderate heat stress”, meaning that individual trees can moderate climate enough to reduce some risk of heat stress.

Figure 17: Close up of tree comfort shadows at 7 am and 12 pm in the Caledon study area.



As perceived temperatures were lower in locations shaded by trees, providing access to areas shaded by trees can have public health implications.

Figure 18: Perceived temperature in an open, unshaded location in the Baseline simulation (dotted blue); and directly under a tree in Intensive Green Scenario (IGS) refers to Scenario 2 (dashed green).



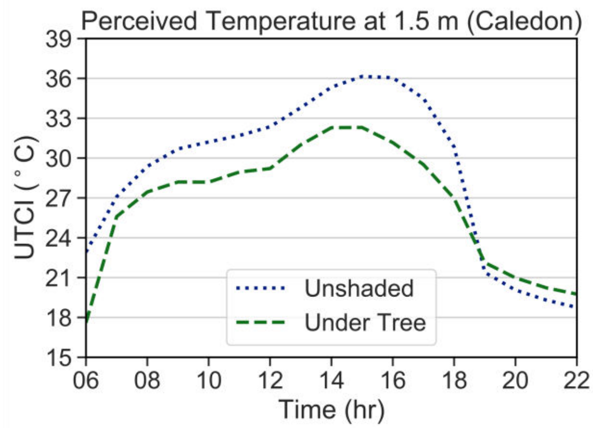
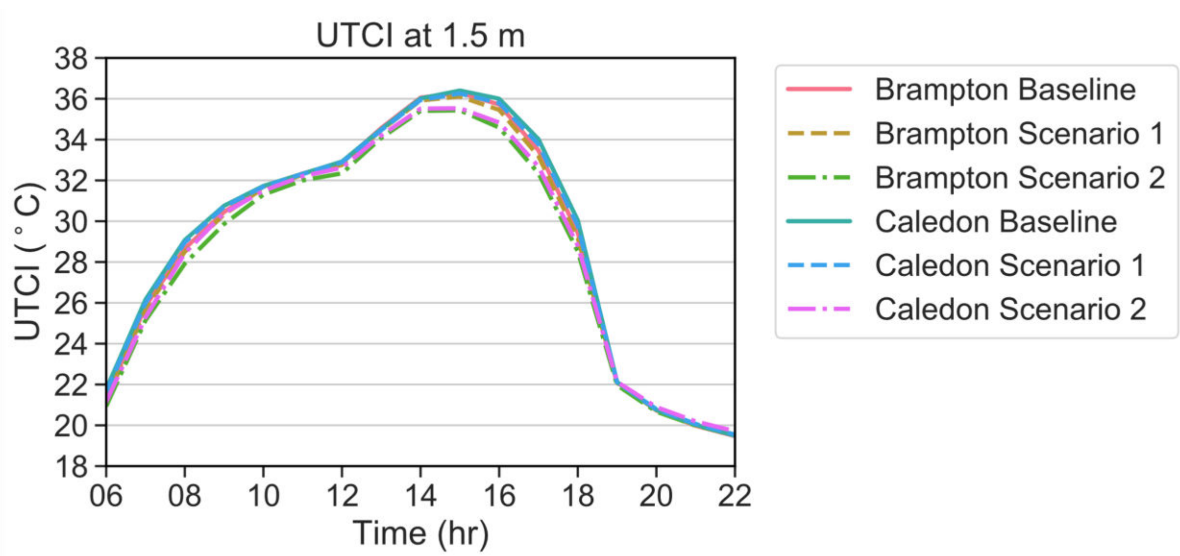


Figure 19: Spatially averaged hourly perceived temperature (UTCI) for all renditions of both study areas, for Moderate Green Scenario (MGS) refers to Scenario 1 and Intensive Green Scenario (IGS) refers to Scenario 2.



5. Conclusions

Extreme heat events, made more likely by the urban heat island effect and the impacts of climate change, are a public health threat, particularly in vulnerable neighbourhoods. The natural and rural areas of the Greenbelt were cooler than urban settlements in the Greater Golden Horseshoe during the July 2018 extreme heat event. The Greenbelt's URVs in the Region of Peel were cooler than surrounding non-natural areas. These URVs provide opportunities for communities to cool off, and they also provide a "cooling shadow" that extends into neighbourhoods and can be extended by reforestation in areas adjacent to the URVs.

Exposure to extreme heat events can be mitigated to some extent by increasing urban tree cover. A maximum perceived temperature of 11ºC was achieved by modeling tree canopy cover increases in two heat vulnerable urban neighbourhoods adjacent to URVs in the Region of Peel. The temperature lowering benefits modeled trees provide is greatest in the evening, when the urban heat island is also most intense. This can have significant public health implications, as nighttime temperatures are related to adverse health outcomes associated with heat events.

This modeling shows that increasing tree cover effort returns greater cooling benefits. It is also clear that reforestation presents a greater opportunity for cooling than spaced-out landscape trees. The cooling impact of trees is evident at both the larger neighbourhood and the local scale, with individual trees even showing impact on perceived temperatures. Large publicly owned lands like school yards present an opportunity for urban forests that could provide cooling to residents and children. Perceived temperature was most improved directly under trees, so access to treed locations should also be considered a cooling opportunity.

While findings here are episode- and region-specific, the overall conclusions and recommendations of this report can help guide decision makers across the Greater Golden Horseshoe.

6. Highlights and Recommendations

Investments in increasing the number of trees, including in urban river valleys, can reduce exposure to extreme heat. Increasing tree canopy cover can make it feel 11°C cooler in the early evening.

To maximize cooling benefits, large trees should be conserved and new trees should be maintained to reach maturity. To provide cooling benefits, trees need to survive.

Provide public access to areas with high/dense tree cover for cooling benefits, like URVs and where appropriate, extend forest cover around URVs to increase their "cooling shadow".

When possible, reforestation should be prioritized over planting spaced out landscape trees to provide greater cooling benefit. Where space permits, full tree coverage with closed canopies instead of spaced out landscape trees (typical in many suburban parks and yards) can be a better cooling strategy.

School grounds are opportunities for tree canopy increases. Some of the greatest cooling impacts occurred on or near school properties. These are both areas of opportunity and potential need, as young children and people undertaking physical exercise outdoors (e.g. during recess) can be more vulnerable to extreme heat events. Similar public lands with vulnerable populations like long-term care and other seniors' care facilities, hospitals, and subsidized housing likely provide similar opportunities.

Prioritize tree planting where the cooling effect can circulate freely downwind to other areas. In all the simulations, air temperature reductions traveled downwind (North) of trees. However, in areas of poor ventilation less cooling shadow was observed.

Increase tree cover in parking lots to reduce "hot spots". Paved areas surrounded by buildings (e.g. parking lots) are some of the hottest areas because of a lack of wind and high urban heat island effect.

It can feel 3°C (UTCI) cooler because of an individual tree, showing all landowners have a role to play. The findings of this research are relevant to all property owners.

Educate the public on the cooling benefits of URVs and tree cover. Along with the potential risks of extreme heat, the benefits that natural infrastructure and trees can provide should be communicated widely.

7. Future Research

The findings of this research raise further questions about the potential impact these temperature changes might have on air quality in these neighbourhoods. Decreasing air temperature can result in reduced biogenic emissions of smog precursors such as volatile organic compounds, reduced rates of photochemical reaction rates and ozone formation. Additionally, leaves on trees can act as a source of dry deposition for pollutants. An in-depth analysis of how the results presented above relate to air quality is needed to get a better understanding of the public health impacts of this type of strategy.

A thorough cost-benefit analysis could also help assess growing trees versus other approaches like modifying urban surfaces.

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