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Health-Informed Heat Mitigation Approach

Case Study of The Regional Municipality of York

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Health-Informed Heat Mitigation Approach: Case Study of The Regional Municipality of York

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in collaboration with the Greenbelt Foundation and Mitacs Canada.

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Preface

Enriching the urban greenery cover is introduced as an important strategy to urban heat island mitigation to provide cooling benefits. This assessment presents combined statistical and simulation approaches to estimate co-benefits associated with increasing the urban greenery cover in York Region. The combined framework provides evidence-based predictions to support decision-making processes pertaining to heat mitigation strategies. The co-benefits associated with intensifying the greenery cover are related to microclimate improvements, health responses, and economic benefits. The statistical framework employs regression modelling to analyze public health datasets and predict mortality records and emergency department visits based on changes in the outdoor environment. The microclimate simulations utilize an environmental assessment tool to assess the impacts of greenery cover on ambient temperature, outdoor heat stress, and building energy consumption.

The framework was applied to two residential neighbourhoods in York Region (Markham Village and East Woodbridge) to represent residential neighbourhoods in Southern Ontario. Markham Village and East Woodbridge were chosen as both neighbourhoods have vulnerable populations and potential planting space and urban heat islands, respectively. A historical dataset was constructed for the Region, integrating meteorological measures and daily health records. Policymakers can utilize this method for estimating community health responses and economic benefits considering the changes in the urban environment.

Developing a holistic statistical-simulation approach to evaluate the associated benefits of enriching the urban greenery cover is an emerging research topic and the information provided in this report is based on current knowledge and understanding. As new research and developments of modelling approaches continue to proceed, the information contained in this report may not represent the most accurate or up-to-date knowledge. It is strongly advised that independent research and verification of the information is conducted for other case studies before making any decisions or taking any action based on the information provided.

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List of Abbreviations

GC	**Greenery cover** includes tree canopy and ground vegetation cover (grass cover, shrubs and bushes). Three levels of greenery cover intensification are proposed: reference GC (current condition), Moderate GC, and Intense GC.
TC	**Tree canopy**: the tree crowns that provide shading to ground and buildings.
GVC	**Ground vegetation cover** includes grass cover, shrubs, and bushes.
UHI	**Urban heat island**: this defines the increase in temperature in an urban area that becomes warmer than its surroundings due to human activities.
Hmdx	The Canadian temperature-humidity index (**humidex**); it describes how hot and humid weather is perceived by human beings. Humidex also defines the outdoor heat stress and degree of outdoor comfort.
MOR_all	**Daily all mortality records** regardless of age or cause.
EMR_all	**Daily all emergency department visits** regardless of age or cause.
MOR_EC	**Vulnerable mortality records** consider cases defined as elderly (> 65 years old) **and** diagnosed by cardiorespiratory causes.
EMR_EC	**Vulnerable emergency department visits** consider cases defined as elderly (> 65 years old) **and** diagnosed by cardiorespiratory causes.
Amb_C	**Cause-based ambulance calls** include causes of breathing problems, cardiorespiratory, heat/cold exposure, stroke accidents, and loss of consciousness.
LagXX	The delayed (lagged) effect of heat on health records. XX refers to the number of days after the heat event (i.e., Lag00 refers to the direct effect of heat on health on the same day).

Executive Summary

A framework was developed to support the decision-making process associated with increasing greenery cover in urban areas considering community health and climate resilience. The framework integrates statistical and simulation approaches to estimate co-benefits associated with increasing the urban greenery cover in York Region. The co-benefits include microclimate improvements, health responses, and economic benefits. The statistical framework employs regression modelling to analyze public health datasets and predict mortality records and emergency department visits based on changes in the outdoor environment. The microclimate simulations utilize an environmental assessment tool to evaluate the impacts of greenery cover on ambient temperature, outdoor heat stress, and buildings' energy consumption. The economic benefits include direct and indirect estimates for health system savings, energy use, and avoiding productivity losses.

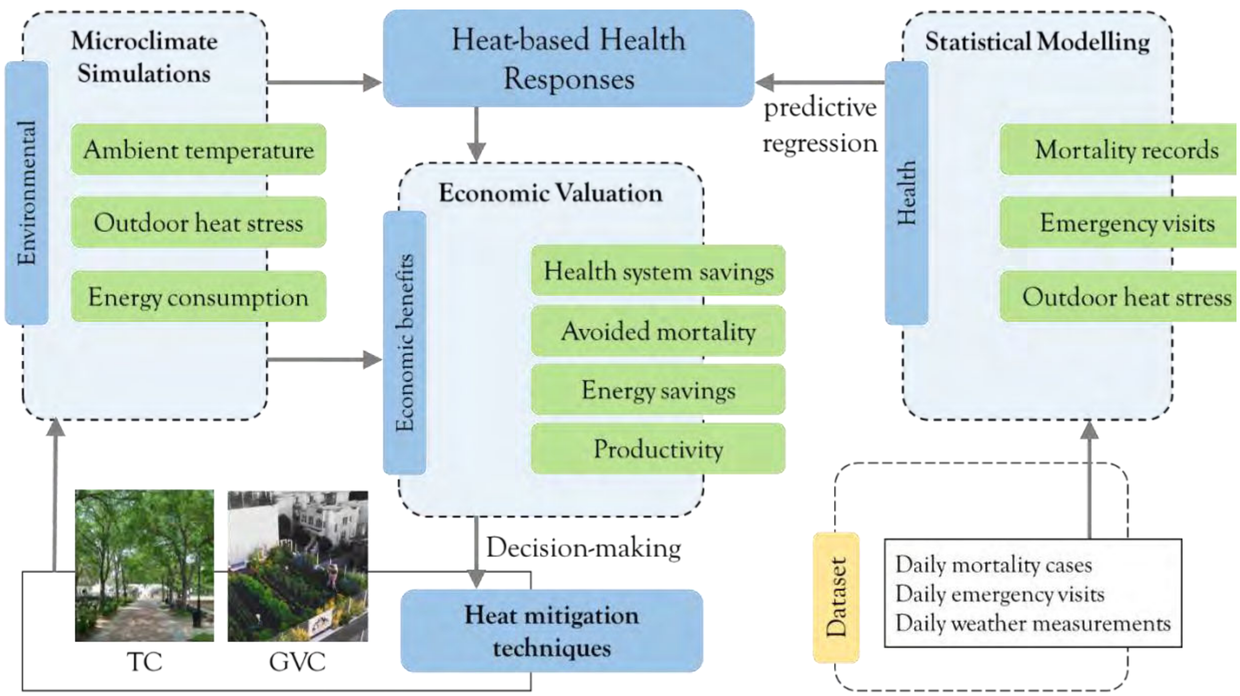


Figure ES-1: Decision-making framework to forecast health responses and economic benefits

The proposed greenery cover (GC) considers enriching the ground vegetation cover (GVC) and tree canopy (TC) as heat mitigation strategies within York Region. The framework was applied to two residential neighbourhoods (Markham Village and East Woodbridge) to assess the environmental, health, and economic benefits of increasing GC. The urban microclimate was modelled proposing enriching the greenery cover into two scenarios: moderate and intense greenery covers. The increase in GC achieved significant reductions in ambient temperature, outdoor discomfort (humidex values), and energy use for cooling purposes to indoor spaces. Figure ES-2 defines the increase in TC for moderate (~<30%) and intense (~>30%) scenarios in many locations in the two case studies and its impact on maximum temperature. It can be observed that larger TC covers are associated with greater reductions in maximum temperature.

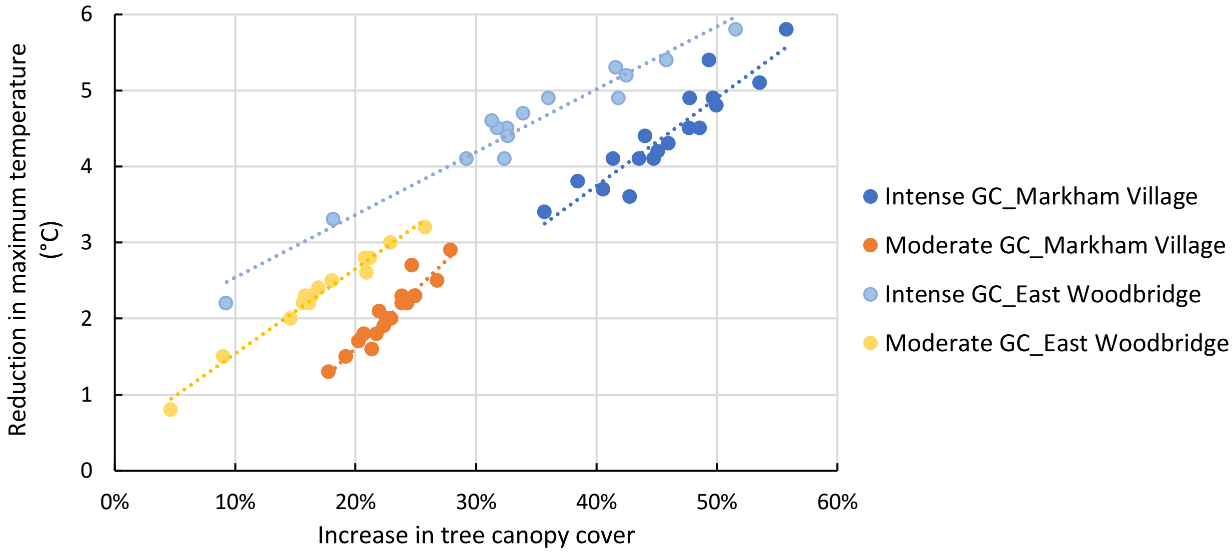


Figure ES-2: Reductions in maximum temperature in association with the increase in the tree canopy

Further, health-based statistical modelling was introduced on population health records and local heat conditions. A historical dataset for York Region was constructed integrating daily humidex values, mortality records, and emergency department visits. The daily health records were retrieved from the Research Data Centres using death and hospitalization microdata of Statistics Canada respecting data confidentiality and following Statistics Canada's guidelines and restrictions. The health records included all-cause records and vulnerable records which were defined by combining cause-based (cardiorespiratory causes) and elderly cases. The statistical modelling employed nonlinear regression analyses to predict the health records based on the humidex values. The predictive regression model forecasts the health records based on expected changes in heat conditions (humidex values). Thus, forecasting the changes in health records is related to changes in outdoor heat conditions that are associated with increasing greenery cover within the Region. The study considered increasing the GC from a reference condition to an Intense GC within two weather scenarios: an extreme heat wave and a typical summer season. Figure ES-3 illustrates the changes in daily all-cause mortality records when increasing the GC from reference case to intense condition during both weather scenarios.

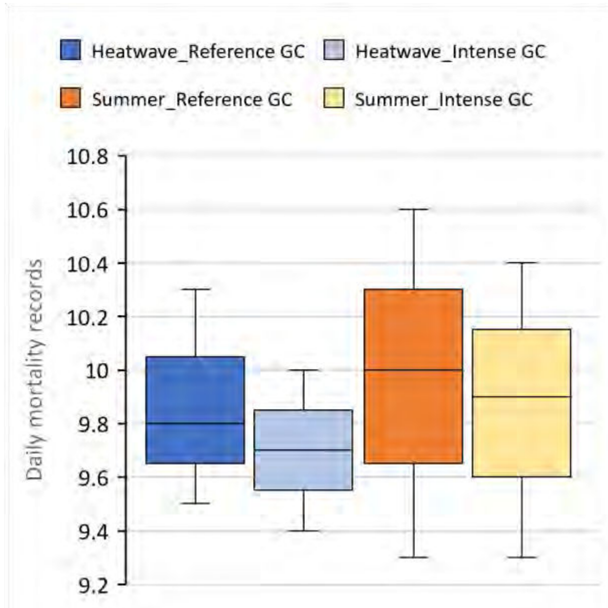


Figure ES-3: Predictions of daily all-cause mortality records in York Region when applying the Intense GC scenario

The economic benefits were estimated as the direct and indirect benefits of increasing the urban greenery cover for reducing costs associated with emergency department visits, avoiding premature mortality, increasing energy savings, and avoiding workers' productivity losses.

The integrated framework presented in this report intends to support stakeholders and decision-makers in developing heat mitigation strategic plans to improve community well-being and population health. This research is a pilot study that gives a more comprehensive understanding of the benefits of greenspace for health and well-being. However, the health study was conducted based on available data. One of the primary limitations was the lack of data that could be used to analyze health outcomes related to greenspace exposure. Moreover, the study only focused on main urban areas in the region; other expanded areas and other specific health outcomes and impacts (e.g., heat exhaustion on outdoor workers or school children) may not have been measured or accounted for in the analysis. For example, future studies could consider the impact of direct exposure and physical existence within greenspaces during heat events. It is important to recognize these limitations in the study, as they highlight the need for future research to build upon the existing findings and explore additional health outcomes and impacts that could result in more holistic understanding of the impact of greenspace on health outcomes.

1. Background & Scenarios

The combination of climate change, Urban Heat Island (UHI), and heat wave events leads to higher daytime temperatures, causes excessive heat stress for residents, and increases heat-related illness and mortality[1]. In particular, the consequences of UHI and the frequency, intensity, and duration of the heat waves around the world are becoming more evident[2]. The severe impacts of heat waves are associated with multi-day heat stress, warm nights, and increased relative humidity. The heat warnings are issued considering regional climatology and health evidence according to local climatic conditions. For example, Environment and Climate Change Canada issues heat warnings across Southern Ontario when the daytime maximum temperature is forecasted as ≥ 31˚C, when the night-time minimum temperature is forecasted as ≥ 20˚C, or when the temperature-humidity index (humidex) is forecasted as 40 degrees or more for two consecutive days[3]. If the conditions are forecasted to continue for three or more days, an extended heat warning is issued. In the last 20 years, 60 heat warnings and 37 extended heat warnings were issued for the City of Toronto [4]. Moreover, hot days, defined as a maximum temperature above 30˚C, are expected to increase in the Greater Toronto Area (GTA) from 20 days/year in 2010 to 66 days/year in 2050 based on severe climate change scenarios[5]. Simultaneously, severe health impacts are expected to increase due to changes in the frequency and intensity of heat events[6]. The Canadian Environment Health Atlas (CEHA) and the Toronto Public Health Department estimated that there are 120 annual deaths in the GTA because of exposure to high temperatures[7]. The predictions indicate that heat-related mortality will more than double by 2050[8]. Given population growth projections and large urban transformation for the region as well as the expected impacts of climate change, understanding how greenery cover can reduce UHIs and protect people during heat events is critical.

Heat mitigation strategies and preserving vegetation cover have been shown to improve the urban environment within the strategic planning for new and existing urban settlements[9]. The cooling effect of intensifying the greenery cover in cities is associated with blocking solar radiation and the evapotranspiration of vegetation coverage. Green spaces within cities can include public green spaces like parklands, street vegetation, cemeteries, and other open green spaces; they also include trees and vegetation on private properties like backyards. This cover is considered part of the natural reservoir for air quality and humidity content that are required for the ecological balance in the region. Preserving this natural cover influences the ecological system, thermal behaviour, and community health.

This study aims to estimate the co-benefits associated with increasing the urban greenery cover in The Regional Municipality of York (i.e., York Region). The co-benefits include environmental enhancements, community health responses, and related economic benefits. The developed approach uses a statistical-simulation predictive model to compare current conditions in York

[1] (Jandaghian and Akbari 2018; Santamouris 2020)
[2] (Shukla et al. 2022)
[3] (Environment and natural resources 2020)
[4] (Toronto Public Health 2022)
[5] (Environment and Climate Change Canada 2019; Toronto Public Health 2022)
[6] (Fischer and Schär 2010)
[7] (Environment and Climate Change Canada 2019)
[8] (Pengelly et al. 2007)
[9] (Wang, Berardi, and Akbari 2016; Berardi and Wang 2016)

Region with a scenario of intensifying the greenery cover to estimate the role of green elements in mitigating the impacts of hot temperatures. Quantitatively, the results reveal the impact provided by ground vegetation cover and tree canopy in terms of reduced mortality, health system savings, and lower energy use. Stakeholders and policymakers can utilize the findings of this study to inform local and regional policies to improve community well-being and population health.

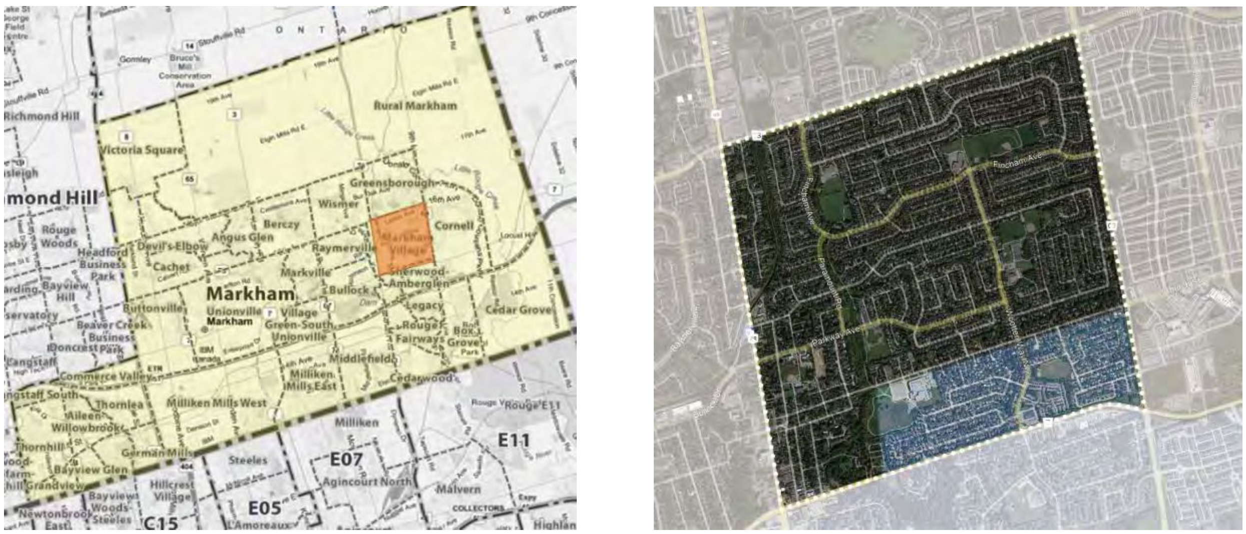


Figure 1: The studied neighbourhood in Markham Village

Figure 2: The studied neighbourhood in East Woodbridge

1.1. Case Studies Presentation

This study assesses the impact of increasing the urban greenery cover in York Region. The case study includes two residential neighbourhoods in the cities of Markham and Vaughan to represent the urban typology in the region. The first case study is a residential neighbourhood in Markham Village as shown in Figure 1. This neighbourhood has an area of 4.2 km^2, with 93% of its buildings being used for residential activities. Other building usages are related to commercial, educational, and recreational activities. The existing tree canopy of the neighbourhood inhabits 36% of the total area (see also Table 1). The second case study is a neighbourhood located in East Woodbridge as shown in Figure 2. The neighbourhood has an area of 6.1 km^2. The building usages include 80% residential, 16% commercial, and 4% for other activities. The existing tree canopy of the neighbourhood represents 12% of the total area (see also Table 2). The two neighbourhoods in Markham Village and East Woodbridge were chosen to represent vulnerable populations considering UHI behaviour and potential planting spaces.

1.2. Greenery Cover Scenarios

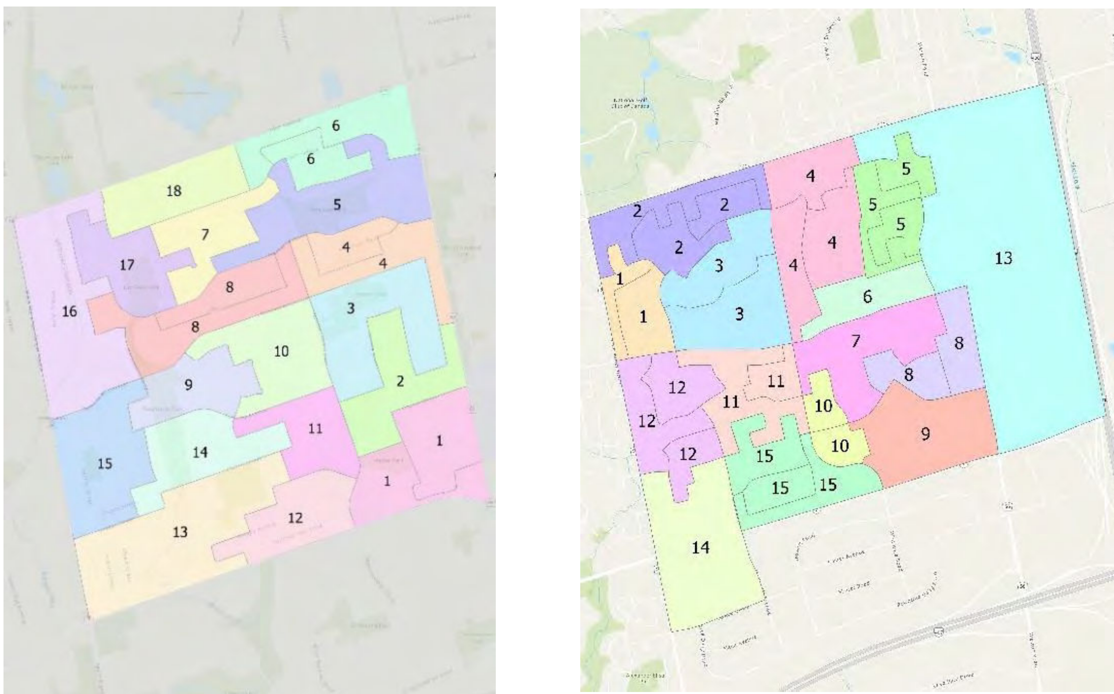


Figure 3: DA distribution for Markham Village (left) and East Woodbridge (right)

The urban greenery cover (GC) in the case studies integrates the ground vegetation cover (GVC), including grass and shrubs, and tree canopy (TC). The tree canopy reduces temperatures by providing shade to the ground, roads, and buildings, while both covers contribute to air cooling by evaporation and urban surface cooling. The study considers the percentages of greenery cover associated with the dissemination area (DA) related to the total land area. The areas distribution is coded based on DA administrative classification. The coded DA distribution is proposed for both neighbourhoods and listed in Figure 3. The study investigates two scenarios for increasing the greenery cover: 1) the intense greenery cover (Intense GC) scenario, which defines the maximum allowable tree canopy and vegetation cover, and 2) the moderate greenery cover (Moderate GC) scenario, which provides around 50% of the allowable tree canopy and vegetation cover. The maximum allowable area refers to available spaces for planting trees; this includes municipal parks, roadsides, urban interspaces between buildings, etc. The existing (reference) and maximum allowable greenery covers were provided by York Region based on available spaces to develop new green covers for each DA. Drawing on a previous study for the GTA[10], the reference GVC is assumed to be 25% of the land area. This assumption was used for all the DAs. The buildings' footprint was determined by mapping the two neighbourhoods using a 2022 spatial layer of the respective neighbourhoods. Tables 1 and 2 provide percentages for the reference GC, Moderate GC, and Intense GC at DA level for Markham Village and East Woodbridge, respectively. The increased areas of GC are based on the maximum allowable areas for GC. For example, in Markham Village DA 1, the Intense GC scenario includes adding planting area of 144,358 m^2 to reach a total tree canopy coverage of 82.1% of the dissemination area.

Table 1 – Reference GC, Moderate GC, and Intense GC in Markham Village

DAs	Buildings (%)	Reference TC		Added area for Moderate GC (m^2)	Added area for Intense GC (m^2)	Moderate TC (%)	Intense TC (%)	Moderate GVC (%)	Intense GVC (%)
		Area (m^2)	%						
1	18.89	92,648	32.1	72,179	144,358	57.1	82.1	50.0	75.0
2	16.41	82,849	42.5	39,501	79,002	62.8	83.1	50.3	70.5
3	13.69	98,843	37.9	63,360	126,719	62.2	86.5	54.3	78.6
4	26.22	78,953	39.4	38,649	77,297	58.6	77.9	49.3	68.5
5	20.73	77,113	26.6	80,695	161,390	54.5	82.4	57.9	85.8
6	24.40	69,195	27.8	61,569	123,138	52.5	77.2	54.7	79.4
7	24.07	48,474	30.4	35,187	70,373	52.4	74.5	52.1	74.1
8	23.59	113,209	43.3	46,774	93,547	61.1	79.0	47.9	65.7
9	17.60	66,173	42.5	33,350	66,700	63.9	85.3	51.4	72.8
10	23.84	80,934	37.9	46,468	92,936	59.7	81.5	51.8	73.6
11	19.69	56,237	37.2	34,691	69,382	60.2	83.2	53.0	76.0
12	21.98	62,084	34.8	40,308	80,616	57.4	79.9	52.6	75.2
13	14.04	149,585	35.7	104,182	208,364	60.6	85.4	54.9	79.7
14	17.55	76,472	39.2	43,637	87,273	61.6	84.0	52.4	74.8
15	14.64	96,230	37.1	61,948	123,896	61.0	84.8	53.9	77.7
16	17.62	145,069	40.4	74,384	148,768	61.1	81.8	50.7	71.4
17	19.89	51,809	29.5	47,072	94,143	56.3	83.1	56.8	83.6
18	25.39	50,341	28.0	42,878	85,756	51.9	75.8	53.9	77.8
TOTAL	**19.51**	**1,496,218**	**35.7**	**966,829**	**1,933,658**	**58.8**	**81.8**	**53.1**	**76.1**

[10] (M. Dardir and Berardi 2021)

The Intense GC scenario includes a tree canopy that provides abundant shading to roads and buildings. Figure 4 shows some examples around the Greater Toronto Area of intense greenery covers. According to previous case studies[11], this intense scenario can be achievable in urban spaces. The increase in tree canopy area is related to the available land area for planting. As the available planting area is limited in Markham Village, the intense greenery cover is assumed to overlay the roads completely and to provide over-shading to buildings' roofs. Whereas the Moderate GC scenario provides some shading to urban surfaces and building surfaces. In Markham Village, the tree canopy is proposed to increase from 1.5 km^2 for the current condition to 2.5 km^2 for the moderate cover and 3.4 km^2 for the intense cover (a maximum increase of 1.9 km^2). In East Woodbridge, the tree canopy is proposed to increase from 0.75 km^2 for the current condition to 1.5 km^2 for the moderate cover and 3 km^2 for the intense cover (a maximum increase of 2.2 km^2). The maximum increase reflects an average percent increase of 46% and 38% in Markham Village and East Woodbridge, respectively.

Table 2 – Reference GC, Moderate GC, and Intense GC in East Woodbridge

DAs	Buildings (%)	Reference TC		Added area for Moderate GC (m^2)	Added area for Intense GC (m^2)	Moderate TC (%)	Intense TC (%)	Moderate GVC (%)	Intense GVC (%)
		Area (m^2)	%						
1	20.65	32,061	15.9	48,635	97,269	32.1	48.3	49.1	73.3
2	19.03	97,129	24.9	84,016	168,031	33.9	43.0	46.5	68.0
3	18.75	63,312	14.1	127,321	254,642	35.3	56.6	53.3	81.6
4	22.14	68,896	14.4	112,376	224,751	30.7	47.0	48.5	72.0
5	23.68	36,437	13.1	68,244	136,487	31.2	49.2	49.6	74.2
6	24.81	23,416	14.0	39,060	78,119	30.4	46.7	48.4	71.7
7	17.79	44,375	13.9	89,205	178,410	34.8	55.7	52.9	80.7
8	24.67	29,097	12.7	48,147	96,293	27.3	41.9	45.9	66.9
9	20.50	26,923	7.5	106,270	212,540	33.3	59.1	54.6	84.1
10	19.81	32,582	25.3	22,293	44,586	30.0	34.6	42.3	59.6
11	23.88	39,183	13.5	68,815	137,629	30.5	47.5	48.8	72.5
12	20.39	61,361	16.7	88,890	177,779	32.6	48.5	49.2	73.5
13	22.96	100,150	6.2	422,989	845,977	29.1	52.0	51.0	77.0
14	20.60	52,501	10.9	126,247	252,494	31.8	52.6	51.3	77.6
15	23.64	43,397	12.5	75,893	151,786	28.2	43.9	46.9	68.9
TOTAL	**21.67**	**750,820**	**12.3**	**1,528,397**	**3,056,793**	**31.2**	**50.0**	**50.0**	**75.0**

[11] (M. Dardir and Berardi 2021; Jänicke et al. 2016; Berardi, Jandaghian, and Graham 2020)

Figure 4: Examples of intense greenery covers in the GTA
(Source: Google Maps)

1.3. Weather Scenarios

The proposed weather scenario modelled is a worst-case scenario of a heat wave that is expected to occur within the next 5 years in Southern Ontario. This scenario was developed by Environment and Climate Change Canada (ECCC) based on modelling and a previous heat wave that occurred in British Columbia in 2021. The extreme weather scenario extends for 2 weeks (from June 18 to July 2) with two peaks on June 24th and June 28th. This scenario forecasts the ambient temperature and outdoor heat stress in terms of humidex values. Humidex is a dimensionless quantity that describes how hot and humid weather is perceived by human beings. According to Environment Canada, humidex defines the degree of comfort as follows:

The degree of comfort (Humidex values)
• 20 to 29: Little to no discomfort • 30 to 39: Some discomfort • 40 to 45: Great discomfort; avoid exertion • Above 45: Dangerous; heat stroke quite possible

Figure 5 illustrates the forecast of the outdoor heat stress index (humidex) and temperature during the expected heat event. It is worth mentioning that these dates are not related to a specific year. The meteorology forecast includes days with a maximum ambient temperature of 39°C and an average ambient temperature of 27.7°C. It also predicts the humidex with a maximum value of 54 and an average value of 33.9.

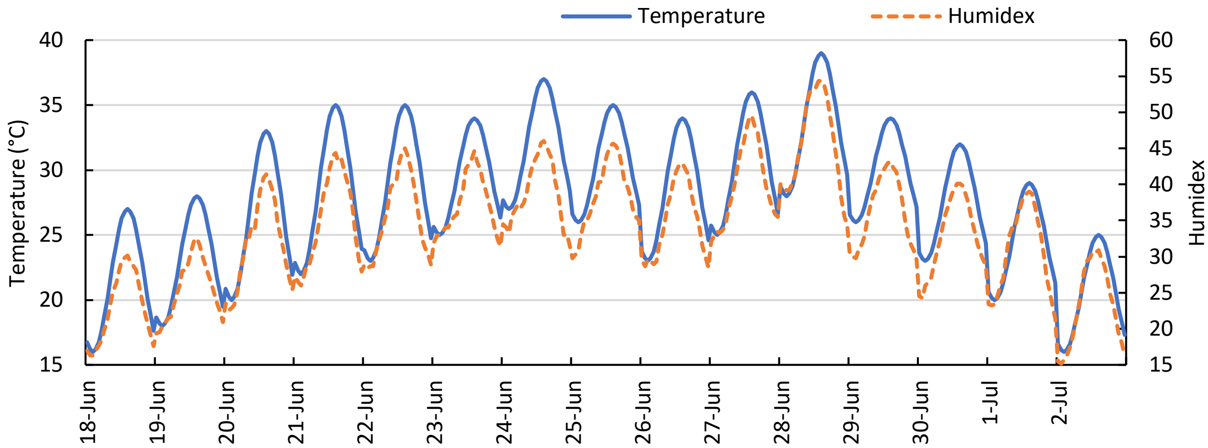


Figure 4: Forecast of humidex and temperature during a heat event

The study also considers a typical summer season extending from May 1 to September 30 (150 days) to test the changes in regular conditions. The typical season does not include the extreme weather scenario. While it is not a forecast-based scenario, the typical season is based on the historical measurements in the GTA and uses the weather data file of the Toronto International Airport weather station.

2. Health-Informed Framework

The study framework follows a novel integrated approach by combining statistical modelling with microclimate simulations to investigate the impact of increasing the urban greenery cover on the urban microclimate and heat-related community health responses. The framework intends to predict community health records, including mortality cases and emergency department visits, and associated economic benefits estimates. The enhancements in greenery cover include increasing TC and GVC. Microclimate simulations were developed using an updated validated version of the Urban Weather Generator (UWG) to predict environmental behaviour including changes in ambient temperature, outdoor heat stress, and building energy consumption. A statistical approach was followed by integrating historical data on meteorological measures and population health records to determine the impact of changes in ambient conditions on community health. This approach uses predictive regression models to correlate data and predict the anticipated health response. The predictive regression outputs are utilized in forecasting health records based on outdoor ambient conditions. Then, an economic valuation-based module is integrated to estimate the economic benefits associated with outdoor thermal behaviour and community health responses. Policymakers can utilize this method for estimating community health responses and economic benefits considering the changes in the urban environment. The illustration in Figure 6 describes the integrated framework based on weather and health data to assess the associated benefits of increasing urban greenery cover.

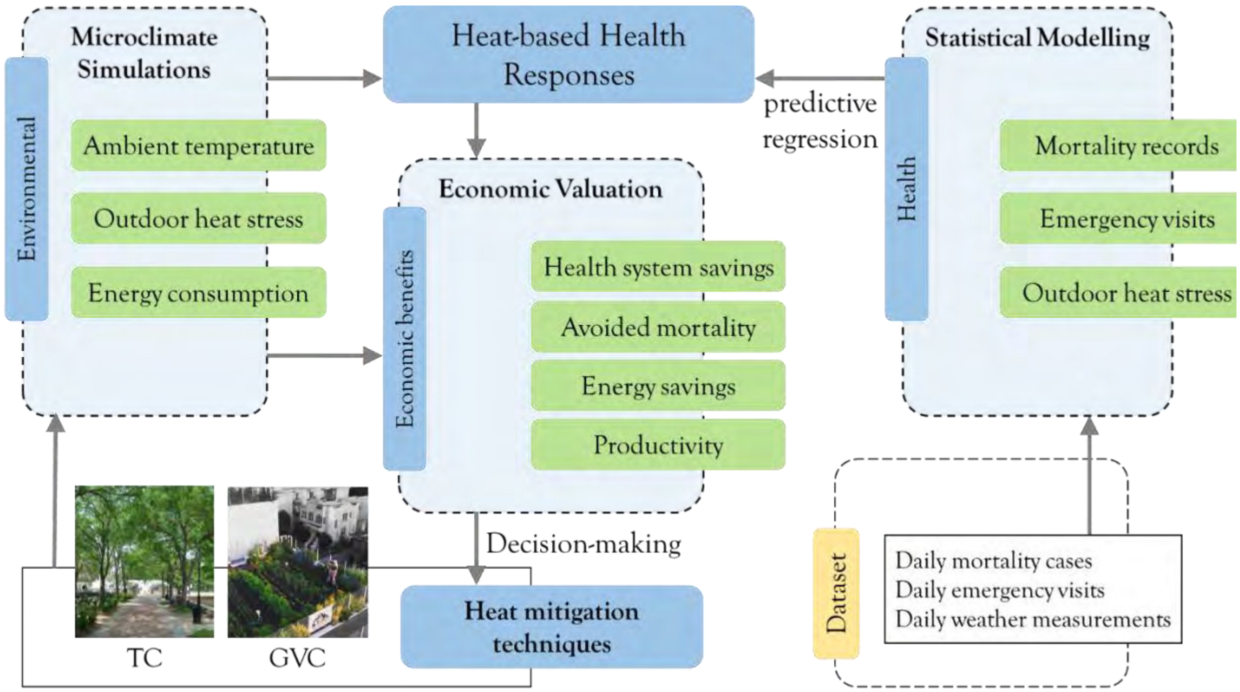


Figure 5: Decision-making framework to forecast health responses and economic benefits

2.1. Simulation Approach

The simulation approach was developed utilizing the updated version of the open-source code of the microclimate model of UWG[12] that simulates the environmental changes in urban microclimates. The model assesses the effect of increasing the urban greenery cover on the urban microclimate and energy use of buildings. The updated version promotes better prediction of the evaporative cooling effect, more realistic shading behaviour, further adaptability to urban surface variety, and adaptability to various heat mitigation strategies. The UWG is concerned with urban microclimate evaluation and assessment of heat mitigation strategies (e.g. green roofs, green facades, cool surfaces). The UWG is an open-source MATLAB code which promotes integrating outputs of other statistical models to predict health, social, and economic community responses. This makes UWG unique from i-Tree models[13] which are mainly concerned with forest management, environmental risks, diversity in tree species, and removal ability of specific air pollutants. The UWG model was used to assess the heat mitigation scenarios associated with intensifying the vegetation cover and tree canopy of the urban area. The simulation was conducted in Markham Village and East Woodbridge during the extreme weather scenario and the typical summer season. The study monitors the outdoor thermal performance in terms of ambient temperature and outdoor heat stress. It also tracks the indoor energy use of buildings assuming that all buildings are using active cooling systems to maintain indoor temperature at a comfortable level. Thus, outdoor heat mitigation would help in reducing the energy use required for cooling. The simulation monitors outdoor environmental changes while applying reference, moderate, and intense greenery covers.

[12] (M. Dardir and Berardi 2021)
[13] (Nowak 2021)

2.1.1. Outdoor heat stress

Table 3 – Reductions in humidex in Markham Village

DAs	Change in daily average humidex			Change in daily maximum humidex				
	Reference GC	Moderate GC	Intense GC	Reference GC	Moderate GC	Intense GC	The increase in tree canopy for Intense GC	The increase in Ground vegetation cover for Intense GC
1	32.3	30.9 *(-4.3%)*	28.7 *(-11.1%)*	52.1	48.8 *(-6.3%)*	44.6 *(-14.4%)*	50.0%	50.0%
2	32.3	31.1 *(-3.7%)*	29.3 *(-9.3%)*	51.8	49.2 *(-5.0%)*	45.6 *(-12.0%)*	40.6%	45.5%
3	32.4	31.1 *(-4.0%)*	29.1 *(-10.2%)*	52.2	49.1 *(-5.9%)*	45.2 *(-13.4%)*	48.6%	53.6%
4	32.2	31.0 *(-3.7%)*	29.0 *(-9.9%)*	51.7	49.0 *(-5.2%)*	45.0 *(-13.0%)*	38.5%	43.5%
5	32.7	31.0 *(-5.2%)*	28.5 *(-12.8%)*	53.0	49.1 *(-7.4%)*	44.1 *(-16.8%)*	55.8%	60.8%
6	32.8	31.2 *(-4.9%)*	28.9 *(-11.9%)*	53.2	49.5 *(-7.0%)*	44.8 *(-15.8%)*	49.4%	54.4%
7	32.5	31.1 *(-4.3%)*	29.1 *(-10.5%)*	52.4	49.3 *(-5.9%)*	45.2 *(-13.7%)*	44.1%	49.1%
8	32.1	31.0 *(-3.4%)*	29.2 *(-9.0%)*	51.5	49.0 *(-4.9%)*	45.4 *(-11.8%)*	35.7%	40.7%
9	32.0	30.8 *(-3.8%)*	29.1 *(-9.1%)*	51.2	48.5 *(-5.3%)*	45.0 *(-12.1%)*	42.8%	47.8%
10	32.2	30.9 *(-4.0%)*	28.9 *(-10.2%)*	51.7	48.7 *(-5.8%)*	44.7 *(-13.5%)*	43.6%	48.6%
11	32.4	31.1 *(-4.0%)*	29.1 *(-10.2%)*	52.1	49.1 *(-5.8%)*	45.0 *(-13.6%)*	46.0%	51.0%
12	32.3	30.9 *(-4.3%)*	29.0 *(-10.2%)*	51.8	48.7 *(-6.0%)*	44.9 *(-13.3%)*	45.1%	50.2%
13	32.5	31.1 *(-4.3%)*	28.9 *(-11.1%)*	52.7	49.5 *(-6.1%)*	45.0 *(-14.6%)*	49.7%	54.7%
14	32.4	31.1 *(-4.0%)*	29.2 *(-9.9%)*	52.1	49.2 *(-5.6%)*	45.3 *(-13.1%)*	44.8%	49.8%
15	32.4	31.0 *(-4.3%)*	29.1 *(-10.2%)*	52.2	49.2 *(-5.7%)*	45.2 *(-13.4%)*	47.7%	52.7%
16	32.3	31.1 *(-3.7%)*	29.1 *(-9.9%)*	52.0	49.3 *(-5.2%)*	45.4 *(-12.7%)*	41.4%	46.4%
17	32.6	31.0 *(-4.9%)*	28.8 *(-11.7%)*	52.6	49.0 *(-6.8%)*	44.5 *(-15.4%)*	53.6%	58.6%
18	32.5	31.0 *(-4.6%)*	28.8 *(-11.4%)*	52.6	49.2 *(-6.5%)*	44.7 *(-15.0%)*	47.8%	52.8%

The microclimate evaluation of the case studies is presented in terms of average and maximum humidex values. Table 3 shows average and maximum humidex values during the extreme weather scenario while applying reference, Moderate, and Intense GCs in Markham Village, and Table 4 presents these values for East Woodbridge. The application is associated with the DAs during the extreme weather scenario. The model calculates the hourly humidex values in response to the associated GC. Then, the daily average and maximum values were calculated based on simulation outputs. The tables reveal the progress in the thermal environment in terms of reducing humidex values due to increasing GCs. The reductions in humidex values are presented as percentages of enhancement regarding the reference conditions. For example, the daily average humidex DA-1 in Markham Village is reduced from 32.3 for the reference GC to 28.7 while applying the Intense GC, and this refers to an average reduction of 11.1% in humidex due to increasing the GC to an intense level. When we consider the daily maximum reductions in humidex values, it can be stated that the daily average humidex can be reduced by 11.1±3.3%, achieving a maximum daily reduction in humidex of 14.4% for DA-1 in Markham Village. The percentage of reduction in humidex for each case is presented between parentheses in the tables.

Table 4 – Reductions in humidex in East Woodbridge								
	Daily average humidex			Daily maximum humidex				
DAs	Reference GC	Moderate GC	Intense GC	Reference GC	Moderate GC	Intense GC	The increase in tree canopy for Intense GC	The increase in ground vegetation cover for Intense GC
1	33.0	31.9 *(3.3%)*	30.3 *(8.2%)*	53.5	51.3 *(4.1%)*	47.7 *(10.8%)*	32.4%	48.3%
2	32.8	32.1 *(2.1%)*	30.7 *(6.4%)*	53.2	51.7 *(2.8%)*	48.6 *(8.6%)*	18.2%	43.0%
3	33.1	31.8 *(3.9%)*	29.8 *(10.0%)*	54.1	51.2 *(5.4%)*	46.8 *(13.5%)*	42.5%	56.6%
4	33.1	32.0 *(3.3%)*	30.3 *(8.5%)*	54.0	51.6 *(4.4%)*	47.8 *(11.5%)*	32.6%	47.0%
5	33.3	32.1 *(3.6%)*	30.1 *(9.6%)*	54.3	51.8 *(4.6%)*	47.4 *(12.7%)*	36.1%	49.2%
6	33.1	32.0 *(3.3%)*	30.2 *(8.8%)*	53.8	51.4 *(4.5%)*	47.5 *(11.7%)*	32.7%	46.7%
7	33.1	31.9 *(3.6%)*	29.9 *(9.7%)*	53.9	51.2 *(5.0%)*	47.0 *(12.8%)*	41.8%	55.7%
8	33.1	32.2 *(2.7%)*	30.5 *(7.9%)*	53.9	51.9 *(3.7%)*	48.1 *(10.8%)*	29.3%	41.9%
9	33.5	31.9 *(4.8%)*	29.9 *(10.7%)*	54.9	51.6 *(6.0%)*	47.4 *(13.7%)*	51.6%	59.1%
10	32.7	32.3 *(1.2%)*	31.2 *(4.6%)*	52.7	51.8 *(1.7%)*	49.6 *(5.9%)*	9.3%	34.6%
11	33.2	32.1 *(3.3%)*	30.1 *(9.3%)*	54.1	51.7 *(4.4%)*	47.5 *(12.2%)*	34.0%	47.5%
12	33.2	32.1 *(3.3%)*	30.4 *(8.4%)*	54.1	51.8 *(4.3%)*	47.9 *(11.5%)*	31.8%	48.5%
13	32.8	31.3 *(4.6%)*	29.4 *(10.4%)*	53.9	50.9 *(5.6%)*	47.0 *(12.8%)*	45.8%	52.0%
14	33.3	31.9 *(4.2%)*	30.0 *(9.9%)*	54.6	51.7 *(5.3%)*	47.6 *(12.8%)*	41.7%	52.6%
15	33.2	32.2 *(3.0%)*	30.4 *(8.4%)*	54.3	52.0 *(4.2%)*	48.1 *(11.4%)*	31.4%	43.9%

The results show the daily average and maximum values of humidex. Referring to the existing humidex values (presented in Tables 3 and 4) associated with reference GC within all DAs of the two neighbourhoods (presented in Tables 1 and 2), DAs with less existing greenery cover have higher average and maximum values of humidex. For example, DA-9 in East Woodbridge has recorded the highest average humidex value (33.5) while having only 7.5% tree canopy cover. Figure 7 shows the relationship between the daily average humidex and reference tree canopy cover for all DAs in the two neighbourhoods. Based on the existing data, the linear regression has established a significantly fitted model with an R-squared value of 0.88 which strengthens the resulting association. The results reveal that there is a reduction of 0.33 in average humidex with each 10% increase in tree canopy cover. These results are recommended to identify the most vulnerable areas in terms of outdoor heat stress in association with existing greenery cover.

The results in Tables 3 and 4 also show the percentage reduction in humidex while applying the Moderate and Intense GC scenarios. Within both neighbourhoods, humidex values in all DAs have been reduced by increasing the GC in the scenarios. It can be concluded that increasing the greenery cover helps the urban microclimate in reducing heat stress in all areas.

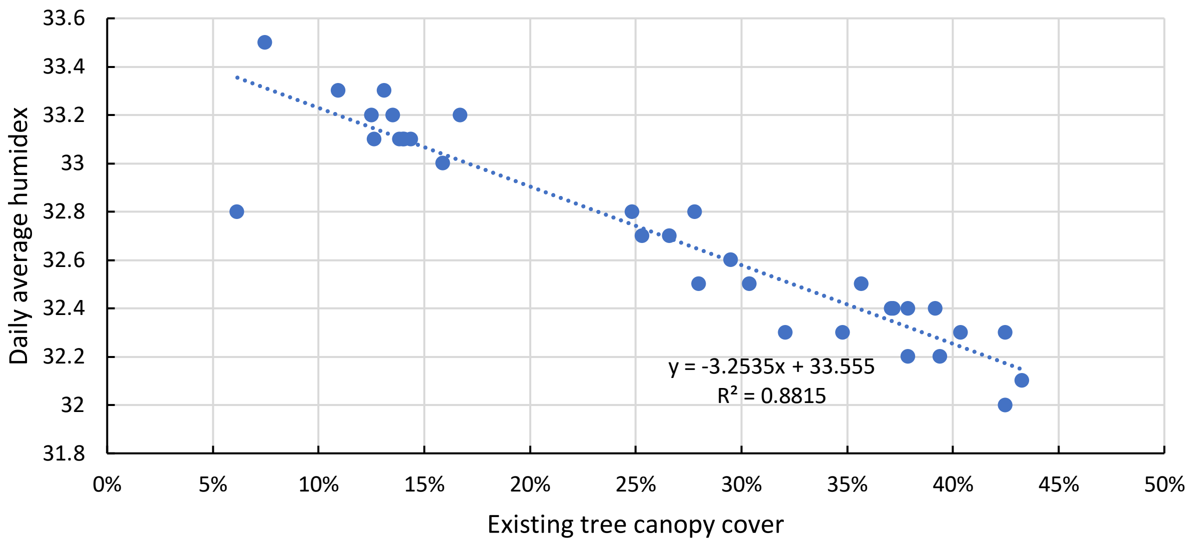


Figure 6: Linear regression of daily average humidex in association with reference tree canopy cover

In Markham Village (Table 3), the results show a 9% to 12.8% reduction in the average humidex while applying the Intense GC scenario, and a 3.4% to 5.2% reduction while applying the Moderate GC scenario. In values, the reduction in daily average humidex ranges from 2.9 to 4.2, and the reduction in daily maximum humidex ranges from 6.1 to 8.9. DAs with the highest increases in greenery cover receive greater reductions in the humidex. In DA-5, the reduction in daily average humidex is 1.7 (5.2%) for Moderate GC and 4.2 (12.8%) for Intense GC, and the reduction in daily maximum humidex is 3.9 (7.4%) for Moderate GC and 8.9 degrees (16.8%) for Intense GC.

It is noticed that, by applying the Intense GC scenario within all areas, the daily maximum humidex is shifted from extremely dangerous conditions (maximum humidex ~ 52) to great discomfort conditions (maximum humidex ~ 45). Regarding the average humidex, the distribution of average humidex values in Markham Village is shown in Figure 8 associated with DAs. Applying the Moderate GC scenario, the daily average humidex maintained some discomfort conditions (daily average humidex > 30). However, by applying the Intense GC scenario, the daily average humidex is pushed away from some discomfort conditions to no-discomfort conditions. This refers to the great capability of Intense GCs to provide cooling potential and comfortable conditions during heat events that could result in a reduction in heat-related illnesses.

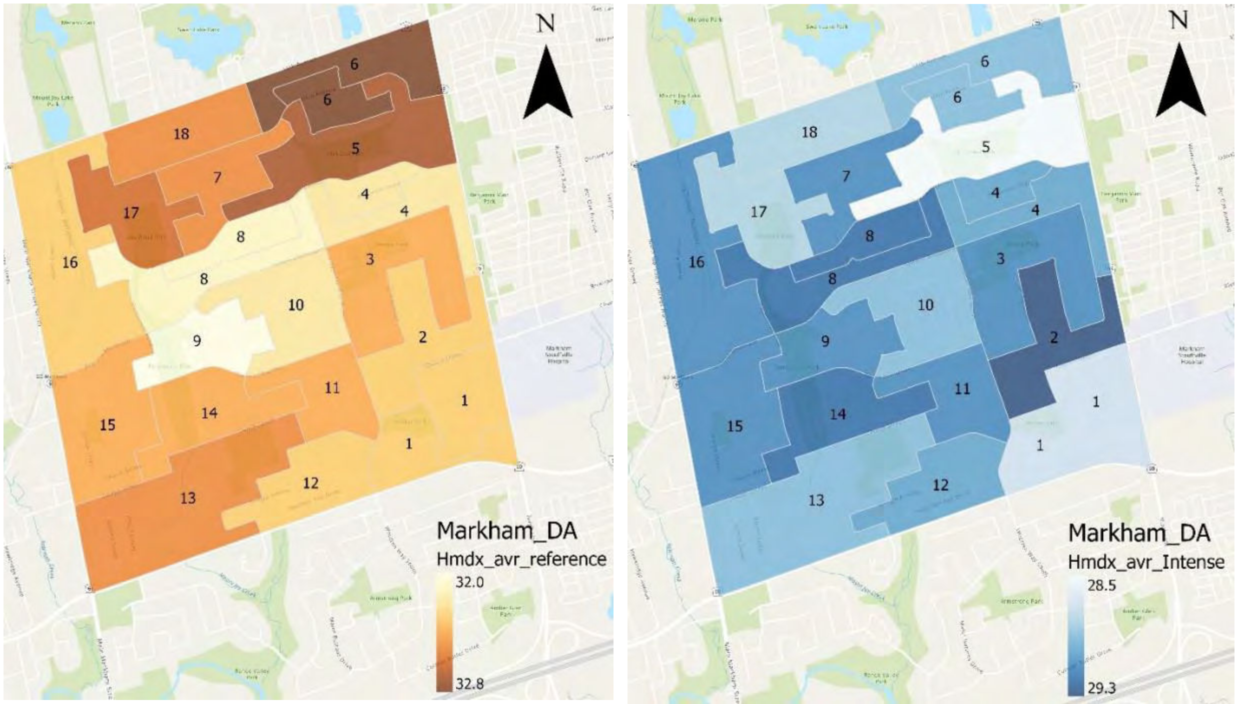


Figure 7: Average humidex during the extreme weather scenario in Markham Village distributed by DA applying reference GC (left) and Intense GC scenario (right)

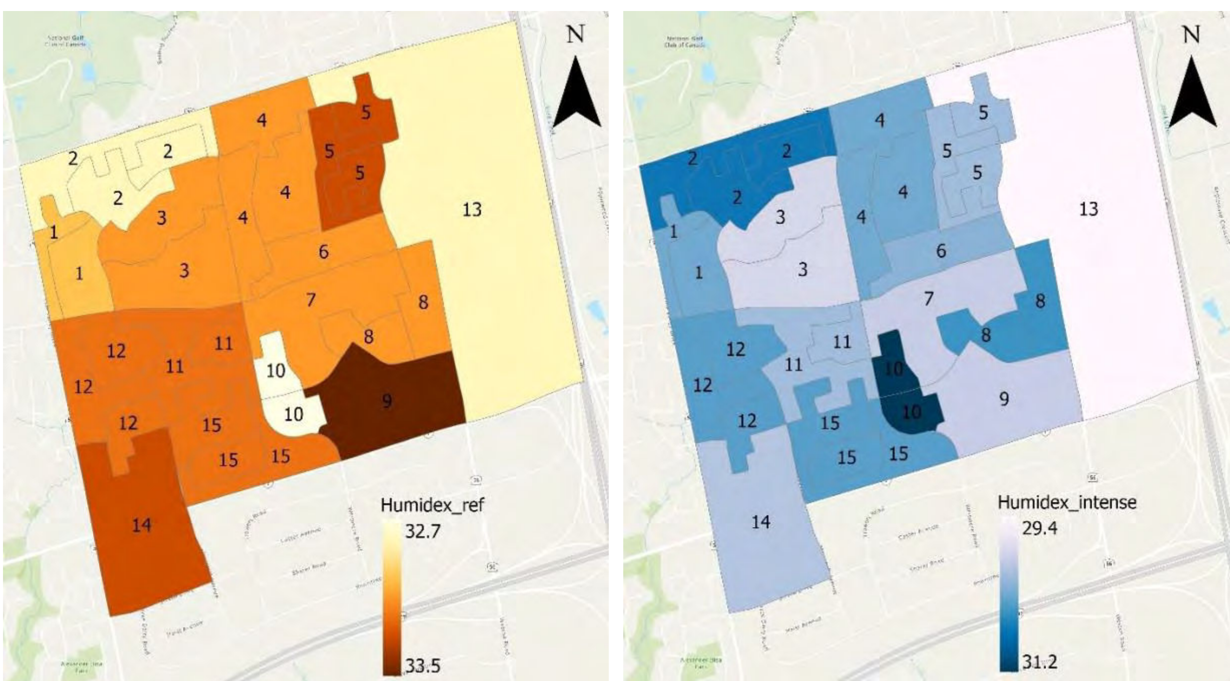


Figure 8: Average humidex during the extreme weather scenario in East Woodbridge distributed by DA applying reference GC (left) and Intense GC scenario (right)

In East Woodbridge (Table 4), the results show a 4.6% to 10.7% reduction in the average humidex while applying the Intense GC scenario. The reduction in daily average humidex ranges from 1.5 to 3.6, and the reduction in daily maximum humidex ranges from 3.1 to 7.5. Due to higher humidex values in the neighbourhood, the daily maximum humidex dropped 7 from an average of 54 degrees to 47 degrees. Again, DAs with the highest increases in greenery cover receive greater reductions in humidex values. In DA-9, the reduction in daily average humidex is 1.6 (4.8%) for Moderate GC and 3.6 (10.7%) for Intense GC, and the reduction in daily maximum humidex is 3.3 (6%) for Moderate GC and 7.5 (13.7%) for Intense GC. The distribution of average humidex values is shown in Figure 9 associated with DAs. The daily average humidex is shifted from 33 to 30 providing comfortable conditions to some DAs during the heat event.

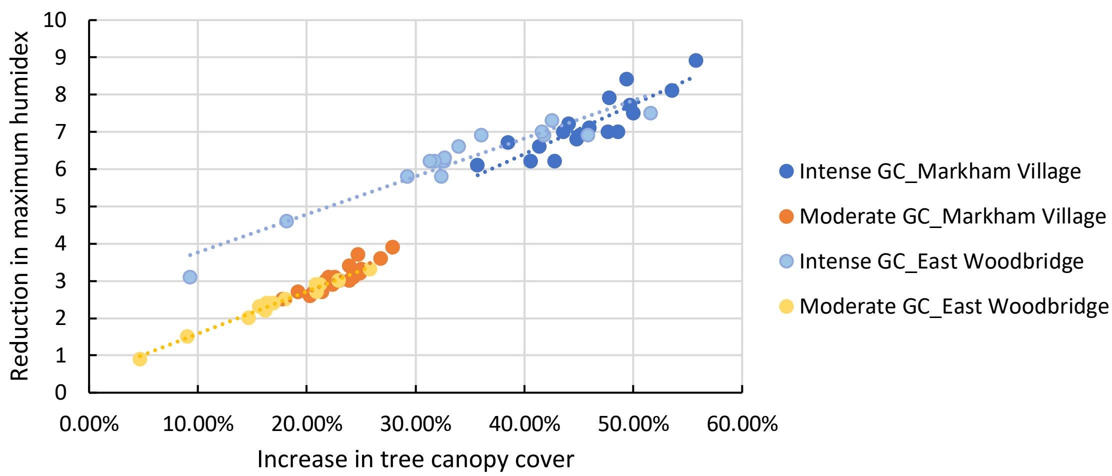


Figure 9 - Reductions in maximum humidex in association with the increase in the tree canopy

Figure 10 includes the reductions in maximum humidex for all DAs in association with the increase in tree canopy cover for Moderate and Intense GCs. It can be concluded that the reductions in outdoor heat stress (humidex) are related to the percent increase in greenery cover within the area. The greater the increased greenery cover, the cooler the outdoor environment.

Table 5 – Reductions in humidex in both neighbourhoods (total areas)

		Daily average humidex			Daily maximum humidex		
		Reference GC	Moderate GC	Intense GC	Reference GC	Moderate GC	Intense GC
Markham Village	Extreme weather scenario	32.0	30.5 *(4.7%)*	28.1 *(12.2%)*	52.2	49.0 *(6.1%)*	44.5 *(14.8%)*
	Typical summer season	18.9	17.9 *(5.3%)*	16.2 *(14.3%)*	40.6	38.2 *(5.9%)*	34.1 *(16.0%)*
East Woodbridge	Extreme weather scenario	32.9	31.5 *(4.3%)*	29.3 *(10.9%)*	54.3	51.5 *(5.2%)*	47.1 *(13.3%)*
	Typical summer season	19.5	18.7 *(4.1%)*	17.2 *(11.8%)*	42.1	40.2 *(4.5%)*	36.5 *(13.3%)*

Moreover, the total areas of both neighbourhoods were investigated during the extreme heat scenario (2 weeks of a heat wave) and the typical summer season (150 typical summer days). Table 5 presents average and maximum humidex values in both neighbourhoods applying the reference GC, Moderate GC, and Intense GC scenarios. Referring to the existing condition, it can be noticed that East Woodbridge has lower performance (higher humidex values) than Markham Village in all cases. For example, during the extreme weather scenario, the daily maximum humidex has reached 52.2 in Markham Village and 54.3 in East Woodbridge. This is due to the limited present greenery cover in East Woodbridge related to its large area (existing TC is 35.7% in Markham Village and 12.3% in East Woodbridge).

During the extreme weather scenario, the daily average humidex has been reduced by 1.5 for Moderate GC and 3.9 for Intense GC in Markham Village. It has also been reduced in East Woodbridge by 1.4 and 3.6 for Moderate GC and Intense GC, respectively. Figures 11 and 12 show the hourly behaviour of humidex during the heat event in both neighbourhoods. Greater reductions in humidex are observed during the daytime. Large reductions are also noticed on days with extreme conditions. For instance, on June 28, the daytime maximum humidex is reduced from 52.2 degrees for the reference GC to 47.4 for the Moderate GC and 44.5 for the Intense GC in Markham Village. It is also reduced from 54.3 for the reference GC to 51.5 for the Moderate GC and 47.1 for the Intense GC in East Woodbridge. This reflects the importance of the greenery cover in helping to protect the environment and community during exceptional weather conditions.

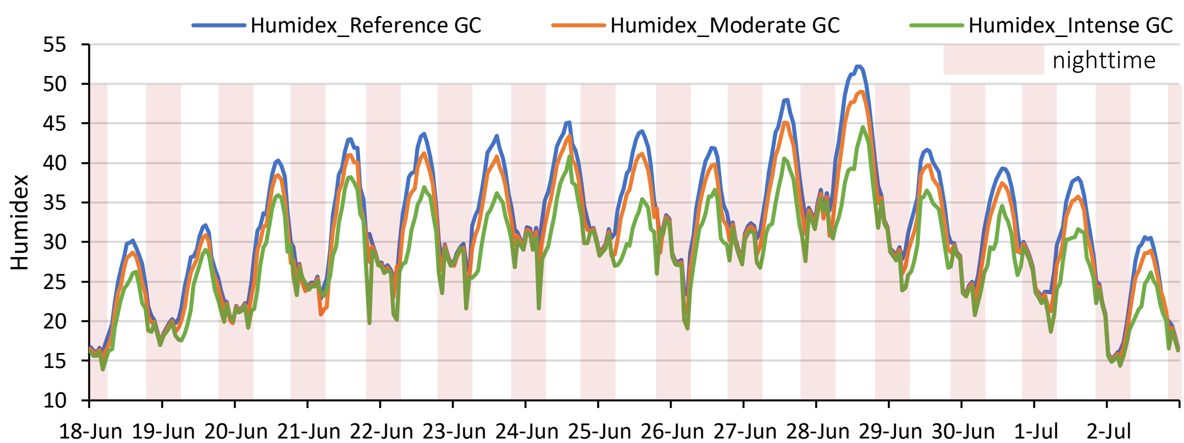


Figure 10: Hourly humidex values in Markham Village during the extreme weather scenario

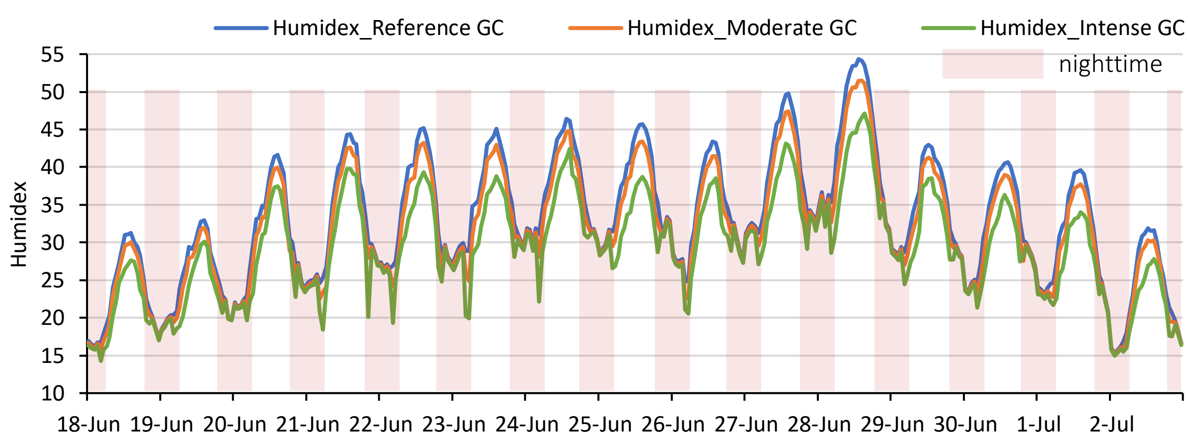


Figure 11: Hourly humidex values in East Woodbridge during the extreme weather scenario

During the typical summer season, the daily maximum humidex has been reduced from 40.6 for the reference GC to 38.2 for the Moderate GC and 34.1 for the Intense GC in Markham Village. It has also been reduced from 42.1 for the reference GC to 40.2 for the Moderate GC and 36.5 degrees for the Intense GC in East Woodbridge. This means that, by applying the Intense GC scenario, the heat warning conditions in Southern Ontario (when humidex > 40) can be avoided during a typical summer keeping the region thermally safe and comfortable during normal summer conditions.

2.1.2. Ambient temperature

Table 6 – Reduction in ambient temperature while applying Moderate and Intense GCs

Neighbourhood	DAs	Daily average Temperature (°C)			Daily maximum temperature (°C)		
		Reference GC	Moderate GC	Intense GC	Reference GC	Moderate GC	Intense GC
Markham Village	1	25.8	24.3 *(-5.8%)*	22.2 *(-14.0%)*	36.1	33.8 *(-6.4%)*	31.3 *(-13.3%)*
	2	25.7	24.6 *(-4.3%)*	22.7 *(-11.7%)*	35.8	34.1 *(-4.7%)*	32.1 *(-10.3%)*
	3	25.9	24.5 *(-5.4%)*	22.5 *(-13.1%)*	36.2	34.0 *(-6.1%)*	31.7 *(-12.4%)*
	4	25.7	24.4 *(-5.1%)*	22.4 *(-12.8%)*	35.6	34.1 *(-4.2%)*	31.8 *(-10.7%)*
	5	26.2	24.5 *(-6.5%)*	21.9 *(-16.4%)*	36.9	34.0 *(-7.9%)*	31.1 *(-15.7%)*
	6	26.3	24.7 *(-6.1%)*	22.4 *(-14.8%)*	37.1	34.4 *(-7.3%)*	31.7 *(-14.6%)*
	7	26.0	24.6 *(-5.4%)*	22.6 *(-13.1%)*	36.3	34.2 *(-5.8%)*	31.9 *(-12.1%)*
	8	25.6	24.5 *(-4.3%)*	22.7 *(-11.3%)*	35.4	34.1 *(-3.7%)*	32.0 *(-9.6%)*
	9	25.5	24.3 *(-4.7%)*	22.6 *(-11.4%)*	35.2	33.6 *(-4.5%)*	31.6 *(-10.2%)*
	10	25.7	24.3 *(-5.4%)*	22.3 *(-13.2%)*	35.6	33.8 *(-5.1%)*	31.5 *(-11.5%)*
	11	25.9	24.6 *(-5.0%)*	22.5 *(-13.1%)*	36.1	34.1 *(-5.5%)*	31.8 *(-11.9%)*
	12	25.8	24.4 *(-5.4%)*	22.4 *(-13.2%)*	35.8	33.8 *(-5.6%)*	31.6 *(-11.7%)*
	13	26.0	24.6 *(-5.4%)*	22.3 *(-14.2%)*	36.6	34.3 *(-6.3%)*	31.7 *(-13.4%)*
	14	25.9	24.6 *(-5.0%)*	22.7 *(-12.4%)*	36.0	34.1 *(-5.3%)*	31.9 *(-11.4%)*
	15	25.9	24.5 *(-5.4%)*	22.6 *(-12.7%)*	36.2	34.0 *(-6.1%)*	31.7 *(-12.4%)*
	16	25.8	24.6 *(-4.7%)*	22.5 *(-12.8%)*	36.0	34.2 *(-5.0%)*	31.9 *(-11.4%)*
	17	26.1	24.5 *(-6.1%)*	22.3 *(-14.6%)*	36.5	34.0 *(-6.8%)*	31.4 *(-14.0%)*
	18	26.1	24.5 *(-6.1%)*	22.3 *(-14.6%)*	36.5	34.2 *(-6.3%)*	31.6 *(-13.4%)*
East Woodbridge	1	26.5	25.5 *(-3.8%)*	23.8 *(-10.2%)*	37.4	35.2 *(-5.9%)*	33.3 *(-11.0%)*
	2	26.3	25.6 *(-2.7%)*	24.1 *(-8.4%)*	37.1	35.6 *(-4.0%)*	33.8 *(-8.9%)*
	3	26.7	25.4 *(-4.9%)*	23.3 *(-12.7%)*	38.0	35.2 *(-7.4%)*	32.8 *(-13.7%)*
	4	26.7	25.6 *(-4.1%)*	23.8 *(-10.9%)*	37.9	35.6 *(-6.1%)*	33.4 *(-11.9%)*
	5	26.8	25.6 *(-4.5%)*	23.6 *(-11.9%)*	38.2	35.7 *(-6.5%)*	33.3 *(-12.8%)*
	6	26.6	25.6 *(-3.8%)*	23.7 *(-10.9%)*	37.7	35.4 *(-6.1%)*	33.3 *(-11.7%)*
	7	26.6	25.4 *(-4.5%)*	23.4 *(-12.0%)*	37.8	35.2 *(-6.9%)*	32.9 *(-13.0%)*
	8	26.6	25.7 *(-3.4%)*	23.9 *(-10.2%)*	37.8	35.8 *(-5.3%)*	33.7 *(-10.8%)*
	9	27.1	25.5 *(-5.9%)*	23.4 *(-13.7%)*	38.9	35.7 *(-8.2%)*	33.1 *(-14.9%)*
	10	26.2	25.7 *(-1.9%)*	24.7 *(-5.7%)*	36.6	35.8 *(-2.2%)*	34.4 *(-6.0%)*
	11	26.7	25.6 *(-4.1%)*	23.6 *(-11.6%)*	38.0	35.6 *(-6.3%)*	33.3 *(-12.4%)*
	12	26.7	25.6 *(-4.1%)*	23.8 *(-10.9%)*	38.0	35.7 *(-6.1%)*	33.5 *(-11.8%)*
	13	26.4	24.9 *(-5.7%)*	22.9 *(-13.3%)*	37.9	34.9 *(-7.9%)*	32.5 *(-14.2%)*
	14	26.9	25.5 *(-5.2%)*	23.5 *(-12.6%)*	38.5	35.7 *(-7.3%)*	33.2 *(-13.8%)*
	15	26.8	25.7 *(-4.1%)*	23.9 *(-10.8%)*	38.2	36.0 *(-5.8%)*	33.6 *(-12.0%)*

The ambient temperature was modelled at the DA level in both neighbourhoods. Table 6 presents the average and maximum temperatures in Markham Village and East Woodbridge. The reduction in ambient temperature also responds to the intensity of the greenery cover as the greatest reductions have been observed with greater greenery cover percentages.

During the extreme weather scenario in Markham Village, the maximum reduction in daily average temperature is 1.7°C while applying the Moderate GC and 4.3°C while applying the Intense GC, and the maximum reduction in daily maximum temperature is 2.9°C while applying the Moderate GC and 5.8°C while applying the Intense GC. While in East Woodbridge, the maximum reduction is 3.7°C and 5.8°C in daily average and maximum temperatures, respectively, while applying the Intense GC scenario. Figure 13 includes the reductions in maximum temperature for all DAs in association with the increase in tree canopy cover for Moderate and Intense GCs. It can be observed that larger TC covers are associated with greater reductions in maximum temperature. Tracking Moderate and Intense GCs in both neighbourhoods, the reduction rate in temperature follows a non-linear behaviour. If an optimum GC is required, it is recommended to conduct a parametric analysis considering all study variables[14].

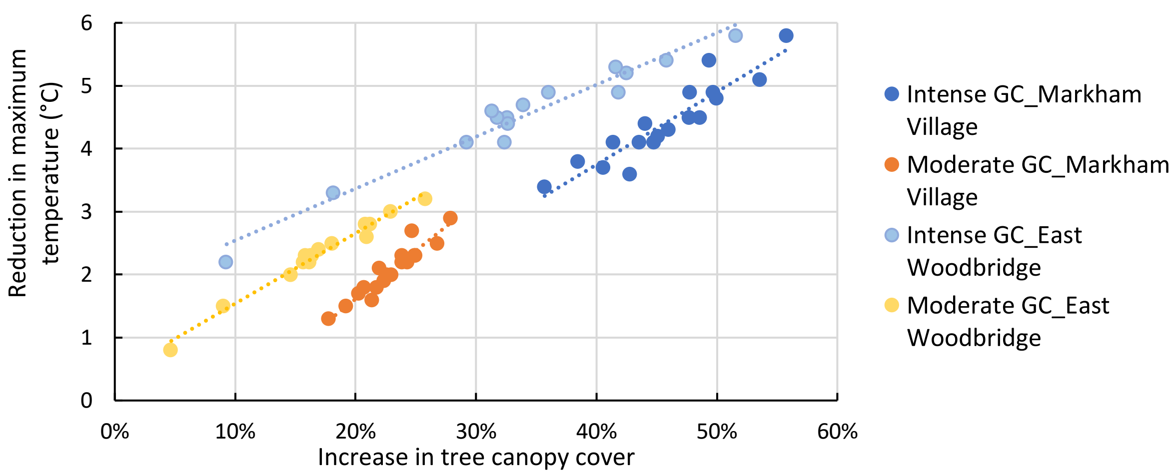


Figure 12: Reductions in maximum temperature in association with the increase in the tree canopy

Table 7 assesses the total area of both neighbourhoods during the heat event and typical summer season. During the extreme weather scenario, the results show 1.5°C and 1.3°C reductions in daily average temperature when applying the Moderate GC scenario in Markham Village and East Woodbridge, respectively. While they show 3.9°C and 3.6°C reductions in daily average temperature when applying the Intense GC scenario in Markham Village and East Woodbridge, respectively. Regarding the daily maximum temperature, the results report a maximum reduction of 5.2°C in East Woodbridge when applying the Intense GC scenario.

[14] (M. Dardir and Berardi 2021)

Table 7 – Reductions in temperature in both neighbourhoods (total areas)							
		Daily average Temperature (°C)			Daily maximum Temperature (°C)		
		Reference GC	Moderate GC	Intense GC	Reference GC	Moderate GC	Intense GC
Markham Village	Extreme weather scenario	25.5	24.0 *(5.9%)*	21.6 *(15.3%)*	36.2	34.0 *(6.1%)*	31.4 *(13.3%)*
	Typical summer season	16.6	15.6 *(6.0%)*	13.9 *(16.3%)*	31.8	29.6 *(6.9%)*	27.3 *(14.2%)*
East Woodbridge	Extreme weather scenario	26.4	25.1 *(4.9%)*	22.8 *(13.6%)*	38.2	35.5 *(7.1%)*	33.0 *(13.6%)*
	Typical summer season	17.3	16.4 *(5.2%)*	14.9 *(13.9%)*	33.2	31.4 *(5.4%)*	28.7 *(13.6%)*

Figures 14 and 15 explain the temperature behaviour during the heat wave when applying reference, Moderate, and Intense GCs. It is observed that the Intense GC reduces ambient temperatures even more during the hottest days of heat waves (see June 28) helping in reducing peak temperatures during the daytime. Normally, days qualify as very hot when the ambient maximum temperature is > 30°C. Within this heat event, 11 days qualify as very hot days; meanwhile, by applying the Intense GC scenario, the amount of very hot days is reduced. Only one day in Markham Village and three days in East Woodbridge remain > 30°C during the extreme heat event.

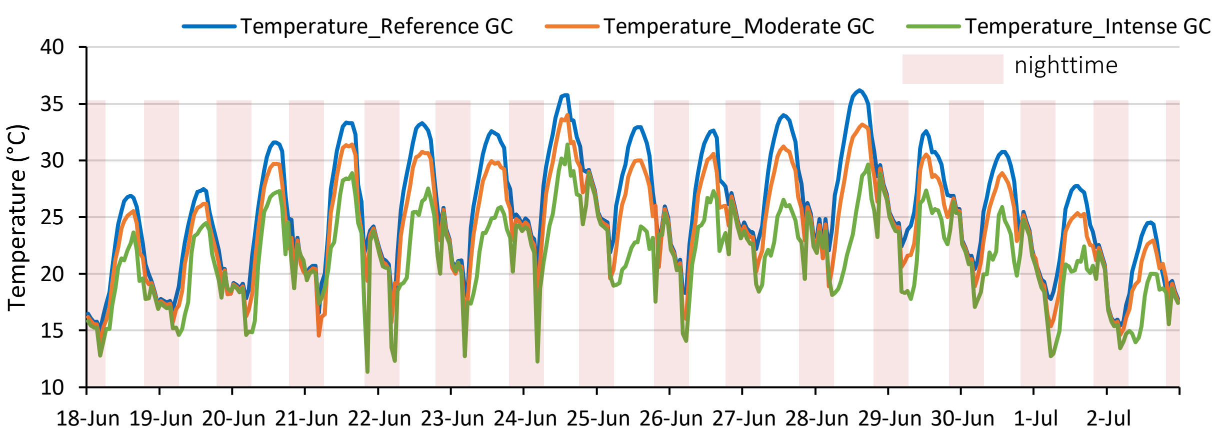


Figure 13: Ambient temperature in Markham Village during the extreme weather scenario

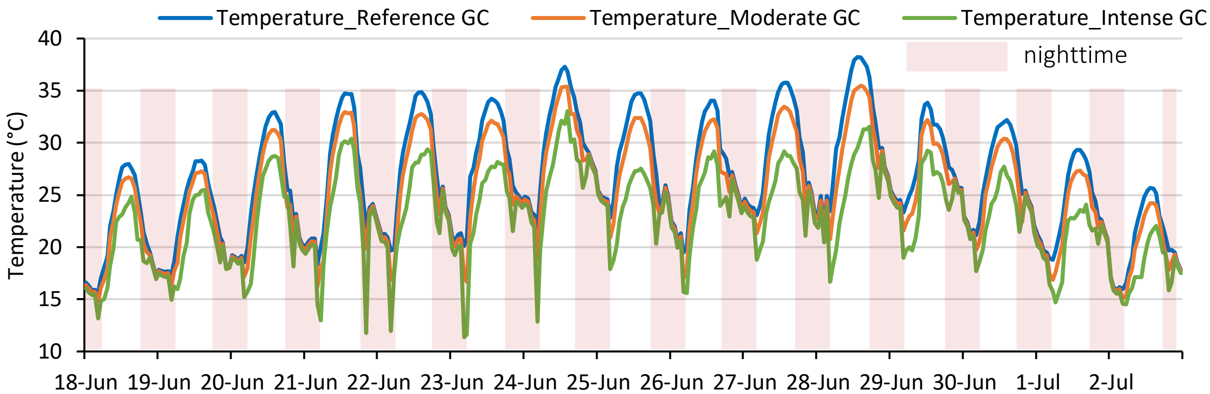


Figure 14: Ambient temperature in east Woodbridge during the extreme weather scenario

When applying the Intense GC scenario, we can observe significant reductions in the nighttime ambient temperatures. The daily minimum temperature in both neighbourhoods has been recorded between 11°C and 18°C. Cool nighttime temperatures provide comfortable conditions and maintain healthy physiological and psychological responses[15]. The great potential of cool nighttime temperatures contributes to the environment and body recovery from heat conditions. This cool temperature can also be utilized for night cooling, cross-natural ventilation, thermal storage systems, and other passive techniques[16] to provide extra cooling for the neighbourhood during the daytime.

During the typical summer season (Table 7), the results show 1°C and 0.9°C reductions in daily average temperature when applying the moderate GC scenario in Markham Village and East Woodbridge, respectively. While they show 2.7°C and 2.4°C reductions in daily average temperature when applying the Intense GC scenario in Markham Village and East Woodbridge, respectively. Regarding the daily maximum temperature, the results report a maximum reduction of 4.5°C in both neighbourhoods when applying the Intense GC scenario. Tracking the hot days within the neighbourhoods, 6 days in Markham Village and 14 days in East Woodbridge qualified as very hot (when the maximum temperature is > 30°C). By applying the Intense GC scenario, no hot days are recorded in both neighbourhoods during the typical summer season.

2.1.3. Energy Consumption

Building energy consumption refers to the electrical consumption for appliances and cooling. Active electric-based cooling systems are assumed for all buildings. Different building usages are considered within the neighbourhoods at the DA level. Accordingly, there is a substantial difference in the reference consumption between East Woodbridge, which hosts more commercial activities, and Markham Village. The energy consumption is presented in Table 8 in megawatts (MW), which refers to the cumulative daily electric power in each location.

[15] (Min, Lee, and Min 2021)
[16] (M. A. Dardir 2017; Chan, Riffat, and Zhu 2010)

Table 8 – Energy savings in average daily consumption (MW)						
DAs	**Markham Village**			**East Woodbridge**		
	Reference GC	Moderate GC	Intense GC	Reference GC	Moderate GC	Intense GC
1	65.5	59.7 *(-8.9%)*	46.5 *(-29.0%)*	50.8	48.9 *(-3.7%)*	44.6 *(-12.2%)*
2	37.4	34.1 *(-8.8%)*	26.9 *(-28.1%)*	94.7	92.2 *(-2.6%)*	89.1 *(-5.9%)*
3	45.9	43.8 *(-4.6%)*	38.3 *(-16.6%)*	114.0	111.1 *(-2.5%)*	100.1 *(-12.2%)*
4	61.3	55.4 *(-9.6%)*	43.3 *(-29.4%)*	137.7	131.6 *(-4.4%)*	126.5 *(-8.1%)*
5	76.0	71.9 *(-5.4%)*	56.8 *(-25.3%)*	85.8	82.6 *(-3.7%)*	77.1 *(-10.1%)*
6	76.2	72.0 *(-5.5%)*	62.3 *(-18.2%)*	50.1	48.3 *(-3.6%)*	42.9 *(-14.4%)*
7	46.0	41.8 *(-9.1%)*	32.7 *(-28.9%)*	74.9	71.4 *(-4.7%)*	66.6 *(-11.1%)*
8	72.0	64.8 *(-10.0%)*	52.0 *(-27.8%)*	69.1	67.4 *(-2.5%)*	61.2 *(-11.4%)*
9	31.5	28.2 *(-10.5%)*	22.1 *(-29.8%)*	143.8	134.2 *(-6.7%)*	111.3 *(-22.6%)*
10	59.9	53.3 *(-11.0%)*	41.1 *(-31.4%)*	30.2	30.0 *(-0.7%)*	28.6 *(-5.3%)*
11	35.1	31.6 *(-10.0%)*	24.1 *(-31.3%)*	84.5	82.2 *(-2.7%)*	71.9 *(-14.9%)*
12	46.2	41.6 *(-10.0%)*	32.1 *(-30.5%)*	97.1	93.5 *(-3.7%)*	88.8 *(-8.5%)*
13	83.0	77.8 *(-6.3%)*	63.4 *(-23.6%)*	743.0	700.7 *(-5.7%)*	586.6 *(-21.0%)*
14	44.1	42.0 *(-4.8%)*	36.9 *(-16.3%)*	181.1	172.1 *(-5.0%)*	147.4 *(-18.6%)*
15	47.1	43.2 *(-8.3%)*	34.3 *(-27.2%)*	102.9	100.7 *(-2.1%)*	91.3 *(-11.3%)*
16	77.9	72.0 *(-7.6%)*	57.5 *(-26.2%)*	-	-	-
17	45.0	42.5 *(-5.6%)*	35.0 *(-22.2%)*	-	-	-
18	54.4	50.0 *(-8.1%)*	39.5 *(-27.4%)*	-	-	-
Extreme weather scenario	**964.3**	**884.1 *(-8.3%)***	**682.4 *(-29.2%)***	**1847.0**	***1789.5* *(-3.1%)***	**1612.8 *(-12.7%)***
Typical summer season	**665.3**	**584.5 *(-12.1%)***	**419.2 *(-37.0%)***	**1377.7**	**1270.4 *(-7.8%)***	**1063.7 *(-22.8%)***

The greatest reductions are associated with greater increases in greenery cover and are related to building types within each DA. During the extreme heat event, applying the Moderate GC scenario achieves energy savings of up to 10.5% in Markham Village and up to 6.7% in East Woodbridge. While applying the Intense GC scenario achieves energy savings of up to 31.4% in Markham Village and up to 22.6% in East Woodbridge.

In total, during the extreme heat scenario, the average daily energy saving is 80 MW (equals 3.3 MWh) when applying Moderate GC and 282 MW (equals 11.8 MWh) when applying Intense GC in Markham Village. The average daily energy saving is 58 MW (equals 2.4 MWh) when applying Moderate GC and 234 MW (equals 9.8 MWh) when applying Intense GC in East Woodbridge. During the typical summer season, the average daily energy saving is 81 MW (equals 3.4 MWh) when applying Moderate GC and 246 MW (equals 10.3 MWh) when applying Intense GC in Markham Village. The average daily energy saving is 107 MW (equals 4.5 MWh) when applying Moderate GC and 314 MW (equals 13.1 MWh) when applying Intense GC in East Woodbridge.

2.2. Statistical Approach

Historical datasets for York Region were built containing daily health data and weather measurements for 17 years (from 2003 to 2019) focusing only on warm and hot seasons (from May to September) each year. The dataset was built using the records from the main urban settlements in York Region that have larger populations (Markham, Vaughan, Richmond Hill, Newmarket, and Aurora). The health data contain daily mortality records and daily emergency department visits. The health records were classified by cause and age into **all-cause records** and **vulnerable records** which were defined by integrating cause-based and elderly cases. The cause-based cases are the health records diagnosed by cardiorespiratory diseases at the time of hospital registration or death. The cardiorespiratory causes are described by the International Statistical Classification of Diseases and Related Health Code, Tenth Revision (ICD-10). The list of selected causes and more details about this statistical approach was published by M. Dardir, Wilson, and Berardi (2022)[17]. Elderly cases are the health records classified as elderly (> 65 years) at the time of hospital registration or death. The vulnerable records consider cases defined as elderly and diagnosed by selected causes.

The daily cause-based ambulance calls (Amb_C) are also traced within the Region. A relationship between Amb_C and municipal tree canopy was established by Graham et al.[18]. The authors confirmed a significant negative correlation (Spearman Rank correlation, $\rho = -0.094$) between TC and cause-based ambulance calls frequency. The cause-based ambulance calls included conditions of breathing problems, cardiorespiratory morbidity, headaches, heat/cold exposure, stroke accidents, and loss of consciousness. In our study, we assumed similar behaviour and used their published correlations to predict cause-based ambulance call behaviour based on the changes in greenery cover. The daily weather measurements were obtained by Environment Canada from the Toronto Buttonville Airport weather station (43.86N -79.37W), which is located 10 km away from Markham Village and 17 km away from East Woodbridge. The daily health records were retrieved from the Research Data Centres (RDCs) using Statistics Canada’s microdata of the Canadian Vital Statistics - Death Database (CVSD) for mortality counts including age, date of death, the underlying cause of death, and place of occurrence of death. The dataset also used the Canadian Census Health and Environment Cohort (CanCHEC) linked to the National Ambulance Care Reporting System (NACRS) to provide the daily counts of emergency department visits. The CanCHEC_NACRS database provides emergency department registrations including age, date of the medical service registration, the main and secondary diagnostic causes, and postal codes of residence. The conducted analyses respected data confidentiality and followed Statistics Canada’s guidelines and restrictions.

The dataset was built on a daily scale for humidex, all-cause mortality (MOR_all), vulnerable mortality (MOR_EC), all-cause emergency department visits (EMR_all), and vulnerable emergency department visits (EMR_EC). Both all-cause and vulnerable records were included as dependent variables in statistical models to evaluate their responses. The lagged impact of humidex on health records was considered for a week (the day of occurrence and 6 days after the incidence) to assess the possible impact of humidex on health records within this period. The developed method utilizes a correlational statistical approach by conducting a log-linear regression analysis among variables following a Poisson distribution. The analysis was conducted based on the month factor (May to September) to control the overdispersion behaviour and to enhance model fitting[19]. The daily counts were included in the dataset as one observation daily. In total, 24,145 mortalities (cases) and 410,115 emergency visits (cases) in 2,600 days (observations) were included in the dataset. The proposed approach delivers an evidence-based relationship to predict community health responses based on local environmental measures.

[17] (M. Dardir, Wilson, and Berardi 2022)
[18] (Graham et al. 2016)
[19] (Xie et al. 2013)

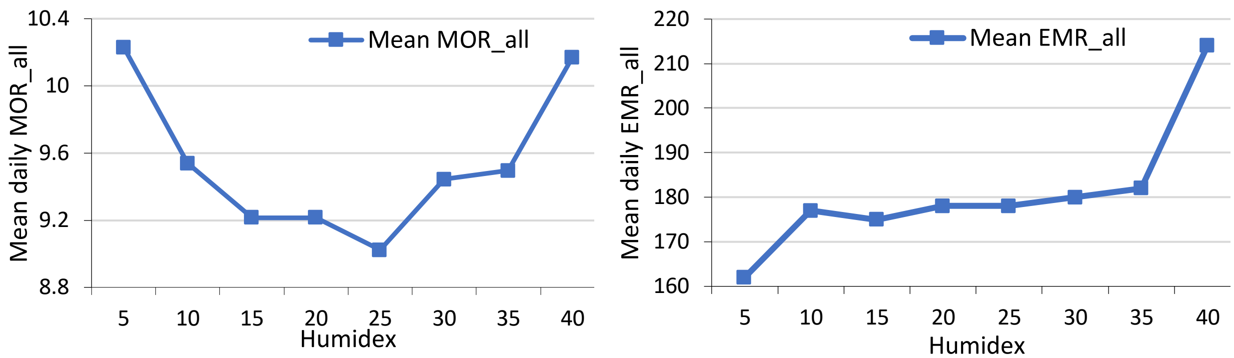


Figure 15: Average daily all-cause mortalities and emergency department visits in association with humidex during warm and hot seasons (May to September) for 17 years

The descriptive statistics for York Region, shown in Figure 16, reveal a daily average of 9.3 MOR_all and a daily average of 178.7 EMR_all. The average daily humidex is 21.1 degrees, according to historical records, with a 95% percentile of 31.8 degrees. With higher humidex values during extreme heat events (humidex ~ 40 degrees), the health records have reported higher values than in moderate conditions. The average daily all-cause mortalities reach up to 10.2 and the average daily all-cause emergency visits reach up to 214. With low humidex values, we notice another peak in mortality records. This could be caused by other possible effects of environmental changes that could contribute to mortality rates. Other environmental risks like flooding and storms that can be associated with low humidex values may contribute to higher mortality rates. Other prolonged environmental effects and accidental-based health records can also contribute to these not-heat-based peaks.

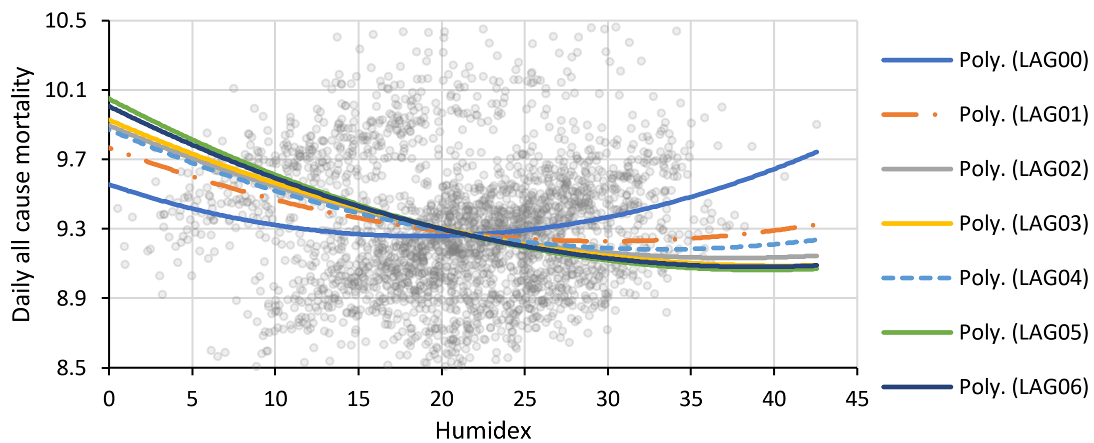
In all regression analyses, variations in humidex value in different months and/or days of the week were considered as a factor variable. Significance (*p-value*), standard error, and degree of dependence (*deg. dep.*) were analyzed to test model behaviour. A lower *p-value* (< 0.05) indicates high statistical significance between variables. The standard error defines the variability around the estimate of a variable, the smaller the standard error, the better the predictive ability of a resulting regression model. The *deg. dep.* indicates how far a variable impacts the dependent variable; the higher the *deg. dep.*, the stronger effect a variable has on the predictive regression.

2.2.1. All-cause Mortalities

The regression analysis was conducted between daily MOR_all records (dependent variable) and daily average humidex. Table 9 shows the predictive regression for humidex-based MOR_all in York Region. The variation in humidex in different months was traced and the impact of humidex on MOR_all was higher in May and June (see coefficient values). This reflects the higher impact of heat on mortality rates in warm seasons (transitional seasons) than in summer seasons. This refers to the possible hazardous impact of climate change on health when heat events occur unexpectedly.

Table 9 – Regression analysis of all-cause mortality				
Log (MOR_all) = 0.004 × Humidex + 2.14 + $n_{(Month)}$				
Parameter	Coeff.	Std. Error	*deg. dep.*	*p-value*
(Intercept)	2.140	0.0277	6610.992	0.000
Month			30.441	0.000
May	0.087	0.0217		
June	0.018	0.0211		
July	-0.048	0.0224		
August	-0.003	0.0217		
September	0	.		
Humidex	0.004	0.0012	10.042	0.002

The lagged effect of heat conditions has also been considered to assess the lagged impact of humidex on MOR_all within this period. The results, shown in Figure 17, confirm the short-term impact of humidex (within 4 days) on mortality, framing the serious and direct impact of heat waves on mortality records. The health responses to the humidex on the same day (Lag00) are the most significant followed by one-day lagged responses. This result was previously proved by a similar study in the GTA by the authors[20]. Many researchers confirmed this conclusion[21] and this impact was noticed in 2021 in British Columbia where mortality counts were tripled during a heat wave[22].



Log (MOR_all) = 0.006 $Hmdx_{(00)}$ - 0.003 $Hmdx_{(01)}$ + 0.001 $Hmdx_{(02)}$ - 0.003 $Hmdx_{(03)}$ + 0.005 $Hmdx_{(04)}$ - 0.004 $Hmdx_{(05)}$ + 0.001 $Hmdx_{(06)}$ + 2.155 + $n_{(Month)}$

Figure 16: Graphical illustration of the lagged effect of humidex on mortality

[20] (M. Dardir, Wilson, and Berardi 2022)
[21] (Harlan et al. 2014; Tsekeri, Kolokotsa, and Santamouris 2020; Kolb et al. 2010)
[22] (Henderson et al. 2022)

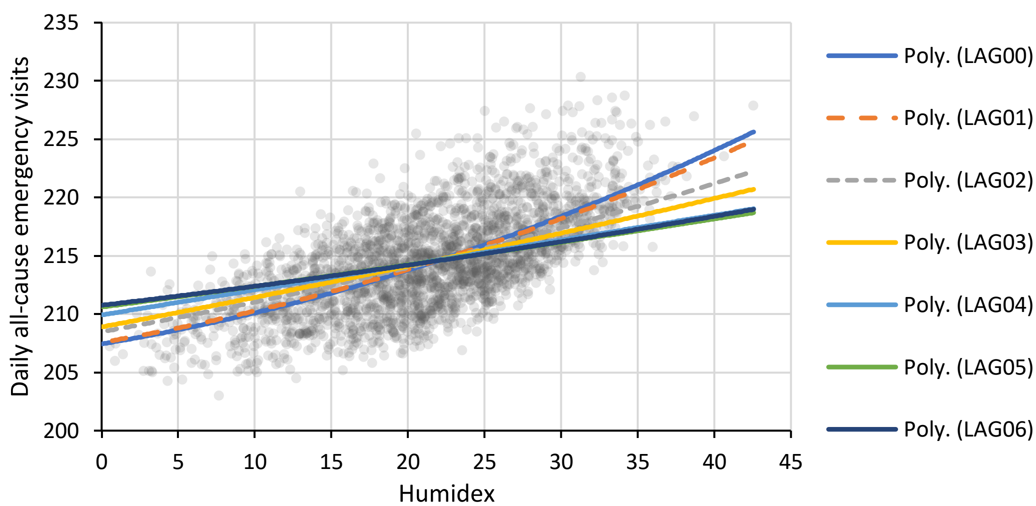
2.2.2. All-cause Emergency Department Visits

The relationship between daily EMR_all and humidex is shown in Table 10 tracking the variations in months and days of the week. The impact of the days' factor on EMR_all was remarkably significant with a high *deg. dep.* value. The visits during the weekdays were significantly higher (63% more) than those on weekends. The impact of humidex was also higher in May and June. Also, the lagged effect of heat conditions on EMR_all has been traced. Similar to mortality rates, Figure 18 confirms the short-term impact of humidex (within the first 2 days) on EMR_all. The direct impact of humidex (Lag00) is the greatest on health responses with the most statistical significance.

Table 10 – Regression analysis of all-cause emergency department visits

Log (EMR_all) = 0.003 × Humidex + 4.653 + $m_{(Day)}$ + $n_{(Month)}$

Parameter	Coeff.	Std. Error	*deg. dep.*	*p-value*
(Intercept)	4.653	0.0074	583327.265	0.000
Day			22248.713	0.000
Weekday	0.627	0.0042		
Weekend	0	.		
Month			94.041	0.000
May	0.027	0.0053		
June	0.010	0.0051		
July	-0.025	0.0054		
August	-0.019	0.0053		
September	0	.		
Humidex	0.003	0.0003	74.594	0.000

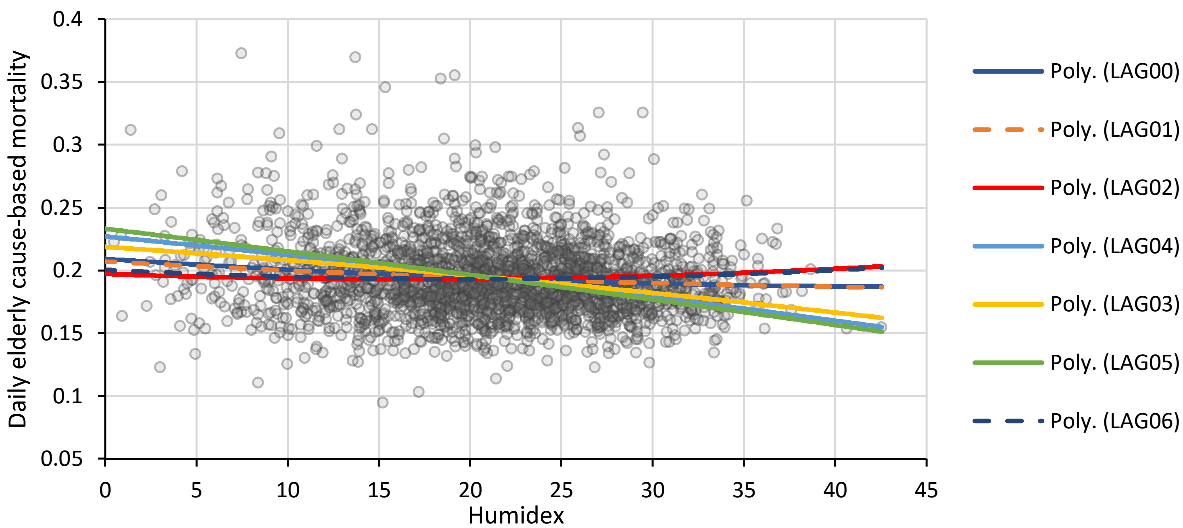


Log (EMR_all) = 0.002 $Hmdx_{(00)}$ + 0.001 $Hmdx_{(01)}$ + 0.001 $Hmdx_{(03)}$ + 0.001 $Hmdx_{(06)}$ + 4.638 + $0.626_{(Weekday)}$ + $n_{(Month)}$

Figure 17: Graphical illustration of the lagged effect of humidex on all-cause emergency department visits

2.2.3. Vulnerable Mortality

As defined above, the vulnerable records consider cases defined as elderly and diagnosed by selected causes. The vulnerable mortality (MOR_EC) suffers from data limitations in the dataset. However, the analysis shows that there is a limited relationship between MOR_EC and humidex. The impact of lagged humidex values on MOR_EC, shown in Figure 19, reveals that a higher effect of humidex on MOR_EC occurs in Lag02 and Lag06 (after 2 to 6 days of heat event). A relatively longer-term impact of heat is observed on MOR_EC that is related to respiratory and cardiovascular causes. The vulnerable mortality shows no response to the factor of months.

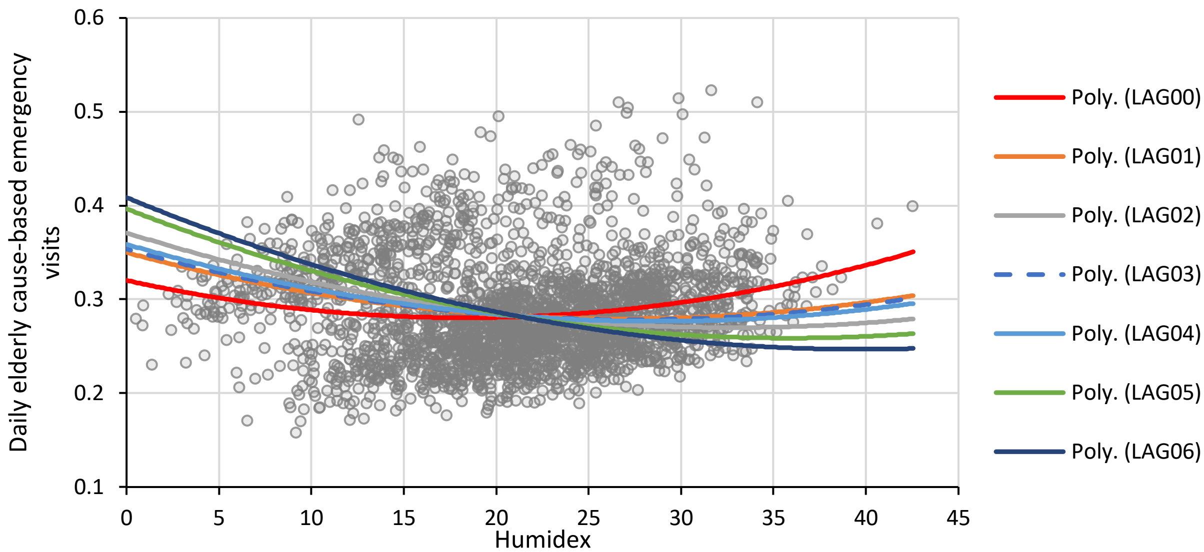


$$Log\ (MOR\_EC) = 0.003\ Hmdx_{(00)} - 0.017\ Hmdx_{(01)} + 0.034\ Hmdx_{(02)} - 0.028\ Hmdx_{(03)} + 0.015\ Hmdx_{(04)} - 0.038\ Hmdx_{(05)} + 0.027\ Hmdx_{(06)} - 1.567$$

Figure 18: Graphical illustration of the lagged effect of humidex on vulnerable mortality

2.2.4. Vulnerable Emergency Department Visits

The relationship between daily vulnerable emergency department visits (EMR_EC) and humidex is established considering the variations in months and days of the week. The variations in humidex in warm seasons (with the highest impact in May) and weekdays have higher impacts on EMR_EC. EMR_EC during the weekdays was 16.5% higher than those on weekends. Unlike vulnerable mortalities, the lagged effect of the heat conditions, shown in Figure 20, shows that there is a larger short-term impact of high humidex values (within the same day) on EMR_EC. The direct impact of humidex (Lag00) is the greatest on health responses with the most statistical significance.



$$Log\ (EMR\_EC) = 0.023\ Hmdx_{(00)} - 0.004\ Hmdx_{(01)} - 0.014\ Hmdx_{(02)} + 0.012\ Hmdx_{(03)} + 0.011\ Hmdx_{(04)} - 0.009\ Hmdx_{(05)} - 0.006\ Hmdx_{(06)} - 1.789 + 0.165_{(Weekday)} + n_{(Month)}$$

Figure 19: Graphical illustration of the lagged effect of humidex on vulnerable emergency department visits

2.2.5. Impact of Extreme Heat

Extreme heat was defined in the dataset when humidex values exceeded their 95th percentile which was found to be 31.8 degrees. Regression analyses were conducted on MOR_all and EMR_all considering the 95th percentile of humidex. The data points (health records) during extreme heat in York Region were limited; however, regression models, shown in Table 11, report higher impacts of humidex on health records than these of the general model that considered all humidex values. Referring to regression coefficients, the 95th percentile of humidex impacts MOR_all by 1.2% while all humidex values have an effect of 0.4% on MOR_all. Also, the 95th percentile of humidex impacts EMR_all by 3.1% while all humidex values have an effect of 0.3% on EMR_all. Thus, the results proved the dangerous sequences of extreme heat on elevating health records.

Table 11 – Regression analysis of MOR_all and EMR_all during extreme heat

	Parameter	Coeff.	Std. Error	*deg. dep.*	*p-value*
Dependent variable:	(Intercept)	1.858	0.5236	12.594	0.000
Log(MOR_all)	Humidex_Pctile95	0.012	0.0155	0.563	0.453
Dependent variable:	(Intercept)	4.186	0.1230	1157.757	0.000
Log(EMR_all)	Humidex_Pctile95	0.031	0.0036	73.296	0.000

2.2.6. Cause-based Ambulance Calls

Cause-based ambulance calls (Amb_C) were defined above by specific causes. Graham et al.[23] previously established the prediction of daily Amb_C in Toronto in association with the municipal tree canopy. In the current study, we used their published correlations to predict the Amb_C behaviour based on the changes in greenery cover assuming the same behaviour in York Region. Figure 21 shows the predicted ambulance calls based on the tree canopy. There was a non-linear behaviour of Amb_C in response to TC cover. There was a large increase in Amb_C when TC cover was below 10%. Generally, the lower the TC cover, the higher the expected Amb_C within the Region. The correlations are adapted to the population of York Region.

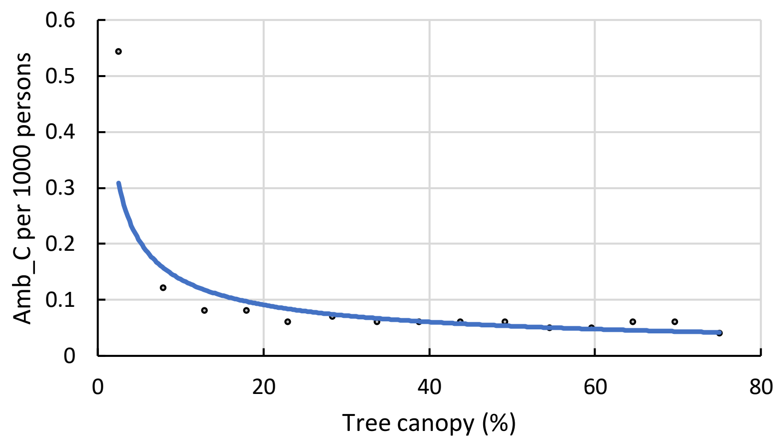


Figure 20: Prediction of ambulance calls based on the tree canopy

2.3. Heat-based Health Predictions

Based on York Region's historical datasets, the statistical outputs are used to predict the changes in health records based on the environmental changes in the case studies. The nonlinear regression built relationships between health records (dependent variables) and humidex values (independent variables). Based on changes in humidex, the prediction of the expected health records is provided. The absolute values of health records predictions are related to York Region rates, assuming similar heat mitigation strategies used in the case studies to be applied around the Region. Based on reference GC, Moderate GC, and Intense GC scenarios and resulting humidex values, the regression models were used to forecast values of MOR_all, MOR_EC, EMR_all, EMR_EC, and Amb_C considering the upgrading conditions in the two case studies. The health responses were predicted during the extreme weather scenario and typical summer season using the simulated values of humidex.

[23] (Graham et al. 2016)

2.3.1. Daily Mortality Counts

The daily MOR_all and MOR_EC were predicted based on the changes in GC scenarios in Markham Village and East Woodbridge in Table 12. The prediction was conducted during the extreme weather scenario and the typical summer season. The table presents the range of daily average values of the health records.

Table 12 – Prediction of all-cause and vulnerable mortalities							
		Daily all-cause mortality* (MOR_all)			Daily vulnerable mortality* (MOR_EC)		
		Reference GC	Moderate GC	Intense GC	Reference GC	Moderate GC	Intense GC
Based on Markham Village	Extreme heat weather	9.9 ± 0.4	9.8 ± 0.4	9.7 ± 0.3	0.19 ± 0.05	0.19 ± 0.05	0.19 ± 0.05
	Typical summer season	10.0 ± 0.6	10.0 ± 0.5	9.9 ± 0.5	0.20 ± 0.20	0.20 ± 0.20	0.20 ± 0.20
Based on East Woodbridge	Extreme heat weather	9.9 ± 0.4	9.8 ± 0.4	9.7 ± 0.4	0.19 ± 0.06	0.19 ± 0.05	0.19 ± 0.05
	Typical summer season	10.0 ± 0.6	10.0 ± 0.6	9.9 ± 0.6	0.20 ± 0.20	0.20 ± 0.20	0.20 ± 0.20
* The absolute rates are region-based predictions							

Assuming similar scenarios around the Region, during the extreme weather scenario, the forecasted average MOR_all is reduced by one person every 10 days (a 0.1 reduction of the daily average MOR_all) by applying Moderate GC, and reduced by two persons every 10 days by applying Intense GC. During the typical summer season, applying the Intense GC reduces the forecasted average MOR_all by one person every 10 days equivalent to 15 avoided deaths due to heat-related causes every summer season (May-September).

These reductions are doubled if we consider the maximum mortality rates as a worst-case scenario. The forecasted maximum MOR_all is reduced by three and two persons every 10 days if we consider the case study of Markham Village and East Woodbridge, respectively, by applying the Intense GC scenario during the extreme weather scenario. The forecasted maximum MOR_all is reduced by two and one person every 10 days based on Markham Village and East Woodbridge scenarios, respectively, by applying the Intense GC scenario during the typical summer season. The reductions in MOR_all are slightly higher if we considered Markham Village scenarios where a denser greenery cover is available. This refers to the efficiency of denser GCs in reducing mortalities during the hot season.

Figure 22 shows the daily behaviour of MOR_all in York Region based on Markham Village and East Woodbridge when applying the Intense GC during the extreme weather scenario. Greater reductions in mortalities are achieved during peak days of the heat event. For example, based on Markham Village scenarios, on June 28 (a peak of the heat wave), MOR_all was reduced by 0.25 compared to a 0.1 reduction on June 18. The increase in greenery cover provides more protection during heat events, and the reduction in mortalities is even more pronounced during peaks of heat waves.

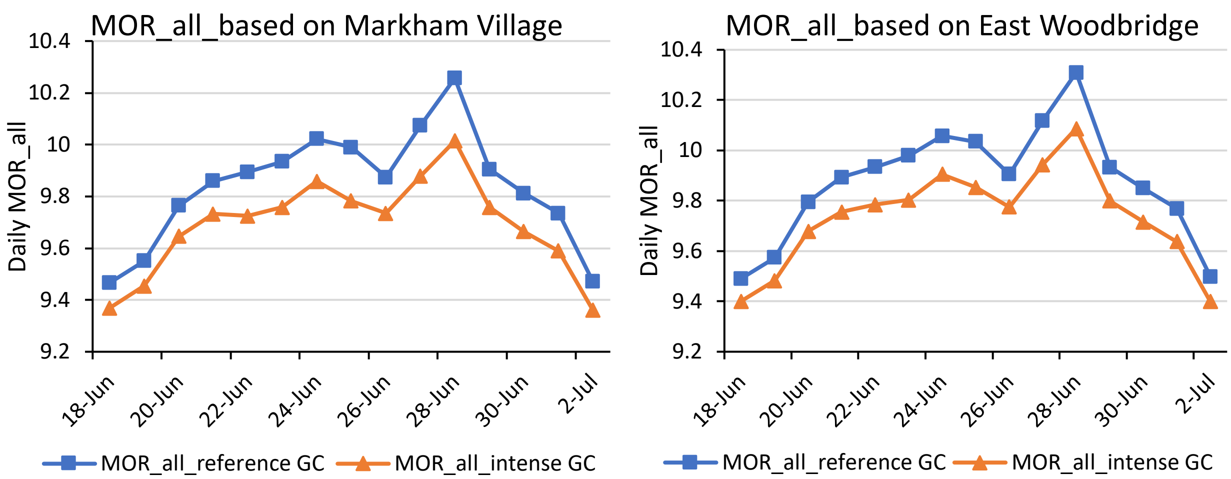


Figure 21: Predictions of MOR_all during extreme weather when applying the Intense GC scenario

Figure 23 shows that the average daily MOR_all is higher during the typical summer season because it takes into consideration the higher mortality rates during warm months (May and June) as indicated by the regression analysis. Applying the Intense GC scenario reduces the predicted MOR_all for both average and maximum values. This reduction is greater during the extreme weather scenario.

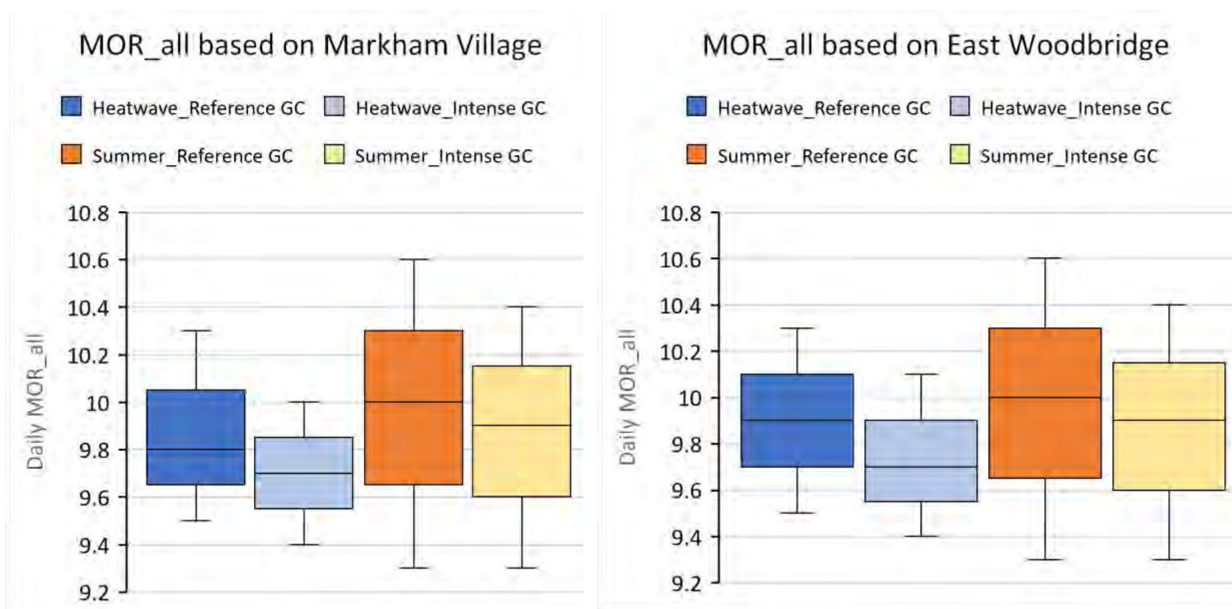


Figure 22: Predictions of all-cause mortality when applying the Intense GC scenario

For vulnerable mortality (MOR_EC), in Table 12, the analysis did not monitor significant changes to the mortality counts, especially in the summer season, between reference, moderate, and intense scenarios. As reported earlier, MOR_EC are more responsive to a lagged period and do not respond instantly to heat conditions. In Figure 24, the predicted period has been extended to include a week after the heat wave to track the lagged impact. We can see that higher MOR_EC occurs on delayed days from heat wave peak days. Occasionally, a slight increase in MOR_EC is recorded in association with Intense GC (see June 26) due to a possible increase in humidity level related to the increased vegetation.

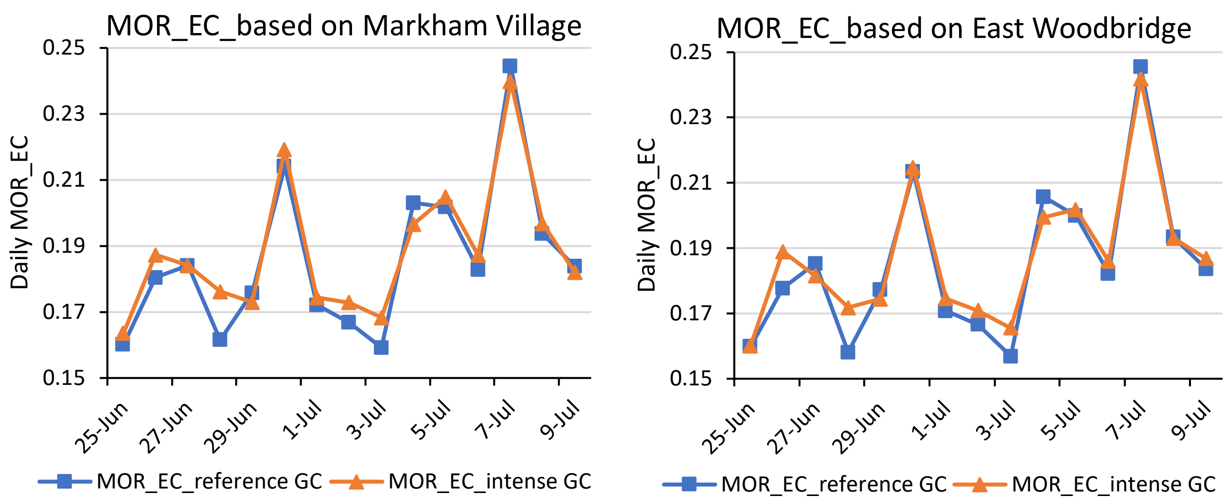


Figure 23: Prediction of vulnerable mortality (MOR_EC) during the extreme weather scenario when applying the Intense GC scenario

2.3.2. Daily Emergency Department Visits

The daily all-cause emergency department visits (EMR_all) are predicted during both the extreme heat event and the typical summer season (see Table 13). During the extreme weather scenario, the daily EMR_all is reduced by 1 to 1.6 visits by applying the Moderate GC and reduced by 2.5 to 4 visits by applying the Intense GC scenario. During the typical summer season, the expected daily average EMR_all is reduced by 1.7 visits. On average, annual EMR_all during the summer season could be decreased by 255 visits based on Markham Village scenarios and 225 visits based on East Woodbridge scenarios.

Table 13 – Predictions of all-cause and vulnerable emergency department visits

		Daily all-cause emergency visits* (EMR_all)			Daily vulnerable emergency visits* (EMR_EC)		
		Reference GC	Moderate GC	Intense GC	Reference GC	Moderate GC	Intense GC
Based on Markham Village	Extreme weather scenario	218.4 ± 6.9	217.4 ± 6.3	215.9 ± 5.4	0.34 ± 0.10	0.34 ± 0.09	0.32 ± 0.07
	Typical summer season	213.5 ± 9.2	212.9 ± 8.8	211.8 ± 8.2	0.38 ± 0.11	0.37 ± 0.11	0.37 ± 0.12
Based on East Woodbridge	Extreme weather scenario	219.0 ± 7.2	218.1 ± 6.7	216.6 ± 5.9	0.35 ± 0.11	0.34 ± 0.10	0.33 ± 0.08
	Typical summer season	213.9 ± 9.4	213.4 ± 8.9	212.4 ± 8.5	0.38 ± 0.12	0.38 ± 0.11	0.37 ± 0.11

* The absolute rates are region-based predictions

Unlike the mortality records, EMR_all is more responsive to heat conditions and EMR_all records are higher during the heat wave, as shown in Figure 25. Also, greater reductions in EMR_all are achieved during the heat wave due to applying the Intense GC scenario.

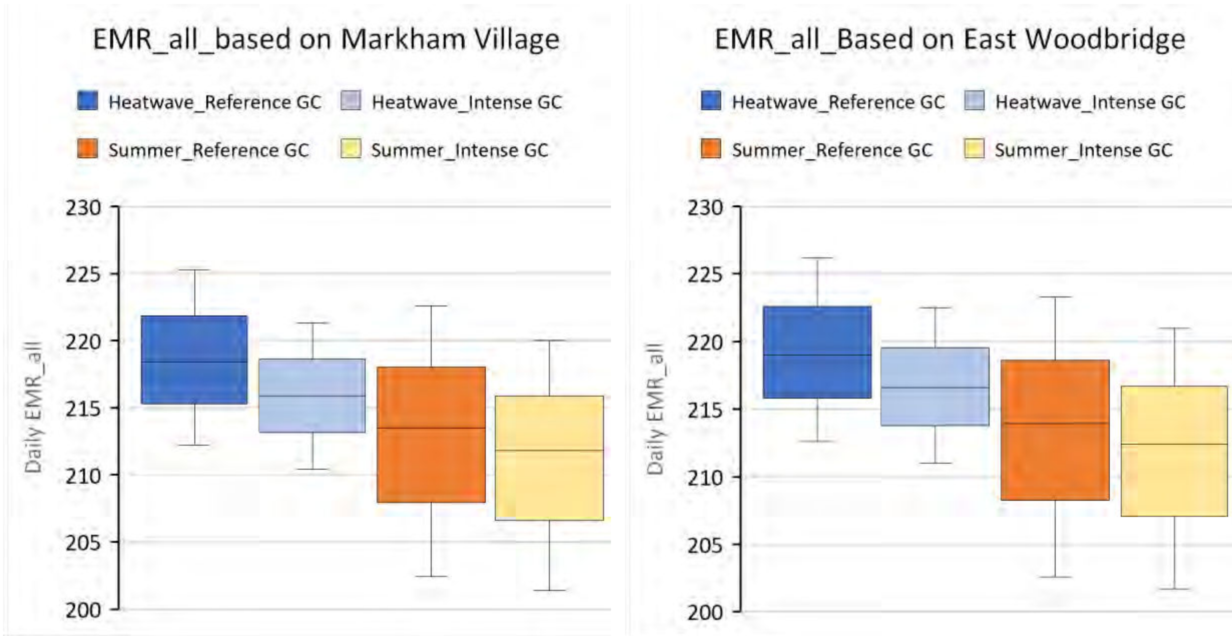


Figure 24: Effect of applying the Intense GC scenario on all-cause emergency visits during the heat wave and summer season

The daily behaviour of EMR_all during the extreme weather scenario, shown in Figure 26, follows the behaviour of MOR_all during extremely hot days. The reductions in the humidex values associated with intensifying the greenery cover reduce the number of all-cause emergency visits, with even greater reductions noticed during the peaks (see June 28).

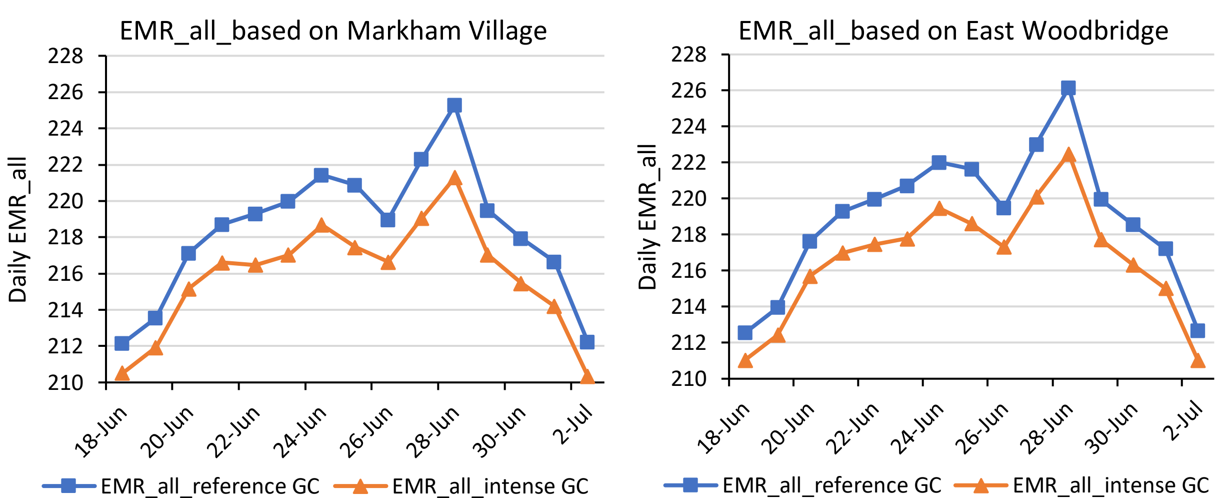


Figure 25: Prediction of all-cause emergency department visits when applying the Intense GC scenario

Unlike vulnerable mortality, vulnerable emergency department visits (EMR_EC), in Table 13, respond directly to heat behaviour. The effect of the Intense GC scenario on controlling EMR_EC is limited; however, as shown in Figure 27, the highest impacts are noticed on extremely hot days.

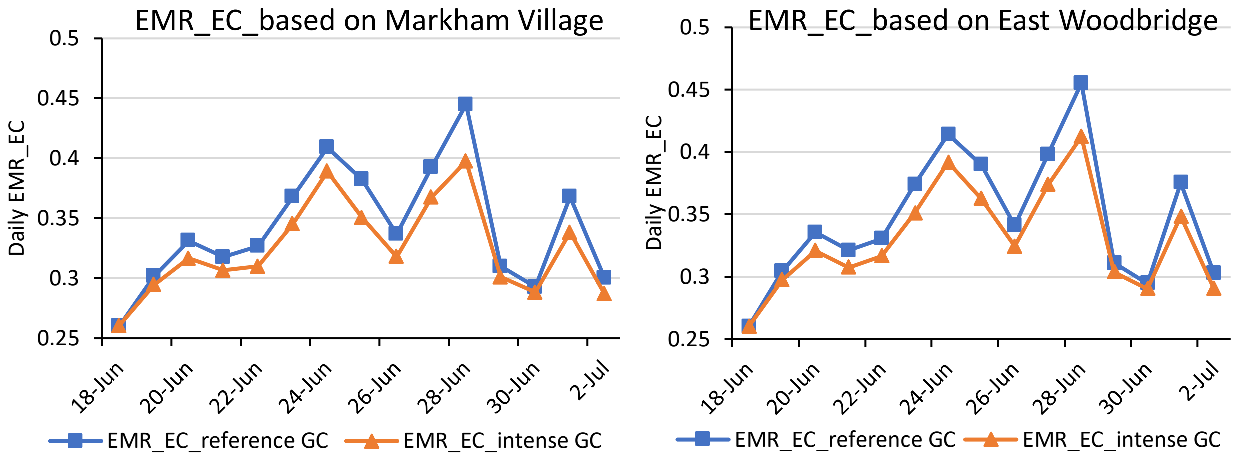


Figure 26: Vulnerable emergency visits predictions during the heat event when applying the Intense GC scenario

2.3.3. Daily Cause-based Ambulance Calls

The daily cause-based ambulance calls (Amb_C) respond to the changes in tree canopy cover as described above. For the analysis, the rates of Amb_C are adapted to the population of York Region. Table 14 shows that by applying the Moderate GC scenario, the daily Amb_C is reduced by 35 and 52 calls based on Markham Village and East Woodbridge scenarios, respectively. By applying the Intense GC scenario, the daily Amb_C is reduced by 56 and 69 calls based on Markham Village and East Woodbridge scenarios, respectively.

Table 14 – Reduction in cause-based ambulance calls respecting the greenery cover

	Ambulance calls*_based on Markham Village			Ambulance calls*_based on East Woodbridge		
DAs	Reference GC	Moderate GC	Intense GC	Reference GC	Moderate GC	Intense GC
Total	159.4	124.0 *(-22.2%)*	103.9 *(-34.8%)*	123.4	71.4 *(-42.1%)*	54.0 *(-56.2%)*

* The absolute rates are region-based predictions

3. Economic Benefits

Mitigating the impact of extreme heat provides direct economic benefits as a result of avoided premature mortality, health system savings, lower energy use, and increased worker productivity. Table 15 lists the benefits, which were included in this study. To calculate the associated benefits at the level of York Region, we assume that the two case studies are a good representation of the entire region, economically and demographically.

Table 15 - List of economic benefits considered in the study

▪ Avoided premature mortality
▪ Health system savings
  o Reduction in ambulatory calls
  o Reduction in emergency department visits
▪ Energy savings
▪ Increased worker productivity

3.1. Avoided Premature Mortality

Extreme temperatures result in higher levels of mortality. All-cause mortalities are used to calculate the benefits of avoided mortality. Based on the statistical modelling, the reductions in humidex based on Intense GC scenario resulted in 15 fewer deaths in York Region in a typical year during the summer season. We adopt the economic cost of an avoided premature death of CAD $7.5 million ($2016) used by Health Canada[24] in a 2021 analysis of the health impacts of air pollution which is equivalent to CAD $8.9 million ($2022). The value is adopted by Health Canada for policy analysis and is the recommended estimate for policy analysis in Canada[25]. It is based on a review of Canadian studies by Chestnut and De Civita (2009)[26] examining the willingness to pay Canadians to reduce the risk of premature death by 1 out of 100,000. As clearly noted by Health Canada, the value is "*not equivalent to the economic worth of an identified person's life, but rather an aggregation of individual values people is willing to pay for small changes in risk*". The annual economic benefit of reduced early mortality attributed to increasing greenery cover during a typical summer season is CAD $133.5 million.

Annual economic benefit of reduced early mortality
15 avoided premature deaths x CAD 8.9 million = CAD 133.5 million (region-based)

3.2. Health System Savings

[24] (Health Canada 2021)
[25] (OECD 2011)
[26] (Chestnut and Civita 2009)

Health system savings are attributed to reducing emergency department visits, ambulance calls, and hospital admissions. Hospital admissions are omitted from this study due to insufficient data. Health system savings, therefore, equals the avoided health system costs attributed to reducing demands on emergency departments and fewer ambulatory calls.

3.2.1. Avoided Costs of Emergency Department Visits

According to Canadian Institute for Health Information, Canadian Management Information System (MIS) database, the cost of an emergency department visit in Ontario[27] in 2018 was CAD $304 which is equivalent to CAD $347 ($2022). The average reduction in emergency department visits was estimated to be 255 visits based on Markham Village scenarios and 225 based on East Woodbridge scenarios. We considered an average reduction of visits in York Region of 240 visits during the summer season associated with applying the intense greenery cover scenario. The annual economic benefit of fewer emergency department visits attributed to the mitigation of hot temperatures provided by the intense greenery cover scenario in a typical summer season is CAD $83,280.

Annual economic benefit of reduced emergency department visits
240 avoided emergency visits x CAD 347 = CAD 83,280 (region-based)

3.2.2. Avoided Costs of Ambulance Calls

The average cost of an ambulance call is CAD $240 in Ontario[28] ($2022). Based on the modelling, the reduction in daily ambulance calls attributed to applying the Intense GC scenario is 56 and 69 calls based on Markham Village and East Woodbridge scenarios, respectively. We considered an average value of 62 for the reduction in daily cause-based ambulance calls around York Region. The daily economic benefit of avoided ambulance calls attributed to the intense greenery cover scenario is CAD $14,880.

Daily economic benefit of reduced ambulance calls
62 avoided ambulance calls x CAD 240 = CAD 14,880 (region-based)

3.2.3. Energy Savings

The cooling effect and shading of adjacent houses and buildings provided by the intense tree canopy and vegetation cover reduce the need for air conditioning and other cooling-related energy use. As noted, during a typical summer season, applying the Intense GC scenario reduces the average daily energy demand by 246 MW and 314 MW in Markham Village and East Woodbridge, respectively. We assume our case studies are representative of the region in terms of behaviour. Accordingly, we considered an average value of 280 MW (neighbourhood-based) for daily energy savings attributed to the Intense GC scenario. Based on the population of York Region in 2022, assuming a normal distribution, we assume that each of the studied neighbourhoods hosts 0.5% of the Region's population. This means that the energy savings for the entire Region when the Intense GC scenario is applied is 200 times the neighbourhood average savings. Based on Ontario Energy Board[29] 2022 summer pricing we apply a mid-peak or tier 2 rate of 11.3 cents per

[27] (Canadian Institute for Health Information 2022b)
[28] (Canadian Institute for Health Information 2022a)
[29] (Ontario Energy Board 2022)

kilowatt hour. The daily economic benefit of energy savings attributed to the Intense GC scenario in a typical summer season per neighbourhood is CAD $1,318.

Daily economic benefit of energy savings
280,000 kW / 24 hours x CAD 0.113 = CAD 1,318 (neighborhood-based)
280,000 kW / 24 hours x 200 x CAD 0.113 = CAD 263,667 (region-based)

3.2.4. Increased Worker Productivity

A small rise in temperature makes individuals more irritable and reduces the concentration and ability of workers to do their tasks properly causing a decline in productivity[30]. During the summer season, outdoor workers in industrial occupations lose on average of 22 hours due to increased breaks attributed to heat exposure[31], equivalent to approximately 1% of total hours worked in a year. Based on a mean hourly wage of CAD $33.86 (August 2022), this is equivalent to an economic loss of CAD $744.92 per outdoor worker every year or CAD $37.25 per hot day, assuming 20 hot days per summer season[32]. Referring to the modelling results, the number of days that qualify as very hot (ambient maximum temperature > 30°C) was reduced by 6 days in Markham Village and by 14 days in East Woodbridge as a result of applying the Intense GC scenario. On average, we considered that the cooling effect provided by the Intense GC scenario reduces the hot days by 10 days, resulting in CAD $372.50 annually per outdoor worker in avoided productivity losses.

A study by Peters et al. (2015)[33] using the Canadian Carcinogen Exposure database estimates that 8.8% of the Ontario labour force work in professions that expose them to dangerous solar radiation. According to York Region's 2016 Census Release Report, 67% of the Region's population is in the labour force. Assuming the same rate in 2022, there are 804,603 people in the labour force. Assuming a similar exposure rate to solar radiation as the Ontario average, 70,805 workers are in professions that expose them to solar radiation. The annual economic benefit of increased worker productivity attributed to the increase in the greenery cover in a typical summer season is CAD $26,374,862.

Annual economic benefit of avoided productivity losses
70,805 workers x $372.5 = CAD 26,374,862 (region-based)

3.2.5. Cost Estimation of Greenery Cover

Table 16 – Ground vegetation cover (GVC) and tree canopy (TC) of the green cover scenarios

	Moderate GC scenario		Intense GC scenario	
	GVC (km^2)	**TC (trees)**	**GVC (km^2)**	**TC (trees)**
Markham Village	0.93	15,106	1.87	30,213
East Woodbridge	0.81	23,881	1.62	47,762

[30] (Government of Canada 2022b; Khan and Karpinski 2018)
[31] (Canadian Institute for Health Information 2022a)
[32] (Toronto Public Health 2022)
[33] (Peters et al. 2015)

According to the greenery cover scenarios, Table 16 presents the GVC and TC associated with Moderate and Intense GCs. The cost estimation model includes the planting and maintenance cost for the vegetation cover and tree canopy. The cost of vegetation cover includes seeding and care services costs for lawns and shrubs per square meter. It was assumed as CAD $16/m^2$ for the first year plus CAD $8/m^2$/year for an annual cost. The tree canopy cost includes plantation and maintenance costs per tree considering trees of a crown area of 8 x 8 m^2. The cost was assumed as CAD $60/tree for the first year plus CAD $130/tree/year for maintenance services. The annual cost was assumed for the next 5 years (starting in 2023) considering an average forecasted annual inflation rate of 2.5% in Canada. These assumptions are estimated based on landscaping service providers in Ontario and the 2 billion trees commitment project for increasing urban trees by the Government of Canada[34]. The urban area of York Region is assumed to be 675 km^2 (38% of the Region's area), and the average area of the studied neighbourhoods is 5.1 km^2. Assuming similar urban conditions for other neighbourhoods in the Region, Table 17 presents cost estimations for enriching the greenery cover for the neighbourhoods and York Region for Moderate and Intense GC scenarios. The cost estimates declare that enriching the tree canopy allocates around 32% of the financial plan, while the rest is allocated to enriching the ground vegetation cover. A further investigation is recommended to reach the optimum greenery cover that achieves maximum thermal performance and minimum cost[35].

Table 17 – Cost estimation of the green cover scenarios

	Moderate GC scenario		**Intense GC scenario**	
	1st-year cost (CAD)	Annual cost (CAD)	1st-year cost (CAD)	Annual cost (CAD)
Markham Village	+ 15,840,928	+ 9,431,064	+ 31,681,916	+ 18,862,258
East Woodbridge	+ 14,397,756	+ 9,586,978	+ 28,795,512	+ 19,173,956
York Region	+ 1.99 Billion	+ 1.25 Billion	+ 3.99 Billion	+ 2.51 Billion

34 (Government of Canada 2022a)
35 (M. Dardir and Berardi 2021)

4. Limitations

This research promotes more comprehensive understanding of the benefits of greenspace for health and well-being. However, this study has some limitations that have to be taken into considerations for further development of method and approach:

- The health study was conducted based on the available data. There was a lack of data that could be used to analyze health outcomes related to greenspace exposure. The health records do not specify indoor or outdoor exposure prior to an event (death or emergency department visit). Further information would result in more accurate correlations between heat stress exposure and health outcomes.
- Specific health outcomes (e.g., heat exhaustion on outdoor workers or school children) may not have been measured or accounted for in this study. For example, future studies could consider the impact of direct exposure and physical existence within greenspaces during heat events.
- The records of heat-related causes (e.g., sun and heat stroke) were not sufficient in the dataset to construct significantly statistical correlations for health outcomes in York Region.
- The dataset was constructed using health records from the main urban settlements in York Region that have larger populations (Markham, Vaughan, Richmond Hill, Newmarket, and Aurora). An assumption has made that the health outcomes and economic benefits of this dataset represent the Region; however, it can be expected that different health outcomes behaviour could occur in rural areas. Extending the study to rural areas is recommended for further study.
- The economic benefits developed refers to prior studies with assumptions and parameters that may differ from York Region populations. Additionally, the economic benefit calculation assumes other areas in York Region have comparable green cover and canopy cover interventions to the two areas assessed in the study.
- The correlations between cause-based ambulance calls and tree canopy were based a previous study established in Toronto. Similar behaviour to calls frequency was assumed for York Region. Although the calls rates have been adapted to York Region's populations, further studies are recommended to establish unique correlations for York Region.
- The cooling effect was calculated within the modelled neighbourhood, however, the cooling effect of neighbouring and adjacent areas can impact the environmental conditions within the study area[36]. Such effect was not included by the simulation model.
- The proposed intense greenery cover scenario could require special urban design developments, such as providing a pedestrian-friendly environment with limited vehicle accessibility. Such developments may not be practical in some areas and for some municipalities.
- The economic benefits estimates were considered based on the Intense GC scenario; further calculations are required to estimate the benefits for Moderate GC scenario.
- Information such as the time required for tree growth, selected tree species, and the life expectancy of trees was not considered.
- There are other potential benefits of additional canopy cover and green vegetation cover that were not assessed and which could further support the business case for additional green spaces.

[36] (Berardi, Jandaghian, and Graham 2020)

5. Scope of Future Research

Future activities related to the framework and approach presented in this report include enhancing the accuracy and performance of the analyses. They could include:

In this study, the health responses are based on environmental changes and related to humidex values. It means that the health records analyses and predictions are only sensitive to the changes in outdoor thermal conditions. These health records can be responsive to other factors that are not included in this study. These other factors can cause different impacts on health and result in various behaviour patterns and trends in health records. It is recommended to include various environmental, social, and economic factors to conduct a holistic community-based responses model for a future study.

In statistical modelling, further study concerning the behaviour of the dataset itself is recommended. Statistical tests regarding the cycles and seasonality of the data behaviour should be checked.

We used a separate extreme weather scenario to express the impact of climate change, while we did not include extreme weather conditions in the typical summer season. Better heat-based health responses and higher economic benefits were noticed during extreme heat events. It is expected to have more benefits when considering one or more extreme heat scenarios within the summer season.

In cost estimation, a more detailed cost estimation model is recommended considering the life cycle cost, clear maintenance interventions and replacements, operational costs and productivity benefits, and recycling and by-products valuation.

An optimization study that considers maximum performance and minimum cost is recommended for further applications. Investigating other heat mitigation strategies (i.e., green roofs and cool surfaces) and including other direct and indirect economic benefits (i.e., housing valuation, mental health, and hospitalization) are also recommended for future investigations.

6. Conclusions

A framework was developed to support the decision-making process associated with increasing greenery cover in urban areas considering community health and climate resilience. This framework develops statistical modelling based on historical datasets of environmental measures and health records for York Region. It also models the urban microclimate with existing urban features proposing enriching the greenery cover into two scenarios: moderate and intense covers. The microclimate was investigated under two weather scenarios: extreme weather conditions, and a typical summer season. The framework integrates microclimate simulations, statistical modelling, and economic benefits modules to predict the health records and associated economic benefits associated with increasing the urban greenery cover.

The framework was applied to two residential neighbourhoods in York Region representing urban neighbourhoods in Southern Ontario. Markham Village and East Woodbridge were chosen to represent vulnerable populations considering UHI behaviour and potential planting spaces. A historical dataset was constructed for the York Region community, integrating meteorological measures (daily humidex values) and population daily health records (mortality records and emergency department visits) for 17 years (2003-2019) focusing on warm and hot seasons (May to September each year). Both all-cause and vulnerable records of health data were included in the dataset.

The results reported higher impacts of heat events on mortality rates and emergency visits during warm seasons reflecting the possible hazardous impact of climate change on health. By applying the proposed greenery cover enrichments, the estimated health records were reduced due to predicted declines in ambient heat conditions. Intensifying the greenery cover reduced the ambient temperature, outdoor heat stress, and neighbourhood energy consumption. The estimated economic benefits of increasing the urban greenery cover included avoiding premature mortality, health system savings, reduced energy use, and maintaining workers' productivity.

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