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Lowering the Temperature to Increase Heat Equity: A Multi-Scale Evaluation of Nature-Based Solutions in Toronto, Ontario, Canada

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Abstract: Nature-based solutions (NbS) present an opportunity to reduce rising temperatures and the urban heat island effect. A multi-scale study in Toronto, Ontario, Canada, evaluates the effect of NbS on air and land surface temperature through two field campaigns at the micro and meso scales, using in situ measurements and LANDSAT imagery. This research demonstrates that the application of NbS in the form of green infrastructure has a beneficial impact on urban climate regimes with measurable reductions in air and land surface temperatures. Broad implementation of green infrastructure is a sustainable solution to improve the urban climate, enhance heat and greenspace equity, and increase resilience.

Keywords: built environment; climate change; green roofs; green infrastructure; green walls; heat mitigation; temperature; urban agriculture; urban heat island; urban forestry

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1. Introduction

Regional climates and urban microclimates are affected by rising temperatures due to climate change. Globally, projections indicate that temperatures will continue to rise, along with an increase in the frequency and intensity of heat waves [1]. Regionally, in Toronto, Ontario, Canada, heat waves are projected to increase as temperatures continue to warm [2]. As temperatures warm, the urban heat island (UHI) effect is magnified as a result of the surrounding built form [3]. Urban climate regimes and associated heating and cooling loads are impacted by the way in which the built landscape is fashioned [3–7], and this has been well documented in Toronto, Ontario, Canada [8–11].

The natural environment has undergone significant change through urbanisation and land use development. Currently, more than half the world's population lives in urban settings, with nearly all global population growth expected to occur in urban areas by 2050 [12]. Urban areas demonstrate different climate characteristics compared to less built-up areas, contributing roughly 75 per cent of global greenhouse gas emissions [3]. Building density, prosperity, and energy use influence both anthropogenic heat emissions and urban climate conditions [3,4].

As urban climate regimes continue to evolve, the intensity, duration, and frequency of extreme heat events will increase, along with heat-related mortality and morbidity [13–16]. When high temperatures occur for an extended duration, people can experience illness and a reduced quality of life. High temperatures contribute directly to deaths from cardiovascular and respiratory diseases among the elderly and those who are chronically ill, while individuals who are socially disadvantaged remain more vulnerable to the health effects of extreme heat events [15–17]. In addition, rising temperatures enhance the risk of food and waterborne illnesses [15–17]. Aeroallergens such as pollen that can trigger asthma, are intensified by extreme heat events, while ozone and particulate matter are also amplified by rising temperatures, affecting cardiovascular and respiratory disease outcomes [17,18]. Warming temperatures will continue to intensify these issues, aggravating the burden of illness [15,16,19]. Rapid urbanization, social inequity, and an ageing population will further exacerbate the health impacts of rising temperatures. Urban development patterns are dynamic and driven by a number of factors, including economic conditions, population growth, and the cost of land. The built form can exacerbate or mitigate rising temperatures, which includes the spatial distribution of natural features and green spaces. Heat stress affects mortality and morbidity, and disparities in community development and planning patterns can lead to inequitable heat impacts across neighbourhoods, which disproportionately affect vulnerable populations [19,20]. Adverse health outcomes are exacerbated by the urban heat island (UHI) effect through the amplification of daytime heat exposure and warmer nighttime temperatures, which reduce thermal comfort and relief [19]. Sustainable approaches to urban development are necessary to improve the urban climate, enhance heat equity, and increase resilience.

Urban climate research has shown that cities are almost always warmer than their rural or natural surroundings. This increased warmth is attributed to the UHI phenomenon as one of the main examples of inadvertent climate modification in cities due to human activities [21–23]. UHI significantly impacts the everyday lives of urban populations through increased heat stress and other heat-health-related issues [24–26]. Urban residents are particularly vulnerable to heat since the UHI phenomenon amplifies the effects of heat waves in cities [27,28]. Accordingly, studying the temporal and spatial dynamics of air temperature (Ta) changes (i.e., cooling and heating) on the micro- and local scale can advance the understanding of the UHI effect and its mitigation strategies, to support the development of healthier and more comfortable cities [7].

Nature-based solutions (NbS) in the form of green infrastructure reduce the impact of atmospheric warming while providing a plethora of co-benefits that support sustainable development [5,6,29–32]. The International Union for Conservation of Nature has defined NbS as "actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" [33]. This describes five categories of ecosystem-based approaches that include green infrastructure [5,33–35]. The focus of this study is a multi-scale evaluation of the effect of NbS such as green infrastructure on near-surface air temperature and land surface temperature (LST) in Toronto, Ontario, Canada. Green infrastructure has unique characteristics and multiple co-benefits that can be strategically leveraged to address warming temperatures and increase climate resilience in urban areas [5,6,29,30,36].

Literature Review

In this study, the nature-based solution of green infrastructure has been categorised into four application areas, including green roofs, green walls, urban vegetation and forestry, and urban agriculture systems [5,37]. As shown in Figure 1, common functions are shared among the different applications of green infrastructure, while other functions are exclusive to particular applications. The key functions of this study are the near-surface air temperature and LST regulation. Green infrastructure is broadly defined as interconnected networks of natural and engineered green spaces that provide a range of ecosystem services [6].

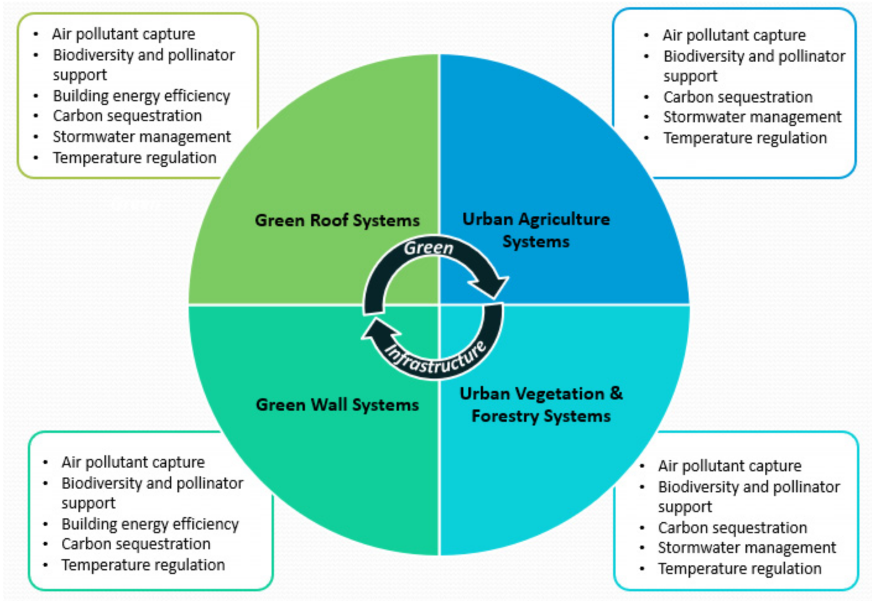


Figure 1. Green infrastructure form and function (Source: [5,6,29–31,36,37]).

Green infrastructure has been shown to have a positive effect on near-surface air temperatures and LST, as a result of shading and evapotranspiration [38,39]. The temperature regulation benefits of green infrastructure vary by application and are influenced by factors including irrigation, local climate, physical dimension, seasonality, and vegetation. Green infrastructure cooling benefits are well-documented [40], occurring actively through evapotranspiration and passively through surface shading [41–46]. In urban settings, the application of green infrastructure can provide cooling capacity, reduce the UHI effect, and moderate temperatures [47–49]. Green infrastructure also increases building efficiency by decreasing building cooling and heating loads through the shade, insulation against temperature extremes, and the combined effect of decreased solar heat gains from urban surfaces and decreased air temperatures [50–52]. Additionally, the application of green infrastructure has improved health outcomes from warming temperatures [6,29,37,43–45,47,48,53,54].

Different applications of green infrastructure can regulate temperature. Various phenomena collaborate on green roofs to regulate temperatures and provide a cooling effect on the urban microclimate [51,52,55]. Green roof foliage and vegetation provide shade and absorb thermal energy through photosynthesis while promoting a cooling effect through evapotranspiration [56]. Green roof applications can also reflect up to 30% of solar radiation and absorb up to 60% through photosynthesis while reducing thermal loading [56,57]. However, temperature regulation capacity in green roofs is determined by the abundance of vegetation, surface area cover, and type of green roof [58,59].

Green roofs and urban vegetation function as an effective UHI mitigation strategy through their cooling effect on the urban microclimate [51,52,55]. The application of urban vegetation and forestry has been shown to effectively regulate near-surface air temperatures and LST by cooling the air below through shading and evapotranspiration [60]. For example, a single tree on a sunny day can provide a cooling capacity equivalent from 20 to 30 kW [41]. Urban vegetation and forestry applications such as tree and shrub plantings in urban corridors are valuable tools to lower temperatures [37,43,49,61].

Near-surface air temperatures and LST can be lowered by the application of vegetation and foliage to vertical building facades (i.e., green walls) as solar radiation is transformed into latent heat through evapotranspiration [62,63]. Temperature regulation through the application of green walls occurs through shade provision, reduced reflected heat, and evapotranspiration [50,64,65]. During the summer season, green walls can protect exterior surfaces from intense solar radiation while simultaneously reflecting and absorbing up to 80% of the radiation within the foliage [62].

Depending on the ratio of vegetation and depth of soil or substrate, the application of green infrastructure such as urban agriculture systems can have a positive effect on near-surface air temperatures and LST [66]. Urban agriculture systems provide other ecosystem services, in addition to air pollution abatement and carbon sequestration [66–68]. These services include the reduction of food miles and carbon footprint associated with conventional agriculture, and improved food security when large-scale production is disrupted by extreme weather events [6,29,37].

In addition to temperature regulation, green infrastructure provides multiple cobenefits, including abatement of ozone, nitrogen dioxide, and particulate matter pollutants [29,56,60,64,69–76], greenhouse gas emissions reductions, and decreases in ambient carbon dioxide concentrations [29,49,56,57,60,64,77–80]. Green infrastructure also provides an effective stormwater management solution for water storage during rainfall events, reductions in overland flow, and prevention of sediment erosion and nutrient loading [5,6,66,81–83]. The application of green infrastructure can also enhance biodiversity and provide pollinator habitat [66,84–87].

Research on green infrastructure and temperature thus far has had a limited focus on single applications and individual benefits [49,55,63,64]. Building on the work undertaken by Anderson and Gough [6], this study evaluates the potential of different applications of green infrastructure to regulate near-surface air temperatures and LST at both the micro and mesoscale in Toronto, Ontario, Canada. This comparative analysis has sought to evaluate the nature-based cooling effect across scales by answering the following questions:

(1) Is there a measurable nature-based cooling effect using a range of green infrastructure applications (Figure 1) across different urban morphologies in Toronto, Ontario, Canada?
(2) Are the nature-based cooling effects of green infrastructure applications in the city visible by satellite imagery?
(3) Are parts of the city warmer due to the concentration of built-up surfaces?

This study evaluates how different treatments can reduce near-surface air temperature at the site level while reducing LST and UHI effects at the city scale. Micro-scale measurements and remote sensing were used to evaluate the impacts of green infrastructure on lowering near-surface air temperature and LST in Toronto, Ontario, Canada.

2. Methods

In this multi-scale study, two data collection campaigns were undertaken across various applications of green infrastructure that included green roofs, green walls, urban vegetation and forestry, and urban agriculture systems. The first data collection campaign to measure the potential of green infrastructure to regulate temperature was undertaken at the microscale using temperature sensors at fixed locations over the course of two summer seasons from July through August 2016 and from July through August 2017 [6]. Anderson and Gough [6] field study undertook a data collection campaign across different applications of green infrastructure (shown in Figure 1) to evaluate how different green infrastructure treatments can reduce near-surface air temperature regardless of location, geography, or land-use type. The methodology is described here for the reader's convenience.

The second data collection campaign was undertaken at the mesoscale using satellite imaging of the whole city of Toronto, Ontario, Canada on 24 August 2016. The purpose of this campaign was to understand the differences between the mesoscale compared to microscale, by analyzing the spatial distribution of LST and the normalized difference vegetation index (NDVI) during a cloud-free summer day. This allowed for a correlation of LST and NDVI to urban form and their changes over different land surface types. LST is an estimate of surface temperature based on the solar radiation received by the satellite from a given location and is not precisely identical to temperatures measured in situ as was performed in the first collection campaign.

2.1. Study Area

Study sites at the microscale were selected to be representative of the four green infrastructure categories and different urban morphologies, in addition to site availability and accessibility constraints [6,37]. Six sites were designated for the field study as shown in Figure 2. Three sites encompassed multiple applications of green infrastructure. The sites chosen for the data collection campaign included the following: (1) the 186 m^2 extensive green roof situated on top of the Environmental Science and Chemistry building (EV) within the University of Toronto Scarborough (UTSC) campus, located in suburban Scarborough; (2) the 46 m^2 rooftop fruit and vegetable garden situated on top of the Instructional Centre (IC) building within the UTSC campus in suburban Scarborough; (3) two (2) urban forest sites situated at the intersection of Military Trail and Ellesmere Road within the UTSC campus in suburban Scarborough; (4) the 750 m^2 multi-application site situated on top of the Carrot Common building complex located in east Toronto, and comprised of (a) a semi-intensive growing roof for herbs and vegetables, (b) an extensive green roof, a green wall, and (c) a medicine garden; (5) the 930 m^2 extensive green roof situated on top of the Mountain Equipment Co-op (MEC) retail establishment, located in downtown Toronto. Figure 2 illustrates that the MEC site is located in the core of the city, situated among high-rise buildings that include residential condominium apartments and commercial office towers. The Carrot Common is situated in a dense urban area comprised of low-rise commercial and residential apartment buildings, east of the downtown core. Each of the UTSC sites is situated within the University of Toronto campus in Scarborough, located in a suburb in the easternmost part of Toronto that is characterized by mixed residential, commercial, and industrial buildings, which range from single-family houses to high-rise apartments, low-rise commercial, and industrial building developments.

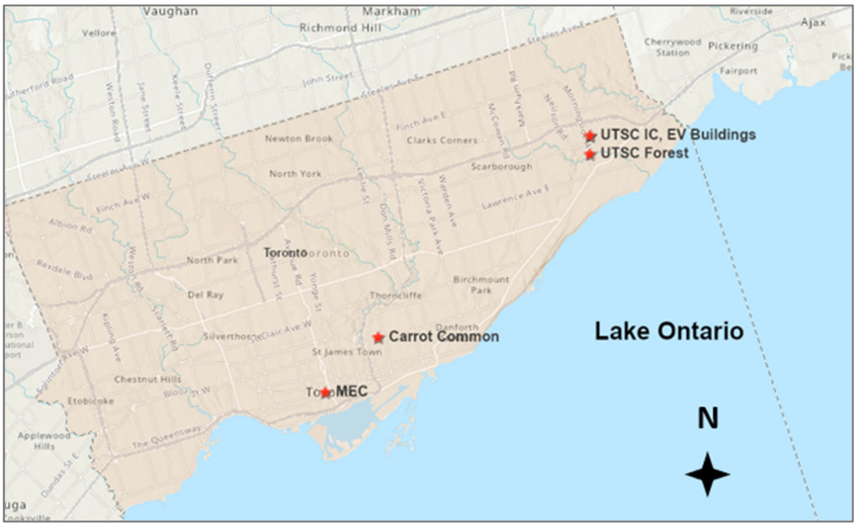


Figure 2. Map of study sites (marked by red stars ★) in Toronto, Ontario, Canada. Sites include: MEC (Mountain Equipment Co-op: **a**. extensive green roof); Carrot Common: **a**. semi-intensive vegetable growing roof, **b**. extensive green roof, **c**. green wall, **d**. rooftop medicine garden; UTSC Forest (2 sites); UTSC IC (Instructional Centre: **a**. rooftop fruit and vegetable garden), and UTSC EV (Environmental Science and Chemistry Building: **a**. extensive green roof) [6].

At the mesoscale, Toronto, Ontario, Canada (43.65° N, 79.38° W) has a continental climate (Köppen Dfb) moderated by the southern proximity to Lake Ontario, part of the largest water body in North America (the Laurentian Great Lakes) and orographically by the Niagara Escarpment to the west. Maximum air temperatures in the city are from 23 to 31 °C with moderate to high humidity. Lake Ontario has a cooling effect on the city, which is dependent on wind speed and direction. This lake effect can exacerbate humidity and night-time minimum air temperatures in the city. When air temperatures over 31 °C can occur for three consecutive days, this is defined as a regional extreme heat event [88]. Coupled with high humidity, the Humidex values can reach 40 °C during a summer heat event [9,10,37,89,90]. To contextualize the study within general climate conditions, the climate normal for Toronto, Ontario, Canada (1981–2010), for the months of July and August for the mean daily air temperature are 22.3 °C and 21.5 °C, respectively [6]. The summer air temperatures for July and August of 2016, respectively, were 23.8 °C and 24.3 °C. These summer temperatures were warmer than the climate normal by two standard deviations [6]. The 2016 summer season was the warmest in Toronto, Ontario, Canada, in over 15 years [6]. The 2017 summer season was cooler with temperatures of 21.8 °C and 20.6 °C for July and August, respectively [6]. The 2017 summer values were cooler than the climate normal by less than one standard deviation [6].

2.2. Data Collection and Schedule

During the first data collection campaign, two locations were established at each site with a control and a green infrastructure treatment position for each of the temperature loggers [6,37]. The control and treatment loci were established approximately from 30 to 50 m apart for each site to minimize any influence from the treatment areas on the control positions. One logger each was placed directly on the control or treatment surface being monitored to capture the flow of air across the logger. The temperature loggers were situated inside of weatherproof shields (i.e., Stevenson screens) and fastened to stable wooden stands that were installed approximately 2.5 cm above the control and treatment surfaces to avert epiclimatic variations and reduce the influence of wind flows on near-surface air temperature. Onset HOBO weatherproof temperature loggers (model U23) were used for data collection, which are specifically designed to collect temperature data in all-weather exterior environments. The HOBO model U23 weatherproof temperature loggers have detection limits that range from −40 °C at its coldest limit to 70 °C at its warmest limit of operational temperatures. It is a high precision instrument with accuracy of ±0.21 °C from 0 to 50 °C (± 0.38 °F from 32 to 122 °F). Data collected from treatment and control loci were compared using a Student's *t*-test [6].

For the first data collection campaign, in situ measurements were taken to evaluate the capacity of green infrastructure to regulate near-surface air temperature at the site level [6]. Monitoring occurred continuously for July and August 2016 and July and August 2017 [6,37]. HOBO temperature loggers were installed at each site to measure and archive hourly near-surface air temperatures on a continuous basis. Standard sampling measurements in climatic studies are taken on an hourly basis [91]. The equipment was tested and calibrated during the spring season of 2016, and intermittent inspections were made between 2016 and 2017 to download data and assess functionality of the temperature loggers. The equipment was calibrated by collectively assembling all the temperature loggers to synchronize the time and to ensure each data logger was simultaneously registering the same values.

During the second data collection campaign, Landsat-8 satellite measurements were taken to evaluate the capacity of green infrastructure to regulate land surface temperature (LST) at the city level. Even though the Landsat mission has lower temporal resolution compared to other satellites that measure LST and NDVI (e.g., Terra, Aqua, and MODIS), it provides a much higher spatial resolution for detailed insight into the distribution of urban heat loads. Due to the number of available Landsat-8 satellite images, EarthExplorer (e.g., https://earthexplorer.usgs.gov/ [92], accessed on 21 June 2022) was used to review and select imagery for further analysis. During the summer seasons between 2016 and 2017, the Landsat-8 passed over Toronto, Ontario, Canada approximately six times each month. During the relevant study period, satellite imagery with the least cloud cover (e.g., 10:03 PM EST on 24 August 2016; path: 18, row: 30) was selected for analysis. While this timeframe is not the warmest period of the day, it still provides useful information about LST and NDVI distribution due to the visible heat retention of built-up surfaces and the cooling effect of vegetation.

For the second data collection campaign, Landsat-8 satellite imagery with a pixel size of 30 by 30 m was accessed and analysed through the Google Earth Engine (GEE), a cloud-based geospatial analysis platform [93]. LST was retrieved from the Landsat-8 Thermal Infrared Sensor (TIRS) Band 10 data using a single-channel algorithm, while NDVI was calculated from Bands 4 and 5 of the Operational Land Imager (OLI) sensor [94–97]. The boundaries of neighbourhoods and locations of city-operated cooling centres were downloaded from the City of Toronto Open Data Portal (e.g., https://open.toronto.ca/ [98], accessed on 21 June 2022). The selected satellite image from 24 August 2016, at 10:03 PM was almost completely cloud-free, with less than five per cent of the city area covered by clouds, thus allowing an analysis of the spatial distribution of LST and NDVI per pixel. GIS and statistical analysis of data from GEE and the City of Toronto Open Data Portal were completed using ArcGIS Pro 2.9.0. software.

3. Results

The data collected through in situ measurements and satellite imagery were used to evaluate the potential of green infrastructure to regulate land surface and near-surface air temperatures.

3.1. Near Surface Air Temperature Regulation

The in situ data collected during the first campaign showed that there was a reduction in temperature between the control and treatment applications across all sites during the summer months of July and August 2016 and July and August 2017 [6]. The maximum average monthly temperature reduction for the 2016 and 2017 summer seasons ranged between 0.3 °C and 1.3 °C, with an average temperature reduction of 0.6 °C and a maximum average monthly temperature reduction of 1.3 °C, depending on location, as shown in Figure 3.

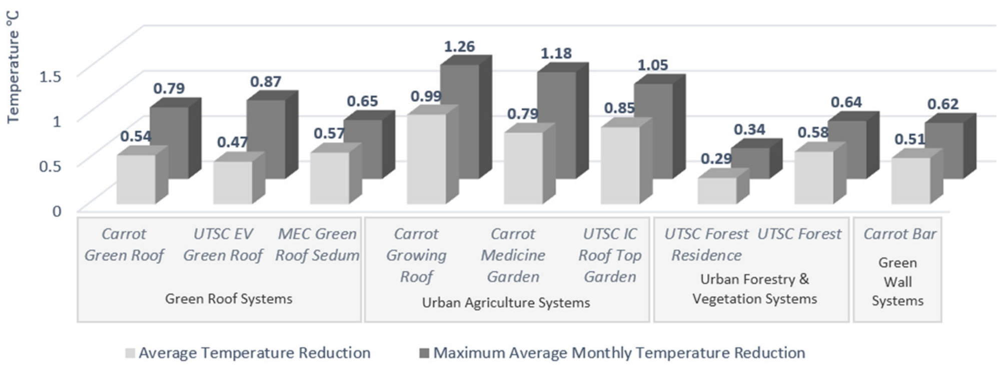
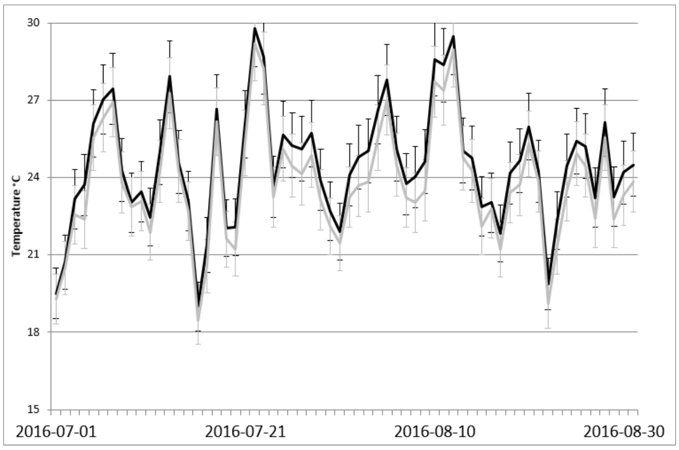


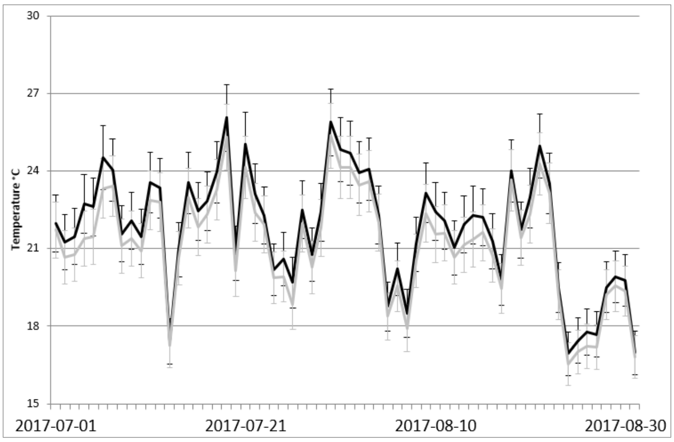
Figure 3. Average temperature reduction in grey and maximum average monthly temperature reduction in black by green infrastructure application for each site from July to August 2016 and July to August 2017 [37].

Of the green infrastructure applications tested, urban agriculture systems showed the greatest impact in regulating temperature, with an observed monthly average reduction in temperature. The application of green roof systems showed an average reduction in the temperature of 0.5 °C with an observed average monthly reduction as high as 0.9 °C on the UTSC extensive green roof located at the Environmental Science and Chemistry building. Urban forestry and vegetation systems showed an average reduction in temperature of 0.4 °C, with an observed average monthly reduction as high as 0.6 °C at the UTSC forest sites. Green wall systems showed an average reduction in the temperature of 0.5 °C with an observed average monthly reduction as high as 0.6 °C on the Carrot bar wall. The daily average of the near-surface air temperature treatment values is less than the control values for most dates when in situ measurements were taken during the 2016 and 2017 summer seasons, as shown in Figures 4 and 5.



Control Treatment

Figure 4. Daily average near-surface air temperature (°C) for control and treatment across all sites for the 2016 summer season. Error bars signify 5% of the measured value, which is consistent with the detection limits of the instrumentation [6].



Control Treatment

Figure 5. Daily average near-surface air temperature (°C) for control and treatment across all sites for the 2017 summer season. Error bars signify 5% of the measured value, which is consistent with the detection limits of the instrumentation [6].

A *t*-test was conducted for the treatment and control loci at each site, and they all had a *p*-value below the 0.001 margins of error, indicating a statistically significant difference in near-surface air temperature between the means of the treatment and control for all green infrastructure applications. An observed reduction in near-surface air temperature between the green infrastructure treatment and control applications was confirmed. The standard deviation for the treatment and control loci at each site is shown in Figures 6 and 7 for the 2016 and 2017 summer seasons, illustrating almost identical behaviour for both seasons [6]. This suggests that green infrastructure treatments lower the measured near-surface air temperature but do not alter its variability.

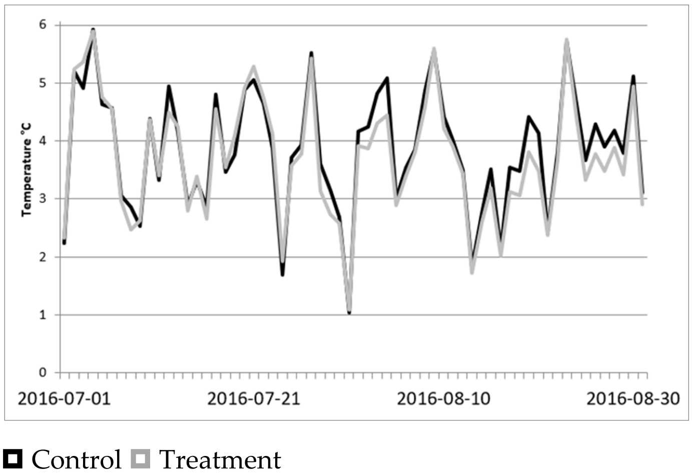


Figure 6. Daily near-surface air temperature standard deviation for control and treatment across all sites for the 2016 summer season [6].

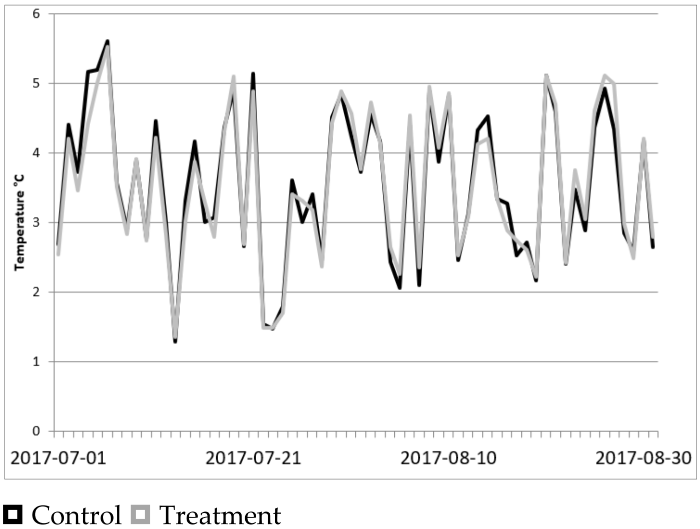


Figure 7. Daily near-surface air temperature standard deviation for control and treatment across all sites for the 2017 summer season [6].

3.2. Analysis of Land Surface Temperature Regulation

The spatial distribution of LST and NDVI for the City of Toronto is shown in Figure 8. Values of LST range between 20 and 38 °C (Figure 8A). Except for water bodies (with LST values as low as 19.5 °C), ravines and associated natural areas are the coolest, with LST values between 22 and 25 °C. Natural areas correspond to densely forested areas, ravines, meadows, wetlands, and successional lands. Other urban green spaces, such as public parks, stand out in particular due to their cooling effect, which is largely dependent on vegetation type. Generally, values vary between 25 and 28 °C, however, homogeneous grass surfaces in parks have higher LST compared to forested parklands. It is important to note that public parks record LST values of up to 5–10 °C lower compared to their built-up surroundings. In contrast to green areas, the highest values are recorded for compact, built-up areas of the city. Industrial areas have the highest LST, commonly reaching above 35 °C. LST changes in relation to the urban form. Compact built-up areas with less vegetation had high LST values of (>30 °C), while built-up areas with green infrastructure applications, such as tree-lined streets or yards planted with shrubs and greenery, had reduced LST values. There was an additional cooling effect associated with proximity to Lake Ontario (the southern extent of the city, as illustrated in Figures 8A and 9A).

NDVI values provide valuable information on the health and density of vegetation. Pixels with NDVI values that range below 0 indicate water bodies; 0–0.2 are bare soil or built-up surfaces; 0.2–0.5 are a mixture of bare soil or built-up surfaces and vegetation; while pixels with values above 0.5 are considered fully vegetated. Ravines, forests, and associated natural features have the highest NDVI values, above 0.5 (Figure 8b). Densely built-up areas, roads, and other impermeable surfaces are well-denoted with low NDVI values (below 0.2). Figure 8 also delineates the locations of city-operated cooling centres that provide various air-conditioned spaces or cooling areas (e.g., swimming pools or splash pads) to the general public during extreme heat events.

Mean LST and NDVI values for the 158 neighbourhoods across the city are shown in Figure 9. Such data is extremely important for decision-makers as it can be useful for prioritising neighbourhoods for green infrastructure implementation.

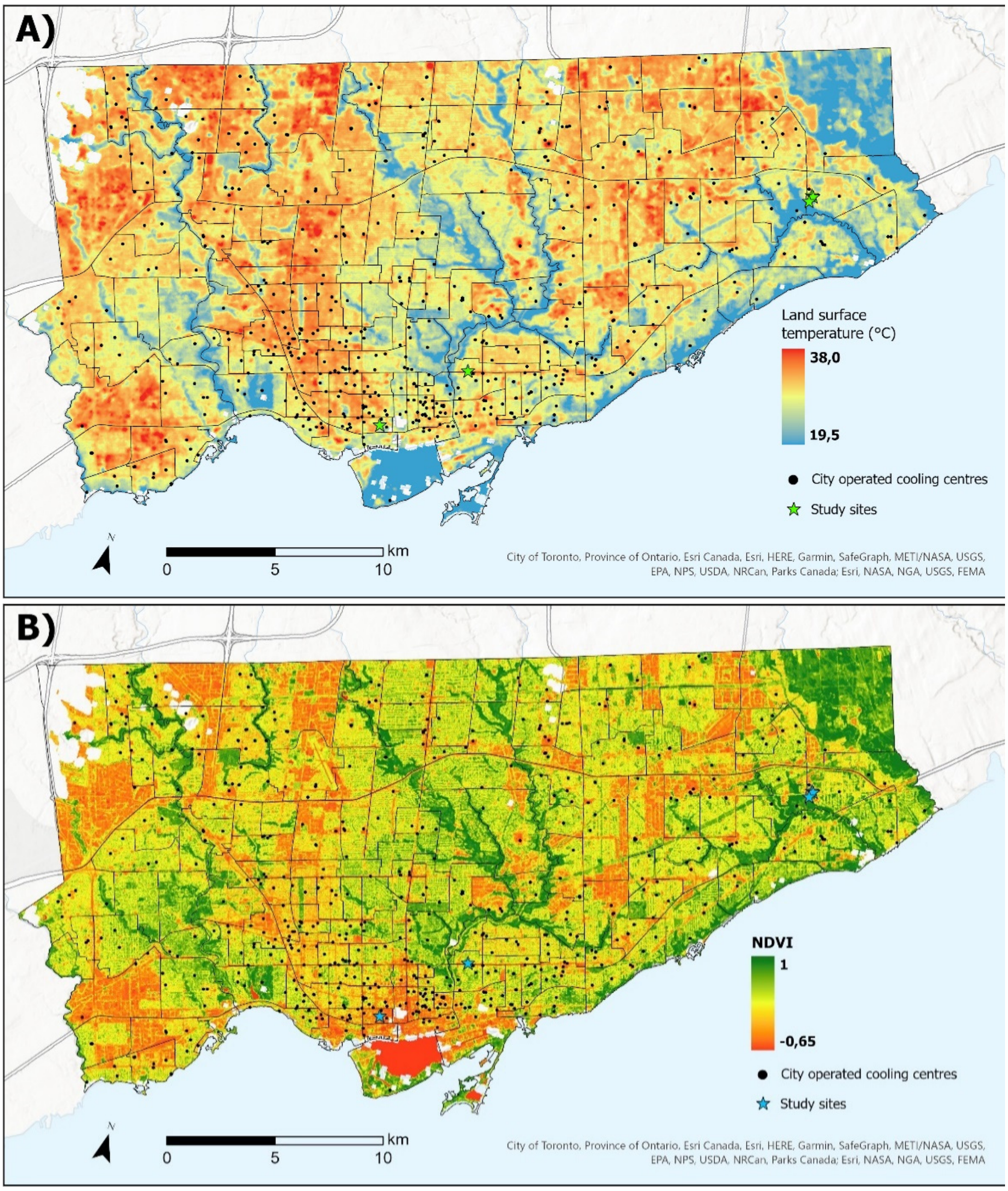


Figure 8. Spatial distribution of LST (**A**) and NDVI (**B**) on 24 August 2016.

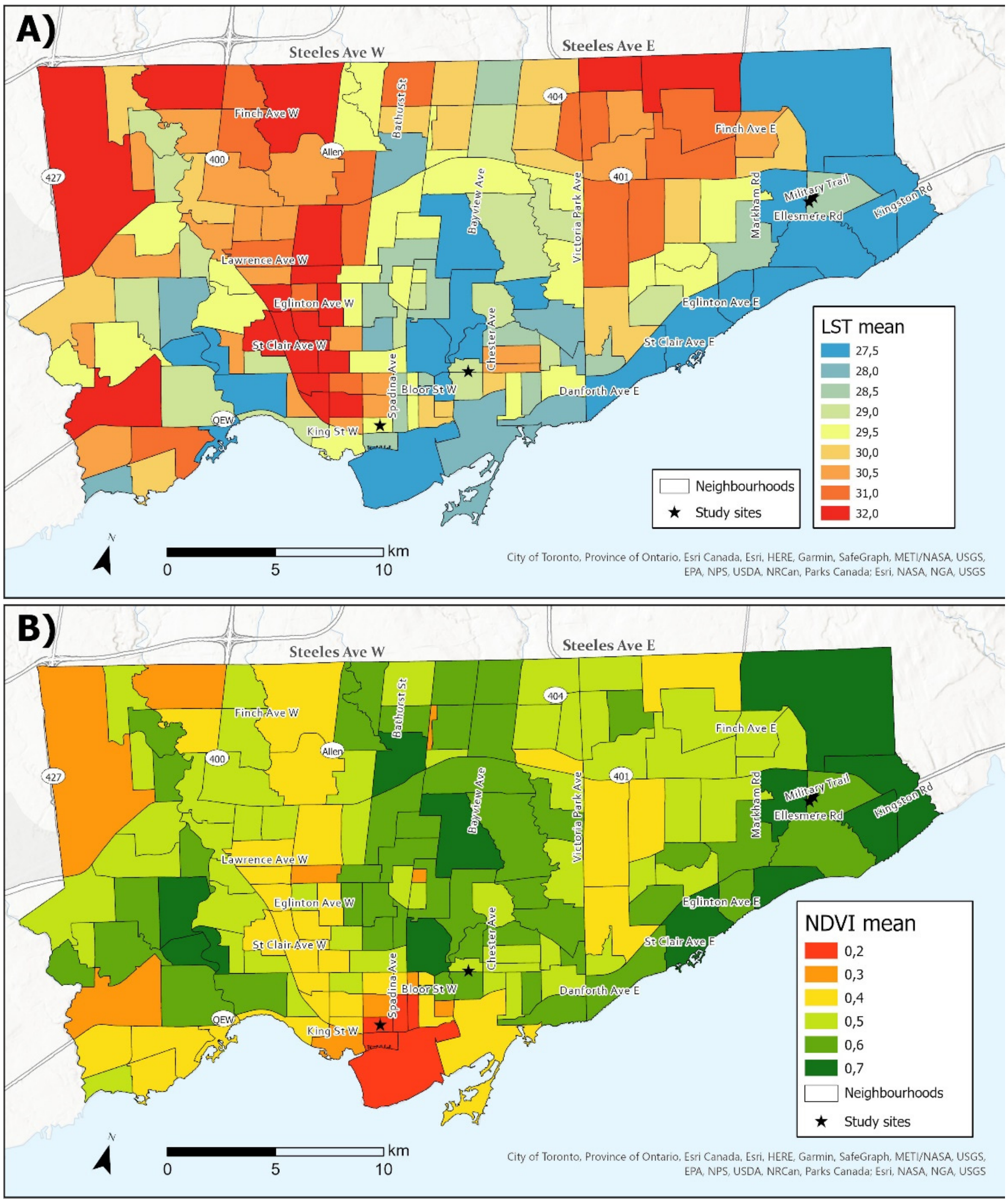


Figure 9. Spatial distribution of mean LST (**A**) and mean NDVI (**B**) on 24 August 2016 in City of Toronto neighbourhoods.

In order to assess how these centres are positioned in relation to heat loads and vegetation levels across the city, linear regression between their LST and NDVI values was undertaken (Figure 10A). Results show that there is a significant inverse correlation between LST and NDVI, with a Pearson correlation coefficient (r) value of −0.71. The correlation coefficient is significant at the 0.05 level. Groupings of centres with low NDVI and high LST can be seen, indicating that many centres are positioned in parts of the city with high heat risk. From visual interpretation, there is an apparent correlation between LST and NDVI. This is also confirmed quantitatively through linear regression undertaken at the neighbourhood level (Figure 10B).

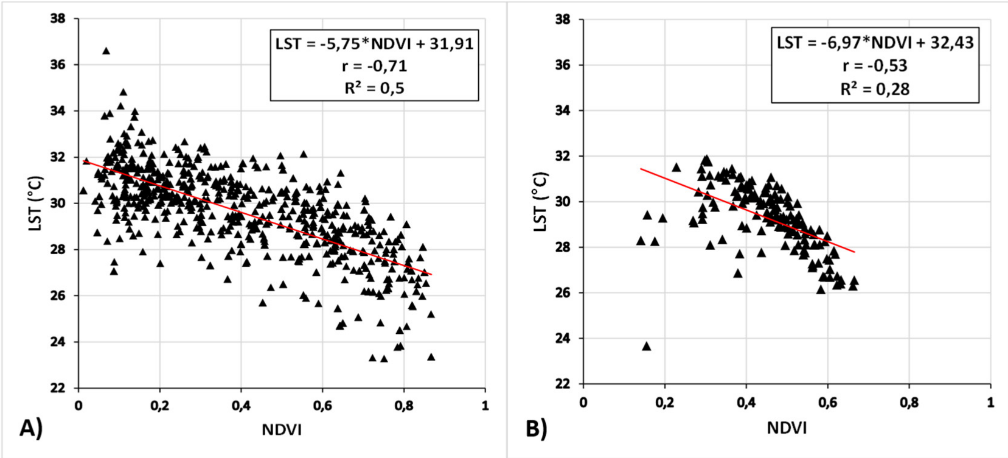


Figure 10. Scatter plots showing: NDVI and LST values in areas with city operated cooling centres (**A**); mean NDVI and LST values for all neighbourhoods (**B**).

The Pearson correlation coefficient value is −0.53, which is slightly lower compared to the results for the city-operated cooling centres. This is due to the outliers that correspond to lakefront neighbourhoods shown in the satellite imagery, whose polygons partially cross over Lake Ontario. Therefore, the values of NDVI and LST decrease, resulting in outlying values. However, the results still indicate a strong relationship between LST and NDVI at the neighbourhood level.

4. Discussion

The results of both data collection campaigns demonstrate that green infrastructure has a beneficial impact on near-surface air temperatures and LST at the micro and mesoscales. Analysis of the data collected to measure the potential of green infrastructure to regulate near-surface air temperature and LST is consistent with the hypothesis that multiple types of green infrastructure can reduce warming temperatures in Toronto, Ontario, Canada, regardless of location, geography, or land-use type. The significant potential of green infrastructure to mitigate the consequences of rising temperatures is recognized in the literature [47–49,55,63,64].

The new findings and analysis of the field data collected in the first campaign [6] are consistent with the hypothesis that multiple applications of green infrastructure are effective in reducing near-surface air temperatures and LST across different urban morphologies in Toronto, Ontario, Canada. This was illustrated in the statistical analysis, which showed green infrastructure has a statistically significant positive impact on the reduction of near-surface air temperatures. This field campaign was designed to assess the potential of various NbS applications to reduce the near-surface air temperatures at the microscale through simultaneous testing of multiple types of green infrastructure in a controlled field experiment [6]. According to the results of this experiment, the reduction in the maximum average monthly near-surface air temperature ranged between 0.3 °C and 1.3 °C across sites. The average temperature reduction ranged from 0.3 °C, which was observed in urban forestry and vegetation systems, to 1 °C, which was observed in urban agriculture systems. Reductions in maximum average monthly near-surface temperature ranged from 0.3 °C in urban forest and vegetation systems, to 1.3 °C in urban agricultural systems. This indicates that urban agriculture systems showed the greatest impact on reducing near-surface air temperature. The urban agriculture systems tested included a semi-intensive green roof and two rooftop gardens. The results are supported by Morakinyo et al. [59], which green roof type is more important than spatial coverage. The fact that urban agriculture systems enhance food security, in addition to regulating the near-surface air temperature, emphasizes the multi-faceted benefits of NbS implementation in urban areas [5,6,30,36]. This finding supports the statement that green infrastructure is a sustainable solution to address multiple climate change impacts and supports the implementation of the UN Sustainable Development Goals [5,6,29–31,36,99].

The second data collection campaign utilized remote sensing observations. Observations gathered from the Landsat-8 satellite confirm that green infrastructure can mitigate urban heat through decreased LST. Trees and dense vegetation predominantly contribute to this cooling effect through shade provision, evapotranspiration, and reduced albedo. On the other hand, flat grass surfaces have a reduced cooling effect and should be secondary to the application of trees, shrubs, and dense vegetation. This is consistent with the findings of previous studies. For example, urban trees tend to be more effective in reducing outdoor air temperatures than other types of vertical and horizontal greenery [100–103]. However, a combination of various types of green infrastructure, such as green roofs and green walls, requires less space and also has the potential to increase the overall efficacy of beneficial impacts [46,64,103–106].

The observed results for compact, built-up areas in this field campaign show there is a link between urban form and LST in Toronto, Ontario, Canada. Industrial areas have an LST value that is 15 °C higher compared to densely forested areas. Additionally, urban areas with more vegetation had significantly lower LST values compared to compact built-up areas, indicating that urban vegetation and forestry systems can lower heat load. These results are in alignment with previous studies that analyzed thermal properties in Toronto using Landsat imagery [107–110]. The study by Rinner and Hussain [107] analyzed the thermal imagery of Toronto on 3 September 2008. On that day, LST values in Toronto ranged between 20 and 37 °C, which are nearly identical to the observed values of this field campaign, which ranged between 19.5 and 38 °C. In addition, Rinner and Hussain [107] found similar cooling effects in the application of vegetation.

Among the multiple recognized UHI mitigation strategies, the application of green infrastructure often emerges as a strategic way to mitigate urban heat. According to Aflaki et al. [111], urban applications of green infrastructure can significantly mitigate UHI intensity, both directly and indirectly, through the reduction of air temperature and mean radiant temperature [111], in addition to LST, as evidenced in this study. Since there are various types of green infrastructure applications and each has the potential to alleviate the UHI effect, cool the ambient air, and create thermally balanced cities [103], the question of the most suitable solution emerges. According to Yenneti et al. [103], simultaneous implementation of two or more urban green infrastructure technologies leads to the best results.

Differences in cooling effects have been studied across diverse applications of green infrastructure. Some studies have shown urban trees have a greater cooling effect than green roofs and walls [100–102]. While trees have been shown to have a greater cooling effect in urban settings, a combination of green infrastructure applications such as green roofs and walls can increase the overall cooling effect as they have fewer spatial requirements than trees [64,104]. Of the green infrastructure applications tested at the microscale in this study, urban agriculture systems showed the greatest impact in regulating near-surface air temperature. At the mesoscale, this study showed that green infrastructure decreases LST through the application of vegetation and forestry systems.

Achieving Heat Equity with NbS

There is a correlation between the lack of green infrastructure and urban heat in Toronto, Ontario, Canada. While the warmest areas of the city have few trees, shrubs, or green space, these are also areas that have been previously identified by the City of Toronto as having both high levels of heat vulnerability (Figure 11) and the lowest median after-tax household income (Figure 12). There is a discernible donut pattern visible on both maps, that shows the hottest areas with the highest heat vulnerability and the oldest building stock, are also the poorest. When compared to Figures 8 and 9, this donut pattern is almost identical in the distribution of higher NDVI values and lower LST values. This represents an inequitable distribution of heat risk.

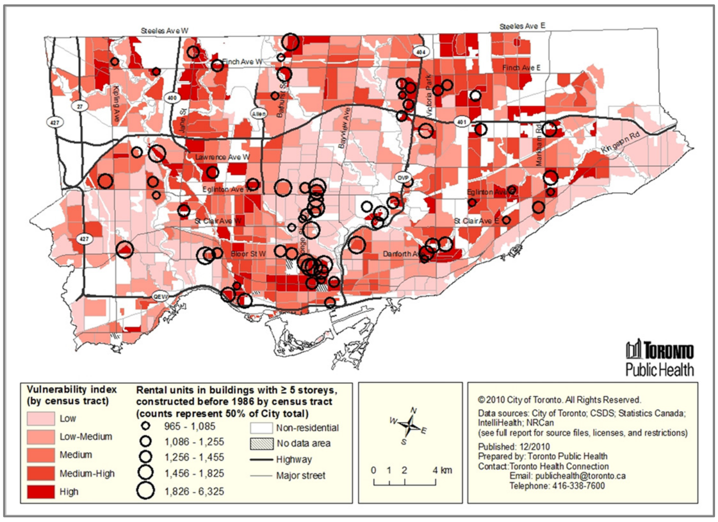


Figure 11. Map of the City of Toronto showing areas of heat vulnerability, in addition to older multi-storey buildings with no air conditioning. (Source: Toronto Public Health, 2010).

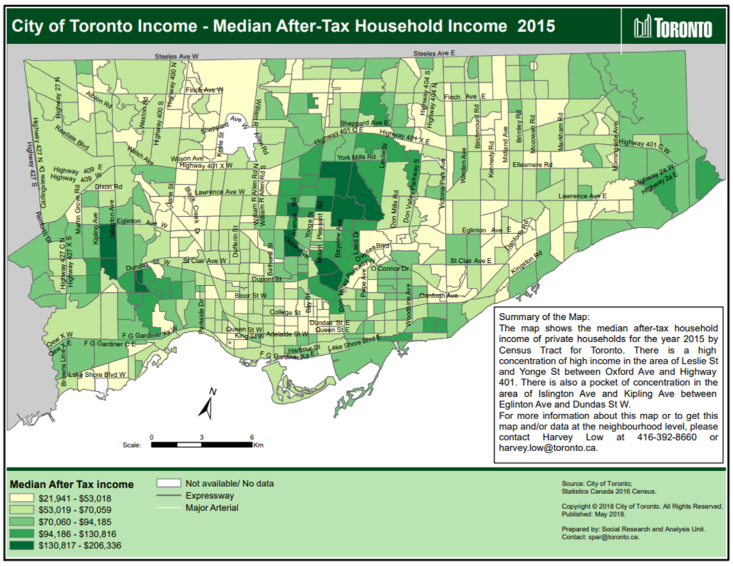


Figure 12. Map of the City of Toronto showing median after-tax household income. (Source: City of Toronto, 2016).

The City of Toronto has endeavoured to address heat vulnerability through the operation of publicly accessible cooling centres for vulnerable citizens with limited personal access to cool spaces. The analysis of city-operated cooling centres shows they are well-positioned in areas with a high heat load. Heat presents a health risk in both densely built-up areas as well as in areas with extensive tree growth and dense vegetation, especially during heat waves. Thus, the positioning of cooling centres in areas with higher NDVI values and low LST is justified. By using micro (pixel-based) and meso (neighbourhood-based) scale satellite data as demonstrated in this study, city authorities can make decisions regarding heat load mitigation. While urban development is inescapable, it is possible to reduce the UHI effect and the inequitable distribution of heat vulnerability.

This comparative study and its analyses present a unique methodology for evaluating the efficacy of NbS and prioritizing neighbourhood areas for green infrastructure implementation. This information can be valuable for the development of heat-health plans and UHI mitigation strategies on the micro- as well as on the neighbourhood scale. A limitation of this study is temporal sampling, as the field campaign was undertaken over two summers during the months of July and August. Results for the two summer field campaigns were similar, which is reassuring from an experimental design perspective, although a longer monitoring period over multiple seasons would be beneficial to explore the seasonality of the different green infrastructure treatments. Future areas of research interest include the following: (1) exploring the impact of green infrastructure treatments during the springtime growing period and the autumn senescence period; in addition to (2) conducting an inter-city comparison using this study methodology to evaluate NbS as a heat mitigation strategy across different urban climate regimes.

5. Conclusions

When high temperatures are sustained for an extended period, a thermal imbalance can occur in urban settings, leading to a reduced quality of life and heat-related mortality and morbidity. Vulnerable populations, including the elderly, individuals who are chronically ill, and those who are socially disadvantaged, are particularly susceptible to the health effects of extreme heat [15–17]. Rising temperatures will continue to exacerbate these disparities and the associated burden of illness [15,16,19]. NbS in the form of green infrastructure provides a viable and sustainable solution to address rising temperatures and increase heat equity.

Although limited to two summer seasons, this study provides unique insight into the impact of various green infrastructure applications on near-surface air temperature regulation and LST in Toronto, Ontario, Canada. Of the applications tested at the microscale, urban agriculture systems demonstrated the greatest cooling effect. Green roofs showed an average reduction of 0.5 °C in near-surface air temperature, with an observed average monthly reduction as great as 0.9 °C. Urban forestry and vegetation systems showed an average reduction of 0.4 °C in near-surface air temperature, with an observed average monthly reduction as great as 0.6 °C. Green wall systems showed an average reduction of 0.5 °C in near-surface air temperature, with an observed average monthly reduction as great as 0.6 °C. At the mesoscale, green infrastructure can mitigate urban heat through decreased LST. Trees and dense vegetation predominantly contribute to this cooling effect through shade provision, evapotranspiration, and reduced albedo. While the nature-based cooling effect varies across applications, it can effectively address warming temperatures through optimization of the built environment. Co-benefits can also be leveraged that include enhanced food security through the implementation of productive green infrastructure such as urban agriculture systems; biodiversity and pollinator support; air pollution abatement; stormwater matter management. Multiple applications of green infrastructure have a beneficial cooling effect on urban heat, in addition to providing a multidimensional intervention to increase climate resilience.

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