Cities and the Environment (CATE)

Volume 15 | Issue 1 Article 1

9-30-2022

Where to Expand Green Infrastructure to Support Equitable Climate Change Adaptation in the City of Toronto?

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Recommended Citation

Regier, Kristen and Conway, Tenley M. (2022) "Where to Expand Green Infrastructure to Support Equitable Climate Change Adaptation in the City of Toronto?," *Cities and the Environment (CATE)*: Vol. 15: Iss. 1, Article 1.
DOI: 10.15365/cate.2022.150101
Available at: https://digitalcommons.lmu.edu/cate/vol15/iss1/1

Where to Expand Green Infrastructure to Support Equitable Climate Change Adaptation in the City of Toronto?

Green Infrastructure (GI) is a potential tool to help cities adapt to climate change. In particular, GI can help moderate high summer temperatures and reduce urban flooding, both of which are expected to become more common with on-going climate change. However, GI is not evenly distributed in many cities suggesting that some neighborhoods are more vulnerable to climate change impacts. Additionally, marginalized communities often lack the resources needed to reduce existing vulnerabilities. This study explores the question: where should GI initiatives be focused to support equitable climate change adaptation in the City of Toronto (Ontario, Canada)? We address this question by applying a GI Equity Index that includes built environment and socio-economic factors to identify neighborhoods' level of need for GI to support climate change adaptation. The spatial location of high need neighborhoods, and their particular characteristics, are examined. Our results highlighted the spatial clustering of very high and low need neighborhoods in Toronto. Three types of neighborhoods were identified as most in need: (1) those vulnerable due to very limited existing GI, (2) those vulnerable due to socio-economic characteristics, and (3) those that lack GI and have marginalized populations based on socio-economic measures. On the other hand, neighborhoods identified as least in need based on the index were relatively uniform in character: all had abundant tree canopy and residents who were high income, highly educated, and disproportionately white. These results highlight the importance of considering both built environment and social vulnerability to support an equitable distribution of GI for climate change adaptation, and that varied opportunities and challenges exist related to increasing GI in different types of vulnerable neighborhoods.

Keywords

urban trees, parks, green roofs, environmental justice

INTRODUCTION

The recent IPCC report (2021) highlights the severity of ongoing climate change and that the impacts will be felt in our local environments. The question is no longer if climate change will impact our lives, but to what degree. Cities face particular challenges with climate change, which are interconnected and often amplified by other environmental challenges due to loss of green space from urbanization (Curtis and Oven 2012; Hobbie and Grimm 2020; Wamsler et al. 2020a; Anderson and Gough 2021). Climate change increases the frequency of extreme heat, which is intensified in cities by the existing urban heat island effect (Byrne et al. 2015; Norton 2015). Flooding from more intense precipitation events is also expected to increase, which is exacerbated by high levels of impermeable surfaces present in urban areas that limit site-level infiltration and increase overland flow (Hobbie and Grimm 2020).

Cities have been identified as an important scale for climate change adaptation initiatives (Benton-Short et al. 2019) due to their increased risks, contribution to climate change through high energy consumption (Sturiale and Scuderi 2019; Sharifi 2020), and the international (and national) communities lack of consensus on how to address climate change (Byrne et al. 2015; Wamsler et al. 2020b). Since climate change impacts will be felt locally, adaptation interventions will have to be tailored to the specific conditions within communities (Beery 2018; Woronieki 2019), particularly as climate change impacts, including more frequent heat waves and flooding, will be felt most heavily by marginalized populations (Debbage 2019; Hobbie and Grimm 2020). This highlights the need for justice-centered climate change adaptation interventions.

Green Infrastructure (GI) is a climate change adaptation strategy that is increasingly adopted by municipalities (Meerow and Newell 2017). While GI is defined in a variety of ways across different fields and in policy discourse (Conway et al. 2020), this study defines it as vegetation or green spaces that are intentionally planned and designed by humans to provide multiple benefits to people (Byrne et al. 2015; Matthews et al. 2015; Meerow and Newell 2017; Benedict and McMahon, 2002). Examples of GI include trees, shrubs, community gardens, parks, green roofs, and green facades (Matthews et al. 2015; Norton et al. 2015; Benton-Short et al. 2019). GI can provide shading and evapotranspiration, moderating hot summer temperatures (Norton et al. 2015; Hobbie and Grimm 2020), and increase water infiltration and slow run-off, reducing localized flooding risk (Gill et al. 2007; Sussams et al. 2015). In addition, GI provides cultural, social and health co-benefits, which can add to the appeal of GI and increase community support for its expansion (Kim and Song 2019; Sharifi 2020).

Recent research suggests that GI is not equally distributed across many cities, with the greatest inequities existing in marginalized communities (Danford et al. 2014; Nesbitt et al. 2019). This is a concern as marginalized communities are also expected to be the communities most impacted by climate change and have the fewest resources to support adaptation (Almeida and Engel 2020; Fitzgibbons and Mitchell 2020). Thus, some communities may be highly vulnerable to climate change impacts due to a combination of built environment and socio-economic factors.

This study applies an equity lens to explore where GI initiatives should be focused to support climate change adaptation in the City of Toronto (Ontario, Canada). We use a GI Equity

Index, modelled after Heckert and Rosen (2016), that considers neighborhoods' built environment and socio-economic conditions to identify different neighborhoods' vulnerability to climate change. Toronto is a large, multi-cultural city with distinct neighborhoods that are becoming increasingly polarized by income and other socio-demographic factors (Hulchanski 2010). Similar to many other cities, Toronto is facing climate-related challenges and has taken initial steps to increase GI to address climate change and other goals (Conway et al. 2020). As a result, Toronto is representative of many other cities in North America and beyond

DISTRIBUTIONAL JUSTICE, CLIMATE CHANGE ADAPTATION, AND GI

Distributional justice of GI refers to the fair spatial distribution of GI, whereby residents of a city all have equitable access to green infrastructure regardless of where they live in the city (Rawls 1999; Schlosberg 2007; Nesbitt et al. 2019). In practice, cities rarely have a just distribution of GI. For example, many studies have identified a positive relationship between household income or neighborhood wealth and tree canopy (Heynen and Lindsay 2003; Landry and Chakraboty 2009; Gerrish and Watkins 2018; Green et al. 2018). Similarly, at the neighborhood scale, racial or ethnic minorities, lower education-levels, and low owner-occupancy rates are also often negatively correlated with GI (Watkins and Gerrish 2018; Riley and Gardiner 2020). Carmichael and McDonough (2018) describe how even when low-income neighborhoods do have access to greenspace, they are often neglected by local government and have problems with crime or perceived crime, suggesting unequal access to high quality GI. Of course, unequal access to quality GI means unequal access to the associated benefits of GI, including those related to climate change adaptation (Watkins and Gerrish 2018).

Marginalized urban populations are both more likely to be impacted by climate change, living in neighborhoods that are more susceptible to high temperatures and/or flooding, and less likely to have the capacity to adapt (Bulkeley et al. 2013; Almeida and Engel 2020). Low-income residents, in particular, often experience economic barriers to adaptive or mitigative resources such as air conditioning, adequate shelter, or the ability to relocate to less impacted locations (Curtis and Oven 2012; Mitchell and Chakraborty 2015; Woroniecki 2019; Hobbie and Grimm 2020).

Lock et al. (2021) found that new GI siting in New Haven (US) is often based on funding opportunities and site-level characteristics, while equity considerations were not emphasized in the decision-making process. Additionally, urban greening initiatives that can reduce vulnerability of the built environment may lead to displacement of marginalized populations, through processes of green gentrification, or are often located in wealthier neighborhoods (Anguelovski et al. 2016; Pearsall and Anguelovski 2016). As a result, several authors identify the need to center social equity in adaptation plans as climate change will exacerbate inequities (Almeida and Engel 2020).

Ultimately, distributional injustice occurs because of human decisions. The current distribution of GI and climate vulnerability is rooted in historical settlement patterns and modern conditions, that cannot be divorced from systems of oppression such as racism (Danford et al. 2014; Riley and Gardiner 2020). Moreover, these decisions are often mediated by the biophysical landscape. For example, in Toronto, linear greenspaces extend inland from Lake

Ontario, reflecting several steeply sloped ravines that were difficult to develop during initial settlement and have more recently been protected (City of Toronto 2019a). In many cases, properties on the edges of the ravines are very expensive due to the views of the expansive greenspace, while also benefiting from the ravines' flooding and cooling potential. To improve distributional justice of GI, communities most vulnerable to climate change based on built environment and socio-economic characteristics should be targeted by GI initiatives to avoid the risk that GI expansion efforts will primarily focus on communities that have lower vulnerability or the capacity to adapt on their own (Heckert and Rosen 2016).

METHODS

Study Area

The study area is the City of Toronto, situated on the northwest shore of Lake Ontario. Toronto is the most populous and one of the most diverse cities in Canada, with a population of 2.96 million residents and a visible minority population of 51.5% (Statistics Canada 2021a). It is located in the Humid Moderate Temperate Eco-Climactic Region (Ministry of Natural Resources 2009), classified as a humid continental climate (Climate-Data 2015). Rainfall intensities are predicted to increase over the next century, contributing to increased urban flood risk (Rincón et al. 2022), while increasing summer temperatures will exacerbate the existing urban heat island effect within the city, where summer heat events already have Humidex values around 40 ℃ (Anderson et al. 2022). Toronto neighborhoods are also increasingly polarized by income and race (Hulchanski 2010), with rising housing costs making many neighborhoods out of reach for much of the population. Additionally, the province and city have densification strategies in place, with most new housing occurring in densely built, high rise units, which often limits space for new GI.

The City of Toronto has developed policies and plans related to GI and Climate Change, including the ResilientTO and TransformTO. The 2019 Resilience Strategy was developed as part of the 100 Resilient Cities project by the Rockefeller Foundation (City of Toronto 2019b). The strategy describes resiliency challenges and a vision for the city, while also identifying goals and actions to fulfill the vision. This strategy has a focus on equity, acknowledging that climate change will not affect all populations similarly (Fitzgibbons and Mitchell 2021). TransformTO is the City of Toronto's climate action strategy, but it is primarily focused on reducing greenhouse gas emissions, not adaptation (City of Toronto 2021a). However, additional plans and by-laws, including the Urban Forest Strategy, Wet Weather Flow Master Plan, green roof by-law and green building standards address the need for more GI in the context of increased heat waves, more intense precipitation events and other climate impacts (Conway et al. 2020).

Equity Index

To identify neighborhoods where GI initiatives should be implemented to support an equitable approach to climate change adaption, an GI Equity Index modelled after Heckert and Rosan's (2016) index was applied to Toronto. We used the 140 Social Planning Neighborhoods defined by the City of Toronto (2021b) as the unit of analysis. Each neighborhood is composed of two to five census tracts and is the geographic unit the city frequently uses to communicate data and set neighborhood priorities.

Heckert and Rosan's (2016) GI Equity Index identifies areas where GI is most needed, with an understanding that the built environment and socio-economic characteristics both influence need. The original index focused on built environment measures that capture air pollution (e.g., proximity to traffic and particulate matter levels) and recreational opportunities (e.g., playground and park access). We revised the built environment measures to reflect factors that are relevant to Toronto's climate change adaptation context that is oriented towards flood events and heat waves. Specifically, we selected built environment factors that are related to exposure to climate change impacts and access to existing GI: percent impermeable surface, percent green roof, percent tree canopy, and park provision (Table 1).

Impermeable surface cover data provided by the City of Toronto, representing localized flood risk due to lack of infiltration potential higher heat island effects (Jesdel et al. 2013; Heckert and Rosan 2016), were initially derived from sub-meter remotely sensed multispectral optical data collected in 2019. Percent impermeable surface was calculated as prevalence (%) of impermeable surface across the total surface area of each neighborhood.

Green roofs were included as a built environment variable because the city has encouraged green roofs on (re-)development projects, and since 2010 has required green roofs on larger buildings to help reduced urban heat island effects and localized flooding (City of Toronto n.d.). The green roof data are from 2021, reflecting completed green roofs based on green roof permit data.

Table 1. Built environment and socio-economic variables in the GI Equity Index.

Variable	Data Source
Impermeable Surface	City of Toronto Open Data –mpermeable-surface-wgs84
Green Roof	City of Toronto Open Data – Building Permits Green Roofs Data
Tree Canopy	City of Toronto Open Data- Forest and Land Cover Data
Park Provision	City of Toronto Parks Department
Visible Minority	City of Toronto Open Data- Neighbourhood-profiles-2016-csv - Total visible minority population
Low-Education	City of Toronto Open Data- Neighbourhood-profiles-2016-csv - Education: No certificate, diploma, degree
Low-Income	City of Toronto Open Data- Neighbourhood-profiles-2016-csv - Prevalence of low-income based on low-income measure, after
Renter (Owner-occupancy)	City of Toronto Open Data- Neighbourhood-profiles-2016-csv - Private households by tenure - renter
Age (65+)	City of Toronto Open Data- Neighbourhood-profiles-2016-csv - Seniors 65+

The combined the area of completed green roof permits by neighborhood was used to calculate the percentage of land occupied by green roofs.

Tree canopy and park provision were the final two built environment variables, reflecting GI that can address heat and flooding through direct shading, evapotranspiration and infiltration of precipitation (Jesdale et al. 2013; Heckert and Rosen 2016; Riley and Gardiner 2020). Data for both variables were obtained directly from City of Toronto staff. Tree canopy represents the percentage of surface area covered by tree and shrub canopy based on high resolution multispectral satellite images and LiDAR Data. The park provision data obtained from the city was expressed as total park area (m^2) per person based on a 500 m walking distance, aggregated by census dissemination area, a metric the city uses to evaluate new park locations. All city parks, including parks in the cities ravines where there is a slope less than 45 degrees and an entrance within 20m of a sidewalk or local road (City of Toronto 2019a). Because there are many dissemination areas per neighborhood, the median park provision value of the neighborhood was used as a measure of central tendency to be representative of the entire neighborhood.

The five socio-economic variables included in the index were those commonly identified as related to marginalization: percent visible minority, percent low-income, percent low-education, percent renter, and percent senior (Table 1). Previous research suggests that race, income and education are often related to lack of political capital needed to trigger government investment (e.g., Jesdale, et al. 2013; Mitchell and Chakraborty 2015; Heckert and Rosan 2016). Additionally, low-income residents often do not have the ability invest in climate change adaptation to reduce their vulnerability or to vote with their feet and move to an area with higher GI presence (Curtis and Owen 2012). Percent renters was included because they often have less agency than homeowners to implement GI around their homes. Finally, we considered seniors because the elderly often face increased risks due to heat exposure (Mitchell and Chakraborty 2015; Heckert and Rosan 2016).

The socio-economic variables were all obtained through the City of Toronto Open Data Portal using the ‘2016 Neighbourhood Profile’, a dataset that includes 2016 census data aggregated by neighborhood. Visible minority was calculated as prevalence (%) of individuals who identify as visible minority, defined as “persons, other than Aboriginal peoples, who are non-Caucasian in race or non-white in colour” (Statistics Canada 2021a). Low-income was similarly calculated based on the Statistics Canada low-income measure, after tax (LIM-AT), which defines a household as low income when its after-tax income is less than half of the median after-tax income of all households in Canada, adjusted for number of people per household (Statistics Canada 2017). For example, in 2016 the LIM-AT cut-off for a four-person household was 48,413 CAD (Statistics Canada 2021b). Percent low education was calculated by the population aged 15+ in private households whose highest education is “no certificate, diploma or degree” (e.g., no post-secondary education), based on the 25% sample data available from Statistics Canada. Percent renter was calculated as prevalence (%) of households by tenure-rent, also based on the 25% sample data available. Finally, percent senior was calculated as the percentage of individuals 65+ in relation to the entire population.

To calculate the GI Equity Index, each data point was standardized to a score between 0 and 1, by subtracting the lowest value from the raw value and dividing by the range for that variable (Heckert and Rosan 2016). All variables were defined to represent a relative disadvantage, so that higher values suggest greater GI need. Thus, the original green roofs, tree canopy and park provision values were subtracted from one to ensure that the scale (0 being least need, 1 representing highest need) was consistent (Heckert and Rosan 2016). The standardized values for each variable were then combined to create the final GI Equity Index score for each neighborhood. The variables were equally weighted, following Heckert and Rosan (2016). The resulting index has a maximum possible score of 9, which represents most need.

RESULTS

Standardized values for the built environment variables are shown in Figure 1. The percentage of impermeable surface ranges from 23.1% to 87.8%, with the greatest impermeable surface concentrated just west of the downtown core. There was also a strong spatial pattern of higher impermeable surface in a u-shape extending from the northeast to northern west-central sections

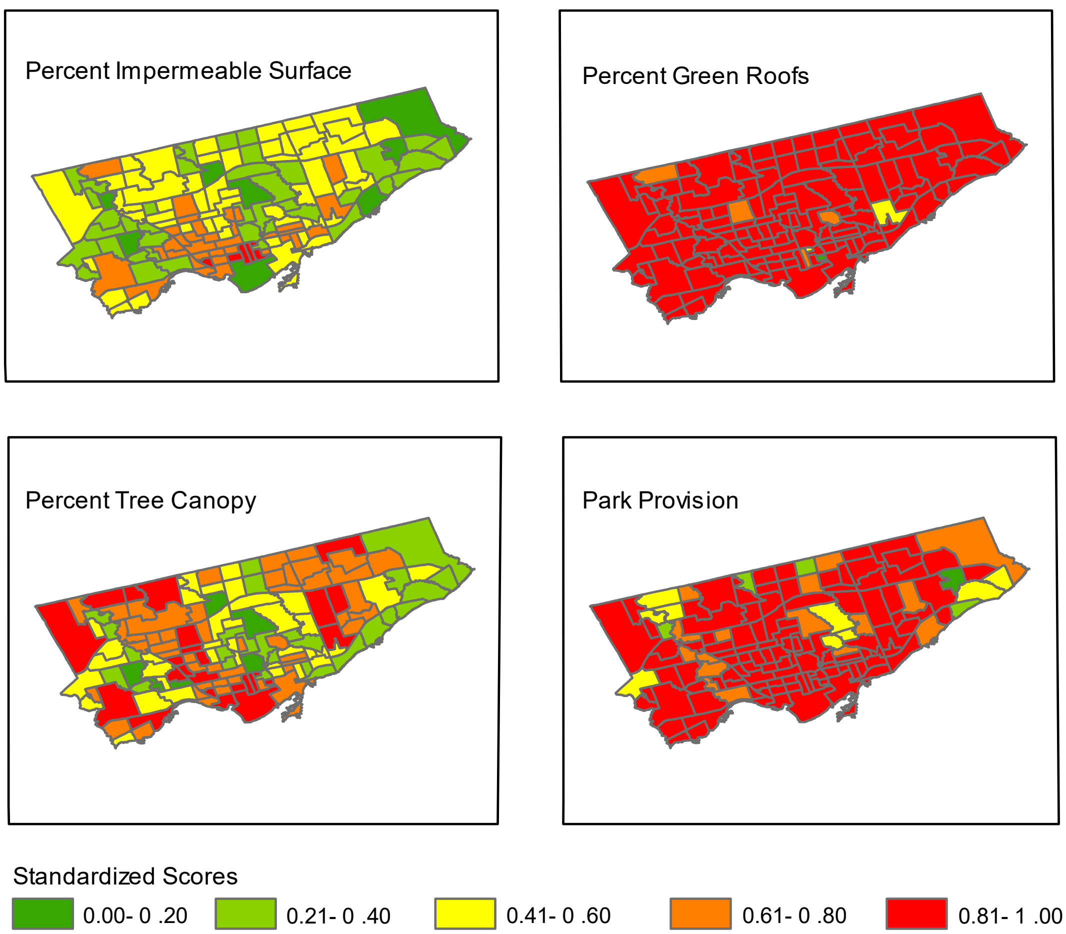

Figure 1. Standardized scores for the built environment variables, by City of Toronto neighborhood.

of the city. Green roofs, expressed as a percent of total surface area, ranged from 0%-0.46%. They did not have a major influence on the final GI Equity Index score because there were only a small number of neighborhoods scattered throughout the city that contained any green roofs, while most of Toronto's neighborhoods have none (and a resulting value of 1).

The percentage of tree canopy ranged from 5.3% to 31.0%. Not surprisingly the pattern is nearly inverse to the one seen for impermeable surface. Exceptions to this are the northeast and northwest edges of the city, where tree canopy is very low but impermeable surface only moderate. The highest level of tree canopy is concentrated in central Toronto and a few neighborhoods in the western part of the city. Park provision ranged from $0.6m^2$ to $199.6m^2$ of park space per person. Park provision was generally higher in three corridors running north to south in the eastern, central, and western sections of the city. Standardized park provision scores show many neighborhoods with high vulnerability because a few neighborhoods, such as Morningside in the southeast, have an average of almost $200m^2$/ person, while many neighborhoods contained less than $20m^2$ of parks per capita.

The socio-economic variables have broadly similar spatial patterns to several of the built environment variables, with highest vulnerability often located in the northern corners of the city (Figure 2). The percentage of visible minority population varied from 11.9% to 94.7%, with a distinct north-south gradient across most of the city. The percentage of the population who were categorized as low education ranged from 2.9% to 39.1%, with a pattern very similar to impermeable surface cover. For both variables, central Toronto and far western neighborhoods have very low vulnerability (i.e., have more White and highly educated residents).

The percent of low-income residents ranged from 4.5% to 45.5% across neighborhoods, with neighborhoods in the central core having the smallest percentage of low-income residents. Although neighborhoods with the largest percentage of low-income residents are scattered throughout the city, there are clusters of lower income residents in the northern and eastern parts of the city.

The percentage of renters ranged from 6.4% to 90.1%., with the majority living in the high-density downtown core. The northeast of Toronto has the fewest renters. Finally, the percentage of seniors varied from 4.8% to 28.0%. There is a small cluster of seniors in central Toronto, while few seniors live in the downtown core. The percentage of seniors was the socio-economic measure that showed the least variation across neighborhoods.

When all built environment and socio-economic variables are combined, the GI Equity Index scores range from 2.98 to 6.60 with a median of 5.14 (Figure 3; Appendix A). In general, neighborhoods with the lowest index score (least need) are clustered in the southwest, center and eastern parts of city. On the other hand, high values (greatest need) are concentrated primarily in the northern west-center and the northeast. In addition, there is a pocket of high values in the downtown core.

Considering the highest need neighborhoods (Table 2), three neighborhood types exist. First, some neighborhoods are highly vulnerable based on both the built environment and socio-economic measures (e.g., Kensington-Chinatown, Miliken and Agincourt North). These neighborhoods are all part of larger clusters of above average equity index scores. The second type of high need neighborhood (e.g., Black Creek, Rustic and Oakridge) is characterized by very high socio-economic vulnerability. On the other hand, the three highest need neighborhoods in this type have relatively low impermeable surface and high park provisioning, suggesting that they are not particularly vulnerable based on built environment alone. The third neighborhood type is characterized by high built environment vulnerability and mixed socio-economic conditions. This neighborhood type includes Bay Street Corridor in the downtown core and Keelesdale-Eglinton West. Both neighborhoods have high impermeable surface, little tree cover, and low park provision. Bay Street Corridor also has young, highly educated residents who are often renters and with lower income. Keelesdale-Eglinton West is close to the median standardized score for percent low-income, visible minority and renters, but has a relatively high percentage of low-education residents.

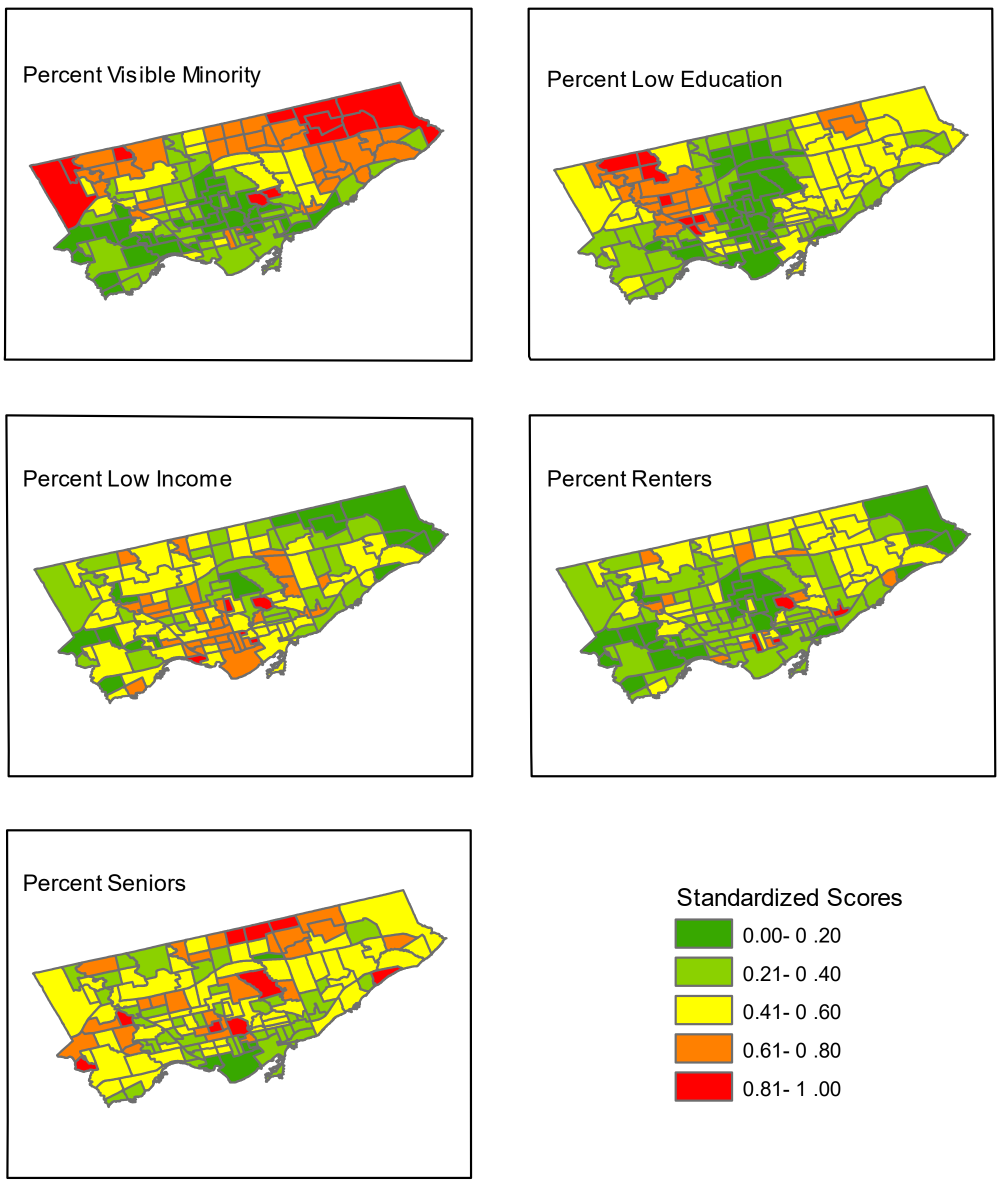

Figure 2. Standardized scores for the socio-economic variables, by City of Toronto neighborhood.

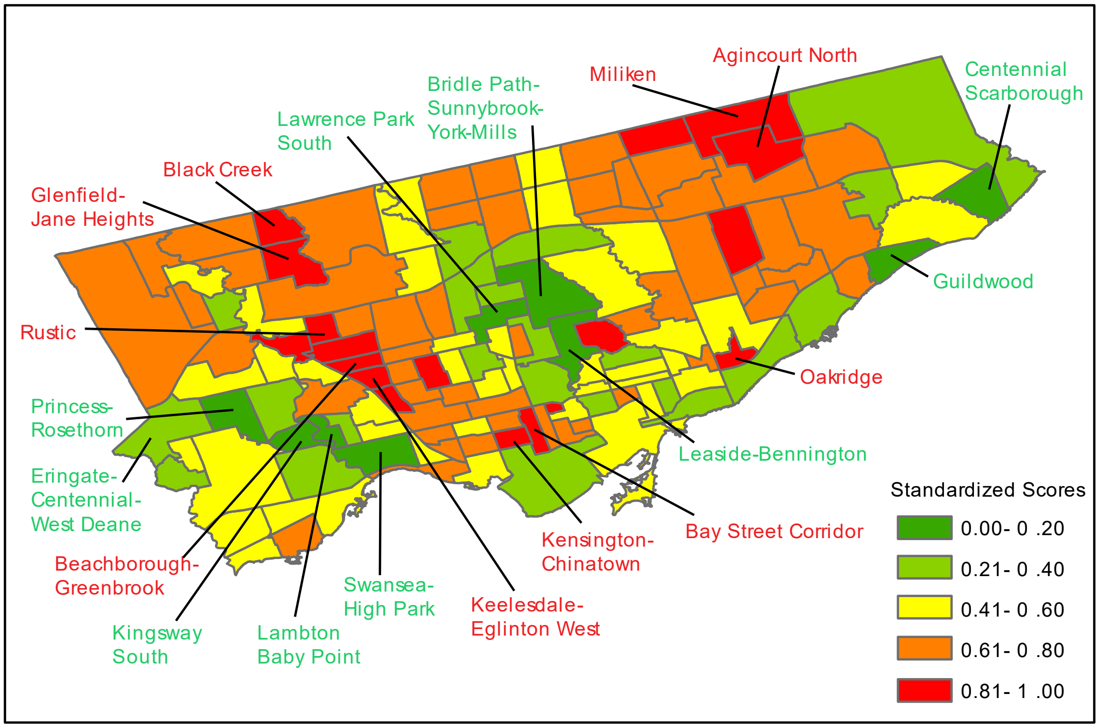

Figure 3. Overall equity index score, by City of Toronto neighborhood. The ten neighborhoods with highest need (red) and lowest need (green) are labelled.

The lowest need neighborhoods, on the other hand, are relatively uniform in characteristics (Table 3): the percentages of low income, visible minority, and renters are among the lowest in the city. In many cases there is also a relatively large percentage of seniors, suggesting that this variable alone is not associated with high need neighborhoods in Toronto. Park provision was variable and green roofs nearly absent from these neighborhoods, but very low impermeable surface and very high tree canopy translated into these neighborhoods having low built environment-related vulnerability.

DISCUSSION

This study sought to understand where green infrastructure initiatives are needed in Toronto to equitably support climate change adaptation. The GI Equity Index highlighted neighborhoods clustered in the northern west-center, northeast and downtown core of Toronto as being most in need of GI investment based on their built environment and/or socio-economic conditions. Lower levels of need were in the center of Toronto and along the southern lakeshore.

The highest GI Equity Index scores (describing highest need) in communities of low-income individuals or visible minority populations support previously documented correlations between built environment, including GI, and race or income (Danford et al. 2014; Nyelele and Kroll 2020; Anguelovski et al. 2021). The inequitable distribution of GI is a result of historical and ongoing systems of oppression (such as capitalism and racism). Under capitalism, GI is often viewed primarily as an amenity. For example, Nesbitt et al. (2019) argue that framing urban trees

Table 2. The built environment and socio-economic standardized values for the 10 highest need neighborhoods based on the overall equity index score. Higher standardized values equal higher need. Numbers in parentheses represent neighborhood rankings, from 1 to 140, with 1 representing the most vulnerable.

Neighborhood	Imp. Surface	Green Roofs	Tree Canopy	Park Prov.	Visible Min.	Low Educ.	Low Income	Renters	Seniors (65+)	Total Score
Black Creek	0.44 *(77)*	1.00 *(1)*	0.82 *(22)*	0.77 *(114)*	0.82 *(9)*	0.96 *(3)*	0.70 *(8)*	0.72 *(12)*	0.36 *(110)*	6.60 *(1)*
Kensington-Chinatown	0.90 *(3)*	0.92 *(125)*	0.88 *(13)*	0.99 *(6)*	0.56 *(48)*	0.41 *(61)*	0.70 *(7)*	0.77 *(6)*	0.44 *(76)*	6.5 *(2)*
Glenfield-Jane Heights	0.50 *(62)*	1.00 *(1)*	0.78 *(28)*	0.83 *(103)*	0.77 *(16)*	1.00 *(1)*	0.52 *(27)*	0.50 *(55)*	0.50 *(59)*	6.41 *(3)*
Rustic	0.39 *(94)*	1.00 *(1)*	0.75 *(39)*	0.85 *(97)*	0.56 *(49)*	0.82 *(7)*	0.66 *(12)*	0.67 *(21)*	0.60 *(33)*	6.30 *(4)*
Miliken	0.59 *(10)*	0.99 *(82)*	0.90 *(7)*	0.93 *(53)*	1.00 *(1)*	0.70 *(41)*	0.43 *(52)*	0.06 *(137)*	0.62 *(30)*	6.22 *(5)*
Bay Street Corridor	0.98 *(2)*	0.88 *(129)*	1.00 *(1)*	0.98 *(10)*	0.60 *(44)*	0.00 *(140)*	0.81 *(4)*	0.74 *(10)*	0.20 *(134)*	6.19 *(6)*
Beechborough-Greenbrook	0.58 *(45)*	1.00 *(1)*	0.70 *(51)*	0.87 *(80)*	0.55 *(53)*	0.76 *(9)*	0.57 *(17)*	0.72 *(13)*	0.42 *(83)*	6.18 *(7)*
Keelesdale-Eglinton West	0.68 *(26)*	1.00 *(1)*	0.86 *(17)*	0.99 *(2)*	0.37 *(71)*	0.99 *(2)*	0.34 *(76)*	0.38 *(96)*	0.49 *(62)*	6.10 *(8)*
Agincourt North (129)	0.53 *(55)*	1.00 *(1)*	0.78 *(29)*	0.94 *(41)*	0.95 *(2)*	0.64 *(18)*	0.41 *(54)*	0.15 *(130)*	0.69 *(18)*	6.09 *(1)*
Oakridge	0.42 *(84)*	1.00 *(1)*	0.51 *(91)*	0.89 *(72)*	0.75 *(23)*	0.50 *(37)*	0.93 *(2)*	0.74 *(9)*	0.31 *(120)*	6.05 *(10)*

Table 3. The built environment and socio-economic standardized values for the 10 lowest need neighborhoods based on the overall equity index score, and the neighborhood rank. Lower standardized values equal lower need. Numbers in parentheses represent neighborhood rankings, from 1 to 140, with 1 representing the most vulnerable.

Neighborhood	Imp. Surface	Green Roofs	Tree Canopy	Park Prov.	Visible Min.	Low Educ.	Low Income	Renters	Seniors (65+)	Total Score
Bridle Path-Sunnybrook-York-Mills	0.08 *(139)*	0.99 *(80)*	0.00 *(140)*	0.79 *(110)*	0.22 *(95)*	0.14 *(121)*	0.10 *(130)*	0.03 *(139)*	0.62 *(29)*	2.98 *(140)*
Centennial Scarborough	0.26 *(124)*	0.92 *(126)*	0.35 *(117)*	0.45 *(132)*	0.38 *(66)*	0.24 *(102)*	0.04 *(139)*	0.00 *(140)*	0.56 *(39)*	3.21 *(139)*
High Park-Swansea	0.30 *(18)*	1.00 *(1)*	0.16 *(138)*	0.62 *(124)*	0.08 *(130)*	0.14 *(120)*	0.16 *(119)*	0.45 *(76)*	0.48 *(63)*	3.38 *(138)*
Guildwood	0.20 *(132)*	1.00 *(1)*	0.26 *(130)*	0.30 *(136)*	0.21 *(100)*	0.28 *(90)*	0.08 *(133)*	0.19 *(127)*	0.94 *(3)*	3.46 *(137)*
Kingsway South	0.35 *(107)*	1.00 *(1)*	0.22 *(134)*	0.92 *(60)*	0.00 *(140)*	0.12 *(128)*	0.00 *(140)*	0.14 *(131)*	0.72 *(15)*	3.46 *(136)*
Leaside-Bennington	0.30 *(120)*	0.98 *(101)*	0.27 *(129)*	0.94 *(43)*	0.07 *(133)*	0.15 *(116)*	0.06 *(136)*	0.26 *(121)*	0.45 *(73)*	3.46 *(135)*
Princess-Rosethorn	0.25 *(125)*	1.00 *(1)*	0.32 *(125)*	0.86 *(89)*	0.09 *(129)*	0.20 *(107)*	0.07 *(135)*	0.11 *(135)*	0.58 *(35)*	3.49 *(134)*
Lambton Baby Point	0.27 *(123)*	1.00 *(1)*	0.16 *(137)*	0.60 *(125)*	0.15 *(116)*	0.29 *(86)*	0.34 *(72)*	0.41 *(86)*	0.35 *(112)*	3.57 *(133)*
Lawrence Park South	0.42 *(86)*	1.00 *(1)*	0.28 *(128)*	0.93 *(51)*	0.06 *(135)*	0.13 *(123)*	0.07 *(134)*	0.29 *(116)*	0.43 *(82)*	3.60 *(132)*
Eringate-Centennial-West Deane	0.25 *(126)*	1.00 *(1)*	0.53 *(85)*	0.50 *(131)*	0.19 *(103)*	0.34 *(77)*	0.13 *(126)*	0.11 *(136)*	0.67 *(21)*	3.71 *(131)*

as amenities has allowed for their commodification according to capitalist principles leading to unjust distributions in many cities. Further, patterns of historical and ongoing exclusion and disenfranchisement of Black, Indigenous, and People of Colour (BIPOC) communities in housing, employment, and standards of care has also contributed to an inequitable distribution of GI (Anguelovski et. al., 2020; Loughran 2020; Herreros-Cantes and McPhearson 2021; Witze, 2021). Given that the inequitable distribution is a result of systems of oppression it should be addressed as such.

The relationship between of high home ownership and low GI Equity Index scores (i.e., least need) is also supported by previous findings (Danford et. al. 2014; Riley and Gardener 2020). Residents who own their property have the agency to install GI on their own, without needing to wait for a landlord or the municipality to act. Individuals who rent usually do not have this ability, which is a basic barrier to GI expansion (Nesbitt et al. 2019; Riley and Gardiner 2020). Homeowners may also be more likely to invest in GI as it can be seen as an investment in their property whereas renters will not experience the financial benefits (Nyelele and Kroll 2020). Further, home ownership is closely tied to (and explained by) income, so it is not surprising that communities with higher homeownership would also have higher incomes and more GI.

The neighborhoods in our study with the highest index scores (i.e., highest need) have high built environment and socio-economic vulnerability, very high socio-economic vulnerability, or high built environmental vulnerability and mixed socio-economic conditions. These of types of neighborhoods are not unique to the Toronto context, but a reminder that different strategies are needed in different contexts. For the first two neighborhood types with marginalized populations, programs are needed to overcome existing barriers residents may face with GI installation and maintenance, including resources (e.g., time, money), knowledge about different GI options and their relationship to climate change adaptation, and the political capital needed to generate investment by the city. Resources are often identified as barriers to GI expansion by residents themselves (Berry 2018; Ureta 2021). Thus, initiatives that provide free or subsidized GI alongside the expertise needed to properly install and maintain GI may help support GI in these neighborhoods.

Previous studies, however, suggest that just having free or subsidized GI programs does not mean that marginalized communities will benefit (Locke and Grove 2016), especially when programs are limited to homeowners (Perkins et al. 2004; Carmichael and McDonough 2018). There are some concerns that opt-in programs reinforce existing inequalities. Thus, new initiatives should be developed within high need neighborhoods to ensure all residents can participate and their needs and concerns are addressed, and generally supporting a just process. For example, initiatives that work with residents to expand GI in public spaces can help address the needs of renters who may lack the authority to install GI around their home. At the same time, a key challenge in marginalized communities is avoiding the types of large-scale greening projects that can facilitate green gentrification and/or place the burden of care on individuals (Anguelovski et al 2016; Carmichael and McDonough 2018). Thus, initiatives to engage communities in determining the variety and location for small-scale GI features, combined with the provision of support to maintain those features, may be the most effective strategies in these neighborhoods.

The third neighborhood type we identified are characterised by very little existing GI and high levels of impermeable surface due to very dense built environments. The challenge in these neighborhoods is determining where additional GI can be located due to lack of space. In this case, green roofs, green walls and other engineered GI (e.g., permeable pavement) may be needed to retrofit existing gray infrastructure to be more resilient to future heat waves and intense precipitation events. Strategies to work with landlords or the companies managing the large multi-family dwelling properties that could be retrofitted to incorporate more GI is needed as much as direct engagement with residents.

One limitation of the study is that the GI Equity Index reflected built environment and socio-economic variables related to climate change vulnerability that were available for the study area. Future updates in Toronto or application of the GI Equity Index for climate change adaptation elsewhere could include additional built environment indicators related to flooding, including urban flood vulnerability existing (storm) sewer capacity and or recent flooding events. Additionally, data on rain gardens and bioswales were not available and have had minimal uptake in Toronto yet are key GI features in many cities that can contribute to climate change adaptation. A second limitation is that our approach used existing quantitative datasets aggregated at the neighborhood-level, but we did not speak with people in the neighborhoods. Future research should explore residents' experiences and perceptions to better understand vulnerabilities and opportunities for GI expansion.

Beyond data limitations, we chose to weight all factors equally, following Heckert and Rosan (2016). While this approach is straight-forward to implement, it implies that are factors are equally important when this may not be the case. Future application of the GI Equity Index should consider differentiate weighting of factors, based on local expert opinions (Mohat and Khirfan 2022) or input from residents and policymakers about GI and climate change priorities.

Climate change is a major concern for urban centers, with the impacts of climate change likely experienced unevenly across a city. GI is a climate change adaptation tool that can help communities adapt to the localized impacts of climate change. Given that neighborhoods' vulnerability to climate change varies based on the built environment and socio-economic conditions, adaptation strategies need to be tailored to specific neighborhood conditions. The GI Equity Index, modified from Heckert and Rosen (2016), identified three types of high need neighborhoods in the City of Toronto. In order to improve distributional equity of GI supporting climate change adaptation, Toronto should focus on GI expansion in the vulnerable neighborhood clusters in the city's northern west-center, northeast and downtown core. However, as not all vulnerable neighborhoods are identical, with varied strategies are required across neighborhoods with different populations and built conditions.

Appendix A –Equity Index scores and standardized variables for all neighborhoods.

Neighborhood	Imperm. Surface	Green Roofs	Tree Canopy	Park Prov.	Seniors (65+)	Low Income	Visible Minority	Renters	Low Educ.	Total Score
Black Creek	0.44	1.00	0.82	0.77	0.36	0.70	0.82	0.72	0.96	6.60
Kensington-Chinatown	0.90	0.92	0.88	0.99	0.44	0.70	0.56	0.77	0.41	6.58
Glenfield-Jane Heights	0.50	1.00	0.78	0.83	0.50	0.52	0.77	0.50	1.00	6.41
Rustic	0.39	1.00	0.75	0.85	0.60	0.66	0.56	0.67	0.82	6.30
Miliken	0.59	0.99	0.90	0.93	0.62	0.43	1.00	0.06	0.70	6.22
Bay Street Corridor	0.98	0.88	1.00	0.98	0.20	0.81	0.60	0.74	0.00	6.19
Beechborough-Greenbrook	0.58	1.00	0.70	0.87	0.42	0.57	0.55	0.72	0.76	6.18
Keelesdale-Eglinton West	0.68	1.00	0.86	0.99	0.49	0.34	0.37	0.38	0.99	6.10
Agincourt North (129)	0.53	1	0.78	0.94	0.69	0.41	0.95	0.15	0.64	6.09
Oakridge	0.42	1.00	0.51	0.89	0.31	0.93	0.75	0.74	0.50	6.05
Steeles	0.48	0.99	0.79	0.91	0.80	0.40	0.94	0.12	0.57	6.00
Brookhaven-Amesbury	0.54	1.00	0.76	0.87	0.31	0.49	0.65	0.64	0.74	6.00
Thorncliffe Park	0.52	0.68	0.64	0.59	0.27	1.00	0.80	0.99	0.50	5.99
North St. James Town	0.81	0.46	0.86	0.96	0.19	0.78	0.65	1.00	0.27	5.99
Weston	0.56	1.00	0.67	0.89	0.38	0.61	0.58	0.68	0.61	5.98
Dorset Park	0.65	0.96	0.89	0.96	0.44	0.43	0.77	0.39	0.46	5.96
Weston-Pelham Park	0.78	1.00	0.93	0.95	0.31	0.39	0.31	0.42	0.83	5.92
Oakwood Village	0.74	1.00	0.84	0.98	0.54	0.34	0.37	0.49	0.61	5.91
South Parkdale	0.61	0.88	0.75	0.97	0.29	0.63	0.40	0.96	0.37	5.87
Briar Hill-Belgravia	0.78	1.00	0.97	0.96	0.43	0.30	0.41	0.53	0.49	5.87
York University Heights	0.59	0.98	0.84	0.84	0.34	0.49	0.69	0.58	0.52	5.86
Mount Olive-Silverstone-Jamestown	0.33	1.00	0.60	0.85	0.26	0.57	0.90	0.58	0.77	5.86
Eglinton East	0.47	0.98	0.69	0.84	0.46	0.52	0.78	0.58	0.52	5.83
Tam O'Shanter-Sullivan	0.41	1.00	0.61	0.92	0.76	0.47	0.75	0.44	0.45	5.81

Humber Summit	0.71	0.79	0.95	0.57	0.62	0.37	0.65	0.28	0.86	5.80
Ionview	0.42	1.00	0.68	0.94	0.39	0.46	0.74	0.65	0.50	5.77
Yorkdale-Glen Park	0.72	0.65	0.97	0.91	0.75	0.30	0.37	0.38	0.71	5.77
Agincourt South-Malvern West	0.54	0.97	0.78	0.87	0.54	0.44	0.88	0.25	0.47	5.74
L'Amoreaux	0.42	1.00	0.67	0.88	0.67	0.46	0.78	0.34	0.51	5.73
Downsview-Roding-CFB	0.41	0.98	0.73	0.89	0.47	0.36	0.55	0.55	0.73	5.67
West Humber-Clairville	0.58	0.97	0.88	0.85	0.44	0.28	0.83	0.30	0.50	5.64
Caledonia-Fairbank	0.57	1.00	0.72	0.98	0.37	0.48	0.29	0.35	0.88	5.62
Kennedy Park	0.37	1.00	0.64	0.97	0.43	0.53	0.69	0.47	0.50	5.60
Henry Farm	0.56	0.94	0.72	0.93	0.19	0.61	0.78	0.68	0.17	5.58
Dovercout-Wallace Emerson-Junction	0.79	0.99	0.88	0.94	0.32	0.31	0.26	0.52	0.54	5.56
Regent Park	0.78	0.00	0.88	0.90	0.08	0.92	0.69	0.82	0.49	5.55
Malvern	0.46	0.99	0.72	0.88	0.37	0.39	0.94	0.28	0.48	5.52
Moss Park	0.83	0.84	0.78	0.98	0.19	0.67	0.32	0.71	0.19	5.52
Woburn	0.37	1.00	0.59	0.81	0.44	0.55	0.77	0.49	0.48	5.50
Wexford/Maryvale	0.56	0.97	0.82	0.91	0.52	0.36	0.52	0.40	0.44	5.49
Dufferin Grove	0.71	1.00	0.77	0.96	0.35	0.33	0.23	0.63	0.49	5.47
Victoria Village	0.42	1.00	0.57	0.65	0.63	0.52	0.56	0.62	0.48	5.45
Church-Yonge Corridor	1.00	0.63	0.97	0.98	0.21	0.52	0.34	0.77	0.04	5.45
Humbermede	0.47	0.99	0.75	0.40	0.39	0.44	0.79	0.49	0.72	5.44
Mount Pleasant West	0.74	0.99	0.74	0.96	0.46	0.40	0.25	0.82	0.08	5.43
Wychwood	0.71	1.00	0.65	0.96	0.74	0.30	0.16	0.54	0.37	5.43
Taylor-Massey	0.43	1.00	0.45	0.83	0.26	0.69	0.65	0.73	0.37	5.41
University	0.76	0.91	0.74	1.00	0.54	0.44	0.21	0.67	0.15	5.41
Hillcrest Village	0.43	1.00	0.62	0.79	0.89	0.42	0.77	0.21	0.27	5.39
Don Valley Village	0.46	1.00	0.61	0.88	0.54	0.46	0.71	0.51	0.22	5.39
Maple Leaf	0.43	1.00	0.69	0.78	0.66	0.26	0.37	0.45	0.71	5.36

Scarborough Village	0.24	1.00	0.35	0.87	0.37	0.68	0.73	0.58	0.54	5.35
Little Portugal	0.84	0.84	0.90	0.99	0.31	0.27	0.19	0.61	0.40	5.34
Newtonbrook West	0.41	1.00	0.62	0.93	0.55	0.53	0.56	0.49	0.24	5.33
Englemount-Lawrence	0.48	1.00	0.66	0.97	0.51	0.41	0.33	0.62	0.35	5.33
Bendale	0.45	1.00	0.64	0.73	0.55	0.46	0.71	0.34	0.45	5.32
Pleasant View	0.48	1.00	0.71	0.90	0.66	0.32	0.63	0.21	0.39	5.32
Kingsview Village-The Westway	0.31	0.98	0.52	0.86	0.49	0.50	0.58	0.50	0.57	5.31
Blake-Jones	0.68	1.00	0.64	0.97	0.29	0.49	0.32	0.47	0.44	5.30
Willowdale East	0.53	0.98	0.59	0.97	0.33	0.63	0.76	0.38	0.11	5.29
Trinity-Bellwoods	0.77	0.94	0.76	0.94	0.40	0.25	0.21	0.49	0.51	5.28
Corso Italia-Davenport	0.67	1.00	0.75	1.00	0.41	0.22	0.16	0.37	0.69	5.26
New Toronto	0.56	1.00	0.78	0.84	0.37	0.50	0.24	0.60	0.38	5.26
Newtonbrook East	0.37	0.99	0.51	0.85	0.68	0.56	0.70	0.35	0.21	5.21
Annex	0.74	1.00	0.63	0.96	0.63	0.34	0.14	0.66	0.09	5.19
Rexdale-Kipling	0.39	1.00	0.59	0.90	0.50	0.34	0.47	0.45	0.54	5.18
Willowdale West	0.42	0.98	0.56	0.93	0.65	0.55	0.54	0.36	0.18	5.18
Rockcliffe-Smythe	0.34	1.00	0.51	0.77	0.50	0.45	0.41	0.44	0.76	5.18
Flemingdon	0.22	1.00	0.33	0.58	0.38	0.74	0.80	0.59	0.52	5.16
Etobicoke West Mall	0.49	1.00	0.70	0.86	0.54	0.34	0.32	0.49	0.41	5.15
Mimico (includes Humber Bay Shores)	0.63	0.99	0.83	0.93	0.45	0.33	0.23	0.50	0.25	5.14
Mount Dennis	0.36	1.00	0.44	0.66	0.33	0.51	0.66	0.56	0.63	5.13
Palmerston-Little Italy	0.77	1.00	0.72	0.95	0.40	0.23	0.11	0.63	0.32	5.12
Roncesvalles	0.74	1.00	0.67	0.96	0.28	0.38	0.16	0.60	0.31	5.10
Danforth	0.77	1.00	0.69	0.99	0.47	0.24	0.17	0.35	0.42	5.08
Islington-City Centre West	0.64	0.94	0.82	0.92	0.52	0.28	0.30	0.42	0.25	5.08
Willowridge-Martingrove-Richview	0.37	0.98	0.59	0.87	0.75	0.26	0.34	0.48	0.43	5.06

Danforth East York	0.71	0.99	0.77	0.99	0.46	0.22	0.21	0.27	0.41	5.04
Junction Area	0.79	1.00	0.85	0.97	0.24	0.22	0.21	0.41	0.31	5.00
Clairlea-Birchmount	0.60	0.55	0.80	0.92	0.37	0.37	0.58	0.33	0.45	4.97
Greenwood-Coxwell	0.67	0.99	0.58	0.93	0.28	0.37	0.33	0.41	0.37	4.93
South Riverdale	0.42	0.99	0.74	0.95	0.31	0.35	0.34	0.40	0.40	4.91
Clanton Park	0.53	0.95	0.76	0.94	0.41	0.25	0.32	0.47	0.27	4.90
Parkwoods-Donalda	0.32	1.00	0.41	0.85	0.44	0.39	0.52	0.64	0.32	4.89
Yonge-St.Clair	0.60	1.00	0.51	0.93	0.79	0.20	0.10	0.66	0.03	4.83
High Park North	0.61	1.00	0.53	0.95	0.41	0.29	0.14	0.71	0.14	4.79
East End-Danforth	0.64	0.94	0.59	0.95	0.33	0.35	0.22	0.47	0.28	4.78
O'Connor-Parkview	0.35	0.97	0.35	0.87	0.41	0.44	0.31	0.56	0.44	4.70
Broadview North	0.32	1.00	0.34	0.80	0.49	0.44	0.19	0.74	0.38	4.69
Forest Hill North	0.48	1.00	0.43	0.93	0.51	0.27	0.19	0.71	0.15	4.67
Playter Estates-Danforth	0.63	1.00	0.54	0.96	0.47	0.22	0.10	0.56	0.19	4.66
Humber Heights-Westmount	0.29	1.00	0.38	0.75	0.99	0.25	0.16	0.39	0.42	4.63
West Hill	0.22	0.98	0.36	0.55	0.46	0.50	0.61	0.41	0.53	4.62
Yonge-Eglinton	0.63	1.00	0.55	0.95	0.38	0.18	0.18	0.66	0.08	4.60
Highland Creek	0.30	0.98	0.50	0.88	0.62	0.15	0.75	0.06	0.33	4.57
Niagara	0.72	0.98	0.88	0.93	0.00	0.22	0.27	0.52	0.04	4.56
Woodbine-Lumsden	0.52	1.00	0.58	0.94	0.39	0.26	0.23	0.30	0.34	4.56
Long Branch	0.47	0.98	0.50	0.87	0.39	0.32	0.13	0.56	0.34	4.56
Bayview Village	0.32	0.99	0.38	0.69	0.52	0.47	0.68	0.42	0.11	4.56
Pelmo Park-Humberlea	0.40	1.00	0.67	0.77	0.43	0.17	0.38	0.13	0.60	4.55
Bathurst Manor	0.28	0.95	0.45	0.92	0.59	0.30	0.27	0.47	0.27	4.50
Westminister-Branson	0.31	0.99	0.46	0.32	0.63	0.49	0.39	0.64	0.25	4.49
Alderwood	0.58	0.98	0.72	0.87	0.51	0.09	0.11	0.17	0.46	4.49
Thistletown-Beaumond Heights	0.23	1.00	0.34	0.42	0.57	0.32	0.62	0.38	0.60	4.48

Casa Loma	0.47	0.95	0.33	0.91	0.84	0.20	0.06	0.64	0.06	4.47
Bayview Woods-Steeles	0.22	1.00	0.31	0.30	1.00	0.34	0.61	0.43	0.24	4.46
Banbury-Don Mills	0.38	0.99	0.42	0.58	0.88	0.22	0.41	0.39	0.19	4.46
Humewood-Cedarvale	0.47	0.99	0.43	0.84	0.37	0.27	0.20	0.69	0.18	4.45
Cabbagetown-South St. James Town	0.38	1.00	0.22	0.89	0.62	0.40	0.18	0.59	0.13	4.43
St. Andrew-Windfields	0.39	0.99	0.41	0.81	0.57	0.28	0.46	0.32	0.18	4.41
Elms-Old Rexdale	0.18	1.00	0.39	0.28	0.37	0.46	0.67	0.47	0.60	4.41
Woodbine Corridor	0.53	1.00	0.39	0.91	0.27	0.28	0.18	0.42	0.31	4.29
Old East York	0.40	1.00	0.48	0.71	0.50	0.22	0.18	0.34	0.40	4.23
Birchcliffe-Cliffside	0.33	0.97	0.38	0.91	0.55	0.24	0.17	0.32	0.36	4.23
North Riverdale	0.50	1.00	0.43	0.94	0.39	0.16	0.14	0.45	0.21	4.22
Waterfront Communities-The Island	0.15	0.80	0.89	0.97	0.09	0.29	0.39	0.63	0.00	4.21
Forest Hill South	0.43	1.00	0.33	0.93	0.70	0.15	0.06	0.48	0.12	4.20
Bedford Park-Nortown	0.46	0.98	0.47	0.99	0.56	0.12	0.12	0.28	0.21	4.20
Cliffcrest	0.19	1.00	0.34	0.70	0.52	0.33	0.35	0.32	0.37	4.13
Stonegate-Queensway	0.38	0.99	0.47	0.86	0.51	0.17	0.08	0.35	0.28	4.09
Runnymede-Bloor West Village	0.65	1.00	0.56	0.98	0.32	0.06	0.05	0.18	0.25	4.06
Markland Wood	0.32	1.00	0.41	0.82	0.90	0.09	0.02	0.23	0.24	4.04
Edenbridge-Humber Valley	0.19	0.99	0.17	0.86	0.71	0.15	0.11	0.45	0.28	3.90
Morningside	0.15	1.00	0.25	0.00	0.46	0.47	0.75	0.40	0.40	3.88
Lawrence Park North	0.55	1.00	0.46	0.98	0.36	0.05	0.11	0.21	0.13	3.87
Lansing-Westgate	0.16	0.99	0.17	0.92	0.37	0.32	0.37	0.42	0.13	3.84
Rosedale-Moore Park	0.31	0.98	0.11	0.83	0.85	0.14	0.07	0.46	0.08	3.83
Mount Pleasant East	0.37	0.96	0.28	0.96	0.42	0.14	0.13	0.44	0.12	3.83
The Beaches	0.52	0.98	0.38	0.87	0.38	0.12	0.02	0.37	0.15	3.80

Rouge	0.00	0.99	0.22	0.67	0.41	0.12	0.83	0.12	0.40	3.76
Eringate-Centennial-West Deane	0.25	1.00	0.53	0.50	0.67	0.13	0.19	0.11	0.34	3.71
Lawerence Park South	0.42	1.00	0.28	0.93	0.43	0.07	0.06	0.29	0.13	3.60
Lambton Baby Point	0.27	1.00	0.16	0.60	0.35	0.34	0.15	0.41	0.29	3.57
Princess-Rosethorn	0.25	1.00	0.32	0.86	0.58	0.07	0.09	0.11	0.20	3.49
Leaside-Bennington	0.30	0.98	0.27	0.94	0.45	0.06	0.07	0.26	0.15	3.46
Kingsway South	0.35	1.00	0.22	0.92	0.72	0.00	0.00	0.14	0.12	3.46
Guildwood	0.20	1.00	0.26	0.30	0.94	0.08	0.21	0.19	0.28	3.46
High Park-Swansea	0.30	1.00	0.16	0.62	0.48	0.16	0.08	0.45	0.14	3.38
Centennial Scarborough	0.26	0.92	0.35	0.45	0.56	0.04	0.38	0.00	0.24	3.21
Bridle Path-Sunnybrook-York-Mills	0.08	0.99	0.00	0.79	0.62	0.10	0.22	0.03	0.14	2.98

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