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Research article

Canopy of advantage: Who benefits most from city trees?

Christopher S. Greene [a, *], Pamela J. Robinson [b], Andrew A. Millward [a]

[a] *Urban Forest Research & Ecological Disturbance (UFRED) Group, Department of Geography & Environmental Studies, Ryerson University, 350 Victoria Street, Toronto, Ontario M5B 2K3, Canada*

[b] *School of Urban and Regional Planning, Ryerson University, 350 Victoria Street, Toronto, Ontario M5B 2K3, Canada*

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ABSTRACT

Urban tree canopy provides a suite of ecological, social, and economic benefits to the residents of urban areas. With an expanding recognition of these benefits among city residents, there is growing concern that access to these benefits is not distributed equally and may represent the presence of an environmental injustice. This study examines the spatial relationship between median household income and tree canopy variables, specifically realized tree canopy cover and potential tree canopy cover, for Toronto, Canada. Toronto provides a strong empirical focus as it is a densely populated urban setting reported to be exhibiting an increase in the geographic polarization of residents based upon household income. Spatial relationships between median household income and tree canopy variables are evaluated using the bivariate Moran's I statistic, a specialized local indicator of spatial autocorrelation (LISA). This method explicitly identified where statistically significant spatial clusters of high and low household income coincide with significant clusters of high and low urban tree canopy, providing the basis for an examination of the policies and management decisions that led to this temporal snapshot. The importance of these spatial clusters is examined from the perspective of understanding the impact of urban change (both socio-demographic and built form), and from the standpoint of improving equality of access to city trees and their benefits resulting from future tree planting decisions.

1. Introduction

With the emergence of urban forestry as a substantive discipline over the last several decades (see Konijnendijk et al., 2006), there has been rapid expansion in the quantity and focus of scholarship relating to city trees. Initially concentrating on definitions and determinants of urban forest structure (Rowntree, 1984; Sanders, 1984; Talarchek, 1990), the research emphasis quickly expanded to include the identification and quantification of a wide range of perceived ecological, social, and environmental urban forest benefits (Dwyer et al., 1992; McPherson, 1992; McPherson et al., 1997). With a considerable area of North American urban forest loss projected from continuing urbanization (Nowak and Walton, 2005), the focus on the quantification of tree benefits was an important step in moving an understanding of the importance of urban vegetation outside the academic sphere and into public focus to inform policy decisions, especially at the municipal level. Coupled with a shifting focus towards sustainability, a consequence of this broader recognition, several of North America's largest cities have undertaken large-scale urban forest studies to quantify the value of this environmental good. In some cases, such as the Million Trees initiatives in Los Angeles (McPherson et al., 2011) and New York (Locke et al., 2010), new commitments to expand urban tree canopy coverage have resulted. With this broader public awareness, however, has come yet another important expansion in the scope of urban forestry research: who receives the benefits of access to the urban forest?

This research paper quantifies the connection between the spatial distribution of urban tree canopy and median household income in Toronto, Canada through the application of a bivariate local indicator of spatial autocorrelation, bivariate Moran's I. This method explicitly identifies where statistically significant spatial clusters of high and low household income coincide with significant clusters of high and low urban tree canopy. Identification of these clusters provide the basis for an examination of the policies and management decisions that led to this temporal snapshot, and

* Corresponding author. Present address: Department of Earth Sciences, Dalhousie University, 1459 Oxford Street, PO BOX 15000, Halifax, Nova Scotia B3H 4R2, Canada.

E-mail addresses: csgreene@arts.ryerson.ca, csgreene@dal.ca (C.S. Greene), pamela.robinson@ryerson.ca (P.J. Robinson), millward@ryerson.ca (A.A. Millward).

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whether any distributional inequalities stemming from these decisions could result in a potential environmental injustice with respect to urban tree canopy.

1.1. Ecological aspects of urban forestry

The benefits of urban trees are considerable. In addition to higher residential property values observed with the presence of greater neighbourhood urban tree cover (Anderson and Cordell, 1988; Sander et al., 2010), city trees provide several ecological services often leading to direct economic benefits for both individual residents and to municipalities. The ability to mitigate storm water runoff through increased interception of rainfall can reduce stress on storm water management infrastructure (Berland and Hopton, 2014; Sanders, 1986; Xiao et al., 1988), thus offsetting maintenance and expansion costs to the responsible municipality, as well as reducing the frequency, and damage, associated with residential flooding (Nowak et al., 2010). The shading properties of city trees, complemented by cooling through evapotranspiration, can play an important role in reducing built surface temperatures in cities at different spatial scales.

At the microscale, individual dwellings with strategically planted trees have been shown to exhibit reduced temperatures and associated reductions in energy for summer cooling (Akbari et al., 2001). Through the simulation of irradiance to evaluate the influence of vegetation in shading on residential heating and cooling in four U.S. cities, McPherson et al. (1988) concluded that shading from vegetation considerably reduced the space cooling requirements in temperate and hot climates. Further research by McPherson and Simpson (2003) concluded that in aggregate, the existing trees in California provide an estimated reduction in annual electricity use for cooling by 6407.8 GWh. At the mesoscale, Greene and Millward (2017) concluded that temperature variation in the surface urban heat island of Toronto is moderately explained by canopy density variables. Energy savings at the household scale provide direct financial benefits to residents and can contribute to additional pollution reduction by offsetting energy generation required to meet cooling demands (Akbari, 2002).

By lessening demand for energy required for air conditioning, urban trees are indirectly responsible for pollution reduction in cities. Moreover, in addition to the ability to remove and sequester atmospheric carbon (Nowak and Crane, 2002; Rowntree and Nowak, 1991), city trees are of great importance to the direct removal of several airborne pollutants common in urban environments (Dwyer et al., 1992; McPherson et al., 1998; Nowak et al., 2006). Examining several urban centres across the United Kingdom, Beckett et al. (2000) demonstrated direct reduction of particulate matter less than 10 μm (PM_{10}), through physical filtration mechanisms, by trees of varying size and age. Formation of ground level ozone is inhibited in urban environments when temperature extremes are minimized; microclimatic temperature moderation by city trees has been shown by Nowak et al. (2000) to lower ozone concentrations. Although results varied by city, season, and the time of day, further work by Nowak et al. (2006) demonstrated significant reductions of several airborne pollutants (O_3, PM_{10}, nitrogen dioxide, sulphur dioxide, carbon monoxide) in cities across the conterminous United States. The ability to estimate and quantify reductions in air pollution is now a routine feature in urban forestry software tools (Nowak et al., 2010).

1.2. Human-centered aspects of urban forestry

While the tangible and intangible values of urban trees are considerable, prior literature indicates access to such benefits may be unequal, often disproportionately benefitting certain socio-demographic groups while reducing access for others. A positive relationship between median household income and proximity to tree canopy cover has been established in several notable studies with a focus on North American cities, though the strength of this positive relationship varied by urban centre. Examining the Chicago metropolitan region, Iverson and Cook (2000) concluded there was a moderately strong correlation between household income and landcover, particularly land-cover classes with trees. As a part of a study examining ecosystem services and riskscapes related to the urban heat island in Phoenix, Jenerette et al. (2011) observed an increasingly strong, positive spatial correlation between income and vegetation presence over three decades. Similar results were found by Landry and Chakraborty (2009) when examining the distribution of street trees in Tampa Bay, with lower proportions of street trees more common in the right of ways of lower income neighbourhoods.

Furthermore, other variables have been found that exhibit significant relationships with the spatial distribution of urban tree cover at the micro-scale (i.e., how the percentage of urban tree canopy varies among sub-city units such as census aggregation units). Several recent studies have identified a positive relationship between level of resident education and proximity to trees. Examining the participation in a voluntary tree planting program based in Toronto, Greene et al. (2011) observed a positive relationship between the proportion of the population with post-secondary qualifications and rate of program participation, though the proportion of variation explained varied by sub-region. In addition to the observed correlation in household income and vegetation abundance, Iverson and Cook (2000) also noted a negative relationship between household density and vegetation, particularly trees. Other authors have uncovered connections between the ethno-cultural background of city residents and their relationship to trees (Berland et al., 2015; Conway and Bourne, 2013).

1.3. Positioning urban forestry in an urban sustainability framework

The importance of maintaining and expanding urban vegetation, particularly urban trees, transcends more reductionist questions of ecological benefits or human benefits, and can be positioned as a necessity to achieve stronger sustainability outcomes. Strong approaches to sustainability focus on natural capital assets, with sustainability only being achieved when an equal or greater amount of natural capital is transferred to future generations (Costanza and Daly, 1992; Goodland, 1995; Rees, 1995). When viewed through a lens of strong sustainability, and with the considerable suite of benefits provided by the urban forest to city residents, this resource should be considered a natural capital asset, one that can considerably improve the quality of living in dense urban environments (Bassuk and Whitlow, 1988; Nowak et al., 2001). With this recognition of urban tree canopy as a natural capital resource, however, comes an obligation to consider the social principles of sustainability, particularly intergenerational, intragenerational, and geographic equity (see Haughton, 1999 for detailed descriptions). Considering this ethical paradigm of strong sustainability, over the long term it is imperative to ensure that the benefits of urban trees are protected for future generations (i.e., intergenerational equity), particularly when those benefits could aid in offsetting some of the potential impacts of climate change. In the short-term, it is also important to consider how those benefits are spatially distributed, and to whom (i.e., geographic and intragenerational equity).

With growing interest from academics and policy makers concerning studies that identify unequal access to the benefits of the urban forest for residents of several large North American cities, it is reasonable to infer these inequalities could constitute an environmental injustice. It is challenging, however, to definitively conclude that this inequality does indeed constitute injustice, as the definition of an environmental injustice remains contentious (Agyeman and Evans, 2004). The body of literature examining the urban forest through an environmental justice lens has more commonly focused on descriptive studies of inequality (e.g., Jenerette et al., 2011; Landry and Chakraborty, 2009; Troy et al., 2007); there are fewer examples of research that have examined the more normative dimension of justice (e.g., Heynen and Lindsey, 2003; Heynen et al., 2006) or on deconstructing the underlying processes leading to observed inequalities (e.g., Conway et al., 2011; Heynen et al., 2006; Perkins et al., 2004).

Consequently, many urban forestry studies addressing access to tree canopy have tended to align with earlier conceptualizations of environmental justice as distributive justice, with less focus on procedural justice, or justice as recognition (see Walker, 2010, for a detailed review). This focus on identifying inequalities may in part be related to a more recent shift in environmental justice studies from a focus on environmental harms to include environmental goods (Bell, 2004). As such, understanding who has access to the urban forest, and who does not, remains an important prerequisite to developing an understanding of the processes leading to those inequalities and is a primary focus of the present study.

A persistent challenge when determining whether some level of distributional inequalities in access to the benefits of city trees is acceptable, or whether unequal access has become injustice, can be related to the difficulty of assigning a standard of minimum resident access. For urban environmental managers this question is particularly relevant as they must specifically operationalize what should be the acceptable amount of canopy and at what minimum distances to canopy should a resident should have access? This standard for urban canopy is particularly difficult to establish in an urban forestry management process for several reasons.

One challenge is related to competing perceptions of greenspace and the value of shade trees. In more socio-demographically diverse, North American cities there is a lack of common agreement about the “benefits” of greenspace. What is viewed as an environmental good to one group of residents can be perceived as a place of danger, or potential for harm, by another group of residents (Ching-hua et al., 2005; Herzog and Chernick, 2000; Sreetheran and Konijnendijk van den Bosch, 2014), or may be contrary to cultural preferences. Examining the tree species preferences of residents in Toronto, Canada from different cultural backgrounds, Fraser and Kenney (2000) observed significant differences among the groups surveyed; specifically, respondents of British origin were more likely to prefer shade trees than Italian and Portuguese respondents who tended to prefer fruit trees over shade trees. When considered collectively, these studies suggest that efforts to expand green space (which includes the urban forest) to meet a minimum fractional canopy standard may be viewed as undesirable by members of the group lacking access to this environmental good.

1.4. Toronto: a city of growing income inequality

The City of Toronto, Canada, is one North American city where resident socio-demographic characteristics are highly influential concerning the spatial arrangement of dwellings, and the associated presence of urban vegetation. The current City of Toronto's jurisdictional boundaries product of amalgamating six separate municipal units in 1998 (Schwartz, 2004). In addition to Toronto's pre-settlement variation in biophysical conditions and vegetation types, each pre-amalgamation municipal unit pursued independent planning objectives over time and were subject to different socioeconomic processes and land use histories resulting in a considerable variation of built urban form (e.g., population density; see Fig. 1). These former municipal units are now subcomponents of a single city representing the most populous urban area in Canada and the fourth largest in North America (O'Toole, 2013).

Though spatial heterogeneity in urban form can lead to analytical complexity, this complexity does not necessarily negate the ability to detect patterns of spatial inequality in access to environmental goods, manifest as tree cover. Spatial patterns of socio-demographic inequity were examined by Hulchanski (2010) and Walks and Twigge-Molecey (2013), who concluded that not only is income inequality growing in Toronto, but that income is becoming more polarized and segregated (or clustered) in geographical space. These findings provide strong motivation for further investigations of the spatial arrangement of environmental goods and their relationship to resident income. Therefore, investigating bivariate spatial association may better detect and delineate distributional inequalities across the study area. Specifically, this research seeks to determine if the distribution of urban trees across Toronto is associated with resident income. Because there is a proven trend towards increasing polarization of income (Hulchanski, 2010; MacLachlan and Sawada, 1997; Walks and Twigge-Molecey, 2013), and if a significant relationship between income and tree canopy cover exists, then it is reasonable to conclude there is also growing polarization in access to tree canopy that corresponds to the distribution of resident income.

2. Methodology

This research uses median household income (MHI) for residents of Toronto and, by employing aspatial and spatial methods, seeks to determine whether and to what degree there is a relationship between tree canopy cover and resident affluence. In this study, tree canopy is defined as follows: total canopy is the sum of realized canopy cover and potential canopy cover. Realized canopy cover is defined as existing tree canopy cover, while potential canopy cover is defined as ground level pervious surface (bare soil, open space) that could be utilized as plantable space, and does not include areas with the potential for green roofs, rooftop gardens, or green facades. Note, a summary of abbreviations is provided in Table 1.

Identifying present patterns of inequality is required to begin to understand the impacts of past policy decisions and processes resulting in these identified patterns. By examining the potential for inequitable spatial access to city trees, this research can contribute to future policy decisions related to urban forest management. Should inequitable access exist, identification of such communities or neighbourhoods experiencing inequity could become targets for higher priority tree planting, especially considering Toronto's ambitious goal to increase its tree cover by 10–12 percentage points in the coming decades (City of Toronto, Parks, Forestry and Recreation, Urban Forestry, 2013a).

Two questions related to the spatial distribution of urban tree canopy in the City of Toronto are examined in this study, each of which have important implications for environmental justice contextualized through resident access to city trees and the benefits they provide: 1) are there broad, categorical differences in the presence of tree canopy from the perspective of income, and 2) are there spatial clusters in which concurrent polarization of household income and urban tree canopy occurs.

The first line of enquiry uses ANOVA to examine whether access to tree canopy differs among broader categories of resident income. The second line of enquiry examines the relationship of canopy

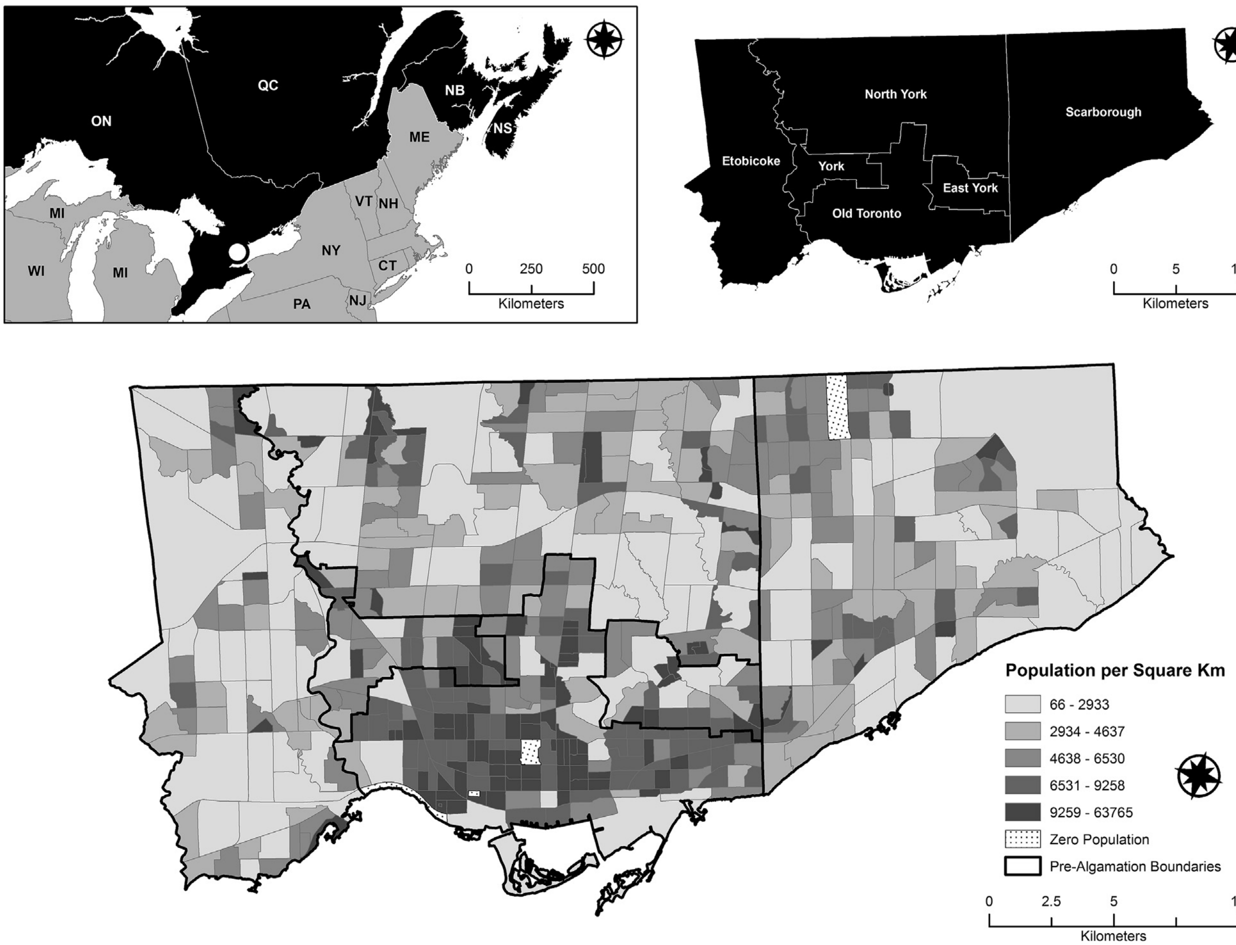

Fig. 1. Population density of Toronto, Canada (2006) by census tract with superimposed pre-amalgamation boundaries (see inset for identification).

Table 1
Summary of abbreviations.

Abbreviation	Description
CT	Census Tract
DA	Dissemination Area
LISA	Local Indicator of Spatial Correlation
MHI	Median Household Income
PCC	Potential Canopy Cover
RCC	Realized Canopy Cover
TCC	Total Canopy Cover

variables and MHI across space using a local indicator of spatial autocorrelation (LISA). The census tract (CT) was selected as the common geographic unit (or zone) for this analysis and all subsequent methods discussed because it is one of two geographic boundaries used by Statistics Canada to gather and disseminate census data. The CT was selected over the smaller dissemination area (DA) unit to constrain the sample size.

The study area is composed of 531 CTs (equivalent to 3577 DAs); as sample sizes become large (i.e., the use of DAs as an analytical unit) there is an increased likelihood of very small changes (of questionable practical importance) being identified as statistically significant. Sub-city census units such as census tracts in (Canada) or block groups (the United States) are commonly used (e.g., Greene, et al., 2011; Schwarz et al., 2015; Troy et al., 2007) when considering tree canopy variables in conjunction with socioeconomic or sociodemographic variables. It is important to recognize, however, that it is common to choose these units of analysis for convenience rather than from an understanding of the scale of the spatial process (Kedron, 2016).

Median household income (MHI) for 2006 was selected as the focus for analysis because this variable is consistent with those used in many environmental justice studies identified in the literature. Data from the 2006 Canadian Census was selected over the more recent 2011 Canadian Census as these data were better matched temporally to the available land cover data. A Log_{10} transformation (assume base 10 in all subsequent references to log) was applied to the MHI variable to reduce strong positive skew in the raw data. Once transformed, the quartile breaks for the re-expressed variable were calculated. Each CT was assigned an ordinal value based on its associated median income; a CT falling within quartile 1 (Q1; upper limit = $44,057) was assigned an ordinal value of 1 and a nominal designation of low income. A CT falling within quartile 2 (Q2; upper limit = $53,572) was given an ordinal value of 2 and a nominal designation of medium income. Subsequent quartiles (Q3 and Q4) were assigned ordinal values of 3 (high income; upper limit = $66,169) and 4 (very high income; maximum = $246,341), respectively.

Data describing Toronto's tree canopy were derived from QuickBird satellite imagery classified by the USDA Forestry Service. This imagery was originally collected in summer 2007 and was acquired as part of the *Every Tree Counts* study of Toronto's urban forest resource (City of Toronto, Parks, Forestry and Recreation, Urban Forestry, 2013b; Nowak et al., 2013). The classified imagery was obtained through the City of Toronto's Open Toronto data portal and was provided as eight land cover classes: tree canopy, water, bare earth, buildings, pavement, transportation, grass/shrub, agriculture. Pixels classified as existing tree canopy cover or "realized tree canopy cover", further referenced as "RCC", were isolated and extracted. Classes representing plantable space (i.e., pixels classified as bare earth or grass/shrub) or "potential tree canopy cover", further referenced as PCC, were identified and reclassified to a single class. These target canopy land cover classes (RCC and PCC) were then aggregated from pixel level to the chosen geographical unit (i.e., the CT) and expressed as a percentage of coverage of the CT. Separate ANOVA procedures were applied to the percentage of tree canopy variables (realized, potential, and total tree canopy), each classified by the income categories described previously. Informed by previous studies (Hulchanski, 2010; Walks and Twigge-Molecey, 2013), higher income categories were expected to have significantly higher geographically proximate mean tree canopy coverage.

To further inform the nature of the relationship between MHI and percentage of tree canopy coverage, the significance and associated strength of correlation between the percentage of tree canopy variables and the Log of MHI were evaluated. Due to the heterogeneity of urban form; the previous findings of increasing polarization of income in Toronto (see Hulchanski, 2010; MacLachlan and Sawada, 1997; Walks and Twigge-Molecey, 2013); as well as the variation in the relationship between income and canopy in the literature, a weak to moderate correlation is expected in this study. A weak correlation supports the assertion that there may be a lack of understanding of the spatial relationship between the target variables. In other words, polarization of income and canopy would violate the assumptions of correlation as there tends to be coincidence in space among the tails of the distribution of each variable, but not in the middle.

Finally, the relationship of tree canopy variables and MHI across space may not be geographically linear; in fact, significant spatial clusters of extreme values for canopy variables and MHI are assumed to exist across the study area. A local indicator of spatial autocorrelation or "LISA" (Anselin, 1995) was applied to identify the location, significance, size, and nature of spatial clusters of correlated extreme values between canopy and resident income variables. Where more traditional measures of autocorrelation such as Getis-Ord Local G^* and Local Moran's I^* identify spatial clusters of extreme values for a single attribute (Anselin, 1995; Getis-Ord, 1992), the measure selected for this analysis (i.e., bivariate Moran's I^*) identifies spatial clustering of extreme values between two attributes (Anselin et al., 2002). Three attribute pairs were examined using this technique: RCC-MHI, PCC-MHI, and TCC-MHI (spatial distributions of input variables are illustrated in Fig. 2). For this analysis, neighbouring features were defined through contiguity criteria; adjacent CTs were considered neighbours if any segment or corner of their spatial boundaries coincided with any segment or corner of the spatial boundary of the focal CT (an overview of the methodology is provided in Fig. 3).

3. Results

3.1. Difference of means tests using ANOVA

No significant differences in means were observed for PCC among the MHI categories. However, significant differences between MHI categories were observed for RCC and TCC (mean differences and associated model significance values are provided in Table 2). Of note is the observed positive relationship between RCC and MHI for the study area; as the MHI group increases so too does mean RCC, though significant differences favour the higher MHI groups. More specifically, the very high MHI group exhibits a significantly larger mean RCC when compared with other income groups. Although less than the very high MHI group, the mean RCC of the high MHI group is significantly greater than the observed means for the low MHI and medium MHI groups. A similar trend is observed in the relationship between TCC and MHI groups, with mean values of TCC again increasing with MHI group. The trend is weaker, however, with only one category (very high MHI) exhibiting significantly larger mean values than all other income groups.

3.2. Bivariate correlation

Apart from potential canopy, there is a moderately strong correlation between canopy variables and the log of median household income (Pearson correlation coefficients for variable pairs and associated significance are shown in Table 3). The strongest positive correlation ($r = 0.452$, $p < 0.001$) is observed between the variables RCC and log of MHI. Correlation between TCC and log MHI was also moderately strong ($r = 0.369$, $p < 0.001$), but less than the correlation observed with the RCC. The correlation coefficient between PCC canopy and the log MHI was not significant at the 95% confidence level, but was at the 90% level ($r = -0.077$; $p = 0.078$).

3.3. Bivariate Moran's I

When examining the RCC–MHI variable pair, many CTs do not belong to any significant cluster of variable extremes. The largest significant areal cluster of high MHI and high RCC CTs (Fig. 4A, cluster i) is present in the central portion of the study area. This cluster contains portions of several neighbourhoods locally recognized as more affluent (e.g., Forest Hill South, Rosedale-Moore Park, Lawrence Park North and Lawrence Park South, Bridle Path-Sunnybrook-York Mills). A geographically smaller, yet still significant, spatially coincident cluster of high MHI and high RCC (Fig. 4A, cluster ii) is evident in the western portion of the study area and includes sections of neighbourhoods bordering a significant river system and ravine network (e.g., Edenbridge-Humber Valley and Kingsway South neighbourhoods) running through Toronto (i.e., the Humber River). Clusters of low MHI and low RCC are present in the southern central portion of the study area (Fig. 4A, cluster iii). This cluster of low MHI – low RCC extends west along historical rail lines and into more heavily populated areas that exhibit lower median incomes (e.g., Dufferin Grove, Kensington-Chinatown, Trinity Bellwoods, Palmerston-Little Italy, Little Portugal). Bordering this area of low MHI – low RCC to its south is a cluster of CTs that exhibit high MHI and low RCC.

Similar to the analysis of RCC and MHI, a considerable geographic area across Toronto exhibited no significant spatially coincident clusters of PCC and MHI. Where significant clusters of spatially coincident variables are observed, a loose centre-periphery pattern is evident. Two significant clusters of high PCC and high MHI are present on the eastern and western edges of the study area. The eastern most cluster (Fig. 4B, cluster i) includes several CTs that encompass portions of a large urban park (i.e., Rouge Park), an area that includes historic farmland and large natural areas including forest stands, wetlands, and open meadow (Wilson, 2012). The western most cluster of CTs with high PCC and high MHI (Fig. 4B, cluster ii) also contains several features of note, specifically a considerable corridor for electricity transfer lines, a large public park, as well as golf courses. Several proximate clusters of low PCC and low MHI were observed in the central southern portion of the study area (Fig. 4B, cluster iii). Moreover, several CTs within this cluster also correspond to spatial aggregations of low realized canopy and low median income.

When TCC and MHI are examined (Fig. 4C), there appears to be a

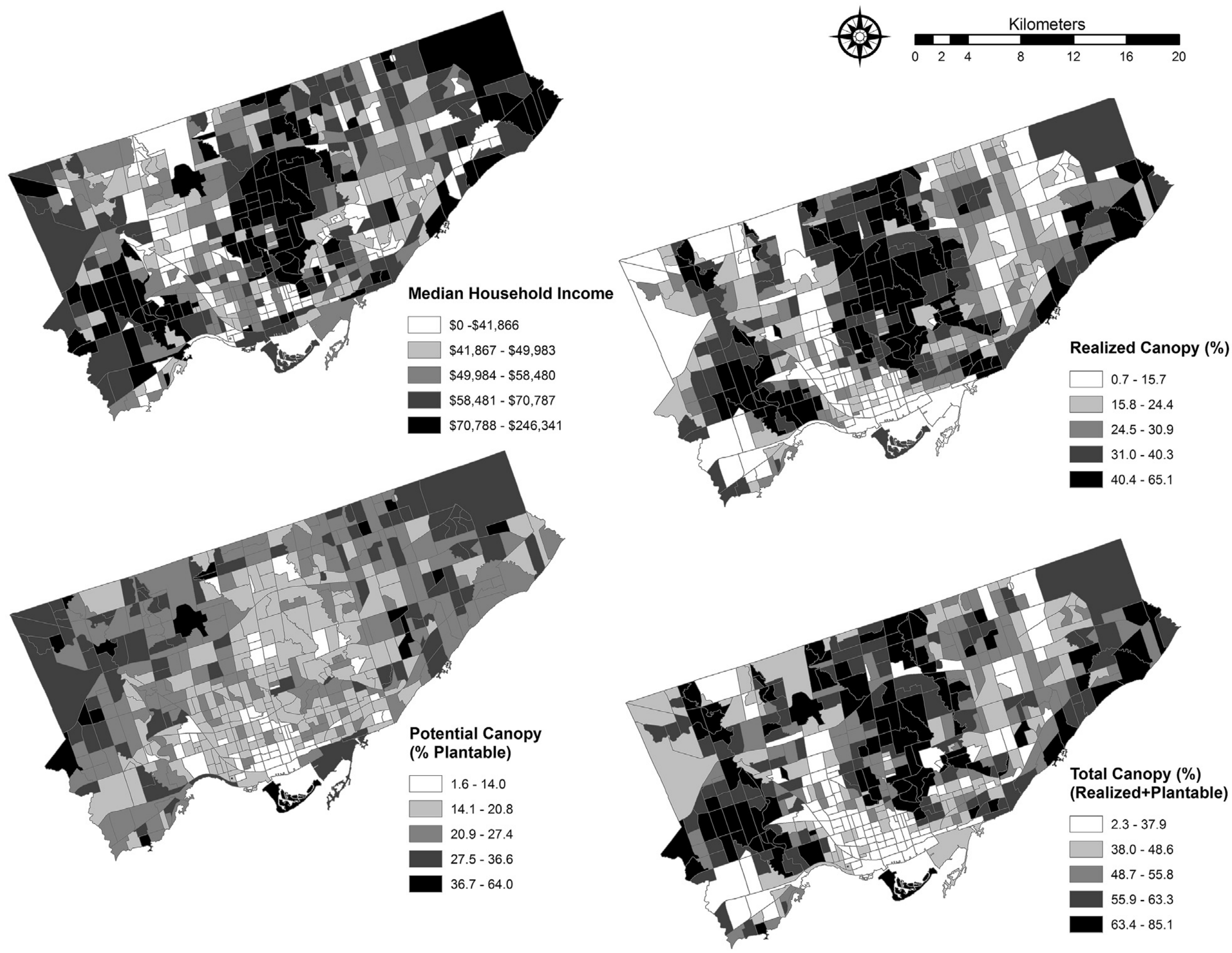

Fig. 2. Distribution of input variables for bivariate local indicators of spatial autocorrelation analysis (local Moran's I) for Toronto, Canada (2006–2007). All variables are classified using quintile classification.

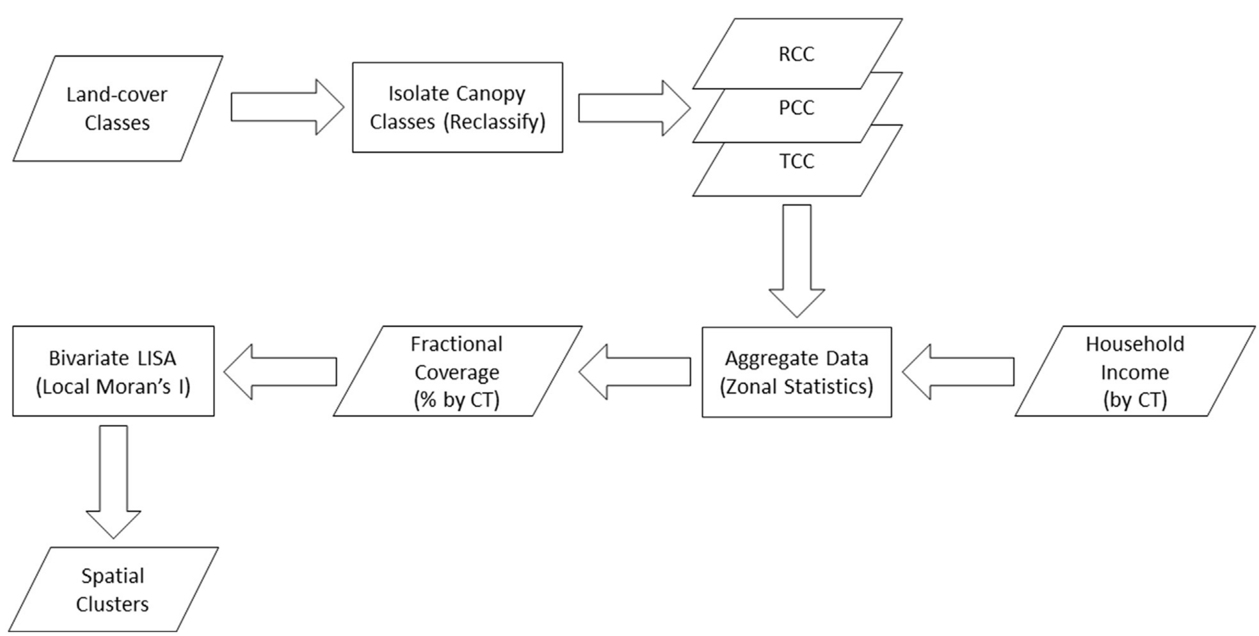

Fig. 3. Overview of data preparation and analysis to produce bivariate spatial clusters.

Table 2
Summary of analysis of variance (ANOVA) post-hoc mean comparisons of tree canopy type according to median household income by census tract for Toronto, Canada (2006–2007).

Log of Median Household Income (MHI)		Mean Difference (I − J)		
I	J	Total Canopy Cover (%)	Realized Canopy Cover (%)	Potential Canopy Cover (%)
Low	Medium	−1.85213	−2.25912	0.40662
	High	−3.81220	−3.70035[b]	−0.11277
	Very High	−14.36465[c]	−15.46080[c]	1.09678
Medium	Low	+1.85213	2.25912	−0.40662
	High	−1.96008	−1.44122	−0.51939
	Very High	−12.51252[c]	−13.20168[c]	0.69015
High	Low	3.81220	3.70035[a]	0.11277
	Medium	1.96008	1.44122	0.51939
	Very High	−10.55244[c]	−11.76046[c]	1.20954
Very High	Low	14.36465[c]	15.46080[c]	−1.09678
	Medium	12.51252[c]	13.20168[c]	−0.69015
	High	10.55244[c]	11.76046[c]	−1.20954

[a] $p < 0.05$.
[b] $p < 0.01$.
[c] $p < 0.001$.

Table 3
Summary of Pearson correlation coefficients (or “r”) between tree canopy types and median household income by census tract for Toronto, Canada (2006–2007).

	Log of Median Household Income	Potential Canopy Cover (%)	Realized Canopy Cover (%)	Total Canopy Cover (%)
Log of Median Household Income	1	−0.077	0.452[a]	0.369[a]
% Potential Canopy Cover	−0.077	1	−0.074	0.438[a]
% Realized Canopy Cover	0.452[a]	−0.074	1	0.864[a]
% Total Canopy Cover	0.369[a]	0.438[a]	0.864[a]	1

[a] $p < 0.001$.

considerable influence of the RCC component with strong agreement between clusters defined in Fig. 4A and C. This agreement is supported by the strong correlation coefficient observed between RCC and TCC ($r = 0.864$; $p < 0.001$).

4. Discussion

Results of the aspatial and spatial approaches used in this study to understand urban tree canopy cover, and its relationship with resident wealth, converge toward a common conclusion: in Toronto, there is a measurable inequality of access to the urban tree canopy based on median household income. In the context of Toronto, findings indicate that the relationship between access to urban tree canopy and MHI is significant but not linear across space. This observed non-linearity is a function of both historical and contemporary socio-demographic and economic processes manifest across the urban and suburban land use pattern and form.

The central cluster (Fig. 4A, cluster i) of high RCC and high MHI, for example, is an area of historic affluence. Many of the CTs contained within this cluster have exhibited consistently higher MHI than the central metropolitan area average since the 1970s (see Hulchanski, 2010). Within this geographic area there are several residential areas composed of a higher than average number of single detached dwellings. As an example, of the 2440 dwellings in the Bridlepath-Sunnybrook-York Mills neighbourhood (located near the centre of Fig. 4A, cluster i) recorded in the 2006 Canadian Census, 2205 (or 90%) were single detached dwellings and 1565 (or 64%) of those dwellings were constructed before 1970 (City of Toronto, Social Development, Finance Division, 2008a). With an average dwelling value of $1,491,568 in 2006 (City of Toronto, Social Development, Finance Division, 2008a), and exhibiting an average forest canopy cover of 55.6% (City of Toronto: Parks, Forestry, and Recreation, 2013b), it is reasonable to infer that the stability of this neighbourhood over a long period (i.e., older dwellings, lower rates of new construction, consistent socio-demographic characteristics) has contributed to the establishment of a more extensive tree canopy over a long time period. With the demonstrated increase in property value in the presence of mature trees (e.g., Anderson and Cordell, 1988; Conway et al., 2010), it is reasonable to hypothesize that this disproportionately high RCC, when compared to the city average, may be linked in some capacity to elevated property values in this area. Although this neighbourhood is an extreme exemplar, portions of other neighbourhoods falling within this cluster exhibit similar characteristics and have been subject to the same historical protection from the pressures of redevelopment.

In contrast, there have been considerable redevelopment and intensification initiatives in the pre-amalgamation municipality of old Toronto that contains the downtown core and older neighbourhoods with smaller lots and increased density. Moreover, many condominiums are now being built in the downtown area and traditional central business district (Rosen and Walks, 2015) which traditionally has been largely non-residential. As an example, in 2006 the Waterfront Communities area of the city (just south of Fig. 4A, cluster iii) has 15,705 dwellings, of which 14,035 (or 89%) are classified as apartment buildings (a classification that includes condominiums) of five stories or more (City of Toronto, Social Development, Finance Division, 2008b). Of the total number of dwellings, 14570 (over 92%) were constructed after 1970 and 5460 (nearly 35%) were constructed in the period of 2001–2006 (City of Toronto, 2014). Building density above municipal guidelines is being allowed by the municipality, perhaps encouraged, in exchange for increased development fees or an agreement for the developer to provide infrastructure related to these developments (Rosen and Walks, 2015). However, this increased density is expected to preclude any significant expansion of tree canopy cover in an area already lower in RCC and PCC due to several associated barriers to establishing and supporting tree growth such as space

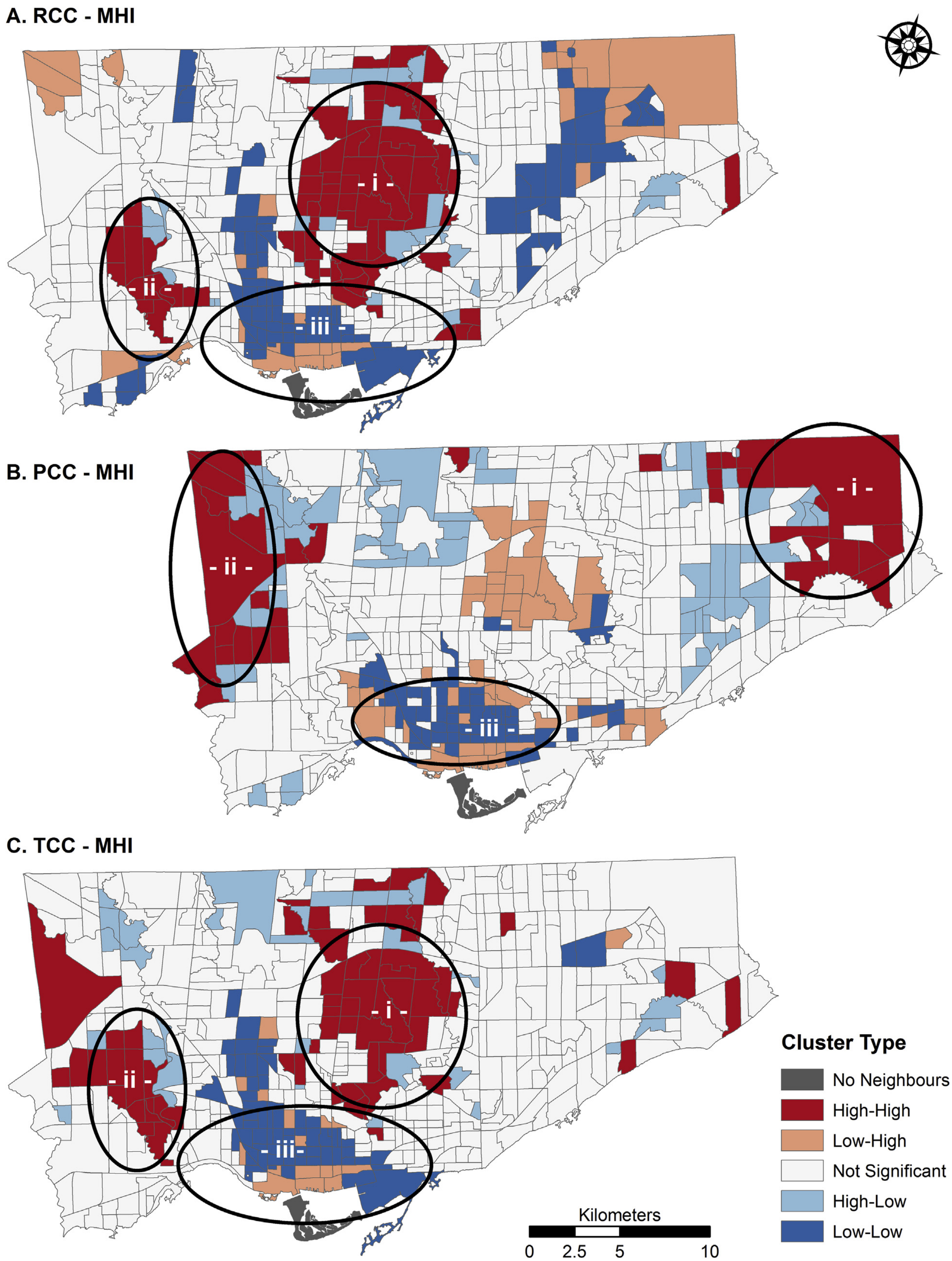

Fig. 4. Results of bivariate local indicator of spatial autocorrelation analysis examining the relationship by census tract between (A) percent realized canopy cover and median household income, (B) percent potential canopy cover and median household income, and (C) percent total canopy cover and median household income for Toronto, Canada (2006–2007).

constraints for growing, lack of light from building shadows, and lack of soil volume.

This example of high-rise residential development along Toronto's waterfront is also of interest due to the deviation from *a priori* assumptions about the relationship between RCC and MHI. Though the previous discussion has identified factors that likely influence the lack of tree canopy, higher levels of MHI is rarely identified in the literature as a determinant of lower tree canopy cover. This deviation from the collective literature is likely a consequence of the city's reinvestment in the inner city, largely through high-rise condominium developments transforming the downtown core from a primarily commercial function to an area of mixed use (Rosen and Walks, 2015). The demand to live in more “walkable” neighbourhoods with immediate proximity to employment and transit, as well as opportunities for entertainment and leisure has attracted a higher proportion of young professionals with high levels of education and above average household incomes resulting in upward pressure on real estate values and displacing those that rely on affordable housing to other areas of the city (Lehrer and Wieditz, 2009). With very few (or extensive) areas with low MHI but high RCC identified in this study, it appears that many of those displaced through neighbourhood transitions are more likely to migrate to areas with lower MHI and in areas of lower associated RCC, thus exacerbating the present geographic polarization of urban tree canopy cover.

Similarly, the presence of clusters of low MHI but high RCC are also interesting anomalies due to their deviation from *a priori* assumptions about income and tree canopy coverage in contrast to the previous example. Examining socio-demographic change over two decades in several south-eastern Australia neighbourhoods, Luck et al. (2009) demonstrated that in some cases, past socio-demographic data better predicted present tree canopy distribution than the more contemporary socio-demographic makeup of that same neighbourhood. This finding indicates it is possible for a neighbourhood to change, either through gentrification or decay, but the longevity of trees may lead to canopy artifacts reflective of past socio-demographic and economic conditions. As a result, these clusters of high canopy—low income are likely to be a legacy of that area prior to experiencing neighbourhood change (Boone et al., 2010; Luck et al., 2009) and likely contribute to the weaker model fits reported in previous studies of tree canopy and socio-demographic data (e.g., Heynen and Lindsey, 2003; Landry and Chakraborty, 2009; Perkins et al., 2004).

In addition to better understanding the processes leading to unequal access by city residents to urban forest canopy, the specific type of clusters identified in the bivariate LISA analysis offer a potential opportunity to reduce inequality through strategically targeted planting efforts. When considering which clusters are important to identifying priorities that address distributional inequalities, of least concern are cluster types representing high amounts of realized canopy (i.e., high-high or high-low). Regardless of whether income is in the lowest or highest quartile, the residents living in these spatial clusters benefit from better access to tree canopy cover, and its associated benefits, than do many other large residential proportions of the study area.

The most prohibitive areas to decrease distributional inequality of access to the benefits of urban trees are related to the spatial clusters representing significantly low values of total tree canopy (realized + potential) and low household income (Fig. 4C, cluster iii). In addition to having reduced access to RCC, these clusters exhibit less opportunity to expand tree canopy in the future to address unequal access. This challenge can be conceptualized by considering the original classified satellite imagery. If a pixel is not classified as RCC, or as an area with the potential to expand canopy, then the pixel represents a barrier to planting (e.g., it is classified as water, dwelling, road, or some other impervious surface). With limited pervious surface available to plant new trees, several options to reclaim impervious surface at street level may be considered, through: 1) pavement removal or building demolition; or, 2) sub-surface engineering solutions including suspended pavement systems providing improved soil conditions below impervious surface (Smiley et al., 2006).

Although removal of pavement and demolition has been successful in expanding potential planting areas in a shrinking city with high vacancy rates (Frazier and Bagchi-Sen, 2015), this approach may not be feasible in a growing city like Toronto which has experienced a population growth of 4.5% from 2006 to 2011 (City of Toronto, 2012), constructed 70,000 new residential units between 2009 and 2013 (City of Toronto, 2014), and is pursuing further intensification (Lehrer et al., 2010). Growing cities that are attempting to maintain or increase density may have to implement smaller scale reclamation of impervious surface at a higher cost; the District of Columbia, for example, invested $1.22 million from 2010 to 2012 and reclaimed a total of approximately 7500 m^2 (or 80,303 ft^2) of impervious surface as of 2012 (Thomas, 2012), some of which was earmarked for the planting of trees.

Over the shorter term, clusters of spatially coincident high PCC and low MHI offer the greatest opportunity for improving access to canopy benefits in urban residential neighbourhoods currently lacking adequate access to trees. The increased availability of pervious surface in these locations for tree planting is less financially burdensome than reclaiming impervious surface or constructing engineered solutions (e.g., suspended pavement). Furthermore, if planted in large areas of pervious surface, tree mortality may be lower than with the same number of trees planted in engineered sub-sidewalk growing spaces (Bassuk and Whitlow, 1988; Lu et al., 2011).

There is, however, the potential for a conundrum: by targeting these high PCC − low MHI locations, a significant sub-region of less affluent city residents may be ignored through an inherent flaw in benefit-cost analysis. Managers applying cost-benefit analysis (CBA) frequently prioritize variables in the decision—making process that can easily be monetized over variables where artificial prices have been applied, and have greater associated uncertainty (Ackerman and Heinzerling, 2002; Hanley and Barbier, 2009) such as distributional criteria. Because equality of access is more intangible than pollution reduction or temperature mitigation, distributional criteria are prone to be displaced in lieu of efficiency criteria (e.g., maximizing ecosystem services, reducing cost per tree planted). Consequently, urban locations with little pervious surface and low MHI could be systemically excluded as a priority for future tree planting and, therefore, become more vulnerable to further polarization across income lines if decision makers do not explicitly commit to prioritizing the creation of a standard of access for city residents to tree canopy.

Environmental decision-making that gives preference to one of three subsystems or spheres of sustainability (i.e., ecological, social, economic) commonly results in trade-offs to one or both of the remaining spheres. To some extent these trade-offs are a consequence of the incompatibility of some underlying assumptions among these three subsystems (McGuire, 2012). Prioritizing tree planting based on one metric within a single sphere of sustainability principles is expected to result in similar outcomes. In other words, making a commitment to improving equality of access to urban trees (i.e., a social principle of sustainability) could result in the reduced aggregate return of economic and ecological benefits with inadequate investment in urban forest management expressed as fixed or shrinking budgets.

Planting trees in urban locations with considerably less pervious surface is economically less efficient than planting in locations with higher percentages of pervious space. These economic inefficiencies may be translated into increased investment in the short-term (e.g., the reclamation of impervious surface, construction of engineered planting solutions) or from longer term losses from increased mortality related to the more challenging urban growing conditions for trees (Koeser et al., 2013; Lindsey and Bassuk, 1992; Lu et al., 2011; Nowak et al., 2004). Although there are likely to be some opportunities to reduce the cost of planting if coordinated with scheduled reconstruction of roads or sidewalks, the fixed physical conditions in patterns of current urban form make it difficult to change decision-making and outcomes, thereby influencing the overall cost per tree planted.

Moreover, there are several ecological trade-offs to consider. The first is a direct function of harsh urban growing conditions. Many ecosystem services have a direct relationship to tree size, related in large part to the leaf area of the tree (Givoni, 1991; McPherson, 1992; Peper and McPherson, 1998). Planting trees in hostile urban growing conditions, that include highly compacted soil, reduces growth rates (Close et al., 1996; Smiley et al., 2006) and limits the maximum size of planted trees (Bassuk and Whitlow, 1988; Kozlowski, 1999), though it has been suggested that reduced maximum size is more likely with late successional species (Quigley, 2004). Without adequate soil conditions, trees planted in engineered solutions are more likely to grow at reduced rates, reach a maximum size less than the potential of the species, and thus diminish the potential leaf area and subsequent collective capacity for these trees to deliver ecosystem services.

There may also be an additional trade-off related to the loss of potential multiplicative effects that emerge from the spatial arrangement of trees. Depending on the target ecosystem service, a fixed number of isolated trees provide a diminished level of that service than if the same number of trees were organized spatially as a stand with contiguous canopy (e.g., Greene and Millward, 2017). Thus, if the municipality prioritizes principles of equity in future tree planting initiatives, and focuses primarily on reducing distributional inequalities resulting in the displacement of planting to expand high quality forest patches, some proportion of ecosystem services gained as emergent properties above the collective sum of individuals, will also be lost.

The methodology developed in this study has several limitations. The inclusion of isolated pixels in the analysis will result in an exaggerated area of potential canopy by CT. Because land cover data is derived from sharpened QuickBird imagery, a single isolated pixel represents an area of 0.372 m^2 (0.61 m $\times$ 0.61 m), an area inadequate to establish mature trees. Furthermore, these data are aggregated to areal units (i.e., zones) convenient for the analysis but are defined somewhat arbitrarily and are thus subject to the modifiable areal unit problem. Because CT boundaries are defined by using permanent features to maintain a stable population range, these boundaries may artificially truncate underlying socio-demographic patterns and/or vegetation patterns. Several studies (e.g., Jelinski and Wu, 1996; Fotheringham and Wong, 1991; Oppenshaw and Taylor, 1979) have demonstrated the unpredictability of statistical outcomes as different zoning schemes were applied to the same base data. Aggregating the data of this study to a different system of zoning (e.g., dissemination areas or neighbourhoods) may result in somewhat different analytical outcomes.

Perhaps most important to the discussion of methodological limitations is that the analyses performed in this research subsumes data describing land cover that may be appropriate for planting trees; however, the associated land use designation may not be deemed appropriate for tree canopy expansion. Private land use such as electricity corridors, recreational fields, golf courses, and cemeteries can support mature trees, but in many cases afforestation efforts would interfere with the intended use of the space. Electricity corridors have long tracts of open low-growing vegetation; while these areas provide ideal conditions for many urban tree species, tree growth is actively suppressed to prevent potential interference with transmission lines. Public land such as parks could yield additional prospects for afforestation; however, urban parks are expected by city residents to provide access to a variety of activities, some of which conflict with the presence of trees. Similarly, larger protected areas, though covered with highly pervious surface, represent significant natural heritage sites providing their own ecosystem services and aesthetic values but are likely to be excluded from tree planting efforts due to their special status.

5. Conclusions

This study has identified a significant spatial relationship between median household income and the fractional coverage of tree canopy in Toronto, Canada. More specifically, these findings signal: 1) there is a measurable inequality in access to the urban canopy in Canada's largest city, which signals the need for new municipal government efforts to remediate this potential ecological injustice, and 2) the method used here could be further refined and developed to better inform the actions taken by municipal government staff to respond to the inequality identified.

Beyond these specific results, this research presents a novel method of considering the spatial distributional inequalities of the urban forest and provides a methodological framework for use by researchers focusing on environmental justice studies in North American cities. Understanding distributional inequalities related to an environmental good such as the ecological, social, and economic benefits of the urban forest advances the capability of policy makers to address environmental injustice directly through strategic tree planting efforts. It is important to recognize, however, that making the decision to address one of the subsystems of sustainability, in this case addressing a social principle of sustainability in reducing distributional inequalities, induces the requirement for trade-offs in the remaining ecological and economic spheres. Accepting that trade-offs will occur, however, does not imply that addressing these inequalities should not be a priority. It is important that municipal decision-makers, parks staff and city planners recognize that cost is not synonymous with value; providing better access to environmental goods such as city trees is not always easy to quantify and even more difficult to monetize. Despite the increased expenditure per tree planted, the aggregate value (economic, environmental, and social) of planting a tree in a community underrepresented by this environmental good may be greater than the value to a community that is already well covered with tree canopy. This tension between cost and value is important for municipal decision-makers to acknowledge, and consider that efforts to respond to urban sustainability demand reconciliation between sustainability's three imperatives.

While this research focuses on the urban forest as a case study, the methodological approaches used herein could be expanded for use with the evaluation of several other environmental amenities. Furthermore, this study has important implications for policy makers by providing a practical method to identify and spatially quantify where inequalities of access to an urban environmental good occur and, in so doing, informing decision makers where to target interventions that can address inequalities of access.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jenvman.2017.12.015.

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