Journal of Environmental Management 163 (2015) 134–145

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Neighbourhood-scale urban forest ecosystem classification

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ARTICLE INFO

Article history:
Received 1 April 2015
Received in revised form
7 August 2015
Accepted 11 August 2015
Available online 28 August 2015

Keywords:
Ecosystem classification
Urban forest
Neighbourhood
Management
Cluster analysis

ABSTRACT

Urban forests are now recognized as essential components of sustainable cities, but there remains uncertainty concerning how to stratify and classify urban landscapes into units of ecological significance at spatial scales appropriate for management. Ecosystem classification is an approach that entails quantifying the social and ecological processes that shape ecosystem conditions into logical and relatively homogeneous management units, making the potential for ecosystem-based decision support available to urban planners. The purpose of this study is to develop and propose a framework for urban forest ecosystem classification (UFEC). The multifactor framework integrates 12 ecosystem components that characterize the biophysical landscape, built environment, and human population. This framework is then applied at the neighbourhood scale in Toronto, Canada, using hierarchical cluster analysis. The analysis used 27 spatially-explicit variables to quantify the ecosystem components in Toronto. Twelve ecosystem classes were identified in this UFEC application. Across the ecosystem classes, tree canopy cover was positively related to economic wealth, especially income. However, education levels and homeownership were occasionally inconsistent with the expected positive relationship with canopy cover. Open green space and stocking had variable relationships with economic wealth and were more closely related to population density, building intensity, and land use. The UFEC can provide ecosystem-based information for greening initiatives, tree planting, and the maintenance of the existing canopy. Moreover, its use has the potential to inform the prioritization of limited municipal resources according to ecological conditions and to concerns of social equity in the access to nature and distribution of ecosystem service supply.

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1. Introduction

The term ecosystem tends to invoke images of forests, mountains, and other natural settings. However, most people will spend their lives in urban ecosystems, with approximately 80% of North Americans and greater than half the population worldwide currently residing in cities (United Nations, 2014). These trends have important implications for how societies interact with nature and, perhaps more importantly, how urban ecosystems can provide sustainable benefits for cities. There is a growing recognition among city inhabitants of urban forests and the diverse array of ecosystem services they provide for urban inhabitants (Duinker et al., 2015; Nowak and Dwyer, 2007). For example, stormwater retention and moderation of urban heat island effects by urban forests are highly beneficial for both city infrastructure and human health (Nowak and Dwyer, 2007).

Ecosystem services and their connection to healthy urban forests are now becoming recognized as essential components of sustainable cities and integral to municipal climate change action (Demuzere et al., 2014; Grove, 2009). As a result, many municipal governments are investing in the development of urban forest strategies that seek to protect and expand urban forest resources

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http://dx.doi.org/10.1016/j.jenvman.2015.08.008
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(Kenney and Idziak, 2000; Ordóñez and Duinker, 2013). Nevertheless, many important areas of urban forest research and management remain underdeveloped and unexplored. One question that remains unanswered is how to stratify and classify the urban landscape into units of ecological significance and at spatial scales best suited to strategic planning and sustainable urban forest management. The urban landscape is highly heterogeneous and characterized by an especially complex interaction of social and biophysical processes (Cadenasso et al., 2007; Grove et al., 2006b). Consequently, to adequately assess urban forest structure and function, and to inform decision making in urban forestry, some form of landscape stratification and classification is necessary.

Ecosystem classification may present an effective approach for addressing these challenges. It enables researchers and practitioners to evaluate and manage complex multifactor systems. By allowing for the organization of ecological processes into logical and relatively homogeneous management units, classification frameworks make valuable tools for ecosystem-based planning and decision support (Hargrove and Hoffman, 2005; Klijn and Udo de Haes, 1994). Ecosystem classification provides a holistic approach to management by expanding focus from a single resource or amenity (e.g., timber supply in forestry) to the structure and function of the entire ecosystem (Bailey, 2009). Moreover, urban ecosystem classification can address the heterogeneous and hierarchical nature of social-ecological systems (Cadenasso et al., 2007) by enabling the stratification and classification of landscapes at spatial scales identified as important for maintaining desirable ecosystem functions and services. However, ecosystem classification for environmental and natural resource management remains untested in urban settings. Consequently, advancements in urban ecology and the ecosystem concept have not been addressed in ecosystem classification.

The field of urban ecology has made important strides regarding the definition of the ecosystem concept over the past several decades and represents an important knowledge frontier. One such advancement within this discipline is the recognition that urban ecosystems are not limited to biophysical components and processes, but that social workings and practices are also integral to the structure and function of these ecosystems (Lister, 2008; Pickett et al., 2011). This integrated approach to investigating and characterizing urban ecosystems is captured in the shift from envisioning ecology in cities to the ecology of cities (Grimm et al., 2000). Research that examines ecology in cities tends to focus on characterizing previously established ecosystem patterns and processes, and how they differ in the urban environment compared to more natural, or undisturbed, settings (Grimm et al., 2000). In contrast, the approach of viewing the ecology of cities explores the structure and function of urban ecosystems, inclusive of their human components.

Ecosystem classification within traditional ecology and natural resource management in non-urban settings has a much longer history and broader research base (Omernik, 1987). For example, forest ecosystem classification has been employed by forest practitioners for decades in many regions across Canada (e.g., Keys et al., 2003). At broader spatial scales, hierarchical, ecological land classifications based on physiographic, climatic, and biological conditions have been developed for several types of resource management and biodiversity conservation (Klijn and Udo de Haes, 1994; Omernik, 1987). Despite their maturity and uptake, these approaches to ecosystem classification are designed for natural landscapes, and as such they are silent on the dynamic social processes and built environments that typify urban areas and fall short when applied to urban forest ecosystems.

Conventional approaches to classification in urban settings contrast sharply with those of more natural landscapes. While some research exists on biophysical classifications of cities (e.g., Brady et al., 1979), most often boundaries are delineated and units are classified by social factors, such as ownership, jurisdiction, and land use (Borgström et al., 2006). Thus, these approaches ignore key biophysical determinants of ecosystem structure and function. Land use has been a ubiquitous approach to classifying urban landscapes for planning purposes (Anderson et al., 1976), and is indeed used often in urban forest planning and management (Steenberg et al., 2013). Land use is highly influential on the structure of city tree communities as it describes the intensity of human activities and often the amount of available growing space (Jutras et al., 2010; Nowak et al., 1996), but it fails to capture important variability in the structure and function of urban forests. For example, within residential land uses there can be considerable amounts of variability in affluence and density, which have been found to be strong predictors of urban vegetation (Berland, 2012; Grove et al., 2014).

Describing and managing urban forest ecosystems, in light of this new paradigm that calls for research that more tightly integrates social and biophysical components, is necessary though challenging (Alberti et al., 2003; Ives and Kendal, 2014). Urban ecosystem classification may provide a useful tool for practitioners while also presenting an opportunity to move some of the theoretical advancements of ecology into urban forest practice. The discipline of urban forest science, and the practice of urban forestry, has advanced sufficiently over the past decades to now warrant a classification system tailored to its purposes and not borrowed from forestry or urban planning in a best-fit scenario.

The purpose of this study is to develop and propose a framework for an urban forest ecosystem classification (UFEC). Specifically, the research objectives are to: 1) develop a multifactor classification framework that integrates ecosystem components characterizing the biophysical landscape, built environment, and human population; 2) test the framework by applying it to classify urban forest ecosystems in Toronto, Canada, at the neighbourhood scale using hierarchical cluster analysis; and 3) interpret the biophysical and social structure of the resulting ecosystem classes and its implications for urban forest management. The intent of these research objectives is not only to make a practical contribution to urban forestry with the proposed UFEC, but also to make theoretical contributions to the understudied areas of urban forest ecology and ecosystem classification systems in urban landscapes.

2. Classification framework

In conceiving the UFEC framework for application in this study, we propose three broad categories of ecosystem components: the biophysical landscape, the built environment, and the human population (Fig. 1). This section describes each component and the reasoning behind its inclusion in the framework. The selection of a suitable variable or variables to measure ecosystem components is dependent on both locally and regionally available data. Variables selected for this study are described in Section 3.2.

The human component and, to a lesser degree, the built environment represent novel components for inclusion in the definition and classification of ecosystems. While the recognition that humans are integrated components of urban ecosystems, and not external forces of disturbance, has been widely accepted in urban ecological theory (e.g., Alberti et al., 2003; Grimm et al., 2000; Pickett et al., 2011), there are few examples of applied research that take this approach. Cadenasso and colleagues have advanced work on urban land cover classification by integrating natural and built components to better account for urban landscape heterogeneity (Cadenasso et al., 2007). However, to our knowledge, no studies have developed or applied ecosystem classification

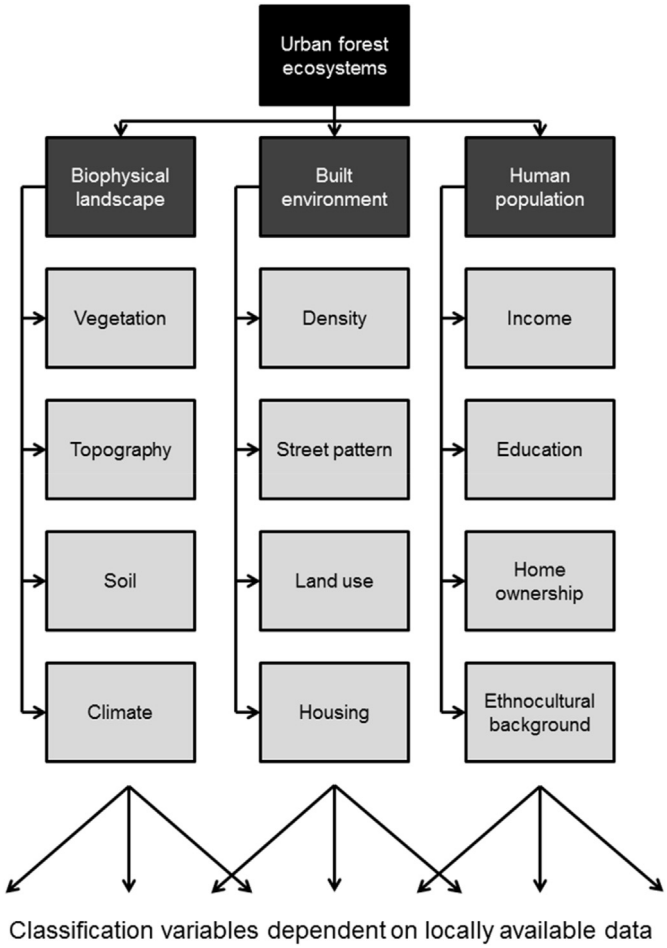

Fig. 1. Design of the framework for urban forest ecosystem classification (UFEC).

methods that have integrated variables describing the human population.

2.1. Biophysical landscape

Biophysical factors have the most prominent lineage within ecosystem classification in natural resource management (Omernik, 1987). As with non-urban forest ecosystems, urban forest structure and function are determined to some degree by pre-existing vegetation, soil type, topography, and climate (Nowak, 1994; Pickett et al., 2001). These influences are especially true in forested urban parks, residual woodlands, and other more naturalized settings. Vegetation is the first biophysical component in the proposed UFEC framework, as it is conceptually and logistically important in the context of sustainable urban forest management. The most common variable used to represent urban trees is canopy cover, owing to the relative ease of data acquisition and modest costs of processing (Nowak et al., 1996). However, more detailed tree inventories are also useful for urban forest classification. In addition to tree canopy cover, open green space (i.e., grass, shrub, and/or herbaceous cover) and relative stocking are other important variables for describing urban vegetation (Cadenasso et al., 2007; Kenney et al., 2011). Stocking is the ratio of canopy cover to total green space, where total green space is defined as tree canopy cover and open green space.

Topography is included in the UFEC as a biophysical ecosystem component because it influences the ecological processes within urban forests through exposure, drainage, light availability, and microclimate (Bailey, 2009; Klijn and Udo de Haes, 1994). Topographic variables are commonly used in ecosystem classifications, most prominent of these variables being slope gradient, slope/topographic position, and aspect (Bailey, 2009; Keys et al., 2003). In the urban landscape, where our UFEC is concerned, we suggest limiting the representation of topography to slope and/or slope position, given their combined influences on both the natural processes and patterns of urban development, where steeper terrain often remains forested due to higher costs and elevated safety risks (e.g., erosion or slope failure; Heynen and Lindsey, 2003). Soil type is also included as a biophysical component because it is an important driver of tree species suitability and growth (Millward et al., 2011). The physical and chemical properties of soil greatly influence forest ecosystem structure and function and thus soil type is commonly used in ecosystem classification (Bailey, 2009; Zhou et al., 2003).

Climate is an important determining factor in ecosystem structure and function at spatial scales broader than what is typically encountered in cities; it is a key driver of tree species distribution (Hargrove and Hoffman, 2005). We have included climate as an ecosystem component in the UFEC framework in anticipation of future UFEC applications in other regions or across multiple cities. Since climate has also been central in the development of the broader-scale ecological landscape classifications for the determination of ecoregions (Host et al., 1996; Omernik, 1987), we suggest that ecoregion data, rather than raw climate data, would be a logical data choice to represent climatic influence on urban forest ecosystems. However, climate variables (e.g., temperature, precipitation, growing degree days) are not included in this study, since these data are unlikely to be highly influential on urban forest ecosystem variation within a single city. Importantly, the urban heat island effect and microclimates can produce considerable climatic variability within city limits (Huang et al., 2011), although data one these effects could be difficult to obtain and may, in part, be captured in other ecosystem components, including existing canopy cover, building density, and topography.

2.2. Built environment

Unlike non-urban forest landscapes, the built environment and urban infrastructure are significant determinants of ecosystem structure and function within cities (Grove, 2009; Pickett et al., 2001). The type, orientation, and density of buildings and road networks, as well as the extent of impervious surfaces and other grey infrastructure, determine the physical space available for trees and other vegetation. Additionally, urban form and land use in general have been shown to be indicative of the presence and magnitude of stressors that affect tree growth and survival (Jutras et al., 2010; Nowak et al., 2004). Thus, the built environment is also indicative of environmental quality and the vulnerability of urban forest ecosystems.

Density is one of the most frequently used metrics in the assessment of urban form and the built environment (Churchman, 1999), and is included as an ecosystem component in the UFEC framework. However, density is a somewhat contentious term and has a number of definitions and measurements (Churchman, 1999). One important distinction is between building intensity and population density. Building intensity refers to the physical characteristics and coverage of the built environment in a defined area (Forsyth, 2003). Population density is a simple area-based metric of people per geographic unit (e.g., km^2). Much of the existing research on the relationships between urban vegetation and the built environment employ the latter (e.g., Grove et al., 2014; Pham et al., 2013; Troy et al., 2007). However, building intensity and

population density are not necessarily correlated in all instances, though they tend to be referred to interchangeably as density (Forsyth, 2003). We therefore recommend that both of these dimensions of density be included in UFEC development and applications.

In addition to density, neighbourhood-based research often incorporates land use mix and street pattern as the three main metrics of urban form (Conway and Bourne, 2013; Krizek, 2003; Southworth and Owens, 1993). As previously mentioned, land use is influential on the physical structure of urban forests (Nowak et al., 1996) and is included as an ecosystem component in the framework. Street pattern is also included as an ecosystem component. City streets represent a highly identifiable spatial network in the urban landscape and have long been used in urban stratification and boundary delineation (e.g., census boundaries, neighbourhoods, city wards, municipal boundaries). Street patterns, like road density and block size, are metrics of urban form that are influential on vegetation patterns (Conway and Bourne, 2013). Additionally, city-owned trees along streets and in public rights of way and their management comprise a significant share of municipal urban forestry (Maco and McPherson, 2002).

Lastly, housing type and age are frequently identified as important drivers of urban ecological processes in residential and mixed-use areas (Conway and Hackworth, 2007; Conway and Bourne, 2013; Grove et al., 2006b). While housing has important implications for socioeconomic background that will be captured in the human population ecosystem components, it is also a determinant of the physical environment. Housing type is highly influential on building intensity and is generally indicative of the type and amount of green space available for urban trees and other vegetation (Grove et al., 2006a; Troy et al., 2007). For example, single-family, detached housing is commonly associated with higher canopy cover (Troy et al., 2007). Additionally, housing age is influential on urban forest structure and is often indicative of tree size and a more extensive, mature canopy (Boone et al., 2010; Zipperer et al., 1997).

2.3. Human population

The influential human component of urban forest ecosystems is what sets them apart from most other forest ecosystems in the context of both classification and management. While nearly all ecosystems on the planet are influenced by humans to varying degrees, urban forests in particular are characterized by dense human settlement, altered physical environments, land use competition, and a myriad of other sociopolitical and socioeconomic influences that shape ecosystem structure and function (Konijnendijk et al., 2006). A growing body of research points to demographic and socioeconomic influences on the distribution and structure of canopy cover and urban vegetation (e.g., Grove et al., 2006a; Heynen and Lindsey, 2003; Pham et al., 2013; Troy et al., 2007). The most consistent theme to emerge in this research is the positive association of socioeconomic status with urban tree cover (Grove et al., 2014). Specifically, income and education represent important determinants of urban forests and are both included in the UFEC framework as ecosystem components.

Homeownership is also included as an ecosystem component. Land tenure can affect urban forests in a number of fashions, especially in residential land uses (Boone et al., 2010). There is certainly correlation with the abundance of renters and housing type and the built environment (Boone et al., 2010). However, residents can directly influence the urban forest through various land management practices, or an absence thereof (Grove et al., 2006b). For one, homeowners, unlike renters, have direct legal control, and often obligation (e.g., tree by-laws), over their landscaping practices (Grove et al., 2014). Also, renters tend to be a more mobile population and less likely to invest resources in maintaining property vegetation (Troy et al., 2007).

Lastly, ethnocultural background is included as an ecosystem component as it can influence urban forest ecosystem structure. Ethnocultural groups differ in their connections to trees, which can result in different landscaping practices and influence the willingness to plant and maintain trees on their properties (Fraser and Kenney, 2000; Greene et al., 2011). A number of studies also address urban forests and ethnocultural background from an environmental justice perspective, where visible minorities and marginalized populations are often situated in neighbourhoods with less abundant green space and tree cover (e.g., Heynen et al., 2006; Landry and Chakraborty, 2009). While there are certainly instances of different ethnocultural groups preferring an absence of tree cover on their property (Fraser and Kenney, 2000), the latter issue highlights the importance of considering equity in the distribution of urban forest ecosystem services.

2.4. Ecosystem boundaries

A core intention in the development of our UFEC framework is that city neighbourhoods, in addition to representing a logical spatial level for management (Manzo and Perkins, 2006; Steenberg et al., 2013), also represent a consistent unit of analysis and bounding mechanism for urban forest ecosystems. Consequently, for the test application of the UFEC we stratified the study area by neighbourhood. Often in ecosystem classification, landscapes are pre-stratified by climate, biogeography, topography, and other biophysical variables. In other instances, expert-based boundary delineation for stratifying landscapes is used prior to analysis (Hargrove and Hoffman, 2005; Hessburg et al., 2000). Arguably there are elements of both in this approach. Since this classification method attempts to minimize within-class heterogeneity of biophysical variables, but also of the human population and built environment variables, more traditional biophysical stratification and boundary delineation would not be appropriate. Therefore, neighbourhoods were selected to minimize trade-offs in both structural and functional homogeneity. However, it should be noted that, like ecosystems, neighbourhood boundaries are frequently subjective, ephemeral, or continuous (Galster, 2001). Despite their long history in urban planning, neighbourhoods remain difficult to define and map, and the implications and uncertainties around doing so in UFEC applications should be considered.

Neighbourhoods tend to be characterized by comparatively homogenous socioeconomic and structural conditions (Boone et al., 2010; Galster, 2001). Similar physical conditions in the built environment will certainly correspond to more homogenous ecosystem structure, but urban vegetation also tends to reflect the practices and values of the human population (Grove et al., 2006b). Group identity and the neighbourhood effect, where residents will maintain their lawns and trees in ways that conform to their neighbours, will also reinforce vegetation homogeneity within neighbourhoods (Grove et al., 2006a; Zmyslony and Gagnon, 2000).

The notion of ecological trade-off between structurally different but functionally similar components is not entirely unique to urban landscapes. Bailey (2009) illustrates the example of floodplain ecosystems, which consist of a number of heterogeneous features (e.g., active and inactive channels, islands, and wetlands) that comprise a single functional unit. That the unit is classified according to system function and not structure alone is important if the purpose of the classification is floodplain management or a related field of research or practice. The research and/or management purpose of classifications must be considered in their design (Bailey, 2009). For example, within a single forest landscape,

ecosystem classification for timber management and wildlife management might differ significantly in both classes and boundaries. Classification in forestry tends to focus on tree species composition and age structure, while wildlife management may focus on species distribution ranges and habitat connectivity. The aim of the ecosystem classification in this study is to characterize the urban forest in such a way that accounts for the social–biophysical interaction and spatial heterogeneity that influence the supply of ecosystem services at a scale that is relevant to decision makers and the citizenry.

3. Methods

3.1. Study area

The study was conducted in Toronto, Canada (Fig. 2). Toronto is the provincial capital of Ontario, with a total population of 2,615,060 and population density of 4151 persons per km^2 as of 2011. It is a culturally diverse city, with 49.9% of Torontonians born outside of Canada and 46.9% identifying as a visible minority. Population growth rate in Toronto was 4.3% between 2006 and 2011 (City of Toronto, 2013a). The City of Toronto's Social Policy Analysis and Research section has designated 140 discrete neighbourhoods, which have since been used in urban forest policy development (City of Toronto, 2013b).

Toronto covers an area of 635 km^2 with a mean elevation of 113 m above sea level. It has a continental climate with hot, humid summers and cold winters, though its climate is also influenced by its proximity to Lake Ontario (Roots et al., 1999). The mean annual precipitation is 834 mm, with 710 mm falling as rain (Environment Canada, 2008). Toronto has a mean July temperature of 22.2 °C, a mean January temperature of −4.2 °C, and a mean annual temperature of 9.2 °C (Environment Canada, 2008). Toronto lies in the Deciduous Forest Region, in the Mixedwood Plains Ecozone, which is typically dominated by sugar maple (*Acer saccharum*), red oak (*Quercus rubrum*), white pine (*Pinus strobus*), and eastern hemlock (*Tsuga canadensis*), and characterized by fertile soils and extensive waterways (Ontario Ministry of Natural Resources [OMNR], 2012). Dominant tree species in Toronto's current urban forest include Norway maple (*Acer platanoides*), sugar maple, Manitoba maple (*Acer negundo*), green ash (*Fraxinus pennsylvanica*), and white spruce (*Picea glauca*). Urban forest canopy cover is highly heterogeneous across city neighbourhoods, ranging from a minimum of 2.4% to a maximum of 61.9% (Nowak et al., 2013).

3.2. Data sources and preparation

A variety of spatially explicit, quantitative variables (Table 1) were used to measure the 12 urban forest ecosystem components described in Section 2. Selection of variables was informed by the literature and, where necessary, restricted by the availability of data for the study area. Percent canopy cover, grass/shrub cover, and percent stocking were measured using land cover data derived from 2007 QuickBird satellite imagery (0.6 m per side pixel resolution) and City of Toronto planimetric data, which were created by the University of Vermont's Spatial Analysis Laboratory (City of Toronto, 2010). Building footprints were also derived from these land cover data. While there is some associated error in this method given the potential for tree canopy to overhang lower buildings (Pham et al., 2013), these data were found to be more accurate than the building footprint polygons from municipal cadastral datasets.

A digital elevation model (DEM) with 10-m horizontal and 1-m vertical resolution (OMNR, 2006) was used to derive percent slope gradient, which was averaged at the neighbourhood scale, and topographic position index (TPI), which is a measure of the relative position (i.e., elevation) of a given DEM pixel to neighbouring pixels (Weiss, 2001). Percent depression (TPI < -1 standard deviation [SD]), level (-1 SD $\leq$ TPI $\leq$ 1 SD), and hilltop (TPI $>$ 1 SD) slope positions were calculated in each neighbourhood following the methods described by Weiss (2001). Soils data were retrieved from georeferenced quaternary/surficial geology maps (OMNR, 1980), which provide a description of typical soil textures (i.e., sand, silt, clay) for each deposit class. While useful, these data are less preferable than soil survey data, which were not available for the City of Toronto. However, soil texture derived from surficial geology has been used previously in ecological landscape classification (e.g., Host et al., 1996) and was considered an acceptable approach for this study.

Building site coverage, measured as the mean building footprint to parcel ratio in a given neighbourhood, was the variable selected to represent building intensity (Forsyth, 2003). Floor area to parcel ratio would have been a preferable metric, though again these data are seldom available for municipalities at a spatial level useful to UFEC. Street pattern was assessed using mean block size, measured as the mean size of contiguous parcel blocks in a given

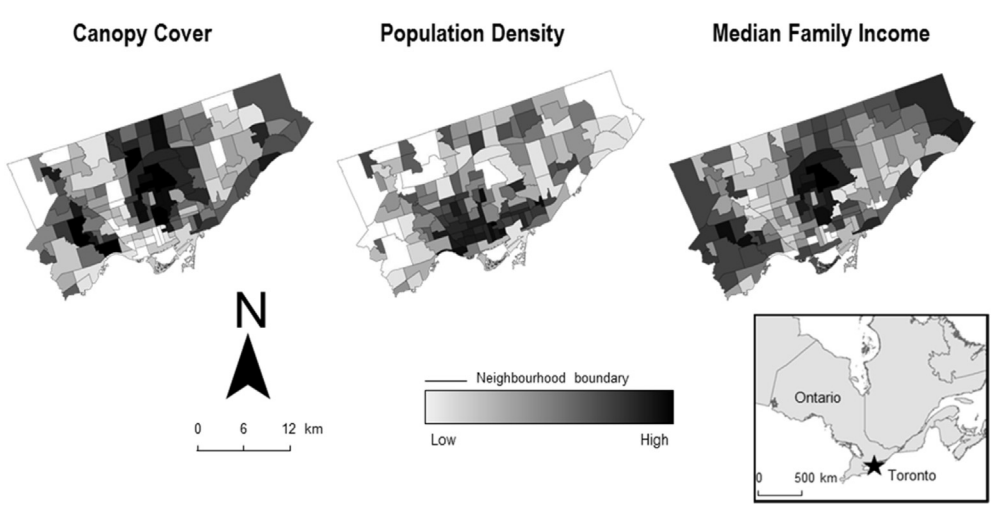

Fig. 2. The City of Toronto and its 140 neighbourhoods, showing the distribution of three selected variables from each of the biophysical landscape, built environment, and human population categories of ecosystem components.

Table 1
Variables selected to measure the 12 ecosystem components in the urban forest ecosystem classification (UFEC) framework.

Variable code	Description
Biophysical landscape	
Vegetation	
CNPY	Canopy cover (%)
GRSS	Grass/shrub cover (%)
STCK	Stocking (%)
Topography	
SP-1; SP2; SP3	Slope position (% depression, flat, and/or hilltop)
SLOP	Mean slope gradient (%)
Soil	
SL-1; SL-2; SL-3	Dominant soil texture type (% sand, silt, and/or clay)
Built environment	
Density	
BLDG	Mean building site coverage (%)
POPD	Population density (population/km^2)
Street pattern	
BLCK	Average block size (m^2)
Land use mix	
LU-1; LU-2; LU-3; LU-4	Residential, commercial, government and institutional, and/or resource and industrial (%)
Housing[a]	
SDET	Single-detached house (dwellings/10,000 people)
APT5	Apartment building with five or more storeys (dwellings/10,000 people)
PC-1; PC-2; PC-3	Period of construction before 1946, between 1946 and 1980, and/or between 1981 and 2006 (dwellings/10,000 people)
Human population	
Income	
INCM	Median family income ($)
Education	
UNIV	Population with a university certificate, diploma, or degree (individuals/10,000 people)
Homeownership	
OWNR	Percent of owner-occupied private dwellings (%)
Ethnocultural background	
IMGT	Population with immigrant status (individuals/10,000 people)
MNTY	Population that is a visible minority[b] (individuals/10,000 people)

[a] Selection and aggregation of housing data found to be valid when examining patterns of urban vegetation by Conway and Bourne (2013) and Conway and Hackworth (2007).
[b] Statistics Canada defines visible minority as non-Aboriginal people whose race is non-Caucasian and/or whose colour is non-white.

neighbourhood (Krizek, 2003). Land use refers to observed and current use (i.e., not planned land use or zoning). Data were derived from DMTI Spatial Inc., and included residential, commercial, government and institutional, and resource and industrial classes.

All variables describing the human population, as well as population density and housing data, were derived from Statistics Canada 2006 census data. The 2006 census was used in place of the 2011 census given the 2007 vintage of the land cover data. Data were obtained within the Toronto census subdivision at the census tract (CT)-level and were aggregated to the neighbourhood scale. All neighbourhood boundaries are pre-determined by the City of Toronto's Social Policy and Analysis Research Unit and correspond to those of existing CTs. Each neighbourhood is comprised of one to 10 CTs, with an average size of 4.5 km^2, and boundaries were delineated according to former and existing planning areas, service area boundaries, and natural and built features (e.g., rivers and roads). Each census variable was aggregated to the neighbourhood scale by summing total counts of all CTs within a neighbourhood, and standardized as variable counts per 10,000 people. The one exception was median family income, which was aggregated by population-weighted average.

3.3. Analysis and classification

Cluster analysis refers to a collection of techniques for examining relationships among data and is used to classify similar objects (e.g., neighbourhoods) into mutually exclusive groupings with the purpose of maximizing within-group homogeneity and between-group heterogeneity (Hair et al., 2010; Jongman et al., 1995). The term heterogeneity in this context corresponds to distance in multivariate data space (e.g., Euclidean distance). Cluster analysis is a commonly used tool for classifying ecosystems (Hargrove and Hoffman, 2005; Host et al., 1996; McNab et al., 1999; Mora and Iverson, 2002) and for developing neighbourhood typologies (Mikelbank, 2011; Reibel, 2011). We used hierarchical cluster analysis to determine natural groupings in the 140 neighbourhoods based on the 27 input variables (Table 1) measuring the 12 ecosystem components in the UFEC framework (Fig. 1). Hierarchical cluster analysis was selected given the smaller sample size and the hierarchical nature of ecological systems (Zhou et al., 2003), as well as the capacity to make between-group comparisons in the final classification (Jongman et al., 1995). It is critical that the selection of input variables for cluster analysis has a strong theoretical grounding, as variable selection is highly influential on the final clusters produced (Hair et al., 2010). Moreover, the analysis will always produce clusters regardless of their theoretical validity (Hair et al., 2010). Therefore, a theoretical grounding based on current research on urban forest ecology and management was used to build the UFEC framework first, and then to guide variable selection for the Toronto analysis.

Cluster analysis used Ward's method, which is a hierarchical, agglomerative method that begins with n clusters comprised of individual objects that are successively grouped in such a way as to reduce overall variance (Jongman et al., 1995). Ward's method is recommended when continuous variables are used and is supported as valid for the application of cluster analysis in ecosystem classification research (Jongman et al., 1995; Kent and Coker, 1995; McNab et al., 1999). Other non-hierarchical, partitioning methods, such as k-means, are arguably more suited to larger samples and more-natural forest settings with less spatial heterogeneity

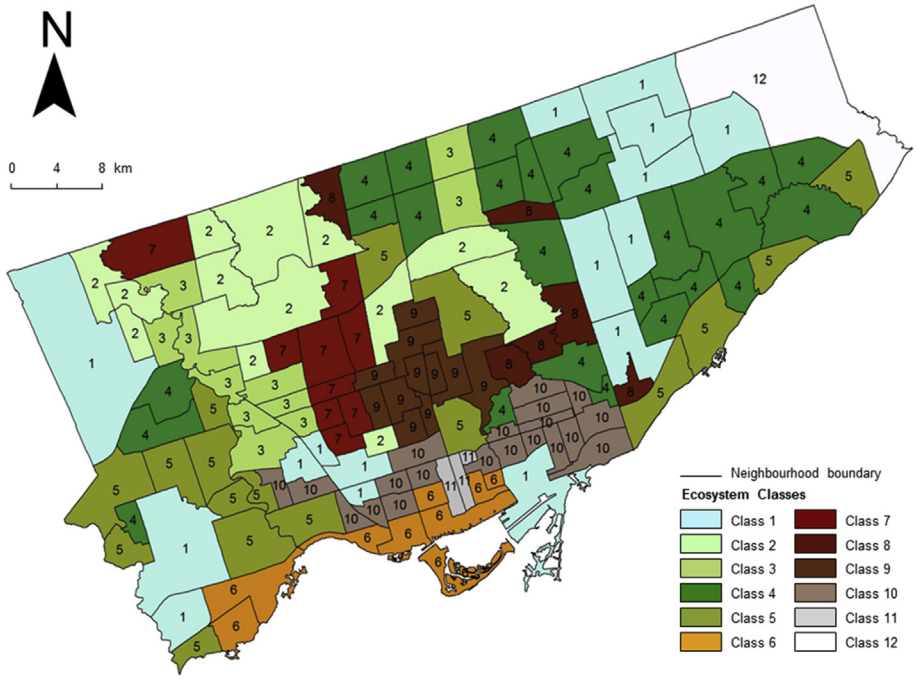

Fig. 3. Application of urban forest ecosystem classification (UFEC) to the City of Toronto.

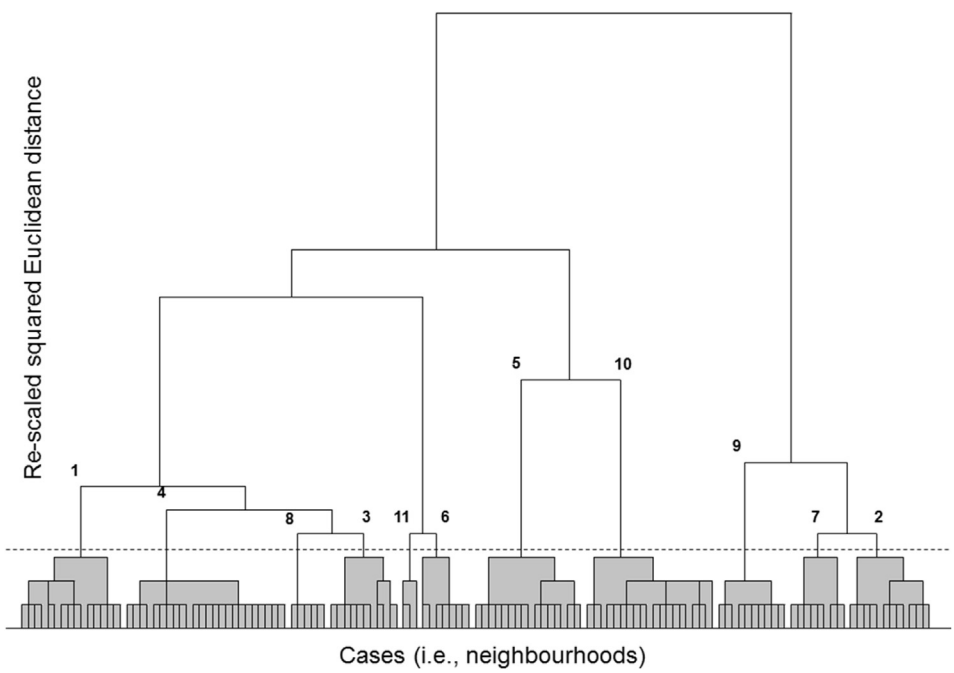

Fig. 4. Dendrogram showing the hierarchical clustering of neighbourhoods and the distance between clusters in multivariate data space (i.e., re-scaled squared Euclidean distance). The dashed line indicates the level at which the 11 clusters were identified.

(Hargrove and Hoffman, 2005). Given their different units of measurement, each variable was standardized prior to analysis using its maximum value, so that values ranged between 0 and 1 (Jongman et al., 1995). Because the Rouge neighbourhood in the northeast corner of Toronto is primarily comprised of a forested national park with some surrounding residential and agricultural land use, it was removed from the analysis as it represented a considerable municipal anomaly.

4. Results

In this UFEC application, a total of 11 clusters were identified in the cluster analysis, yielding a total of 12 urban forest ecosystem classes with the omitted Rouge neighbourhood designated as Class 12. Ecosystem classes ranged in area from 4 km^2 to 132 km^2, with an average area of 53 km^2, and consisted of three to 25 city neighbourhoods. The highest tree canopy cover was found in Classes 5 and 9, which were also the wealthiest and least

Table 2
Ecosystem classes identified in the test application of the urban forest ecosystem classification (UFEC) framework in the City of Toronto.

Class	Description
Class 1 ($n = 16$)	Industrial Parkland (132 km^2) — Extensive open green space, with low canopy cover and stocking — Level terrain and sand soils — Moderate building site coverage, population density, and block size — Mixed residential and industrial land uses — Newer, owner-occupied, detached housing — Moderate income with lower education and high ethnocultural diversity
Class 2 ($n = 13$)	Mixed residential neighbourhood (79 km^2) — Extensive open green space, with moderate canopy cover and stocking — Primarily level terrain with clay soils and infrequent steep and forested slopes — Moderate building site coverage and population density with larger block size — Primarily residential land uses — Mixed detached and apartment housing, with owners and renters — Moderate income and education with high ethnocultural diversity
Class 3 ($n = 11$)	Mixed residential neighbourhood – steep terrain (38 km^2) — Extensive open green space, with moderate canopy cover and stocking — Clay and sand soils with abundance of forested ravines and valleys — Moderate building site coverage and population density with larger block size — Primarily residential with some industrial/commercial land uses — Mixed detached and apartment housing, with owners and renters — Moderate income with high ethnocultural diversity and low education
Class 4 ($n = 25$)	Typical residential neighbourhood – newer and outer (122 km^2) — Extensive open green space, with moderate canopy cover and stocking — Level terrain and sand soils — Low building site coverage and moderate population density and block size — Primarily residential land uses — Mixed detached and apartment housing, with owners and renters — Moderate income and education with higher ethnocultural diversity
Class 5 ($n = 17$)	Affluent and forested neighbourhood – lower density (86 km^2) — Very high canopy cover and stocking — Steep and variable terrain with sand soils — Low building site coverage and population density with moderate block size — Primarily residential land uses — Owner-occupied, detached housing — High income and education with low ethnocultural diversity
Class 6 ($n = 8$)	Waterfront Hardscapes (27 km^2) — Very low vegetation cover and low stocking — Level terrain with silt soils and fill — High building site coverage and population density — Mixed residential and industrial land uses — Abundant apartment tower housing of varying periods of construction with low ownership — Low income with moderate education and ethnocultural diversity
Class 7 ($n = 9$)	High density residential neighbourhood (32 km^2) — Low canopy cover and stocking with moderate open green space — Variable terrain and clay soils — Moderate building site coverage and population density with small block size — Primarily residential with some industrial/commercial land uses — Owner- and renter-occupied detached housing — Moderate income and ethnocultural diversity with low education
Class 8 ($n = 6$)	Towers in the park (19 km^2) — Moderate canopy cover and high stocking — Primarily level terrain with sand soils and infrequent steep and forested slopes — moderate building site coverage and population density with very large block size — Mixed residential and industrial land uses — Primarily apartment tower housing and low ownership — Low income, moderate education, and very high ethnocultural diversity
Class 9 ($n = 11$)	Affluent and forested neighbourhood – higher density (25 km^2) — Very high canopy cover and stocking with low open green space — Variable terrain and clay soils — Moderate building site coverage with high population density and small block size — Primarily residential land uses — Mixed, older detached and apartment housing — High income and education with low ethnocultural diversity
Class 10 ($n = 20$)	Typical residential neighbourhood – older and inner (35 km^2) — Low canopy cover and open green space with high stocking — Variable terrain and sand soils — High building site coverage and population density with small block size — Primarily residential with some institutional land uses — Older, owner- and renter-occupied housing — Moderate income and education with lower ethnocultural diversity

(*continued on next page*)

Table 2 (*continued*)

Class	Description
Class 11 ($n = 3$)	The Downtown Core (4 km^2) — Very low canopy cover, open green space, and stocking — Primarily level terrain — Very high building site coverage and population density with small block size — Mixed land use — Primarily apartment tower housing and low ownership — Low income and high education and ethnocultural diversity
Class 12 ($n = 1$)	Peri-urban forest (38 km^2) — High canopy cover and open green space — Variable terrain with sand and clay soils — Moderate building site coverage with very low population density and very large block size — Primarily forested with some residential land uses — Newer, owner-occupied, detached housing — High income and ethnocultural diversity with low education

ethnoculturally diverse. The lowest tree canopy cover and highest population and building density were found in Class 11, which covered the commercial and institutional centre of the city. Mapping of the 12 ecosystem classes (Fig. 3) showed that most classified neighbourhoods showed some spatial aggregation, especially those associated with the more-densely built urban core (e.g., Classes 6, 9, 10, and 11).

The dendrogram (Fig. 4) illustrates the hierarchical and agglomerative grouping of individual neighbourhoods into clusters of increasing size. Determining the appropriate grouping level to derive clusters and, as such, the final number of ecosystem classes is a heuristic process (Hair et al., 2010). We determined grouping level based on a natural break in the dendrogram (Zhou et al., 2003) and with the objective of maintaining a manageable number of meaningful ecosystem classes.

Each ecosystem class was interpreted and named (Table 2) using synoptical tables summarizing variable values within each class (Appendix A). Several of the ecosystem classes were interpreted as variants of a single type and were paired in the naming convention. This was done to improve the organization and clarity of the UFEC where class conditions were complementary along one or more key social-ecological gradients. The Affluent and Forested Neighbourhoods (i.e., Classes 5 and 9) were assigned both a lower and higher density variant based on population density and building site coverage. The Mixed Residential Neighbourhoods (i.e., Classes 2 and 3) differ primarily in biophysical conditions and have a steep terrain variant. Lastly, the Typical Residential Neighbourhoods (i.e., Classes 4 and 10) were found to have both an inner variant with older housing and higher density and an outer variant with newer housing and lower density. These two classes represent 25% of Toronto's geographic area and 33% of its population. Industrial Parkland (i.e., Class 1) was the most extensive ecosystem, covering 20% of the study area.

5. Discussion and conclusions

The objective of ecosystem classification is to reduce the structural and functional complexity of ecosystems in models while quantifying key social and ecological processes involved in shaping current ecosystem conditions (Bailey, 2009; Cadenasso et al., 2007). In doing so, ecosystem classification can inform researchers, policymakers, and practitioners by relating management needs and decision-making to the current conditions of the natural resource in a more holistic and spatially explicit fashion. Thus, the implementation of UFEC could be instrumental in shifting urban forestry towards a model of ecosystem-based management, where, in contrast, the historical focus has tended towards individual tree care or biophysical ecosystem components only (Konijnendijk et al., 2006).

The specific conditions of the ecosystem classes identified in the classification can inform urban forest planning and management in a number of ways. From the simplest perspective, the UFEC can provide insight for urban greening, tree planting, and the maintenance of the existing canopy. Canopy cover targets are a common feature in strategic planning in urban forestry (Kenney et al., 2011), such as Toronto's own 40% target. However, given that spatial heterogeneity of canopy cover distribution is common across cities (Cadenasso et al., 2007), assessment and target designation at the ecosystem scale will provide managers with more useful information for greening initiatives. These locally-specific designations will also help provide the detail necessary to create realistic future planting targets. For example, a higher canopy target in Class 1, where open green space was abundant and stocking was low, is more attainable than in Class 11, where building intensity is much higher and limited planting space and opportunities for greening exist. Conversely, in older (i.e., housing age) neighbourhoods where canopy cover and stocking are high, such as Class 9, the maintenance of the existing, ageing canopy would most likely become the management priority.

The distribution of canopy cover and associated economic wealth across the ecosystem classes yielded both expected and unexpected findings. Existing research emphasizes the positive spatial relationship between the distribution of canopy cover, and thus associated ecosystem services, and economic wealth (e.g., Grove et al., 2014). Our findings support this observation, as is evident in Classes 5, 9, and 12, which had the three highest canopy cover and income values, respectively. Similarly, low-income residents and minimal tree canopy cover were found in Classes 6, 11, and, to a lesser degree, 1. The UFEC classes with wealthy residents and higher canopy cover also tended to be defined by older and detached housing, which is again consistent with existing studies (Boone et al., 2010; Conway and Bourne, 2013). Tree canopy cover was expected to be strongly associated with homeownership given its association with economic wealth (Troy et al., 2007). While this was found in some cases, Class 9 had the second highest canopy cover at 41.8% but a low ownership rate of just 49.1%. In contrast, Class 1, with a low canopy cover of 15.9%, had a higher ownership rate of 66.9%. Similar disparities between canopy cover, income, and education were also evident (i.e., Class 11). These findings suggest potential scale dependencies of some ecological processes, especially those of an anthropogenic origin like the influence of land tenure on management practices, where established relationships may be stronger at the parcel level than at the neighbourhood level.

Patterns in the distribution of open green space, contrasted with those of tree canopy cover, and appeared to be, in part, a function of building intensity and imperviousness (Berland, 2012) with a greater abundance of open green space in the peripheral ecosystems of Toronto. Open green space, unlike canopy cover, can have a broad range of land uses (e.g., sports fields, institutional grounds, highway rights of way). This difference may explain the variable relationship with socioeconomic background of residents that is not seen with tree canopy cover. This latter point is also important to consider in urban forest planning, where not all open green space can be considered as available planting space (Wu et al., 2008). As expected, stocking also shows these same patterns, though inverted. However, stocking was often found to be low in ecosystems with a high proportion of industrial land uses (e.g., Classes 1 and 6), which highlights industrial properties as potential greening opportunities for municipalities.

Of importance to urban forestry is the relationship of population density and building intensity (collectively referred to hereafter as urban density) with canopy cover, and whether high urban density and the process of densification have negative implications for urban forest ecosystem service supply. Existing theories suggest that canopy cover is likely to decrease as urban density increases due to increases in housing, transportation networks, and other impervious urban features (Cook et al., 2012; Grove et al., 2014). There are certainly instances where this holds true, with Classes 5 and 11 at either extreme. In ecosystems characterized by high urban density, the maintenance and enhancement of public green spaces and parks may be a priority for urban forest management given the lack of space for greening initiatives on other properties. Moreover, these ecosystems (e.g., Class 11) will likely have higher tree planting and maintenance costs due to additional infrastructure needs and higher rates of tree mortality (Jutras et al., 2010; Nowak et al., 2004).

The present study's findings suggest that at the neighbourhood scale, there are instances where other ecosystem components, such as socioeconomic background and land use can be more influential on tree canopy cover than urban density. For example, Class 9 has relatively high urban density and high tree canopy cover. The wealthy residents that characterize this class may, in part, explain this phenomenon, given the existing research on the positive association of tree cover and wealth (e.g., Grove et al., 2014). As another example, Classes 1 and 2 both had moderate population density and building intensity values. However, Class 1 had a much lower tree canopy cover of 15.9% and stocking of 41.8% than Class 2, with 30.6% canopy cover and 54.5% stocking. The high proportion of industrial land uses and their associated abundance of open green space in Class 1 may explain this disparity. More empirical research is required to substantiate these patterns and the relationship between tree cover and urban density.

In addition to aligning management needs and objectives with current ecosystem conditions, ecosystem classification may also be employed in the prioritization of management actions, or 'ecological triage' (Hargrove and Hoffman, 2005; Hobbs and Kristjanson, 2003). Restrictive municipal operating budgets for urban forest management are commonplace across North America (Kenney and Idziak, 2000). Identifying areas where ecosystem service supply is low and opportunities for enhancement exist will help to prioritize strategic urban forest planning initiatives. It is important, however, that this approach is not used to validate underfunding of urban forestry, where challenging and costly sites (e.g., Class 11) are omitted from greening initiatives.

It is also valuable to prioritize limited municipal resources according to other management objectives, such as social equity in the distribution of ecosystem services (Pham et al., 2013). Lower-income neighbourhoods have been shown to be associated with less green space, degraded urban forest health, and lower canopy cover (Landry and Chakraborty, 2009; Pham et al., 2013; Troy et al., 2007). It has also been demonstrated that there are racial and ethnic inequalities in the distribution of urban canopy (Heynen et al., 2006; Landry and Chakraborty, 2009). These inequalities in access to ecosystem services translate into unequal access to the myriad of benefits that the urban forest supplies (Heynen et al., 2006). While Toronto does exhibit exceptions to these patterns (e.g., Class 8), a negative relationship between canopy cover and ethnocultural diversity was observed. In contrast, neighbourhoods with residents having wealthier socioeconomic backgrounds have a greater capacity for self-organization and access to financial resources for urban forest stewardship activities (Grove et al., 2006a; Heynen et al., 2006); these neighbourhoods may be a lower management priority for limited municipal resources. The inclusion of socio-demographic data in the UFEC can aid in the consideration of social equity as far as urban tree canopy distribution is concerned. Moreover, identifying city trees as pieces of green infrastructure can help leverage urban forests in policy development to address and reduce urban poverty (Dunn, 2010).

In this study, we adopted current urban ecological theory pertaining to the social and biophysical processes that shape urban forest ecosystems. However, social-ecological systems like cities, and urban forests within, are also legacies of their own unique conditions and histories (Grove, 2009). For example, the biophysical legacy of Toronto's ravine system and its influence on construction, prominent neighbourhood organization, and other place-specific phenomena likely influenced the results of this study and their generalizability, most notably the derived ecosystem classes. Moreover, the established relationship of low income with high urban density is not as pronounced in Toronto as many other North American cities (Conway and Hackworth, 2007). Future UFEC research and applications will likely yield novel ecosystem classes specific to individual cities. However, the intent of the UFEC design was to provide a science-based tool that allows for the inclusion of ecological theory and local knowledge in the identification and interpretation of ecosystem classes. Ecosystem classification is, in part, an inherently subjective process (Sokal, 1974) and it is hoped that this balance could be beneficial for the efficacy of the UFEC framework and its generalizability to other cities and regions. Lastly, it is hoped that future UFEC research in other cities, countries, and climatic regions could help refine and advance the tool and strengthen the practice of ecosystem classification in cities.

Acknowledgements

Funding for this project was provided by the Natural Sciences and Engineering Research Council of Canada (NSERC) and Ryerson University. We would like to thank the Urban Forest Research and Ecological Disturbance (UFRED) Group at Ryerson University and Eric Greenfield at the USDA Forest Service for their feedback on the study. This research was, in part, conducted and funded during the lead author's Fulbright exchange at the USDA Forest Service's Northern Research Station in Syracuse, New York. Fulbright Canada is a joint, bi-national, treaty-based organization created to encourage mutual understanding between Canada and the United States of America through academic and cultural exchange.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2015.08.008.

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