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Convergence of urban forest and socio-economic indicators of resilience: A study of environmental inequality in four major cities in eastern Canada

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ABSTRACT

Environmental inequality is a phenomenon drawing much attention in the scientific and policy-making debates about urban forests and city greening. Most studies on the subject have shown that socially vulnerable, multicultural neighborhoods are disproportionately affected by the lack of urban forest while richer neighborhoods tend to be greener. But are there differences in the resilience of urban forests between poor and rich neighborhoods? We tackled this question using a newly developed indicator of urban forest resilience, functional diversity, to determine if environmental injustice is also found in the resilience of urban forests in poor neighborhoods. Using Canadian census data at the census tract scale, Sentinel-2 satellite imagery and urban tree inventories, this study investigated if urban forest resilience is also part of the environmental inequality phenomenon in four urban areas in eastern Canada: Toronto, Gatineau-Ottawa, Montreal and Quebec City. Multivariate analysis of the dataset shows that urban forest functional diversity, used as an indicator of resilience, is inversely correlated to a set of variables associated with social vulnerability. The same relationship also exists with canopy cover; a pattern of inequality found in many cities around the world. With these findings, we show that social vulnerability and urban forest resilience are intertwined, meaning that neighborhoods already lacking urban forest are also more at risk of losing it due to a sudden environmental disturbance. When confronted with global change, considering this new insight into urban environmental inequality could be of great importance for maintaining a comfortable living environment for every city-dweller.

1. Introduction

Urban environmental inequality is a problem faced by many cities around the world. The growing body of scientific literature on the subject shows that urban green infrastructure, such as the urban forest (UF), is generally more prevalent in upscale neighborhoods but is scarcer in poorer, multicultural neighborhoods (Nesbitt, Meitner, Girling, Sheppard, & Lu, 2019; Dobbs, Kendal, & Nitschke, 2014; Joassart-marcelli, 2010; Schwarz et al., 2015; Nesbitt & Meitner, 2016; Heynen, 2003). While the density of the UF has been linked with social parameters such as wealth (Schwarz et al., 2015), its diversity has not received the same amount of attention. Because diversity is an effective indicator of resilience (Laughlin, Strahan, Huffman, & Sánchez Meador, 2017; Messier et al., 2019), it becomes especially important in understanding how the urban forest might respond to global change and which population will be the most at risk of losing urban forests valuable to their well-being.

Urban forest is the most important natural element found in many urban areas. It is defined as the sum of all trees and shrubs making up the green cover in urban areas (Jones & Davis, 2017). It is part of the broader Green Infrastructure, which includes vacant lots, grassy areas such as parks and ball fields, water bodies and other natural or managed green spaces (Benedict & Mcmahon, 2006; Mell, 2013). Some authors consider green infrastructure as the designed, or planned, natural elements of cities (Pataki et al., 2011). Urban green infrastructures, especially urban forests, are crucial providers of ecosystem services to city-dwellers (Haase et al., 2014; Dobbs, Escobedo, & Zipperer, 2011; Gómez-Baggethun & Barton, 2013; Dupras, Alam, & Revéret, 2015; Dupras & Alam, 2015; Bissonnette et al., 2018).

The variety of ecosystem services provided by UF is of great benefit to the urban population. Among the many ecosystem services (ES) reported, the increase in property values (Des Rosiers, Thériault, Kestens, & Villeneuve, 2002; Donovan & Butry, 2010; Morales, 1980) and the reduction of the urban heat island (Oke, Crowther, McNaughton, Monteith, & Gardiner, 1989) have been studied for the longest time. More recently, other positive effects of urban forests and trees have been reported, such as an increase in passersby in commercial areas (Wolf, 2007), increase in tourism (Majumdar, Deng, Zhang, & Pierskalla, 2011), increase in community cohesion (Arnberger & Eder, 2012) and increased feeling of security (Kuo & Sullivan, 2001). Positive impacts of natural urban elements on both physical (Lovasi, Jacobson, Quinn, Neckerman, & Ashby-thompson, 2011; Villeneuve et al., 2016) and psychological health (Annerstedt et al., 2012; Carrus et al., 2015; Taylor, Wheeler, White, Economou, & Osborne, 2015) have also been reported. Although ESs are generally perceived as positive, the natural elements providing them might be seen negatively by some (e.g. tree

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blocking the view), adding to the complexity of managing for ES provision as a goal. In general, these ESs, among others, benefit every city dweller living in proximity to UF. However, the distribution of the urban forest, and therefore its benefits, have been shown to be heterogeneous in many urban areas.

The variation in UF cover is in many cases bound to certain socio-economic parameters of the population. The influence of median income and/or property values on the forest cover at the neighborhood scale has been demonstrated in many studies (Nesbitt et al., 2019; Pham, Apparicio, Séguin, Landry, & Gagnon, 2012; Dobbs, Kendal et al., 2014; Heynen, 2006; Landry & Chakraborty, 2009; Schwarz et al., 2015). The density of certain ethnic groups has also been correlated with lower forest cover (Joassart-marcelli, 2010; Landry & Chakraborty, 2009). The differences in tree cover in the latter study (Joassart-marcelli, 2010) were mediated by unequal spending in greening from municipal governments disadvantaging one ethnic group over the majority. A study by Yi et al. (2019) has shown relations between general biodiversity as a function of habitat quality (i.e. fragmentation, conservation status) and socio-economic parameters of the population. This complex and multi-faceted phenomenon known as environmental inequality can be driven by many social, economic and/or policy factors, as well as being variable along time scales (Schwarz, Berland, & Herrmann, 2018). The victims of environmental inequality face a situation where they lack an important part of the UF related ecosystem service provision. While the density of the UF has been correlated with social variables, other forest descriptors such as diversity has not received such attention in recent research. Studying the UF diversity in the context of environmental injustice is of great importance to understanding how global change could affect the well-being of city residents.

The diversity of vegetation has been linked to a number of beneficial impacts by numerous studies in the field of ecology. Increased biomass productivity (Paquette & Messier, 2011), soil microbial activity (Lange et al., 2015) and soil retention are examples of diverse vegetal communities having an advantage over the less diverse. The science of ES also points to an increase in provision from more diverse vegetation (Haase et al., 2014; Quijas, Schmid, & Balvanera, 2010). In this regard, diverse urban forests may have beneficial impacts on city-dwellers well-being; as a few studies have reported higher self-assessment of well-being when diverse urban forest was present in the individual's surroundings (Carrus et al., 2015; Dallimer et al., 2012). Diversity in general, and especially functional diversity, is an effective indicator of a forest's resilience to disturbances. It is a measure of the diversity of key biological characteristics found among tree species in a community. Functionally diverse vegetation has been shown to exhibit more resilience to various types of disturbances (Diaz & Cabido, 2001; Elmqvist et al., 2003; Oliver et al., 2015; Paquette, 2016) although some cases seems to indicate otherwise (Berland & Elliott, 2014). Diverse forests also stabilize the production of some ES from one year to another (Gamfeldt et al., 2013; Manes et al., 2014, 2012; Oliver et al., 2015). A functionally diverse and therefore more resilient forest becomes especially relevant in urban areas, where we know biodiversity in general declines following a rural-urban gradient (Yi, Kreuter, Han, & Güneralp, 2019; Strohbach, Haase, & Kabisch, 2009; Niemelä et al., 2011). The scarcity of natural elements and the high number of ES beneficiaries further emphasizes the social and economic importance of urban forests.

The term resilience is also used frequently in social sciences. For example, Adger (2006, 2000) has shown similarities with social systems. Social-economic resilience is the capacity of a population to cope and adapt to social or ecosystem changes and extreme environmental events (Adger, 2000; Smith, Anderson, & Moore, 2012). Individuals having access to a larger social and financial capital are said to be more resilient to such disturbances (Smith et al., 2012). Social vulnerability (based on an array of social and economic variables) as defined in this study can be used as a way of measuring such resilience. This definition is related to Holling, 1973 definition of ecological resilience which is "a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between population or state variables" (Holling, 1973). Contemporary definitions are widened in the field of complex systems, including aspects of social-ecological system dynamics (Folke, Carpenter, Elmqvist, Gunderson, & Walker, 2002; Walker, Holling, Carpenter, & Kinzig, 2004). It has been shown that poorer or generally more vulnerable populations are more at risk of suffering from environmental stresses. The example of the heat wave that struck France in 2003 showed that socially vulnerable people in cities suffered dramatically higher death rates (Poumadère, Mays, Le Mer, & Blong, 2005).

Research has already shown that environmental inequality in the form of uneven distribution of the UF cover generally disadvantages the more vulnerable populations. However, because diversity is also having an influence on ES production, its distribution could also be linked to social parameters. The main goal of this study is to investigate the relationships between urban forest diversity and key socio-economic factors of the population. We specifically wanted to know if tree functional diversity (a good indicator of urban forest resilience to global change) is related to the socio-economic resilience of city-dwellers. However, studies linking biodiversity and human well-being at the individual scale (e.g. Carrus et al., 2015), as well as social-ecological framework theories hint toward the existence of such a relationship at a larger scale. To answer this question, relationships between urban forest and socio-economical parameters will be studied in four of the largest urban areas in eastern Canada.

2. Method

2.1. Study area

This study looked at the four largest urban areas of eastern Canada in terms of the total number of inhabitants. These include: Toronto (6 341 935 inhabitants), the urban agglomeration of Ottawa and Gatineau (1 414 399), Montreal (4 225 541) and Quebec City (817 408) (Statistics Canada, 2018). The study areas also included suburbs and urban surroundings of each of the four cities. The cities used for analyses were chosen based on two criteria to insure comparability: socio-economic and natural environment data consistency.

Because census data was used in this study as the socio-economic dataset, it needed to be uniform across the studied cities. That is why only Canadian cities were included in the study. Ensuring comparability of diversity data among the study areas was also necessary so the cities included in the analysis are in an area where geographical or climatic factors would not have a great influence on biodiversity. In other words, cities were selected from within the same ecozone, which is a biogeographical scale where species are more taxonomically related than at the larger, biome scale. Most of the largest cities in the country are located in the Canadian "mixedwood plains" ecozone allowing to include the largest population within a single zone. Cities located in the Canadian prairies, such as Winnipeg, or in the Atlantic coast Maritimes region, such as Halifax, were excluded from the sample as they are not located in the "mixedwood plains" ecozone (Marshall, Schut, & Ballard, 1999). The four selected urban areas are those which met both the Canadian census and the natural environment criteria.

2.2. Data

The method used in this study is one that builds upon knowledge from other studies on the mapping of ecosystem services and urban environmental inequality (Dobbs, Kendal et al., 2014; Schwarz et al., 2015). Main differences in methods from previous studies include the use of urban forest diversity data and multivariate statistics. 3 types of data were gathered for this study: satellite imaging to assess urban tree cover, Canadian census data for socio-economic status, and urban tree inventories to calculate forest diversity metrics.

2.2.1. Canopy data

Tree cover data was collected using data from the ESA's (European Space Agency) Sentinel-2 satellite imaging program. This satellite is capable of taking multi-band images at varying resolutions. For this study, bands corresponding to blue, green, red and NIR (Near-Infrared) were used. These wavelengths have been used in many studies to assess vegetation at multiple spatial scales (Dobbs, Nitschke, & Kendal, 2014; Walton, Nowak, & Greenfield, 2008; Yang, Mcbride, Zhou, & Sun, 2005). The NIR band is especially useful for distinguishing between vegetal and non-vegetal ground cover as its absorbance varies greatly between these two types of cover. The resolution of the images using these bands is available at a 10 m by 10 m pixel size. This resolution, while being lower than the ones from other image sources, is still sufficiently precise to capture the urban forest. We do acknowledge that finer grained features of the urban forest might be lost, resulting in an under-estimation of tree cover. As this bias is homogenous across the study area, the possible effect of resolution on the results was disregarded. To ensure maximum foliage and therefore the best tree detection threshold, the images used in this study were taken during the summer (mid-July to mid-September). All images are from the year 2016. The images were treated using the Semi-automatic Classification Plugin in QGIS (Congedo, 2018), and were classified into four categories representing trees, grass, built environment and water. The number of pixels of each class was then counted and transformed into a ratio for each of the census tracts. Across the study area, census tracts are in average comprised of 47% built environment, 27% tree canopy, 26% low vegetation and < 0,5% water.

2.2.2. Socio-economic data

Social, economic and demographic data were obtained through the Canadian Census. The census data was extracted at the census tract (CT) level, which is the smallest geographical unit (as of census year 2011) for which all the needed data is compiled. Canadian census tracts are a subdivision used only for urban areas, which are defined by Statistics Canada as a metropolitan area with a core population of 50,000 or more (Statistics Canada, 2012). The average size of the 2370 CTs in the study area of interest is 8.6 km^2 containing an average of 7512 inhabitants (15 years of age and over).

A total of 17 social, economic and demographic parameters were used for this investigation. Most variables are used in demographic or sociological studies to assess the quality of life, well-being or resilience, as well as other parameters associated with social vulnerability and cultural diversity.

Income from census data is a basic parameter used in nearly all studies about the importance of the natural environment on the well-being of the population. The median household income was used in this study because 1) the median is a better way to evaluate the central tendency of a distribution susceptible to being influenced by outliers, such as when a neighborhood may contain a small fraction of much wealthier people, and 2) family income (as opposed to personal income) reflects economic status in a way that is closer to reality in contexts where every adult in the household might be earning money. Income has been positively correlated to urban tree cover in a number of studies worldwide (Dobbs et al., 2011; Schwarz et al., 2015).

The value of dwellings was used in this study as another measure of wealth. Because wealthier people can afford pricier houses, house value is generally, but not always, correlated with income. It is also a useful metric because it has been shown that house prices increase with the number of trees on residential properties (Des Rosiers et al., 2002).

Social vulnerability is a multi-facetted problem for which a precise assessment is difficult. However, indicators of social vulnerability have been used in many studies, including environmental inequality papers, to describe the situation (Dobbs et al., 2011, 2014; Schwarz et al., 2015). This study builds on prior knowledge and uses multiple indicators to investigate which components of social vulnerability were most associated with urban tree cover (UTC). The variables we used include:

- Proportion of people renting their dwelling;
- Proportion of households under the low-income threshold, adjusted for the number of persons in the household;
- Proportion of single-parent families;
- Proportion of households where housing costs are ≥30% of income;
- Proportion of people who have moved in the last year;
- Proportion of people (15 years and over) without a high school diploma or other higher education diploma;
- Proportion of people 65 years and over
- Proportion of people 65 years and over living alone
- Proportion of 'non-suitable' households (crowding metric compiled by Statistics Canada, based on the number of occupants and the number of bedrooms in a house)

Cultural diversity is an important aspect of urban demographics and has been linked to urban tree cover in some studies (Joassart-marcelli, 2010; Kabisch & Haase, 2014). In this study cultural diversity was assessed using two variables. The first is the Shannon diversity index based on which language is primarily used at home and the number of speakers of each of these languages. The second is the proportion of immigrants (first generation) in the total population. Cultural diversity is interesting in the context of green infrastructure when ecosystem services are considered. Some green infrastructure component might be considered desirable for one cultural group and undesirable for another. As the perception of nature changes, so does the importance and value of resulting ecosystem services.

2.2.3. Urban forest diversity

Urban tree inventories carried out by municipal governments for trees in the public domain were used to assess metrics of urban forest diversity at the CT level. The databases were unified by ensuring a uniform species nomenclature before using QGIS to assign each individual to the respective CT. Inventories show that 294 species of trees and shrubs are present in the study area, a number that varies from 137 (Ottawa) to 249 for (Montreal). In average, census tracts contained 49 different species. Only 97 of the 294 species of trees and shrubs listed in the inventory are native to the "mixedwood plains" ecozone.

Diversity analyses were performed in R (version 3.5.1). Species diversity was assessed with the Shannon diversity index calculated on rarefied species scores (iNEXT Package version 2.0.18). This process allows to control diversity estimation issues in neighborhoods where trees are scarce or very abundant with the use of a rarefaction curve. The curve is created by randomly re-sampling the pool of individuals to plot the average number of species found by sampling n individuals (Gotelli & Colwell, 2001). Functional diversity was assessed the same way using the five functional groups defined by Paquette (2016). Paquette (2016) used a variety of physiological traits for each species of tree and then grouped them based on their trait similarity. The proportion of trees belonging to native species was also calculated for each CT; a species was considered native if its natural range covered at least one of the four urban areas.

2.3. Selection of focal census tracts

As discussed, CTs are created for every urban center. However, as a metropolitan area is comprised of the city core, the surrounding secondary cores and the fringe population cores (Statistics Canada, 2012 – dictionary), much of a metropolitan area is in fact peri-urban or rural. Some CTs are covered with up to 99% agricultural and/or forest land. As this study focused specifically on cities, relevant CTs had to be selected. For this, a criterion based on the relative built surface of each CT was input into the GIS database as a logical request. Therefore, the

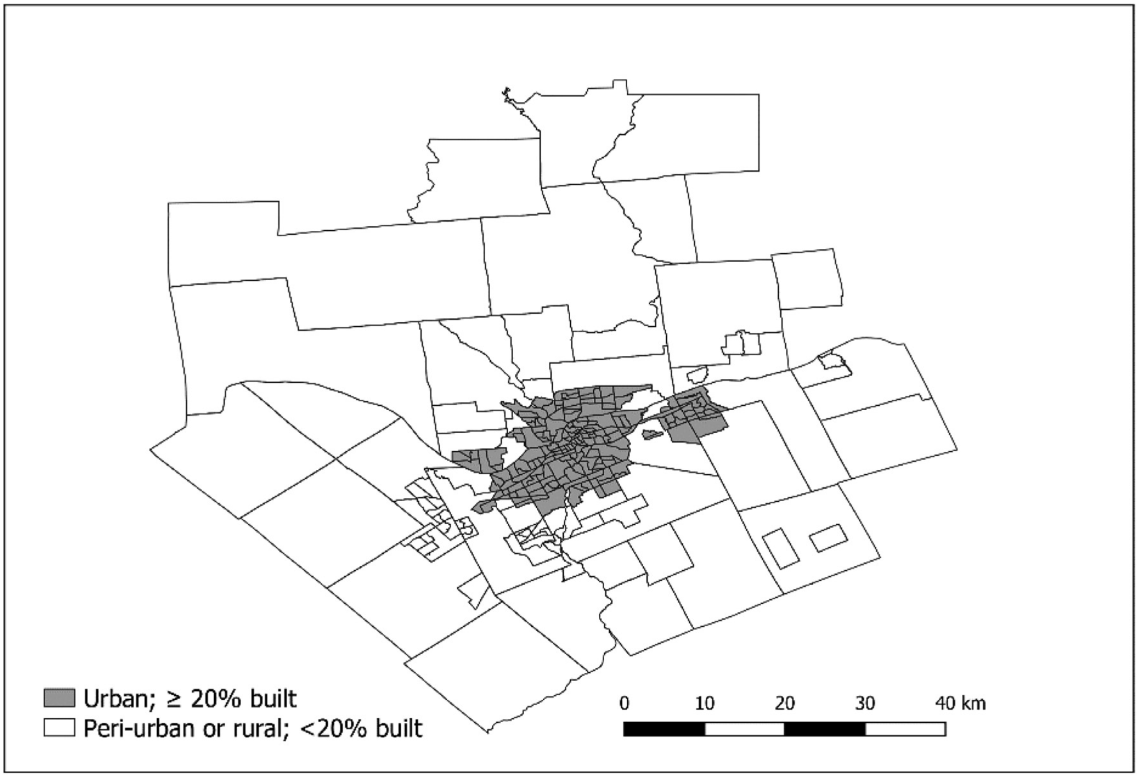

Fig. 1. Example of selection for urban CTs in the Gatineau-Ottawa metropolitan area. CTs with 20% or more of their land cover in the "built" class, thus being used for statistical analysis, are shaded. In this case, 180 of 270 CTs are selected.

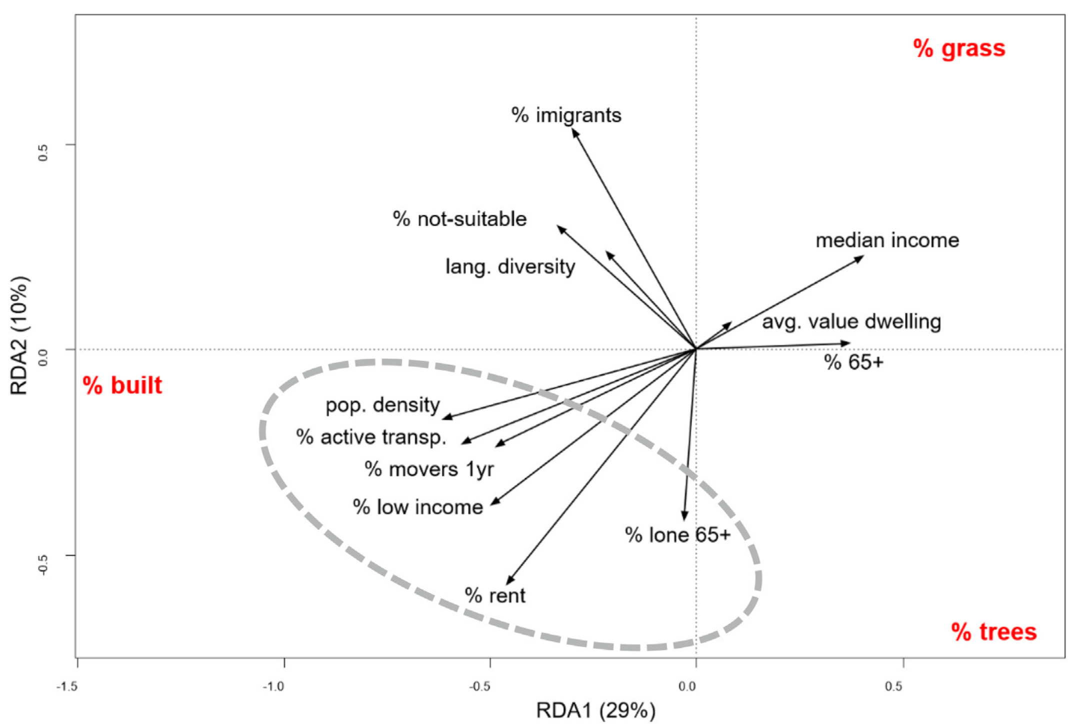

Fig. 2. RDA plot of socio-economic parameters against ground cover classes. The graph shows relationships between social parameters and land cover classes in the 1874 CTs of the four urban agglomerations in eastern Canada. Social variables are shown as arrows and ground cover class as red text. Proportion of variance explained by social parameters is shown on both axes. 12 out of 17 variables are shown here to ease the reading, the excluded 5 having the least impact on explaining the dataset's variance. Dashed ellipse shows variables associated with socio-economic vulnerability.

selected CTs were those where between 20% and 100% of their surface area was of the “built” classification, resulting in 1874 (79%) CTs being selected to be treated statistically (see Fig. 1). Urban agglomerations include multiple cities (main city and suburbs, for example) and some of them had not completed urban tree inventories. Because of this, statistical analyses for tree diversity included only 1161 CTs (of the 1874 used in other analyses). Finally, because the boundary lines of most waterside CTs extend in the body of water, some CTs are comprised of up to 66% “water” cover class. CTs not adjacent to water contain in average < 0,5% water. Thus, because of its very low actual ground coverage, the “water” cover area was subtracted from CT area and therefore not used in statistical analyses.

2.4. Statistical approach

As one objective of this study was to determine which social, economic and demographic parameters influence urban ground cover, we chose to convey multivariate analyses. The selected statistical approach was the redundancy analysis (RDA). Principal Component Analysis (PCA) was also used to test whether urban forest diversity was linked with social variables without considering tree cover. RDA and PCA, as other multivariate techniques, are analyses that work well for datasets with collinear variables (Vyas & Kumaranayake, 2006; Gujarati, 2004), such as census datasets. These analyses, by giving more weight to the parameters that vary the most, are also suited to highlight differences between groups of individuals in the data (McKenzie, 2005). Multivariate analyses such as PCA has also been used in many studies to calculate socio-economic status indexes (Chan et al., 2015; Caro & Cortés, 2012; Michelson, Muñiz, & Derosa, 2013). While calculating such an index is not the aim of the study, a similar approach is used to correlate socio-economic variables to urban ground cover. As these multivariate approaches do not permit prediction, they are well-suited for identifying trends and correlations in large datasets, especially with large numbers of variables. All multivariate analyses were performed in R version 3.5.1 using the Vegan (version 2.5–2) package.

3. Results

The graph in Fig. 2 shows the social parameters that have an impact on urban land cover. As the cover of each CT always adds up to 100%, the three land cover classes are shown equidistant from the origin of the graph. This particularity arises because an increase in one type of cover automatically causes a decrease in one or both of the other covers.

Parameters associated with social vulnerability including proportion of renters (% renter), population density (Pop. dens), proportion of people under the low income threshold (% low income), proportion of people using active transport (% active transport), proportion of recent movers (% movers 1 yr), and proportion of elderly people living alone (% alone 65 +), seem to form a cluster in the lower left portion of the graph. All these parameters vary in the same direction and in the direction of the “built” cover class. They are opposed to the “grass” cover class, and to a lesser extent from the “tree” cover class. The second group of parameters are those associated with economic wealth, including the median income and the average value of dwellings. Interestingly, the proportion of people 65 and older varies in a similar manner. This cluster seems to point away from the “built”, and towards the “grass” cover class. They are to a lesser extent correlated with the tree cover.

Parameters related to cultural diversity, namely the proportion of immigrants and language diversity, along with the proportion of non-suitable dwellings, seem to be negatively correlated with tree cover. These variables are positively correlated with “grass” and “built” cover classes (Table 1).

3.1. RDA for individual cities

RDAs were calculated for each of the four cities to see if the relationships varied from one city to another. The results of these analyses are shown in Table 2 and in Fig. 3. As the primary focus of the study was to explain patterns in the distribution of the urban forest, Table 2 shows only the correlation associated with the “tree” cover class.

Table 2 and Fig. 3 show that although some differences exist among cities, the overall trends (negative and positive) are very similar across the four urban areas. For example, the correlation between tree cover and median income is strong and positive in every urban area except Gatineau-Ottawa, where the link is weak and inversely correlated.

The rarefied species abundances used to calculate diversity ensures that the Shannon index is independent of the number of trees in a given CT. As diversity is a measure related to tree community and not to their number or canopy cover, it was not integrated into Figs. 2 and 3 RDAs. It was rather treated in a separate PCA to find possible correlations with social variables. This PCA is shown in Fig. 4.

The PCA biplot shows species diversity to be closely related to functional diversity along the PC2 axis. Opposed to diversity variables are variables associated with social vulnerability such as the proportion of renters (% rent), people with low income (% low income) and elderly people living along (% alone 65 +), among others. This series of social variables is similar to that observed in the RDA analysis (Fig. 2), which showed a positive relationship between social-vulnerability variables and the “built” cover class. The proportion of indigenous species is also positively correlated with social vulnerability, and inversely with forest diversity metrics. Axis PC1 regroups variables associated with wealth and education on one side, and cultural diversity on the other. The scores of each variable on the first 3 PC axes are shown in table 3.

4. Discussion

The aim of this study was to investigate the relationships between the urban forest and socio-economic parameters for four major urban areas of eastern Canada. We hypothesized that urban green infrastructure, and more specifically tree cover, would be positively correlated with wealth. Our findings agree with existing literature where RDA results show that a cluster of variables associated with wealth is positively correlated with an increase in tree and grass surfaces. There are a number of possible explanations for this pattern. Aesthetic appeal of trees has already been demonstrated in studies (Gómez-Baggethun et al., 2013; Kaplan, 1983) and the choice of a living environment is also influenced by the visual presence of trees and forested areas (Tyrväinen & Miettinen, 2000). As a result, trees have a positive impact on property values (Alexander & DePratto, 2014; Tyrväinen & Miettinen, 2000; Wolf, 2007). Wealthier people are able to afford more expensive houses in more aesthetically pleasing neighborhoods, it is understandable to find a positive relationship between income and tree cover. This economic impact of trees is well-known and has also been observed in other cities (Schwarz et al., 2015), further supporting the validity of the RDA model in our study. It is also important to underline that the effect of vegetation on property prices create the “green gentrification” phenomenon which further increases the displacement of vulnerable populations to areas with low UTC (Wolch, Byrne, & Newell, 2014; Anguelovski, Connolly, Masip, & Pearsall, 2018; Gould & Lewis, 2012).

Although not directly measured in this study, the size of a residential property could have had an impact on the prevalence of grass and tree cover; the bigger the backyard, the more green infrastructure it can support. Because of the inverse relationship between population density and median income, we see that the higher the income, the larger the backyard. Another possible hypothesis would be the number of parks situated in more affluent neighborhoods. While park surface *per se* was not considered in this study, amount of low vegetation and trees could be driven higher by the presence of parks. Other studies

Table 1
Parameters used in the multivariate models integrated at the census tract scale.

	Population density (nb/ha)
Populations social-economical parameters	Median family income ($)
	Average value of dwellings ($)
	Proportion of homeowners (%)
	Proportion of people in low-income situation (%)
	Proportion of single-parent families (%)
	Proportion of people spending ≥ 30% of income on housing (%)
	Proportion of people having moved in the last year (%)
	Proportion (15 y.o. and over) without a high-school diploma (%)
	Proportion (15 y.o. and over) with university diploma (%)
	Average number of school years (number)
	Proportion of people of 65 years and over (%)
	Proportion of people of 65 years and over living alone (%)
	Proportion of 'non-suitable' households (%)
	Language diversity index (number)
	Proportion of first-generation immigrants (%)
	Proportion of people commuting by active transport (%)
Forest diversity indexes	Species diversity index (number)
	Functional diversity index (number)
	Proportion of indigenous species (%)

Table 2
RDA's Correlation coefficients between each social parameter and the density of tree cover in CTs in the four studied cities. Coefficients ≥ |0,3| are in bold font to simplify reading and interpretation.

	Urban area			
Parameter	Toronto	Gatineau-Ottawa	Montréal	Québec
n (Number of Cts)	953	168	642	113
Population density	−0,29	**−0,51**	**−0,41**	**−0,41**
Education index (IEDU)	0,28	−0,26	−0,03	0,15
% univ. diploma	0,21	**−0,31**	−0,08	0,09
% no diploma	**−0,35**	0,08	−0,11	−0,28
% renter	−0,14	**−0,31**	**−0,57**	**−0,64**
% not suitable house	**−0,3**	−0,02	−0,21	−0,26
Avg. Property value	**0,36**	−0,25	0,07	0,23
Median family income	**0,47**	−0,05	**0,43**	**0,52**
% 30% $ for rent	−0,10	0,02	−0,14	−0,05
% imigrants	**−0,40**	0,02	−0,13	−0,26
% 1 yr movers	−0,17	−0,16	**−0,49**	**−0,45**
% low income	−0,26	−0,12	**−0,53**	**−0,59**
% lone-parent family	−0,18	0,13	−0,17	−0,17
Language diversity	**−0,34**	0,02	−0,04	**−0,38**
% 65y +	0,13	0,11	**0,35**	0,09
% lone 65y +	0,07	−0,11	−0,04	**−0,34**
% active transport	−0.15	**−0.5**	**−0.44**	**−0.54**

aimed precisely at evaluating the hedonic value of parks on property prices have shown that a positive relationship indeed exists, and that it is especially important with increasing park size (Crompton, 2005; Troy & Grove, 2008).

Reciprocally, variables encompassing social vulnerability are positively related to the "built" cover class, as shown in the RDA graph in Fig. 2. These variables are the proportion of people in a CT who are: renting their dwelling, under the "low-revenue" threshold (as defined by the Canadian census agency), elderly and living alone, using active transportation, moving at a high rate and living in a high population density. As explained in the introduction, many studies have shown similar results with similar or comparable variables (Pham et al., 2012; Dobbs et al., 2011; Heynen, Perkins, & Roy, 2006; Joassart-marcelli, 2010; Landry & Chakraborty, 2009; Schwarz et al., 2015). With this study, our results show that green inequalities are present in those eastern Canadian cities, adding to the growing body of literature on this subject.

4.1. Urban forest and socio-economic resilience

The most interesting finding of this study is the way urban forest diversity is related to socio-economic vulnerability. The PCA graph in Fig. 4 shows the 'socio-economic vulnerability' group of variables to be inversely correlated with both species diversity and functional diversity. There is consensus in the scientific literature on the existence of environmental inequality and some of the mechanisms involved; the density of natural amenities is unequally distributed along a social gradient. However, the diversity metrics used here are independent of forest cover density or the number of trees. The inequality shown here takes a supplementary form: the one of resilience of the urban tree cover.

Functional diversity is a key component of ecosystem resilience (Paquette, 2016; Thompson, Mackey, McNulty, & Mosseler, 2009). The way it varies along with socio-economic vulnerability and urban forest cover shows that sectors with high socio-economic vulnerability, while having a lower UTC, also tend to display lower urban forest resilience. As explained in the introduction, the lack of urban forest cover can be detrimental to city-dwellers in terms of ecosystem service production and general well-being. In addition to this already low UTC is the low functional diversity of the forest cover which makes this green infrastructure potentially less resilient to exotic pests, diseases and disturbances caused by climate change such as drought, high wind, etc. This means that a sudden environmental change could disproportionately affect the tree cover of areas where socially vulnerable people live.

Few scientific papers have investigated direct relationships between biodiversity and humans in urban contexts. Most papers investigate the relation between diversity and the provision of ES (Manes et al., 2012; Escobedo & Nowak, 2009; Quijas et al., 2010). Although in some studies, diverse natural communities have been associated with increased levels of human well-being in urban and peri-urban environments (Carrus et al., 2015; Dallimer et al., 2012). The Carrus et al. (2015) study showed that the perceived well-being was more than 20% higher in urban areas with high versus low vegetal diversity. These two studies used self-report data of levels of psychological well-being from people living in places with varying levels of species diversity and tree density. To our knowledge, no prior study has dealt directly with the relations between urban tree diversity and populations socio-economic parameters at a scale larger than the individual.

One possible explanation for this phenomenon could be that green infrastructure planners for richer neighborhoods have more money to buy "non-traditional" trees from the nursery. Nurseries produce more of

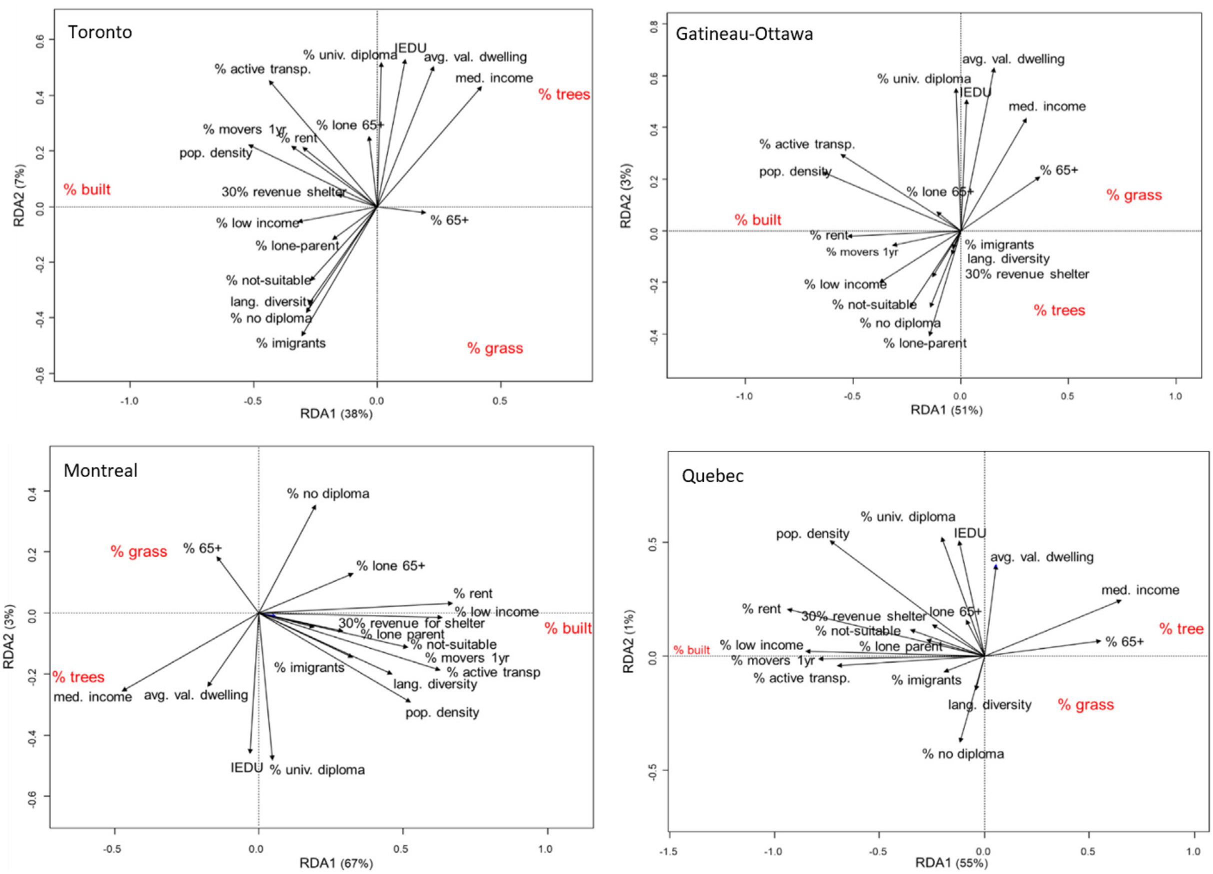

Fig. 3. RDA graphs showing how trees, grass and built cover classes relate to socio-economic variables (arrows) in each individual urban agglomeration.

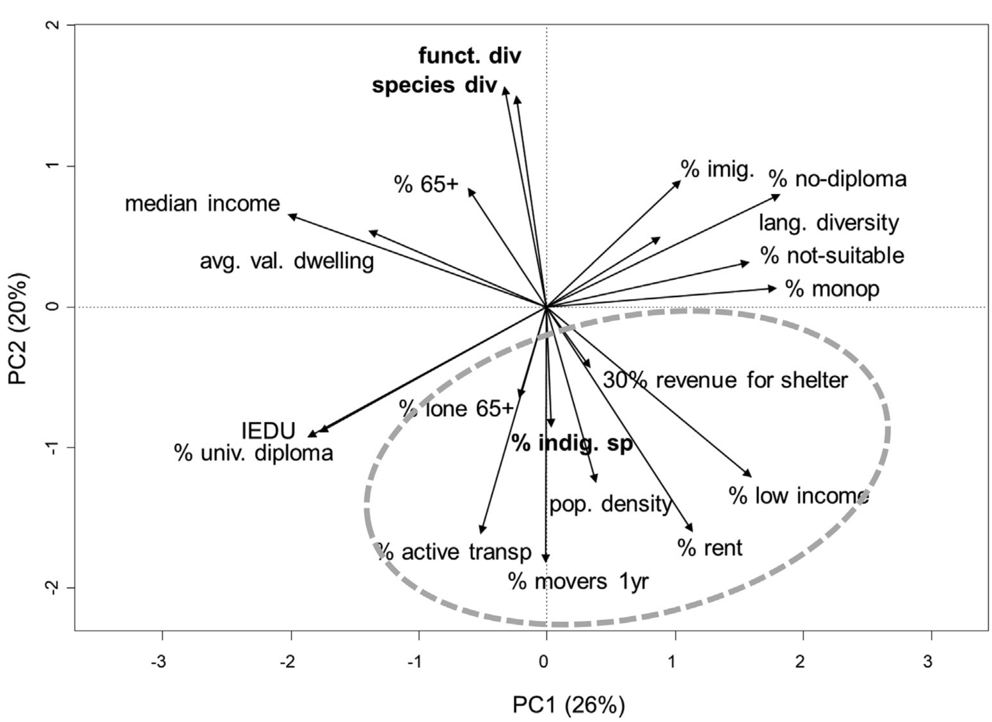

Fig. 4. PCA plot of socio-economic parameters and forest diversity indicators. The graph shows correlations between urban forest species and functional diversity along with social variables. Forest diversity variables are shown in bold text. Ellipse shows variables associated with social vulnerability. Axes PC1 and PC2 are shown on the graph, explaining 26% and 20%, respectively, of the total variance. The first five axes of this PCA explain 75% of the dataset's variance, with 15,3% for PC3, 7,7% for PC4 and 5,6% for PC5.

the "traditional" urban trees to satisfy demand for low-cost, fast-growing, and easy to maintain species. The "non-traditional" tree species, often more visually appealing, and perhaps more resource demanding, might have been bought by neighborhoods who could maintain them at greater cost, leaving a smaller number of the "traditional", easy maintenance tree species for poorer neighborhoods. This explanation could be debated as, historically, streets have been planted symmetrically with identical tree species as this has been deemed more aesthetically pleasing and therefore preferred by wealthy citizens.

Table 3
PCA scores for the Fig. 4 graph showing the 20 variables used to characterize each of the 1161 CTs along the 3 first axes. These 3 axes represent 61,8% of the dataset's variance with 26,0%, 20,5% and 15,3%, respectively. Higher scores (absolute value) represent higher correlation to an axis.

Variable	PC1	PC2	PC3
pop. density	0.450	−1.47	1.07
% active transp	−0.613	−1.91	0.551
IEDU	−2.20	−1.09	1.05
% university	−2.09	−1.05	1.24
% no diploma	2.14	0.946	−0.756
% renters	1.34	−1.88	0.546
% not-suitable	1.86	0.379	1.46
avg. val. dwelling	−1.64	0.640	1.01
median income	−2.38	0.773	0.205
30% rev. shelter	0.405	−0.512	1.32
% immigrants	1.23	1.06	1.82
% mover 1 yr	−0.0065	−2.137	0.73
% low income	1.87	−1.43	0.557
% single parent	2.11	0.159	−0.199
lang. diversity	1.04	0.584	1.91
% 65+	−0.730	0.996	−0.904
% lone 65+	−0.252	−0.759	−1.03
% native sp.	0.043	−1.01	−1.52
funct. diversity	−0.284	1.77	0.995
species diversity	−0.390	1.85	0.808

Another possible explanation for our result is that a greater number of trees growing in poorer neighborhoods were actually not planted but instead established naturally from a limited set of tree species that naturally regenerated. This is supported by our results shown in Fig. 4 where proportionally more indigenous tree species were found in poorer neighborhoods. As 294 species are present in the study area and only 97 are indigenous, it makes sense that the greater the number of indigenous tree species in some neighborhoods, the lower the overall species and functional diversity. Future research is needed to test this hypothesis, however. Investigating whether people of different socio-economic status (richer versus poorer, higher versus lower education levels, for example) express a preference for diverse tree communities could also yield interesting results.

5. Conclusions

With global change bringing uncertainty in the occurrence patterns of environmental and socio-economic disturbances, it is of prime importance to consider the ways our cities could cope and adapt to catastrophic events. The science of social-ecological systems still lacks a good understanding of the linkage between its social and environmental halves. This study adds to the growing body of scientific evidence that green infrastructure does not follow a uniform distribution across urban landscapes, but is in fact driven to some degree by social and economic factors of the population. This study clearly indicates that people already the most in need of the benefits of urban forest are also more at risk of losing it following any disturbance due to both lower species and functional diversity of the forest cover. Ecological resilience and socio-economic resilience are two different terms emerging from disciplines historically separated by a deep divide; it seems however that interdisciplinary research bridging environmental and social sciences is an important step in acquiring new insights into problems traditionally tackled by one or the other. Exploring the ways socio-economic factors and urban forest resilience are linked in city landscapes offers a new and fascinating means for understanding urban socio-ecological system dynamics.

CRediT authorship contribution statement

Félix Landry: Conceptualization, Software, Formal analysis, Writing - original draft. **Jérôme Dupras:** Conceptualization, Supervision, Writing - review & editing. **Christian Messier:** Conceptualization, Supervision, Writing - review & editing.

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