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Abstract

Street trees provide a wide range of benefits for cities. Street tree cover (STC) is explained by urban form, social stratification and lifestyle theories that operate at multiple scales. In this paper we examine how the urban form (street characteristics), social stratification and lifestyle (socio-demographics) account for variations of STC in Montréal. Tree cover was identified from Quickbird images and then overlaid on street segments to compute the STC. Each street segment was nested in a census tract. We used 2-level models with mixed effects and interactions (between street attributes and socio-demographic variables) while introducing a spatial term. Political, socio-economic or other explanatory factors operating at the tract level can potentially explain 17.6% of the variation of STC. Overall, the street characteristics explained more variation in STC than the socio-demographic context. Lifestyle is less important than social stratification. Street length is positively associated with STC; street width and the percentage of duplexes and triplexes are negatively associated with STC, while construction age has a u-shaped effect on STC. Interactions show that STC is higher in expensive and highly-educated areas that have residential streets or streets with large setback (sidewalk). Areas predominantly comprised of low-income households could have higher or lower STC depending on the number of buildings and the percentage of duplexes and triplexes. Streetscape and socio-demographic contexts intertwine to create complex patterns of STC. Greening programs should be designed carefully according to local contexts since certain types of greening can lead to gentrification and displacement of low-income households.

INTRODUCTION

Trees in cities provide a wide range of benefits for urban dwellers. Trees and tree canopy provide ecosystem services such as urban heat mitigation, stormwater runoff reduction and filtering, and noise reduction (see Mullaney et al. (2015) and Roy et al. (2012)). The presence of trees or tree canopy in neighborhoods has been correlated with the following benefits for inhabitants: increased physical activity (Sarkar et al., 2015), improved mental health (Taylor et al., 2015), improved physical health (through stress reduction and increased social cohesion) (de Vries et al., 2013), and less crime (Donovan & Prestemon, 2012; Troy et al., 2012). Street trees are also highly associated with street walkability and livability (Sarkar et al., 2015).

At the same time, urban trees are sources of nuisances or disservices, as termed by some authors (Lyytimäki & Sipilä, 2009). For example, a review by Lyytimäki and Sipilä (2009) shows urban trees may cause damage to physical structures (tree roots, which break up pavements, or tall trees, which may cause maintenance problems), compromise security (green areas are sometimes perceived as unsafe by women) and give rise to health issues (allergies, poisoning). People's perceptions of what they consider to be services and disservices of urban green areas vary across ethno-cultural and demographic groups (Lyytimäki & Sipilä, 2009). Research on the disservices of urban trees that merits increased attention from scholars and public agencies in order to better maximize services and minimize disservices.

Despite such nuisances, studies across various urban contexts increasingly show that urban dwellers from different socio-economic groups highly value and recognize the benefits from trees (Mullaney et al., 2015; Peckham et al., 2013; Shackleton et al., 2015). In the context of rising concerns about urban heat islands and increased flooding due to climate change, investing in green infrastructure in general and trees in particular is politically and socially appealing for urban planners and administrators (Matthews et al., 2015). Cities all over the world are promoting trees in general and street trees specifically (Silvera Seamans, 2013) as a means to improve sustainability.

However, evidence from many cities is showing that urban vegetation in general and street trees in particular are not equally distributed according to socio-economic status. More specifically, across North American cities, low-income households and certain ethno-cultural groups of the population tend to have limited access to trees as well as to benefits provided by trees (e.g. Landry & Chakraborty, 2009; Pham et al., 2012; Schwarz et al., 2015; Tooke et al., 2010). Furthermore, urban greening can result in paradoxical effects, such as increased housing values, gentrification and displacement of low-income people (Wolch et al., 2014). Greening can also lead to negative and unexpected reactions from the public, as the public may not understand benefits provided by street trees. For example in New York City citizen complaints about the 'New Street Tree' program were mostly found in areas that had new plantings (Rae et al., 2010).

The uneven distribution of urban trees and the complexity of ensuring environmental equity raise questions about the physical, ecological and socio-economic correlates as well as the underlying mechanisms associated with urban tree distributions. The distribution of street trees can be city-specific since public policies concerning this issue are determined on the basis of site-specific factors such as climate, geographic conditions, history and preferences (Kirkpatrick et al., 2011). While there is a growing body of literature addressing urban tree cover at the household or parcel scale of analysis, many of these studies focus on residential tree cover rather than on street trees or street tree cover (e.g. Chowdhury et al., 2011; Larson et al., 2010; Shakeel & Conway, 2014). In this article, we focus on street trees. We use street tree cover, hereinafter referred to as “STC”, as an indicator of the presence of street trees.

Studies addressing correlates of street trees focus mostly on socio-economic factors that have been reported at larger geographic scales, such as suburbs in Australia, census block groups in the United States or dissemination areas in Canada (Kirkpatrick et al., 2011; Landry & Chakraborty, 2009; Pham et al., 2013), with only one study (from Bangalore, India) looking at street characteristics (Nagendra & Gopal, 2010). The three Western studies were conducted in very different cities in terms of climate conditions and population density and with different sets of correlates. Kirkpatrick et al. (2011) used two income variables in suburbs of six Australian cities. Landry et al. (2009), examining street trees from an equity angle, used socio-demographic variables and one variable related to the built environment (median housing age) in Tampa, Florida (United States). Pham et al. (2013) looked at socio-demographic variables and two proxies of the built environment (population density and construction age of parcels) in Montréal, Canada. The study conducted in India by Nagendra and Gopal (2010) examined the distribution and diversity of street trees in relation to street width. To our knowledge there is no study that has examined the role of the physical characteristics of streets in shaping STC in an exhaustive way.

More importantly, a large geographic unit (e.g., a block group) typically contains multiple street segments, whereby the coarser resolution of the analysis may mask the heterogeneity of physical characteristics of streets that could be associated with the distribution of STC, e.g., age of housing construction, building density, housing types, presence of a sidewalk and land use. The dispersed scholarship on street trees shows important differences among the studied cities, sometimes presenting contradictory evidence and with few studies presenting an analysis at fine spatial resolutions. For example, Nagendra and Gopal (2010) in their study on Bangalore found that narrow roads had fewer trees and smaller sized trees while wide streets had large trees. The fact that narrow streets, more likely to be residential, have fewer trees or lower tree cover suggests that big trees are not found in areas where the population's need for ecosystem services is highest. Yet Kirkpatrick et al. (2011) witnessed that there was no difference between wide and narrow streets in Hobart (Australia). This wide range of findings makes it difficult to theorize about mechanisms underlying STC and to make generalizations about environmental inequities in tree benefits that could inform urban planning priorities.

Drawing on urban form, social stratification and lifestyle theories that explain urban vegetation (Bigsby et al., 2013; Lowry et al., 2012; Sanders, 1984) our paper investigates correlates of STC at the fine scale of the street level while also considering the socio-economic context of the neighborhood in the case of Montréal (Canada). We use a multi-level and mixed modeling approach to capture the effects of these theories simultaneously at the street and neighborhood scales. We ask the following research questions: 1) To what extent do street-level physical attributes and socio-demographic factors of context account for variation in STC? 2) Which set of correlates is more important? 3) How do street attributes interact with socio-economic context when shaping STC? By exploring these questions, we hope to enrich the discourse about urban tree cover and raise awareness of the topic of street trees in general.

THE CASE OF MONTRÉAL

This study is conducted on the territory of the City of Montréal before the municipal reform in 2002. The city was composed of nine boroughs, a political jurisdiction of Montréal, covering 149 km^2 (Fig 1). In 2006, that area had a population of more than one million people and a population density ranging from 12,000 inhabitants/km^2 in the central boroughs to 5,000 people/km^2 on the outskirts. Of the residential dwellings, 64% were apartments in buildings with fewer than five stories; 14% were apartments in duplexes (two dwellings located one above the other in the building); 10% were single- and semi-detached houses; and 8% were apartments in high-rise buildings (Statistics Canada, 2006). The percentage of streets covered by trees is mapped in Figure 2.

Figure 1. Location and population density of the former City of Montréal, by dissemination area (Statistics Canada, 2006)

Figure 2. Percentage of streets covered by trees, in the former City of Montréal (aggregated by dissemination area)

Due to an invasion of the Emerald Ash Borer (*Agrilus planipennis*) starting in 2011, the City began cutting down 10,000 ash trees on its streets, being the equivalent of 20% of the ash tree population. To compensate for this loss and to address other goals such as mitigating the urban heat island effect, the City is now aiming to increase its citywide tree canopy coverage from 20% to 25% by 2021. For this it plans to plant 300,000 trees, of which 75,000 are street trees and other public trees, together costing over $68 million Canadian dollars (City of Montréal, 2011). Here, a greater knowledge and understanding of the physical and socio-economic factors that influence STC at the scale of the street level could serve Montréal and other cities to efficiently maintain and expand an equitable and sustainable STC (City of Montréal, 2011) and to identify the areas that are deprived in terms of street trees.

THEORIZING AND MODELLING STREET TREE COVER

As proposed by Sanders (1984) and then developed by other authors (e.g. Berland et al., 2015; Bigsby et al., 2013; Lowry et al., 2012; Troy et al., 2007), the distribution of the urban forest is generally affected by three groups of factors: natural factors (e.g., climate, underlying biome, soils, elevation, slope), the urban form (e.g., population density and urban morphology) and drivers of vegetation management systems (e.g., residential landscaping decisions or public management related to social stratification, lifestyle/ecology of prestige, luxury effects). Some authors have recently shown that in specific geographical conditions natural factors are dominant in shaping urban tree cover. For example, in Cincinnati (characterized by a high variability of elevation) Berland et al. (2015) found hilly areas have more trees and these areas are inhabited by either white wealth people or black people. This is explained by historical segregation of the city. In Salt Lake County, a semi- and arid environment, Lowry et al. (2012) found that annual precipitation and aspects (westness) have significant associations with residential tree canopy. As Montreal does not have very specific natural conditions, we did not consider natural factors in our study. Our theoretical framework is hence designed to consider three theories that explain the distribution of STC: urban form, social stratification and lifestyle.

Urban form

This theory builds on and nuances the population density theory which has been put forth to explain the driver of urban vegetation (Troy et al., 2007). The population density theory posits that because people displace native ecosystems, areas with higher population density have less physical space available for urban vegetation. However, empirical research has shown that the relationship between tree cover and population density varies in direction and magnitude from one city to another. For example, the relationship was found to be negative in Baltimore (Troy et al., 2007) and Denver (Mennis, 2006); positive in multiple Australian cities (Luck et al., 2009); and not significant in Toronto (Conway & Hackworth, 2007). In Montréal, Pham et al. (2013) found a negative relationship between residential tree cover and population density, but a positive relationship between STC and population density. In their work in Raleigh and Baltimore, Bigsby et al. (2013) suggest that population density was generally less important than measures of the urban form such as pervious areas and parcel size. Overall, the research therefore suggests that the population density theory alone is insufficient as an explanation of urban vegetation.

The urban form theory also states that tree cover depends largely on the space available for planting. Space available for planting is determined by a set of factors such as parcel size, land use patterns, age of neighborhoods, block perimeter and street density (Bigsby et al., 2013; Conway & Urbani, 2007; Mennis, 2006). Lowry et al. (2012) further characterize urban sprawl using five factors: street connectivity, land use mix, median lot size, residential street density and median block perimeter.

Tree survival studies have shown that urban trees are more likely to survive in wider rather than narrow tree pits (Koeser et al., 2013; Lu et al., 2010; Nowak et al., 1990). Tree pit size depends mostly on the size of sidewalk and building setback (i.e., distance from road to building). Parcel or neighborhood development age is widely discussed in studies of urban vegetation (Conway & Urbani, 2007; Landry & Pu, 2010; Mennis, 2006). The relationship between the age of the development and the vegetation has been found to be u-shape, in other words, tree cover was found to peak in neighborhoods of a certain age and then decline (Grove et al., 2006; Landry & Pu, 2010). This relationship reflects the natural lifecycle of trees (as the neighborhood gets older, trees grow to their full canopy and then die) and the changes in planning practices over time.

Such numerous variables characterizing the urban form need to be considered in appropriate scales. In a dense city such as Montréal, having a complex urban form due to its diverse housing patterns, we believe that the street level is a more appropriate scale than census block group or dissemination area level to examine STC.

Social stratification

The social stratification theory can explain how residents with differential socio-economic statuses can influence tree planting and management on public and private lands, or choose to locate in areas with more green amenities. Two variations of this theory can be used to explain the distribution of trees on public lands, including street trees. The “mobility” explanation suggests that people with greater economic means will move to locations with more amenities such as trees (Troy et al., 2007). The mobility explanation will not be considered in this study because it requires long-term data of residential patterns and real estate markets. The second explanation, proposed by Logan and Molotch (1987), is that people with differential access to power and income can influence public investment in amenities such as trees (Grove et al., 2006).

According to this theory, tree cover is influenced by socio-economic factors at two geographic levels, one being the individual/household level and the other the neighborhood level. At the former level, tree cover is influenced by landscape decisions of home owners, and at the latter through support for public or private management. In this paper, which focuses on public trees, we examine the socio-economic factors at play at the neighborhood level, such as how citizens take part in decision-making to channel municipal investment toward planting and greening activities or how they promote private investments from developers, grassroots organizations or NGOs to this effect (Conway et al., 2011). The following variables are usually used to represent social stratification at the neighborhood level: income (i.e., the percentage of low-income households); education; housing tenure; marginalized racial groups such as Afro-Americans and Hispanics in the United States; or visible minorities and immigrants in Canada (Grove et al., 2014; Pham et al., 2013; Troy et al., 2007). The information is obtained either from census data or by applying marketing data systems such as PRIZM (in the United States).

Lifestyle

This explanation hypothesizes that locational choices and environmental management decisions at the neighborhood level are motivated by group identity and social status associated with lifestyle (Grove et al., 2014). Lifestyle can be correlated with family size, marital status and life stage. For example, Troy et al. (2007) found that Baltimore neighborhoods predominantly inhabited by families with children have more vegetation in their yards than neighborhoods inhabited by singles or couples with no children. Applying this theory to street trees, we argue that advocating for street trees and/or choosing to live in neighborhoods with higher STC has social meaning, namely in that it contributes to the neighborhood identity and quality, but that it does not, in and of itself, qualify as a luxury item.

Similarly to the social stratification variables, lifestyle is usually examined at the neighborhood level. Previous authors also used PRIZM data in the United States (Bigsby et al., 2013; Grove et al., 2014) other census data, such as marital status or the number of families with children (Grove et al., 2014; Troy et al., 2007). Although tree cover could be influenced by individual decision making, social stratification and lifestyle in the mentioned studied are examined at an aggregated level, i.e. in census units. In such studies, individual and neighborhood mechanisms are not distinct one from another.

In the body of literature on urban vegetation cover, a very frequently asked question is which theory best explains the variation in urban vegetation cover (Bigsby et al., 2013; Lowry et al., 2012). Most authors found that the urban form theory is more important than socio-economic factors in influencing residential tree cover. This paper aims to quantify how the urban form, social stratification and lifestyle theories impact STC at their respective scales. We then further examine how the urban form interacts with socio-economic and lifestyle factors (called as socio-demographic factors hereafter).

Multi-level and mixed models with a spatial dependency

We use a multi-level modeling framework to identify associations at different spatial scales. A street segment is examined at the first level of analysis, based on its own tree cover and physical characteristics related to the urban form. A street segment is defined here as a portion of pavement, without the sidewalk, between two cross streets (Figure 3). The street is nested in a neighborhood with a socio-demographic profile featuring social stratification and lifestyle characteristics. The neighborhood in this paper is represented by census tracts, a common proxy used in Canadian studies that consider urban vegetation at the neighborhood level (Conway & Hackworth, 2007; Tooke et al., 2010). Census tracts are small and relatively stable areas that usually have a population between 2,500 and 8,000 persons (Statistics Canada, 2006).

Figure 3. Example of street segment (in black) and setback (arrow) on a map (Source: Open Street Map)

Multi-level and mixed models address several sources of uncertainty that are important in the analysis of geographically-nested data. Fixed-effects models account for baseline differences in the dependent variable across units to identify global associations between independent and dependent variables. Random-effects models allow associations to differ among neighbourhoods and streets. In our analysis, this would have two effects. First, physical urban form and socio-demographic factors relate differently to STC across different census tracts by setting a random intercept. Second, socio-demographic factors relate differently to STC across streets by setting socio-demographic factors with random effect.

Another particularity of our models is the introduction of a spatial term. As shown in previous studies (Landry & Chakraborty, 2009; Pham et al., 2013), urban tree cover is usually autocorrelated spatially. In our data, we also detected such spatial autocorrelation on residuals of models (see the Results section for details). We hence decided to compute a spatial term of STC and included it in our models.

DATA DESCRIPTION, VARIABLE COMPUTATION, MODEL SPECIFICATION

Dependent variable – street tree cover

Our dependent variable is the percentage of a street segment that is covered by trees (Table 1), which we refer to as street tree cover, or STC. In Montréal, most trees in front of houses that have canopy on the street surface are publicly managed by the City or borough administration (including planting, maintenance and removal). We point out, however, that a good tree cover may or may not be the result of a dense planting of trees depending on tree foliage.

Tree cover was identified from very high resolution Quickbird images (60cm, acquired in September 2007). A classification was applied to the images in eCognition 8.1 in order to identify two classes of vegetation: lawn and a combination of trees and shrubs/small trees (Pham et al., 2011). For this paper, we used the trees/shrub class, hereinafter referred to as "trees". Street segments were created from a street polygon of the entire study area provided by the City of Montréal. We then overlaid this map with the tree cover map to obtain the percentage of street surface that is covered by trees.

Table 1. Dependent, independent variables and their summary statistics

	Variable	**Name (unit)**	**Mean**	**Standard deviation**
	Dependent variable			
	PctTree	Percentage of street covered by trees (%)	7.25	10.68
Theories	Level 1 – street characteristics (n=10 800)			
Urban form	Street_Width	Width of the street segment (m)	15.97	7.34
	Street_Length	Length of the street segment (m)	136.05	87.78
	AgeMed	Median year of construction of buildings	1953	28.25
	PctResi	Residential buildings (%)	83.57	27.96
	PctDuTri	Duplex and triplex buildings (%)	41.81	39.26
	N_Build	Number of buildings	13.98	14.37
	Setback	Building Setback (m)	7.20	4.30
	Level 2 – neighbordhood's socio-economics (n=308)			
Social strat.	Val_Dwell	Housing value (thousand dollars)	267.53	79.92
	Uni_Dip	Percentage of university degree holders	16.86	9.61
	Low_inc	Percentage of low-income households	30.26	11.52
	Rec_immi	Percentage of recent immigrants	10.02	7.34
Lifestyle	With_Child	Percentage of households with children	34.86	12.54
	PctFrench	Percentage of French speakers	66.86	24.13

Level 1 independent variables – street characteristics

We chose urban form variables that were identified in the literature as important correlates of urban vegetation and tree cover. These are: width of the street segment, i.e., *street width*; length of the street segment, i.e., *street length*; median age of buildings on the street segment, *construction age*; *percentage of residential buildings*; *percentage of duplexes and triplexes*; *number of buildings*; and building setback, i.e., *setback* (Table 1). It is important to note that *street width* is likely correlated with the type of street, such as arterial, collector or local. Nevertheless, *street width* was designated as a quantitative physical measurement rather than as one referring to a category of use.

Street segments were created from the street map provided by the City of Montréal. To estimate the width and length of street segments, we used the “bounding containers” tool in ArcGIS to measure the two axes of the rectangle that fits the street segment the best. In order to compute the other variables, we joined the street segment map with the parcel and building maps (provided by the City of Montréal). Each parcel and building was associated to one and only one street segment. We then computed the median value of building age per street segment, the average value of the proportion of residential use, commercial use and industrial use; as well as the proportion of duplex, triplex houses by street segment. For each street segment, an average value of building setback was computed. The building setback was defined as the distance between a building and the street, which corresponds roughly to sidewalk width in high density urban areas (Figure 4). These variables do not suffer from multicollinearity problems. Their variance inflation factor (VIF) (Chatterjee & Hadi, 2006) are lower than 2.

Figure 4. Illustration of setback of a street in downtown Montréal. Photo credit: first author

Level 2 independent variables − neighborhood context

To capture effects of neighborhood context on STC, we used the census tracts produced by Statistics Canada (Table 1). We selected a set of variables that proved important in previous tree studies (Bigsby et al., 2013; Grove et al., 2014; Landry & Chakraborty, 2009; Pham et al., 2013; Troy et al., 2007). Exclusion of variables that suffered from multicollinearity was conducted based on the VIF values.

Level 2 independent variables related to the social stratification theory are: *dwelling value*; *percentage of university degrees*; *percentage of recent immigrants* (migrating from 1996 and 2006); and *percentage of low-income households*. The percentage of renters was not retained because it is highly correlated with the percentage of low-income households (Pearson r=0.8, VIF=5.03). At Statistics Canada, “low-income households” is a census variable defined as “income levels [before tax] at which families or persons not in economic families spend 20% more than average of their before tax income on food, shelter and clothing” (Statistics Canada 2006: 143). It is worth noting that although recent immigrants are lumped into one variable, we are aware ethnocultural groups may differ greatly in their preferences for vegetation, and some may prefer less or no vegetation (Fraser & Kenney, 2000). Combining all the groups into one category may mask those variations in preferences. However, the low percentage of each group in the total immigrants would prevent a statistically robust analysis.

Level 2 variables related to the lifestyle theory included two variables that are relevant to the case of Montréal. First, to characterize the family status, we chose the *percentage of families with children* instead of the percentage of married couples, as is done in other studies (e.g. Troy et al., 2007). This is because in the province of Quebec, where Montréal is located, only 38% of couples are in common-law relationships but almost 63% of children are born in a common-law relationships (Bourdais et al., 2014). The second variable is the *percentage of French speakers* as a proxy of cultural and linguistic identities. In Montréal these identities differ among French, English and non-official language speakers. For example, the English-speaking population finds it important to preserve their local community and to express their social and cultural specificity (Boudreau, 2003; Boudreau et al., 2006) through community-building activities, such as high participation in local planning. Differences in identities of these groups can influence locational choices of residence as well as public policies and ordinances related to the environment (Boudreau et al., 2006) and tree protection/planting at the local level (borough, in the case of the City of Montréal). As explained above, we could not introduce each ethnocultural group of the 'non-official language speakers' in the model. Our models might miss nuances of preferences toward urban trees among these groups.

In terms of sample size, researchers have recommended a minimum of five level 1 observations per level 2 group (Maas & Hox, 2005). We removed census tracts that have fewer than five street segments (n=4, or 1.28%). In total, our study area contains 10,800 street segments that are nested in 308 census tracts.

Regarding spatial dependency, we determined the radius of the spatial lag term for the models by comparing values of the Moran's I statistic calculated over the range of 100 to 500 meters. We identified that spatial autocorrelation was maximized at the distance of 200 meters, and therefore computed the spatial lag of STC at this radius.

Model specifications

We implemented multi-level and mixed models within the R version 3.1.2 environment using the lmerTest package (R Foundation for Statistical Computing, 2015). Models were fitted using restricted maximum likelihood estimation to provide unbiased estimates of variance and covariance parameters (Hox, 1998).

We explored several cases of the model by integrating increasing complexity to investigate the role of different model components. In all models we let intercepts vary randomly at the census tract level to account for interdependence among observations. The first of these, Model 1, contained tract-level intercepts only, allowing us to assess variations in STC across census tracts. We expanded this approach to include estimations of coefficients for physical properties of street segments in Model 2, of coefficients for tract-level social stratification variables in Model 3a, and of social stratification and lifestyle in Model 3b. Model 4a considered covariates at the level of the street segment as well as social stratification covariates at the tract level. Model 4b considered all covariates at the street and tract levels. Finally, in Model 5 we introduced all variables of Model 4b and also interactions of four street variables (*PctResi*, *percentage of residential buildings*; *PctDuTri*, *percentage of duplexes and triplexes*; *N_Build*, *number of buildings*; and *Setback*, *building setback*) with all the census variables in order to see how these change their effect across different characteristics of streets. All four street variables were considered to be random. *Street width*, *street length* and *construction age* were not included in interactions as we consider them to be control factors.

We compared model fits using the Akaike information criterion (AIC) and the Bayesian information criterion (BIC). For Model 1 we also computed the intra-class correlation (ICC), which represents the proportion of between-tract variance in the total variance, as follows:

$$ICC = \sigma_u^2/(\sigma_u^2 + \sigma_e^2) \qquad [1]$$

where the variance parameters σ_μ^2 and σ_e^2 represent the within-tract and between-tract variances, respectively.

ICC indicates the proportion of the variance of the dependent variable explained by unaccounted for census tract-level heterogeneity.

RESULTS

Effects of the three theories on STC

Moran's I tests on residuals of the models with and without the spatial lag show that models without the spatial lag suffer from the spatial autocorrelation problems as Moran's I on their residuals varying from 0.12 to 0.17. Models that included the spatial lag variable produce residuals that are not spatially correlated with Moran's I varying from −0.02 to 0.05. This confirms the need to test spatial autocorrelation and introduce a spatial term in the models.

Fixed and random effects of the first four models are shown in Table 2. The spatial lag is significant in all models. AIC indicators indicated that Model 2 (including only street variables; 77,752.50) was better than Model 3a (79066.5) and Model 3b (including only tract variables; 79,062.10). Model 2 was even slightly better than Model 4a (77,760.20) and 4b (77,756.80). Comparing Model 3a and 3b, and Model 4a and 4b, lifestyle variables result in a slightly lower AIC, suggesting that these variables contribute to explaining the variation of STC, albeit to a small degree.

Table 2. Fixed and random effects of the four models without interactions

		Model 1		Model 2		Model 3a		Model 3b		Model 4a		Model 4b	
Theories	**Fixed effects**												
		β	**t-value**	**β**	**t-value**	**β**	**t-value**	**β**	**t-value**	**β**	**t-value**	**β**	**t-value**
Urban form	Intercept	7.38	26.46 ***	-6.21	-12.54 ***	0.73	1.64	-0.84	-0.62	-7.17	-10.37 ***	-8.10	-5.53 ***
	Street_Width			-0.11	-9.04 ***					-0.11	-9.28 ***	-0.12	-9.44 ***
	Street_Length			0.01	6.45 ***					0.01	6.38 ***	0.01	6.38 ***
	PctDuTri			0.00	-2.03*					0.00	-1.88	-0.01	-2.29*
	PctResi			0.04	12.52 ***					0.04	12.39 ***	0.04	12.47 ***
	AgeMed			0.06	8.02 ***					0.06	7.72 ***	0.05	7.52 ***
	AgeMed2			0.00	-4.62 ***					0.00	-4.64 ***	0.00	-4.46 ***
	N_Build			0.13	13.52 ***					0.13	13.46 ***	0.14	13.54 ***
	Setback			0.18	8.55 ***					0.18	8.19 ***	0.18	8.25 ***
	Spatial lag			0.69	44.28 ***	0.80	50.53 ***	0.79	49.38 ***	0.67	41.40 ***	0.67	41.54 ***
Social strat.	Val_Dwell					0.00	1.86	0.00	3.03 **	0.00	2.43 **	0.01	4.05 ***
	Uni_Dip					0.02	1.95	0.01	0.79	0.02	1.54	-0.01	-0.45
	Low_inc					-0.02	-2.06*	-0.03	-2.07*	-0.01	-1.03	-0.03	-1.82
	Rec_immi					0.03	1.75	0.07	3.05 **	0.03	1.61	0.08	3.74 **
Lifestyle	With_Child							0.00	-0.18			-0.02	-1.50
	PctFrench							0.02	2.28*			0.02	2.59 **
	AIC		80193.10		77752.50		79066.50		79062.10		77760.20		77756.80
	BIC		80200.50		77760.00		79092.60		79095.70		77767.60		77764.30
	Random effects												
	Intercept - Census tract		19.89		0.55		0.00		0.00		0.4573		0.31
	Residuals - Street		93.01		77.40		88.51		88.44		77.3206		77.31
	ICC		**0.18**										

*** p < 0.001; ** p < 0.01, *p<0.05

The introduction of street characteristics of the urban form reduced both the variance of STC at the tract level (between-tract variance reduced from 19.89 in Model 1 to 0.55 in Model 2) and the variance at street level (from 93.01 in Model 1 to 77.40 in Model 2). The introduction of social stratification and lifestyle variables substantially reduced variance at the tract level, from 19.88 to 0.00 in Model 3a and 3b, yet not at the street level. This is understandable because street-level variables can explain variation of STC at the tract level but not inversely. This suggests that street variables of the urban form are more efficient in explaining street-level variations of STC, but that social stratification and lifestyle variables are more efficient in explaining tract-level variations of STC. Overall, at both levels, street variables of the urban form are more important than social stratification and lifestyle variables in explaining STC.

Model 1: Variation explained by differences between neighborhoods

The ICC indicates that between-tract variance can explain up to 17.6% of the total variance. This suggests that political, socio-economic or other explanatory factors operating at the tract level and relating to STC can potentially explain 17.6% of the variation of tree cover.

Model 2: Variation explained by street characteristics

Accounting for street-level urban form covariates (Table 2), all variables are significant at $p<0.01$. The most significant variable is *number of buildings* (*N_Build*, t-value=13.52), with STC increasing as the *number of buildings* increases. The second important variable is *percentage of residential buildings* on the street, with a positive association (t-value=12.52). This suggests that a residential street tends to have larger STC than industrial or commercial streets. Not surprisingly, *street width* has a negative and significant association with STC (t-value=−9.04), meaning that the surfaces of wide streets tend to be less covered by trees. This is due to two facts. First, wider streets are less likely to have nearby tree canopy large enough to cover a large proportion of the street surface. Second, wide streets tend to be arterials, which generally have fewer trees.

Setback, the distance between a building and the street, has a strong and significant positive association with tree cover (t-value=8.55): STC is greater on streets with a wider setback. *Street length* also has a positive association with tree cover (t-value=6.45), meaning that STC is greater on longer streets. The two variables concerning the construction age are significant, suggesting that the relationship between *construction age* and STC was U-shaped. Finally, *percentage of duplexes and triplexes* is negatively associated with STC (t-value=−2.03), suggesting that streets having these types of buildings have less STC.

Model 3a and 3b: Variation explained by social stratification and lifestyle

In Model 3b, *dwelling value* is positively significant (t-value=3.03), meaning streets with more expensive houses tend to have more STC. The percentages of *recent immigrants* and of *French speakers* have a positive coefficient (t-value=3.05 and 2.28, respectively). Even after controlling for these variables, the *percentage of low-income households* still has a negative association with STC at $p<0.05$ (t-values=−2.07).

Models 4a and 4b: Variation explained by street characteristics as well as context

In Model 4a and 4b, variable coefficients change slightly compared to the previous models. Variances of errors in random effects are much lower than those in the previous models, suggesting that combining variables at the two levels is more helpful in explaining variations of STC.

Model 5: Interactions between the street characteristics and context variables

Results of the interactions in Model 5 are reported in Table 3. Only significant variables are shown due to lack of space. The AIC value (77,578.8) is lower here than in all other models, suggesting that the inclusion of the interactions contributed to explaining STC. At the street level, *street width*, *street length*, *percentage of duplexes and triplexes* as well as *construction age* are significant with similar coefficients of Model 2. However, three street variables become non-significant (*percentage of residential buildings*, *number of buildings*, and *setback*), although some of their interactions remain significant. At the neighborhood level, the only significant variable is the *percentage of French speakers*.

Table 3. Fixed and random effects Model 5 (with interactions)

	Variables	**β**	**t-value**
	Fixed effects		
Street level	Street_Width	-0.1149	-9.55 ***
	Street_Length	0.008601	5.14 ***
	PctDuTri	-0.09314	-2.66 **
	AgeMed	0.04976	6.90 ***
	AgeMed2	-0.00017	-3.89 ***
	Spatial lag	0.5162	29.50 ***
Census level	French	-0.05973	-2.48*
Interactions	PctResi *Val_Dwell	0.000143	2.73 **
	PctResi * Rec_immi	0.001518	2.24*
	PctResi *French	0.000504	2.17*
	N_Build * Low_inc	-0.00460	-3.14 **
	N_Build * Rec_immi	0.006673	2.90 **
	N_Build *With_Child	-0.00403	-2.63 **
	PctDuTri *Uni_Dip	0.000926	2.31*
	PctDuTri * Low_inc	0.000731	2.18*
	Setback*Uni_Dip	0.01286	2.95 **
	AIC	77578.8	
	BIC	77597.4	
Random effects			
PctResi – Census tract		0.000037	
N_Build – Census tract		0.01428	
PctDuTri – Census tract		0.000022	

Setback – Census tract	0.007152
Residuasl - street	71.3397

We plotted the amount of STC against each socio-demographic variable by using coefficients estimated from Model 5 (Fig. 5). The plots were created separately for three types of census tracts according to their differences in street characteristics. For example, census tracts are considered as having a “low residential level” when the standard deviation of *PctResi* (*percentage of residential buildings*) is subtracted from the mean value of this variable; a “medium residential level” when *PctResi* equals the mean value of this variable; and a “high residential level” when the standard deviation of *PctResi* is added to the mean value of this variable.

Figure 5. Effects of socio-demographic factors across different levels of street characteristics

The most influential interaction takes place between *dwelling value* and *percentage of residential buildings* on the streets, indicating that STC is higher in expensive areas having highly residential streets. STC is also higher in areas inhabited by recent immigrants on highly residential streets. STC is slightly lower in French-speaking areas having a lot of residential buildings on the streets.

STC is lower in areas that are inhabited predominantly by low-income households and by families with children, and that have a large number of buildings. Inversely, STC is higher in areas with a high percentage of recent immigrants and on streets having a large number of buildings. STC is also higher in areas inhabited predominantly by low-income households and by university degree holders in duplexes and triplexes. The only variable that has a significant interaction with *setback* is the *percentage of university degrees*. STC is higher in areas with high levels of education, and the effect is stronger in streets with a larger *setback*.

DISCUSSION

In this paper, we examined the roles of physical street characteristics and neighborhood context on the variation of street tree cover (STC) using two-level and mixed models. We used fine-grained data on street characteristics that allowed us to capture associations between STC and the urban form. Furthermore, the use of mixed effects, a spatial term and interactions in our models allowed us to obtain more robust results. In this section, we will focus on the results of the last and the most complex model, Model 5, because it was the best performing (lowest AIC) and contained the most information.

Street characteristics and the urban form

All our model results indicate that the variables representing the urban form are more important than those representing social stratification and lifestyle. While the *number of buildings* has a positive association with STC, the *percentage of duplex and triplex housing,*(which tends to be high in dense and central quarters in Montréal, has a negative association with STC. Our findings with respect to housing types are similar to previous research, which found higher canopy cover in areas with a higher proportion of single-family homes (Troy et al., 2007). A possible explanation for these findings is tenure modes. Nowak et al. (1990) observed that homeowners, more likely to live in single-family homes, are more likely to engage in the care of street trees than renters who are more likely to live in duplex and triplex houses.

Street width has a negative association with tree cover. Although *street width* is partially confounded here with types of streets, for example arterials are wider than local streets, STC was likewise lower on wider streets. One possible explanation is that the City did not prioritize planting trees along arterials that are not used for walking. To verify this explanation, interviews with the City are needed, which is beyond the scope of this study. Another plausible explanation is that trees are sparsely planted on big streets in order to reserve space for facilities such as power lines and drainage systems, or that trees are restricted by transport engineering standards in order to maintain clear zones for traffic safety (Wolf & Bratton, 2006). The *construction age* has a U-shaped relationship with tree cover, which corroborates previous studies on urban vegetation (Grove et al., 2006; Landry & Chakraborty, 2009; Mennis, 2006).

Socio-demographic context and its interactions with street characteristics

The introduction of socio-demographic variables helps increase the proportion of explained variance of STC at the tract level. Lifestyle variables prove to be important in explaining STC due to the *percentage of French speakers*, although much less so than social stratification variables.

Street characteristics interact very differently with socio-demographic variables. For example, *percentage residential* has a positive interaction with *dwelling values* and with *percentage of recent immigrants*, but a negative interaction with *percentage of French speakers*. *Number of buildings* on the streets also has different interactions with socio-demographic variables: positive interactions with *recent immigrants* and negative interactions with *low-income households* as well as with *families with children*. This means that STC is lower in areas having a high number of buildings and inhabited by the last two groups. Given the economic situation and health status of the latter two groups, these results might raise environmental equity concerns that highlight a greater need for tree cover.

Interestingly, some socio-demographic variables have different effects from one model to another. In the models without interaction, *percentage of low-income households* is negatively associated with STC. In the interactive model, this variable interacts negatively with the *number of buildings* but positively with the *percentage of duplexes and triplexes*. The *percentage of French speakers* has positive effects in the non-interactive models but negative effects in the interactive model. Explaining why STC is lower in French-speaking areas having a lot of residential buildings needs further research. Even if the reasons for these relationships are (still) unclear, these findings highlight the importance of the urban form when considering the relationship between social stratification and STC.

Three social stratification variables that do not change the direction of their coefficients across models are *dwelling value*, *recent immigrants* and *university degrees*, and all three have positive associations with STC. When interacting with the residential variable at the street level, *dwelling values* and *recent immigrants* have positive interactions in streets having a high *number of residential houses*. It is suggested in the literature that residential streets have favorable growing conditions for trees because water and nutrients from residential front yards are more likely to be close to street tree planting pits. Moreover, as residential streets are less exposed to car and pedestrian flows, trees there are less likely to become damaged and vandalized (Jim, 1987; Nowak et al., 1990). The interaction results suggest that in Montréal the influence of the *number of residential houses* on STC is even higher in expensive neighborhoods. This finding would support the social stratification explanation, in that one might expect the differential influence on tree planting associated with socio-economic status to be greater in areas where people live.

The *percentage of recent immigrants* has a positive association with STC, as exemplified with the Côte-des-Neiges and Loyola neighborhoods (marked as 1 and 2 on Figure 2). Côte-des-Neiges, being an older neighborhood with an aging housing stock, was designed in keeping with the urban form principles of the time (mostly constructed before World War II and in the 1950s), which allowed for a high STC. It is usually chosen by new arrivals and university students because of its affordable housing stock, proximity to colleges and universities, abundant public services, such as hospitals and available community support. In 2006, 54% of its population is immigrants, mostly from Asia (Southeast Asia in particular) and North Africa. Of these, more than one third was recent immigrants (INRS-UCS, 2010a). As for Loyola, recent immigrants also made up one third of its immigrant population. Immigrants were principally from Europe (notably Eastern Europe) and Asia (Eastern Asia in particular) (INRS-UCS, 2010b). In this neighborhood, it is common to find detached houses and high-rise buildings on the same street. High-rise buildings are often chosen by recent immigrants for their lower price. Detached houses with gardens and well-vegetated streets contribute largely to the greenness of the neighborhood.

We also found positive associations between STC and high *dwelling value*, especially in highly residential streets and *university degree*. These suggest that households with limited housing budgets and less education tend to live in neighborhoods with a small amount of STC and with less of the benefits provided by street trees. This lack of environmental equity of STC is likely attributed to several mechanisms. The first mechanism is related to the social-stratification explanation of uneven STC distributions related to purchasing power: green and tree-shaded neighborhoods are more expensive (Donovan & Butry, 2010). The second mechanism concerns differences in the motivation behind greening initiatives of neighborhood-based organizations and individuals associated with socio-economic status. A study conducted in Missouri shows that residents from high-income and high-education areas were more willing to fund street tree programs (Treiman & Gartner, 2006). In Montréal, residents do not fund tree programs but they have an influence on where municipal funds are going, especially by exerting pressure on their municipal counselors which are elected every four years. Further contrasting reactions to tree planting were observed in Hobart (Australia), where poor neighborhoods had a hostile reception of new plantings, even to the point of destroying them; while wealthy suburbs exhibited no signs of objection (Kirkpatrick et al., 2011).

CONCLUSION

In this paper, we were able to capture the variations of STC explained by each of the three theories (urban form, social stratification and lifestyle). All three prove to be important in explaining STC, whereby urban form proved to be the most essential, followed by social stratification and lifestyle. Some interactions between street characteristics and socio-demographic variables are significant, suggesting that interactions merit further examination in future studies on urban forests. The interactions observed in this study could be used to better design greening strategies taking into account both the urban form and socio-demographic context. Empirical evidence from Montréal in this paper contributes to enrich and enlarge theoretical frameworks of STC correlates. However, the development, application and interpretation of the models are complex. The selection of variables was made carefully while taking into consideration our knowledge about the study area. Methodology in this paper could be used to model urban tree cover in other cities. The choice of variables and results will depend on physical and socio-demographic particularities of the cities.

Our findings provide insight for urban planners to address possible inequities in the distribution of street trees in order to increase tree cover and reduce heat islands in problematic areas of the city. For example, the careful design of tree planting along wide streets could enhance road safety, and a greater number of trees on commercial streets could render those streets more walkable and livable. In Montréal, where public trees are usually planted on sidewalks, sidewalks in new neighborhoods should be designed wide enough so that trees can grow adequately. In dense areas where wider sidewalks are not possible, urban planners could resort to alternatives such as green roofs or green walls. However, such greening measures might be inferior to trees in terms of their ecosystem value.

Our paper also reveals that high dwelling value and high level of education were associated with more STC, while low-income areas tend to have lower STC, even after controlling for the urban form. These results point to the need to integrate local equity in greening programs. More importantly, greening should be done in a way that avoids creating or exacerbating concerns about environmental inequity. In other words, equity should be a key principal in urban forest programming. Evidence from other cities has shown that greening efforts may create paradoxical effects on equity. Urban planners, local stakeholders, communities and gentrifiers need to collaborate in the planting of trees. They can do so by resisting speculative development, targeting areas inhabited by low-income families, encouraging participative planning, and prioritizing small-scale sites over grand green projects (Wolch et al., 2014). Other strategies can be also useful, such as raising public awareness and informing local residents about plantings and procedures.

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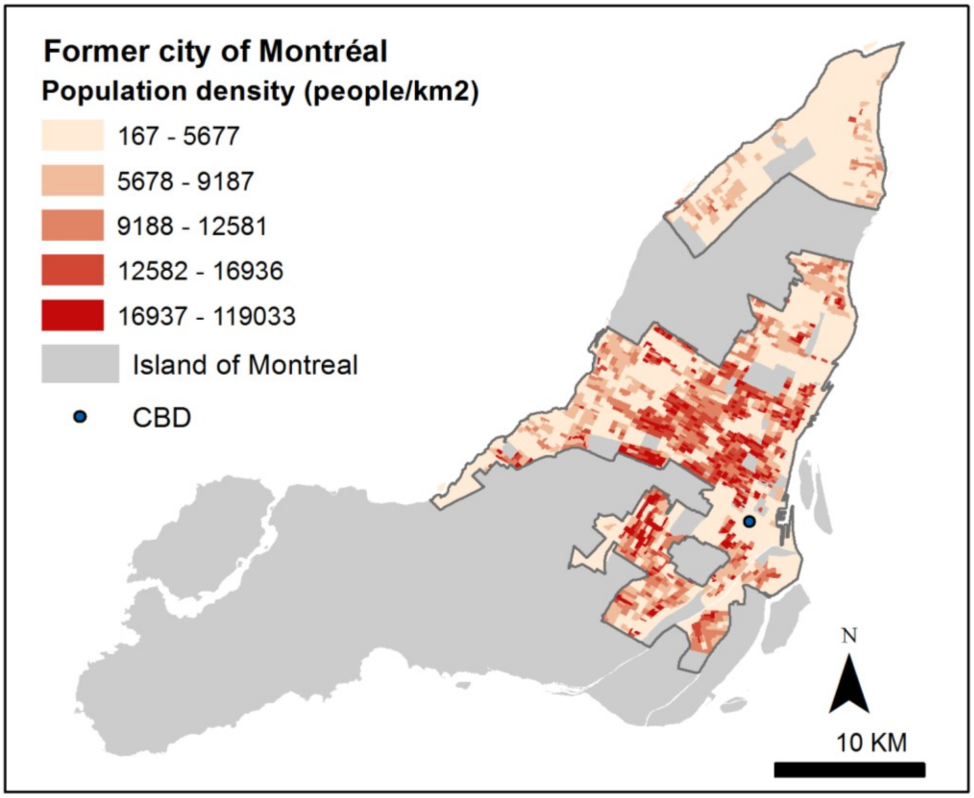


Figure 1.Location and population density of the former city of Montréal, by dissemination area (Statistics Canada, 2006).

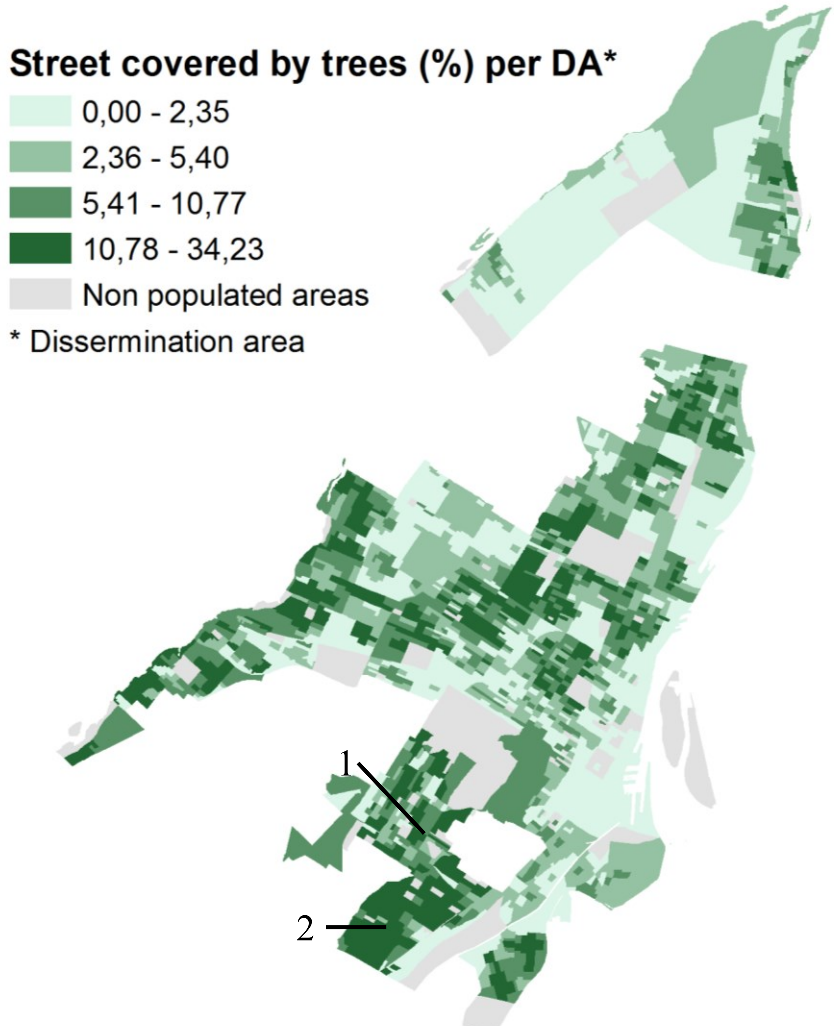


Figure 2. Percentage of streets covered by trees, in the former City of Montréal (aggregated by dissemination area).

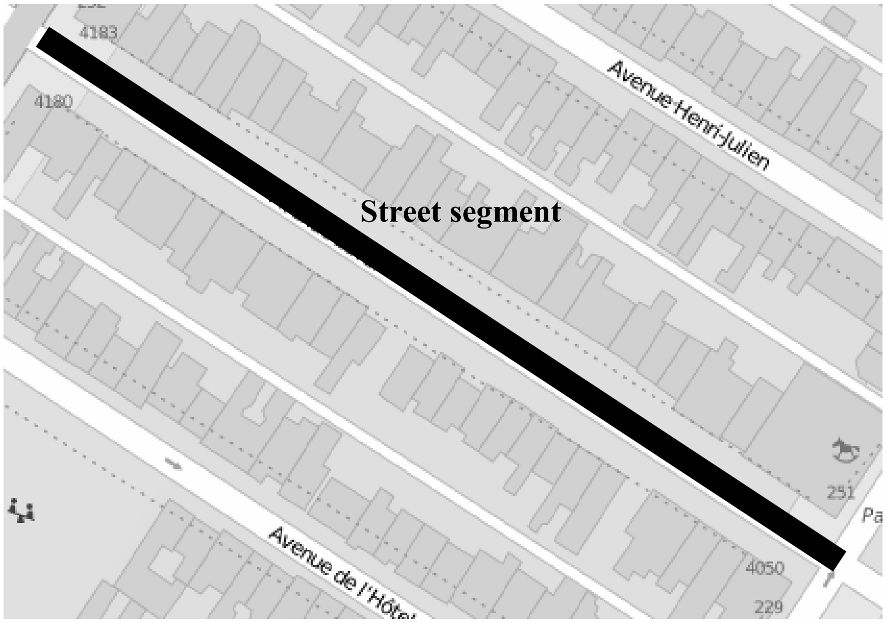


Figure 3. Example of street segment (in black) and setback (arrow) on a map

(Source: Open Street Map)

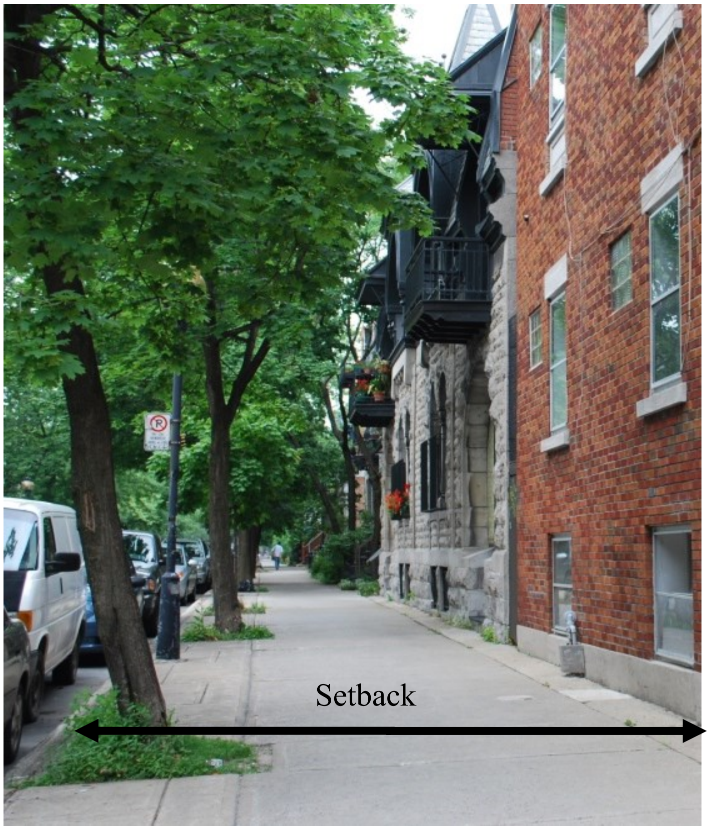
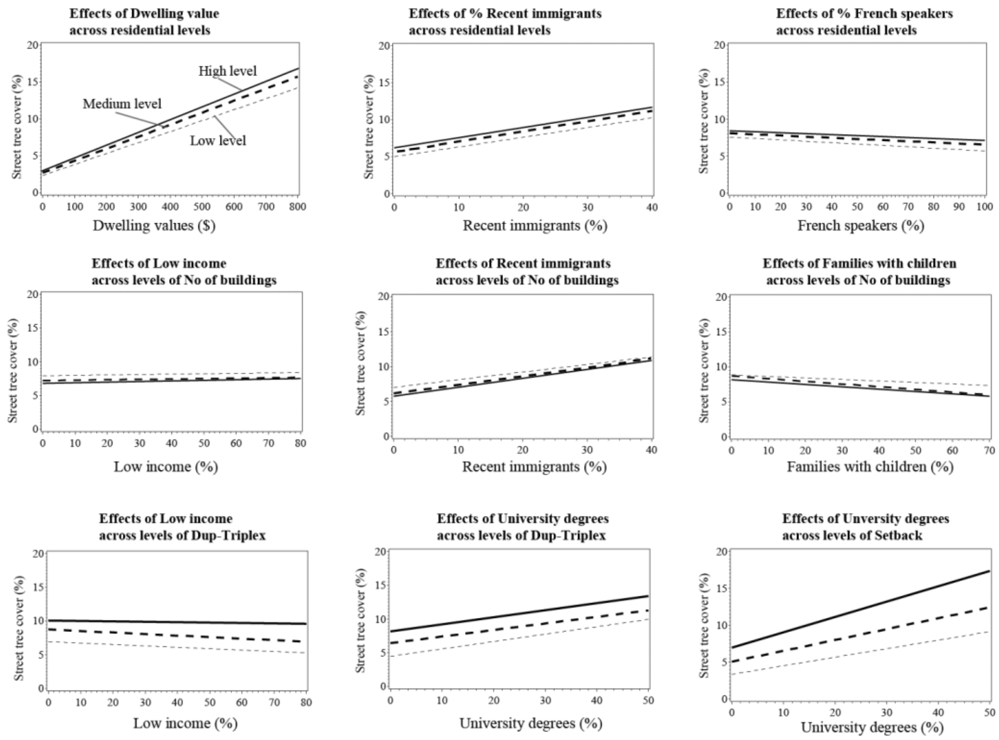


Figure 4. Illustration of setback of a street in central Montréal. Photo credit: first author.



Effects of Dwelling value across residential levels
High level
Medium level
Low level
Street tree cover (%)
Dwelling values ($)
Effects of % Recent immigrants across residential levels
Recent immigrants (%)
Effects of % French speakers across residential levels
French speakers (%)
Effects of Low income across levels of No of buildings
Low income (%)
Effects of Recent immigrants across levels of No of buildings
Recent immigrants (%)
Effects of Families with children across levels of No of buildings
Families with children (%)
Effects of Low income across levels of Dup-Triplex
Low income (%)
Effects of University degrees across levels of Dup-Triplex
University degrees (%)
Effects of Unversity degrees across levels of Setback
University degrees (%)

Figure 5