EQUITABLE DISTRIBUTION OF VEGETATION COVER ACROSS LAVAL

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DAVID SUZUKI FOUNDATION
One nature.

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EXECUTIVE SUMMARY

Green infrastructure provides crucial ecosystem services, including regulating urban temperatures and air pollution, managing stormwater and supporting biodiversity. These features also help reduce stress, improve mood and encourage physical activity, thereby contributing to the overall wellbeing of urban residents. However, at a time when the global population continues to expand, many cities are experiencing rapid urbanization and intensification. Urban development often encroaches on urban green spaces essential to the health and wellbeing of residents and potentially exacerbates environmental inequities for marginalized populations.

This study compared the distribution of total vegetation cover in the municipality of Laval with the Montreal Metropolitan Community (CMM for *Communauté métropolitaine de Montréal* in French) to determine if inequity trends commonly observed in other cities are also present in this historically young municipality. The analyses conducted included both linear regression approaches (i.e., ordinary least squares and geographically weighted regression) and spatial cluster analysis (i.e., Getis-Ord Local Gi* and Local bivariate Moran's I), to generate a better understanding of the spatial distribution of the variables studied.

Analytical results revealed a significant correlation between total vegetation cover and marginalization scores, highlighting marked inequity of vegetation, an important environmental good, across Laval. The most marginalized neighbourhoods, often located near the city centre, have lower vegetation cover, while less densely populated neighbourhoods exhibiting lower marginalization scores, particularly in northern Laval, benefit from more abundant vegetation. Significant spatial clusters where high marginalization scores coincided with reduced vegetation cover helped identify priority areas for future interventions aimed at reducing ecological inequities.

To address these inequities and improve environmental justice, the recommendations of this study include conserving, expanding and implementing green infrastructure in highly marginalized areas. This can be achieved by prioritizing nature-based solutions, notably through demineralization projects (e.g., removing asphalt) or through phytotechnologies, such as vegetated swales, vegetated pavements and bioretention basins, which can increase vegetation cover while enhancing the quantity and quality of ecosystem services. Additionally, converting vacant lots into public parks or institutional green spaces could offer significant ecological and social benefits. Decision-makers are called upon to consider the advantages of natural green spaces over manicured green spaces to maximize benefits for residents.

This study aims to support the municipality of Laval and the CMM in achieving their socio-ecological objectives equitably. The hope is that new strategic documents related to urban planning, as well as climate issues and biodiversity loss, such as the Climate Plan and the Metropolitan Land Use and Development Plan (PMAD), will take equity issues into account. Recognizing the importance of environmental justice in urban planning and the need for targeted strategies to improve vegetation distribution in marginalized neighbourhoods is crucial. Concerted efforts to increase urban vegetation and preserve the existing ones will contribute to creating more resilient and equitable urban environments, thereby improving the wellbeing of all residents.

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LIST OF ABBREVIATIONS

(Terms in italics are in French)

CMM	*Communauté métropolitaine de Montréal* (Montreal Metropolitan Community)
CSRS	Canadian Spatial Reference System
DA	Dissemination area
EPSG	European Petroleum Survey Group
GWR	Geographically Weighted Regression
MAUP	Modifiable Areal Unit Problem
MRNF	*Ministère des Ressources naturelles et des Forêts* (Ministry of Natural Resources and Wildlife)
MTM	Modified Transverse Mercator
NAD83	North American Datum 1983
OLS	Ordinary Least Squares
PMAD	*Plan métropolitain d'aménagement et de développement* (Metropolitan Land Use and Development Plan)
QGIS	Quantum Geographic Information System
QC	Quebec
SHP	Shapefile
TIF	Tagged Image File Format
XLSX	Excel Microsoft Office Open XML Format Spreadsheet file

INTRODUCTION

With global population continuing to expand (Ritchie et al., 2023), many cities and neighbourhoods are experiencing a high rate of urbanization and densification. This process can result in competition and pressure on the green spaces that are part of the urban fabric, potentially impacting the health and wellbeing of urban residents (Ambrey, 2016; Song et al., 2021; Yao et al., 2024). Many studies show that spending time outdoors, specifically in green environments, can enhance a person's wellbeing and overall mental health (Colley et al., 2016; Ferguson, 2019; Song et al., 2021; Wu et al., 2023; Yao et al., 2024). Specifically, visiting urban green spaces is shown to reduce both perceived and physiological stress levels, improve mood and vitality and restore one's attention span (Colley et al., 2016; Yao et al., 2024). People are also more likely to engage in outdoor physical activity if they have access to green spaces (Ambrey, 2016; Frumkin et al., 2017), which, in turn, contributes to the wellbeing of residents in cities that offer numerous natural areas. Moreover, increasing urban trees and green space is shown to alleviate many environmental stressors that accompany living in a highly urbanized area, such as the urban heat island effect, air/noise pollution and flooding (Livesley et al., 2016; Ziter et al., 2019). Despite the known benefits of urban vegetation for health and wellbeing, cities typically trend toward reduced levels of greening with increased urbanization. For example, decreases in urban greenness of nearly 10 per cent have been observed in Canadian cities in recent decades, across all Canadian provinces (Statistics Canada, 2022).

It is well established that urban green spaces — and consequently the associated benefits — are inequitably distributed, with members of equity-deserving communities receiving less access, often referred to as the "luxury effect" (Leong et al., 2018). In U.S. cities, where the majority of such research has taken place, higher vegetation is frequently associated with higher income and predominantly white neighbourhoods (Gerrish et Watkins, 2018; Schell et al., 2020; Watkins et Gerrish, 2018). Recent analyses of the relationship between socio-demographics and green space in Canadian cities show similar trends, with higher income and more highly educated communities associated with higher vegetation (Quinton et al., 2022). Beyond vegetation amount, studies also find that social vulnerability is also associated with forest functional diversity, an indicator of resilience, and that this trend holds across cities (Landry et al., 2020). Thus, both the quantity and quality of urban green space are often reduced in proximity to equity-deserving communities.

In Canada, built-up areas have increased by over 150 per cent since the 1970s, expanding faster than anticipated given the number of new inhabitants and contributing to urban sprawl (Pourali, 2021; Pourali et al., 2022). Like Toronto, Montreal underwent an amalgamation of its city with several sectors that comprise the Montreal Metropolitan Community (CMM for *Communauté métropolitaine de Montréal* in French), including the North Crown, the Montreal Agglomeration, the Longueuil Agglomeration, the South Crown and the city of Laval (**Figure S1**). The separation of the CMM into these regions creates an interesting case study into how this political restructuring might have impacted the population demographics and the allocation of green space. Laval, being the northern neighbour of the island of Montreal, has the interesting characteristic of being densely populated on its southern end, bordering the city centre, while having a developed agricultural sector on its northern border (**Figure S2** and **Figure S3**). To address a knowledge gap, this study aimed to investigate the distribution of vegetation cover within Laval and draw comparisons to the CMM to determine if the trend toward inequity of green space observed in other cities can also be noted in this relatively young municipality.

METHODOLOGY

INPUT DATA

All the spatial data used to investigate the distribution of vegetation cover within the city of Laval and within the larger CMM were obtained by consulting open regional, provincial and federal databases (**Table 1**). All these data were projected to a common spatial reference system prior to analysis (NAD83 (CSRS) / MTM zone 8 (EPSG:2950), using the following software platforms: R, version 4.3.1 (R Core Development Team, 2023) and Quantum GIS, version 3.34.1 (QGIS Development Team, 2023).

STUDY AREAS

The official administrative boundaries of the city of Laval and of all the CMM were extracted as a vector feature class (ESRI *.shp format) from the "Découpages administratifs 1/20000" layer (MRNF, 2024). The boundaries of each dissemination area (DA) from the 2021 Canadian Census (Statistics Canada, 2021a) served as the basis for the rest of this work.

DATA CONFIGURATION

VARIABLE 1 - PERCENTAGE OF TOTAL VEGETATION COVER BY DISSEMINATION AREA (DEPENDENT)

The Metropolitan Canopy Index layer (CMM, 2021) was used to create the dependent variable of this study, representing the percentage of total vegetation cover within each DA. The original Metropolitan Canopy Index layer depicts five land-cover classes on a single map (i.e., low mineral, low vegetation, high mineral, high vegetation and aquatic). The main geometric operations were performed within a loop, where, for each DA, the Metropolitan Canopy Index raster was subset to its extent using the *raster::crop()* function and masked using the *raster::mask()* function to retain only the pixels strictly within the DA boundaries. The number of pixels classified as low and high vegetation (i.e., values 3 and 4) was then counted using the *base::sum()* function. The total vegetation area was extrapolated from the number of selected pixels based on the raster resolution (i.e., 1m). The percentage of vegetation cover for each DA was then estimated by dividing the total vegetation area by the DA's total surface area, which was computed using the *sf::st_area()* function.

VARIABLE 2 - MARGINALIZATION SCORE BY DISSEMINATION AREA: QUÉBEC (INDEPENDENT)

The input data for the independent variable of this study was sourced from the 2021 Canadian Index of Multiple Deprivation, for which an overall marginalization score was generated by averaging the value for each of the four dimensions of multiple deprivation (i.e., Residential instability, Ethno-cultural composition, Economic dependency and Situational vulnerability) for DAs in Quebec (Statistics Canada, 2021b). As a result, marginalization score is ranked from 1 to 5, where a score of 5 indicates complete marginalization and 1 indicates very little or no marginalization (Statistics Canada, 2021b).

TABLE 1. SPATIAL DATA USED.

DATA	FORMAT[1]	YEAR[2]	SOURCE[3]
Administrative Boundaries 1/20000	Vector Feature Class (*.SHP)	2024	Données Québec - (MRNF, 2024)
Dissemination Area (DA)	Vector Feature Class (*.SHP)	2021	Statistics Canada - (Statistics Canada, 2021a)
The Canadian Index of Multiple Deprivation - (QC)	Tabular Data (*.XLSX)	2021	Statistics Canada - (Statistics Canada, 2021b)
Metropolitan Canopy Index	Raster Surface (*.TIF)	2021	Observatoire Grand Montréal - (CMM, 2021)
Metropolitan Land Use	Vector Feature Class (*.SHP)	2022	Observatoire Grand Montréal - (CMM, 2022a)

[1] SHP: Shapefile, TIF: Tagged Image File Format, XLSX: Excel Microsoft Office Open XML Format Spreadsheet file.[2] The year indicated corresponds to the acquisition of the data and not to their publication. [3] The download links for the datasets are accessible by clicking on the reference in the "Source" column.

EXTENDED ANALYSIS

A large part of this project involved determining what type of spatial analysis was most appropriate for this case study. Framing the distribution of environmental inequity in a spatial model is challenging, particularly in finding the most accurate way to quantify the relationships across the study area. In the quest to identify a parsimonious model of relationships for the study area, several parallel analyses were conducted on the data, including both linear regression approaches (i.e., ordinary least squares and geographically weighted regression), and spatial cluster analysis (i.e., Getis-Ord Local Gi* and bivariate local Moran's I).

Each step of the analysis was completed twice: once using the Laval boundaries in isolation, and once in the context of the greater CMM. First, observations with missing values, for the overall marginalization score or percentage of total vegetation, were removed using the *base::filter()* function to ensure analysis on a complete dataset and no spatial outliers.

The ordinary least squares (OLS) regression model was fitted using the *stats::lm()* function. The model summary was generated using the *base::summary()* function to assess the regression coefficients, R^2 value, and statistical significance of the predictors. The standardized residuals were computed using the *stats::rstandard()* function and added to the spatial object for mapping purposes.

The geographically weighted regression (GWR) model was fitted using the *spgwr::gwr()* function. The model was computed with a bandwidth previously found using *spgwr::gwr.sel()* function, and with a Gaussian weighting function (gweight = gwr.Gauss). GWR residuals were extracted from the model output and the standard deviation of the residuals was computed using *stats::sd()*. Standardized residuals were then calculated by dividing each residual by the standard deviation and added to the spatial object for mapping purposes.

For spatial cluster analysis, the *spdep::poly2nb()* function was used to build a spatial weights matrix (i.e., "what is a neighbour") based on Queen contiguity (queen = TRUE). Queen contiguity is also known as "Edges and Corners" contiguity, where any feature touching an edge or vertex of an observation is considered to be a neighbour. The number of neighbours for each region was counted using the *spdep::card()* function, and DAs that did not meet the contiguity condition were removed from the list. The neighbours list was converted into a spatial weights object using the *spdep::nb2listw()* function, with a row-standardized normalization approach (style = "W").

The Getis-Ord Local Gi* statistic was computed for each DA using the *spdep::localG()* function with the previously generated spatial weights object. Standardized z-scores were classified into three categories based on a 95 per cent confidence threshold (i.e., Cold Spot [-Inf, -1.96], Non-Significant [-1.96, 1.96] and Hot Spot [1.96, Inf]) using the *base::cut()* function, and added to the spatial object for mapping purposes.

The Bivariate Local Moran's I statistic was computed using the *spdep::localmoran_bv()* function with the same previously generated spatial weights object and with 499 simulations to run (nsim = 499). The *spdep::hotspot()* function was then applied to the output to classify Bivariate local Moran's I results into spatial association clusters, using a 0.05 significance threshold. The classification into "High-High", "Low-Low", "High-Low", and "Low-High" categories followed the PySAL logic (quadrant.type = "pysal"). The resulting factor vector was added to the spatial object for mapping purposes.

RESULTS AND DISCUSSION

PRELIMINARY OBSERVATIONS ABOUT SPATIAL DISTRIBUTION OF VARIABLES

Prior to conducting further analyses on the spatial data, it was essential to examine the spatial distribution of vegetation cover and marginalization score individually. **Figure 1** and **Figure 2** show the distribution of both variables across the greater CMM, with two zoomed-in samples across Laval.

Across the CMM, vegetation followed a clear concentric pattern radiating from the urban core (**Figure 1**). On the outer margins of the CMM and on the northern border of the Laval peninsula, the percentage of vegetation cover was very high and gets increasingly sparser moving closer to the city centres. This pattern is to be expected, as the more intensely developed an area becomes, the more difficult it becomes to integrate green space into the landscape (Pham et al., 2012). A similar trend also exists when evaluating the distribution of marginalization score across the study area. People living on the margins of the CMM, as well as in the western tip and on the northern border of Laval, tended toward the lowest observed marginalization scores. In contrast, marginalization scores tended toward higher values within the city centres and in locations within the peninsula that are more densely populated (**Figure S2**).

ORDINARY LEAST SQUARES (OLS) REGRESSION

An OLS regression is often used as a preliminary processing step in spatial analysis to determine whether a relationship exists between two variables prior to conducting further analyses with greater spatial capabilities. The OLS assesses how much of the variation in the dependent variable (i.e., Percentage of total vegetation) can be explained by the independent variable (i.e., Marginalization score) and determines if this relationship is statistically significant. The OLS regression conducted for both Laval and the CMM to investigate the relationship between total vegetative cover and marginalization score met all assumptions required to ensure the accuracy of the analysis.

The R^2 value was 0.11 in the local context, which indicates hat only 11 per cent of the variation in

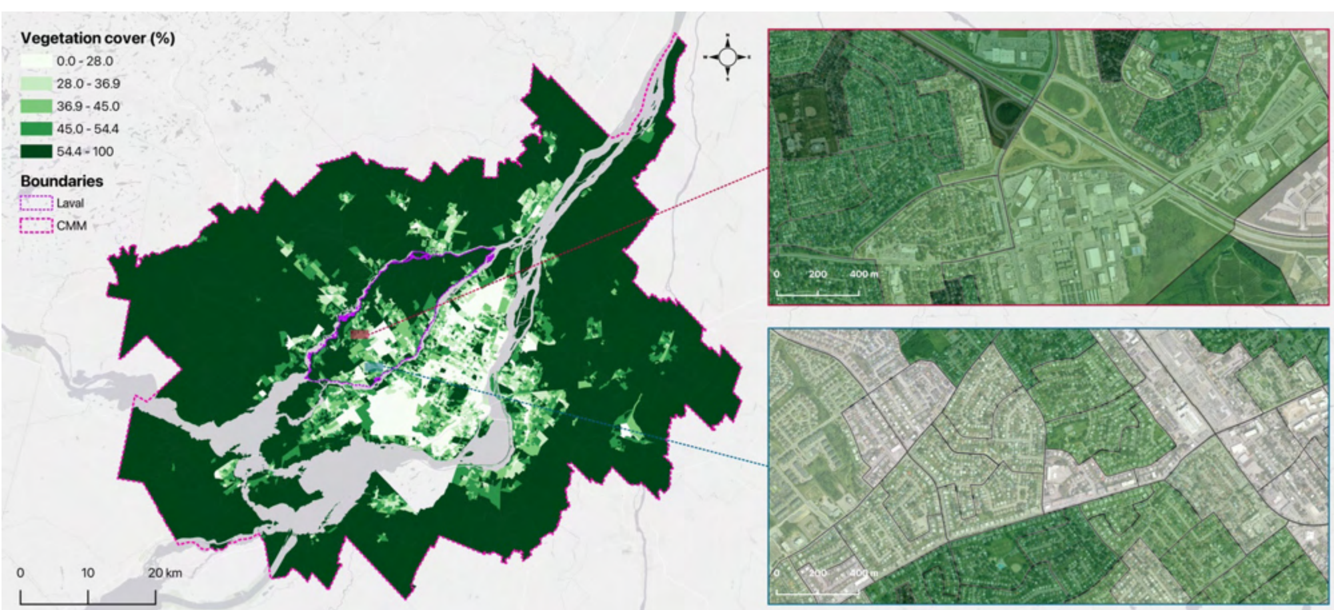

Figure 1. Vegetation Cover across the CMM, with two zoomed-in samples across Laval.

Spatial reference: NAD 1983 (CSRS) MTM Zone 8. Data sourced from the Metropolitan Canopy Index (CMM, 2021); Dissemination Area (Statistics Canada, 2021a). Basemap credited to GrayLight, EsriCanada.

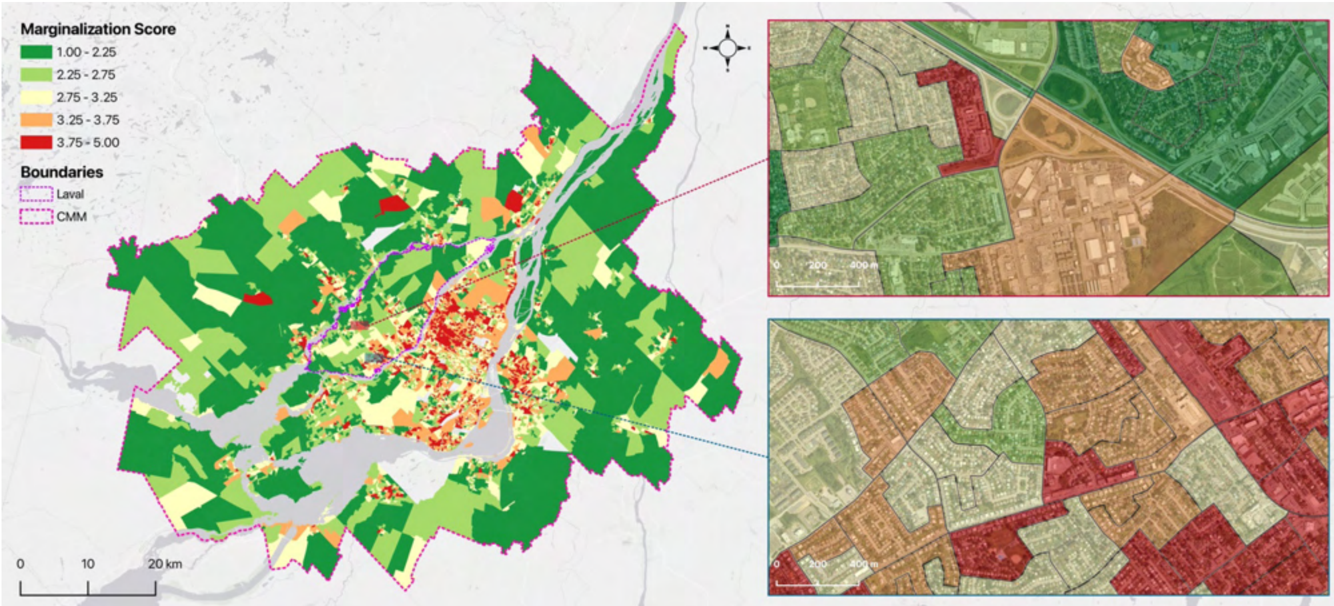

Figure 2. Marginalization Score across the CMM, with two zoomed-in samples across Laval.

Spatial reference: NAD 1983 (CSRS) MTM Zone 8. Data sourced from the Canadian Marginalization Index (Statistics Canada, 2021b); Dissemination Area (Statistics Canada, 2021a). Basemap credited to GrayLight, EsriCanada.

vegetative cover can be explained by marginalization score. While this suggests a weak relationship, the results were still statistically significant ($p \leq 0.001$), meaning that the observed relationship is unlikely to have occurred by chance. Additionally, the histogram of standardized residuals approximates a normal distribution (data not shown), which supports the assumption of normality, and the scatter plot of residuals shows a random and evenly distributed pattern (data not shown), indicating no apparent issues with heteroscedasticity or non-linearity. The same analysis was conducted using the context of the entire CMM to see how the variables may change, and the results remained very similar and still statistically significant ($p \leq 0.001$). However, one notable difference is the higher R^2 value in this model compared to that of just Laval. In this case, adding further context to the model has created a stronger relationship, increasing the value to 0.25.

The analysis reveals clear spatial non-stationarity among the variables. As illustrated in **Figure 3**, a distinct region of over-predicted residuals is visible along the northern border, with particularly large clusters in the northeast and northwest. Similarly, large clusters of consistently under-predicted values can be seen in central Laval. This tendency toward the clustering of residuals (i.e., representative of large over- and under-prediction) suggests the relationship between the variables may vary geographically across the study area. The trends observed in the isolated Laval analysis persist in this broader analysis, with spatial non-stationarity evident across the peninsula, following similar patterns. While OLS regression provides useful insights into the overall relationship between the variables, its inability to account for spatial non-stationarity underscores an important limitation. These results suggest that more spatially adaptive methods may be better suited for this case study.

HOTSPOT ANALYSIS (GETIS-ORD LOCAL GI*)

To confirm the potential for spatial non-stationarity a HotSpot analysis (Getis-Ord Local Gi*) was conducted to identify clusters of significant outliers from the expected spatial trend across the study areas. This test compares an observations neighbourhood mean to the global mean. If the neighbourhood mean is ±1.96 standard deviations from the mean it is considered a hot spot (≥ +1.96) or cold spot (≤ -1.96). It is important to note that an observation flagged as part of a hot spot may not in fact be an outlier itself, but its local neighbourhood is. The large clusters of hot spots and cold spots reinforce the conclusion that there is spatial non-stationarity in the process to consider. Moreover, these clusters appear to highlight areas where high levels of marginalization (**Figure 4**) coincide with low vegetation cover (**Figure 5**). These clusters serve as key areas of

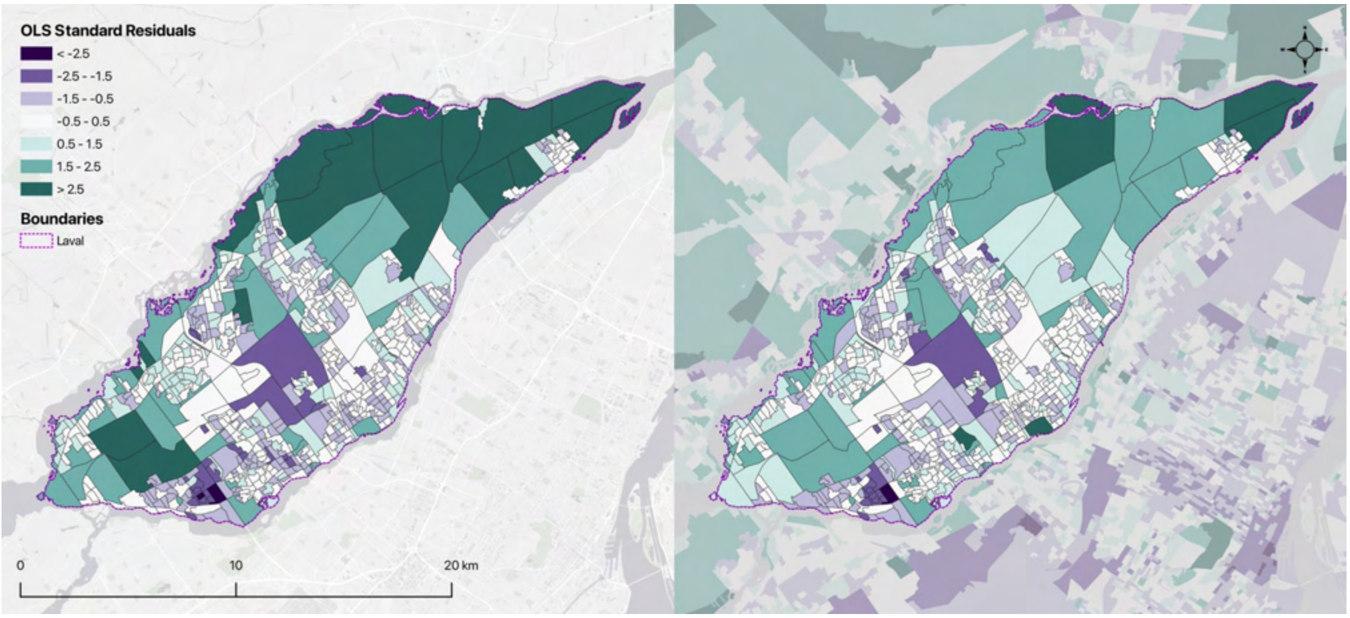

Figure 3. Standard Residuals as a result of an OLS regression.

Local context (left) and in the context of the CMM (right). Spatial reference: NAD 1983 (CSRS) MTM Zone 8. Data sourced from the Dissemination Area (Statistics Canada, 2021a). Basemap credited to GrayLight, EsriCanada.

concern, particularly within Laval, where such spatial patterns may require further investigation and targeted interventions.

The results of the HotSpot analysis align closely with the preliminary observations made earlier regarding the spatial distribution of vegetation cover and marginalization score across the CMM. As described in the initial findings, the northern border of Laval exhibits a high percentage of vegetation cover, with progressively lower coverage closer to the city centre. Similarly, the analysis of marginalization scores indicated lower levels of marginalization in the western and northern areas of Laval, with higher levels in more densely populated areas of the city (**Figure S2**).

GEOGRAPHICALLY WEIGHTED REGRESSION (GWR)

When spatial non-stationary is detected in OLS regression outputs, a GWR is often used as an alternative. Where OLS is a global model (one function for the entire dataset), GWR performs a regression model for every observation based on a local subset of neighbours. This local approach captures the changing strength of the relationship between variables as the search window moves across the study area observation by observation.

A subsequent GWR was then conducted on the study areas to account for the non-stationarity observed in the results of the OLS models. The improvement in the R^2 value (0.48), in the local context, suggests there is, in fact, significant non-stationarity in the process, shifting the strength of the relationship from weak to moderate. On the map of Laval, while there are still large clusters of over- and under-predicted values, they are less extreme compared to OLS (**Figure 6**). A similar result is observed when expanding the geographic focus from Laval to the entire CMM. The R^2 value for this broader extent is slightly higher than for the Laval-specific model, reaching 0.68, which is still within the moderate range. This suggests that incorporating the larger context of the CMM provides a more accurate estimation of the relationship, reinforcing the idea that spatial dependencies across a broader area contribute valuable context to understanding local patterns.

To some, a GWR can be considered controversial since it inherently inflates the model fit, which some describe as overfitting of the model. However, in the context of spatial data, where variables are intrinsically linked to geographic locations, this assumption is not only expected but necessary for accurate modelling. The OLS results further confirmed that applying GWR was the correct next step in the analysis. Comparing the Global Moran's

I statistic for the standardized residuals of the OLS and GWR models provides a useful diagnostic for assessing how well each model accounts for spatial dependence. Although residuals from both models still exhibit statistically significant spatial autocorrelation ($p \leq 0.05$), the switch from OLS to GWR substantially reduced the degree of autocorrelation in both contexts. Specifically, Moran's I statistic decreased from 0.352 to 0.072 in the local context of Laval and from 0.506 to 0.172 in the larger context of the CMM. These results suggest that GWR better captures the underlying spatial structure of the data and leads to a more appropriate model specification.

BIVARIATE LOCAL MORAN'S I

Where Getis-Ord Local Gi* tests the local neighbourhood mean against the global mean, Anselin's Moran's I tests the neighbourhood mean against the local mean AND the observation against the local neighbourhood mean. As a result more relationship types are possible because an observation can be significantly high, nested within a neighbourhood with a mean that is significantly higher than the global mean, resulting in a "High-High" classification. An observation can also be significantly low, but be nested within a local neighbourhood that is significantly higher than the global mean, resulting in a "Low-High" classification.

The bivariate variation of Moran's I extends the analysis to consider two spatially coinciding variables or two attributes of the same features. This approach is particularly useful when the coinciding variables do not exhibit a strong linear relationship but do appear to exhibit clusters in space as appears to be the case in this study. Rather than test an observation's value against the local neighbourhood mean, and the local neighbourhood mean against the global mean for one variable, the bivariate variant tests the observation's value in independent variable (i.e., marginalization score) against the local neighbourhood in dependent variable (i.e., vegetation cover). Thus, a "High-Low" result would indicate a dissemination area with a significantly high marginalization score nested within a local neighbourhood with a significantly low percentage of vegetation cover. In contrast a significant "Low-High" result would indicate a dissemination area with a significantly low marginalization score, nested within a local neighbourhood with a significantly high mean of vegetation cover. The Bivariate analysis based on Local Moran's I statistics was found to be the most useful method for this study given the ability to resolve non-linear relationships between the spatially coinciding variables. Results from the bivariate Moran's I analysis are presented in **Figure 7**.

While a larger area classified as "Non-Significant" was observed in Laval in the local context, the

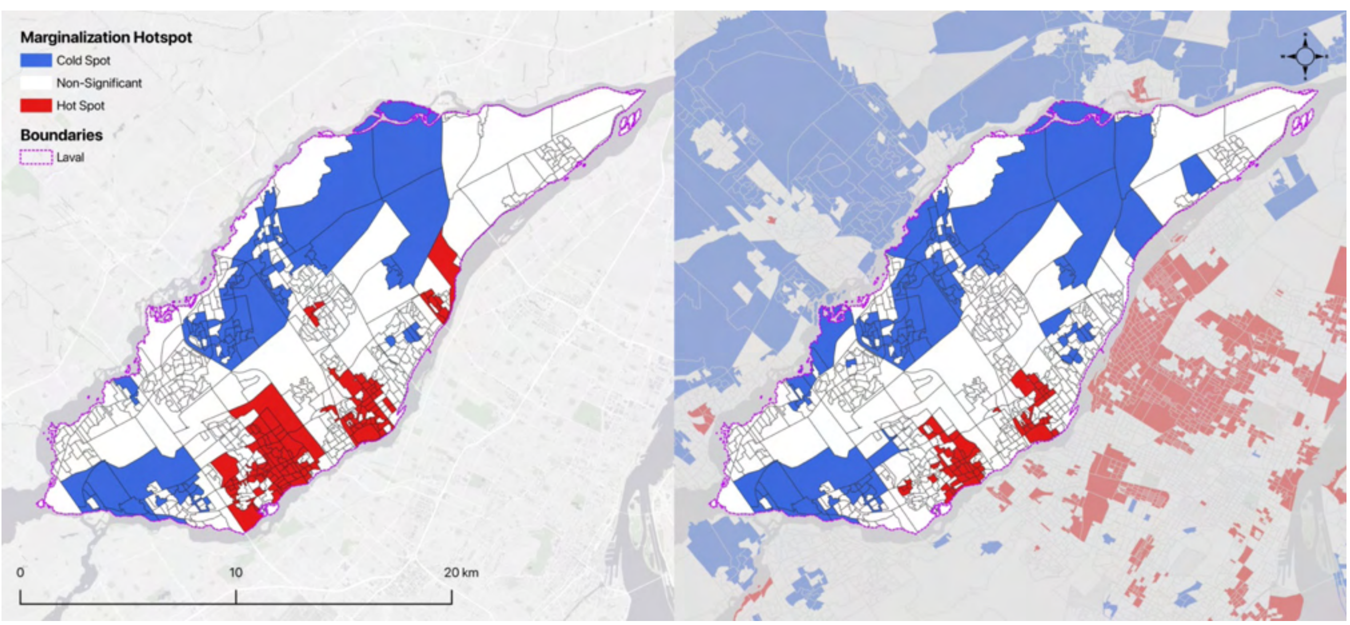

Figure 4. Significance Clusters of Marginalization Score in Laval.

Hotspot Analysis in the local context (left) and in the context of the CMM (right). Spatial reference: NAD 1983 (CSRS) MTM Zone 8. Data sourced from the Administrative Boundaries (MRNF, 2024); Dissemination Area (Statistics Canada, 2021a). Basemap credited to GrayLight, EsriCanada.

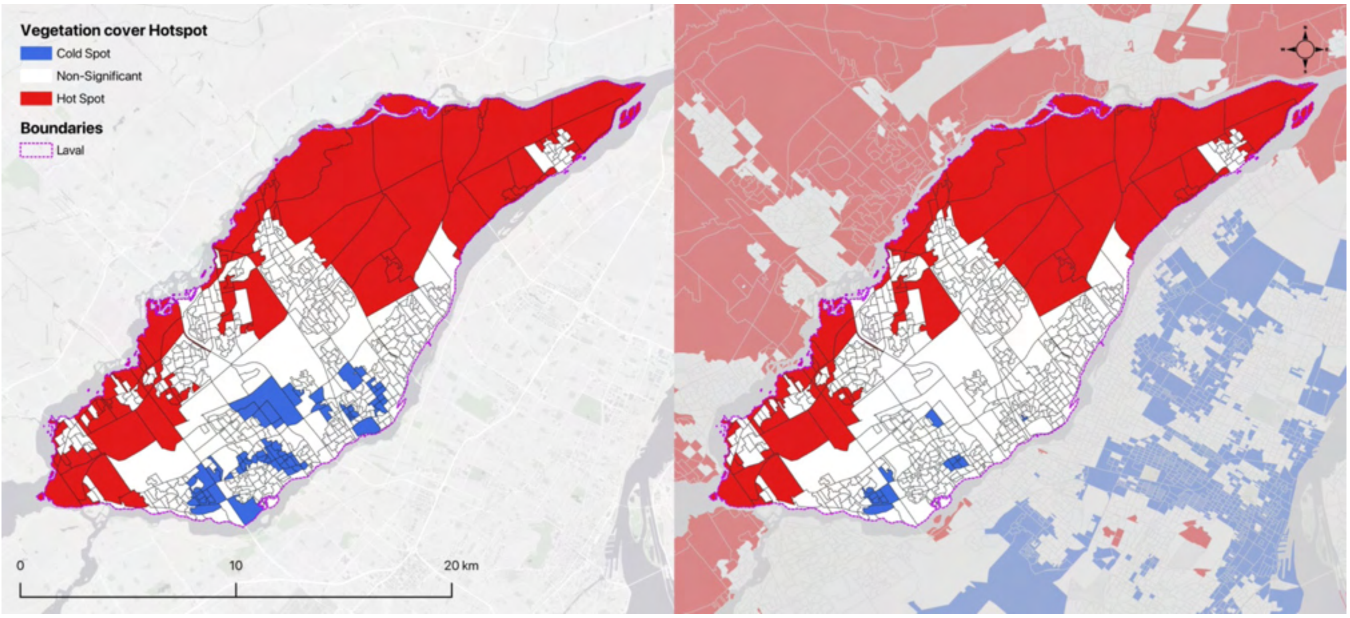

Figure 5. Significance Clusters of Total Vegetation Cover in Laval.

Hotspot Analysis in the local context (left) and in the context of the CMM (right). Spatial reference: NAD 1983 (CSRS) MTM Zone 8. Data sourced from the Administrative Boundaries (MRNF, 2024); Dissemination Area (Statistics Canada, 2021a). Basemap credited to GrayLight, EsriCanada.

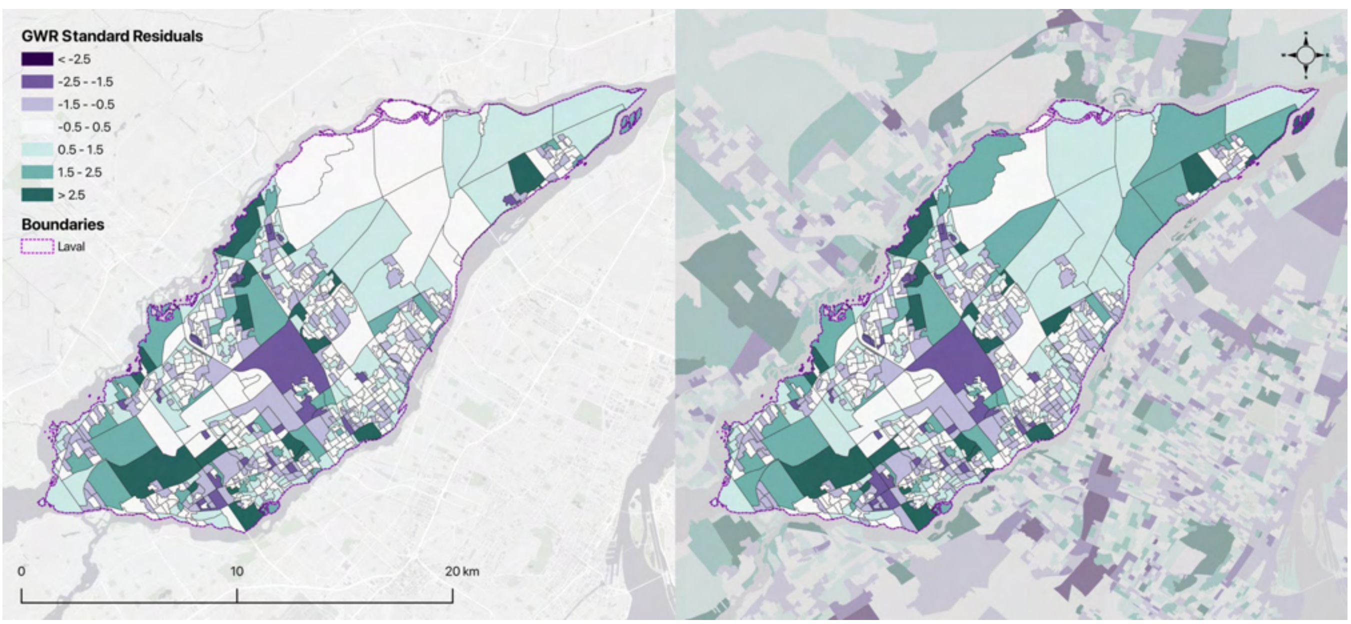

Figure 6. Standard Residuals as a result of an GWR.

Local context (left) and in the context of the CMM (right). Spatial reference: NAD 1983 (CSRS) MTM Zone 8. Data sourced from the Dissemination Area (Statistics Canada, 2021a). Basemap credited to GrayLight, EsriCanada.

results from both contexts (i.e., local context based on the Laval dataset only and the broader context based on the CMM dataset) reveal similar trends (**Figure 7**). As can be expected, there were very few regions that cluster as "High-High" and "Low-Low" in both contexts, suggesting that areas with high overall marginalization score are less likely to be associated with high greenery. On the opposite end of the spectrum, it appears to be uncommon for low-marginalization neighbourhoods to lack sufficient greenery. This pattern is consistent with findings from various studies, which indicate that more affluent and less marginalized neighbourhoods tend to have better access to green spaces and higher vegetation cover (Pham et al., 2012).

In both contexts, a large band of DAs characterized as "Low-High" was observed along the northern border of Laval. Most of these DAs are among the least densely populated in Laval (**Figure S2**) and are located within the agricultural perimeter (Ville de Laval, 2017). Conversely, many DAs characterized as "High-Low" were clustered near the city centre (Ville de Laval, 2024), within some of the most densely populated DAs (**Figure S2**). These patterns closely mirror the findings from the Hotspot Analysis and the preliminary observations, which suggested that areas of high marginalization tend to be more concentrated in urban centres with limited greenery, while less marginalized areas are more commonly associated with higher vegetation cover. Such a distribution is not surprising, as it is common that people with higher marginalization status live in city centres, where there is better access to public transportation and other services, and where the housing is smaller, more compact, and less expensive (Pham et al., 2012).

The results of the Bivariate Local Moran's I analyses provide valuable insights into the spatial relationships between overall marginalization scores and the percentage of total vegetation cover, allowing for the identification of priority areas for interventions aimed at reducing ecological inequities. Importantly, addressing these inequities will not require reducing vegetation cover in low-marginalization neighbourhoods. Instead, efforts need to focus on increasing green infrastructure in high-marginalized areas, as well as conserving or managing existing green spaces to promote more equitable access to environmental benefits. Investigating each of the significant "High-Low" DAs in both contexts helps identify potential opportunities to implement additional green infrastructures or to conserve and manage existing ones.

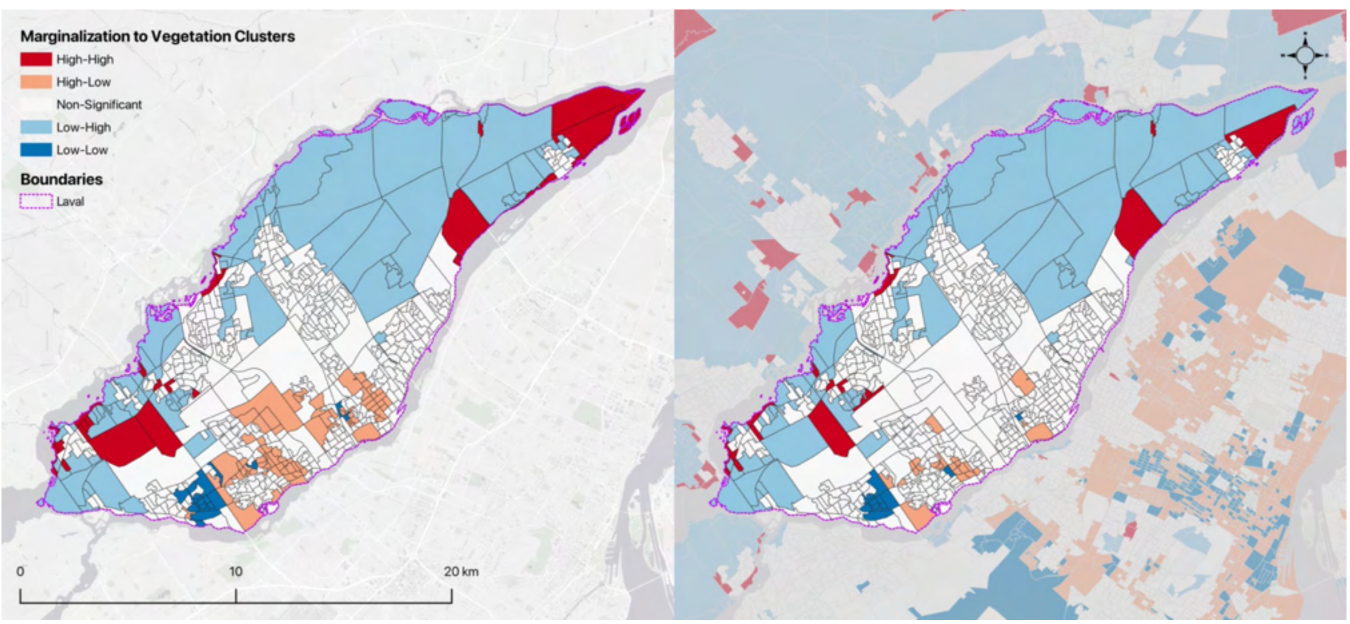

Figure 7. Bivariate Local Moran's I clustering map across Laval.

Local context (left) and in the context of the CMM (right). Spatial reference: NAD 1983 (CSRS) MTM Zone 8. Data sourced from the Administrative Boundaries (MRNF, 2024); Dissemination Area (Statistics Canada, 2021a). Basemap credited to GrayLight, EsriCanada.

GENERAL PROFILE OF "HIGH-LOW" CLUSTERS

The total area of significant "High-Low" DAs is 17.82 km^2 in the local context and 5.07 km^2 in the context of the CMM. Overlaying the significant "High-Low" DAs with metropolitan canopy index (CMM, 2021) and metropolitan land use (CMM, 2022a) reveals heterogeneous patterns (**Table 2** and **Table 3**), highlighting multiple opportunities for decision-makers to promote the equitable distribution of total vegetation in Laval (**Figure 8** and **Figure 9**).

Based on the metropolitan canopy index, the predominance of impervious surfaces within significant "High-Low" clusters is apparent, with these surfaces covering on average 63.99 per cent of the cluster surface in the local context, and 53.11 per cent in the CMM context (**Table 2** and **Table 3**).

When considering the metropolitan land use data, the overall area of significant "High-Low" clusters is predominantly occupied by residential land use, which covers an average of 30.51 per cent of the cluster surface in the local context and 26.34 per cent in the CMM context. Vacant lands account for 9.62 per cent of the cluster surface in the local context, while the percentage increases to 21.07 per cent in the CMM context. Other important land uses include public areas (24.77% and 20.23%), institutional areas (11.77% and 13.58%) and commercial spaces (19.49% and 10.69%), locally and in the CMM context, as shown in **Table 2** and **Table 3**.

IMPLEMENTATION OF NEW VEGETATED INFRASTRUCTURES

The results show that most of the significant "High-Low" DAs identified are predominantly occupied by residential, commercial and institutional lots, separated by public lots, primarily dedicated to roadways. These four land-use types exhibit the highest levels of low mineralization (**Table 2** and **Table 3**), making them promising targets for the implementation of new vegetated infrastructures through demineralization efforts. Numerous inspiring projects carried out on municipal lands demonstrate ways to increase vegetation cover in residential areas, notably through street narrowing to accommodate phytotechnological infrastructures, such as bioretention cells and vegetated swales, as well as permeable tree pits and curb extensions (Fortin Faubert et al., 2023). Narrowing street widths improves neighbourhood safety by reducing traffic speeds. In commercial and institutional areas, parking lots and paved schoolyards undeniably offer opportunities for implementing bioretention areas, replacing asphalt parking spaces with vegetated

TABLE 2. LAND USE TYPE AND CANOPY COVER IN "HIGH-LOW" CLUSTERS ACROSS LAVAL, IN A LOCAL CONTEXT.

LAND USE TYPE	LOW MIN	HIGH MIN	LOW VEG	HIGH VEG	AQUATIC	TOTAL
Agricultural	7 792 (0.04%)	965 (0.01%)	43 926 (0.25%)	10 227 (0.06%)	0 (0.00%)	62 910 (0.35%)
Commercial	2 208 961 -(12.40)	785 664 (4.41%)	315 920 (1.77%)	120 338 (0.68%)	41 318 (0.23%)	3 472 201 (19.49%)
Hydrography	1 931 (0.01%)	4 038 (0.02%)	981 (0.01%)	10 760 (0.06%)	929 (0.01%)	18 639 (0.10%)
Industrial	154 547 (0.87%)	84 735 (0.48%)	29 982 (0.17%)	7 151 (0.04%)	0 (0.00%)	276 415 (1.55%)
Institutional	860 780 (4.83%)	293 532 (1.65%)	620 716 (3.48%)	321 876 (1.81%)	151 (0.00%)	2 097 055 (11.77%)
Parks and recreation	38 644 (0.22%)	2 140 (0.01%)	160 759 (0.90%)	122 674 (0.69%)	2 430 (0.01%)	326 647 (1.83%)
Public	3 165 611 (17.77)	84 662 (0.48%)	893 981 (5.02%)	268 278 (1.51%)	257 (0.00%)	4 412 789 (24.77%)
Residential	1 836 112 (10.31)	1 536 589 (8.62%)	1 366 446 (7.67%)	696 255 (3.91%)	349 (0.00%)	5 435 751 (30.51%)
Vacant	299 757 (1.68%)	35 148 (0.20%)	673 499 (3.78%)	698 879 (3.92%)	7 483 (0.04%)	1 714 766 (9.62%)
Total	8 574 135 (48.12%)	2 827 473 (15.87%)	4 106 210 (23.05%)	2 256 438 (12.66%)	52 917 (0.30%)	17 817 173 (100.00%)

Values in each cell indicate the area (in m^2) of each land use type by canopy cover group (i.e., Land use type by canopy cover), and the values in parentheses present their respective percentage (%) within all significant "High-Low" DAs.

TABLE 3. LAND USE TYPE AND CANOPY COVER IN "HIGH-LOW" CLUSTERS ACROSS LAVAL, IN THE CONTEXT OF THE CMM.

LAND USE TYPE	LOW MIN	HIGH MIN	LOW VEG	HIGH VEG	AQUATIC	TOTAL
Agricultural	7 792 (0.15%)	965 (0.02%)	43 926 (0.87%)	10 227 (0.20%)	0 (0.00%)	62 910 (1.24%)
Commercial	351 594 (6.94%)	128 806 (2.54%)	39 949 (0.79%)	21 127 (0.42%)	0 (0.00%)	541 476 (10.69%)
Hydrography	128 (0.00%)	431 (0.01%)	158 (0.00%)	1 859 (0.04%)	350 (0.01%)	2 926 (0.06%)
Industrial	54 098 (1.07%)	40 079 (0.79%)	9 847 (0.19%)	3 768 (0.07%)	0 (0.00%)	107 792 (2.13%)
Institutional	270 512 (5.34%)	95 889 (1.89%)	196 974 (3.89%)	124 538 (2.46%)	0 (0.00%)	687 913 (13.58%)
Parks and recreation	20 404 (0.40%)	1 417 (0.03%)	108 171 (2.13%)	105 019 (2.07%)	1 628 (0.03%)	236 639 (4.67%)
Public	727 244 (14.35%)	13 792 (0.27%)	198 615 (3.92%)	85 483 (1.69%)	133 (0.00%)	1 025 267 (20.23%)
Residential	417 317 (8.24%)	411 836 (8.13%)	311 671 (6.15%)	193 812 (3.82%)	126 (0.00%)	1 334 762 (26.34%)
Vacant	131 125 (2.59%)	17 893 (0.35%)	412 214 (8.13%)	498 956 (9.85%)	7 483 (0.15%)	1 067 671 (21.07%)
Total	1 980 214 (39.08%)	711 108 (14.03%)	1 321 525 (26.08%)	1 044 789 (20.62%)	9 720 (0.19%)	5 067 356 (100.00%)

Values in each cell indicate the area (in m^2) of each land use type by canopy cover group (i.e., Land use type by canopy cover), and the values in parentheses present their respective percentage (%) within all significant "High-Low" DAs.

grid pavements, as well as creating grass-covered recreational spaces or planting trees (Clément et Ouellet Jobin, 2024; Fortin Faubert et al., 2023). In addition to increasing vegetation and enhancing the landscape, these types of intervention also help mitigate urban heat islands and support groundwater recharge through effective stormwater management (St-Laurent et Petridis, 2019). Although areas with high mineralization present greater challenges for transformation, implementing green roofs remains a viable and attractive solution for buildings (Fortin Faubert et al., 2023).

CONSERVATION AND EXPANSION OF EXISTING VEGETATED INFRASTRUCTURES

Although significant "High-Low" DAs were, on average, predominantly characterized by impervious surfaces, total vegetation coverage across the cluster area was slightly lower, averaging 35.71 per cent in the local context and 46.70 per cent in the CMM context (**Table 2** and **Table 3**). In most significant "High-Low" DAs, vegetation cover was primarily scattered throughout the residential landscape. However, many other DAs contain one or many very distinct green spaces alongside areas characterized by highly built-up areas. Six of the significant "High-Low" DAs (i.e., 24650371, 24650181, 24650155, 24650331, 24650646 and 24650162) were even primarily vegetated and surrounded by smaller mineralized environments (**Figure 8**). The presence of highly vegetated spaces within significant "High-Low" clusters can be explained by the analytical principle of the Local Moran's I, where these zones were identified due to their proximity to less vegetated areas. This contrast between vegetated and highly built-up neighbouring zones highlights the ecological significance of these green areas, as they may serve as critical hubs or corridors, supporting biodiversity and providing a wide range of ecosystem services. Due to their relative scarcity, the existing vegetated infrastructures within significant "High-Low" DAs play a crucial role and are of great importance for both expansion and conservation. What primarily vegetated DAs 24650371, 24650646 and 24650162 all have in common is that the primary land-use type of green areas is attributed to vacant lots (**Figure 9**). Other DAs with lower overall vegetation cover, such as 24650701, 24650649, 24650672, 24650647, 24650169, and 24650114, also include highly vegetated vacant lots. Since these DAs have been identified as requiring priority intervention, their distinct vegetated vacant lots present opportunities for decision-makers to transform them into institutional parks or public green spaces while enhancing accessibility and integrating them into broader urban networks, ensuring sustainable and equitable distribution of their ecological and social benefits (Albro, 2019; Anderson et Minor, 2017).

Vacant lots are often included in municipal economic development strategies due to their potential for local food production, job creation, increased property values and attracting new residents (Montréal, 2019;

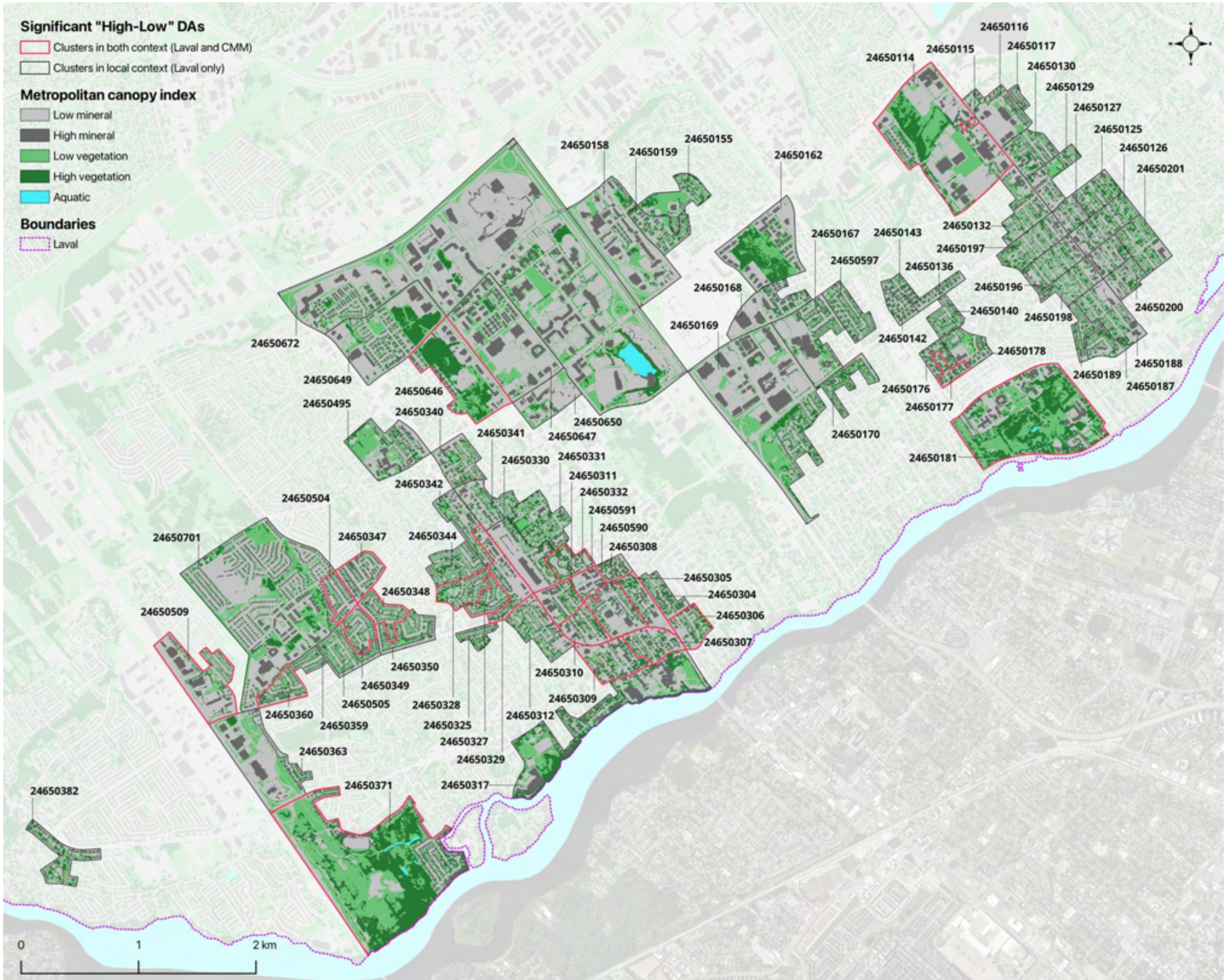

Figure 8. Significant "High-Low" DAs Overlaid on the Metropolitan Canopy Index.

Labels show the 2021 Census DAs codes. Spatial reference: NAD 1983 (CSRS) MTM Zone 8. Data sourced from the Metropolitan Canopy Index (CMM, 2021); Administrative Boundaries (MRNF, 2024); Dissemination Area (Statistics Canada, 2021a). Basemap credited to GrayLight, EsriCanada.

Pagano et Bowman, 2000). However, redeveloping some vacant lands permanently may not be feasible due to various constraints, such as physical factors (e.g., size, layout, location or slope), natural factors (e.g., flood risk, wetlands and protected areas) or technical factors (e.g., zoning or contamination) (Pagano et al., 2000). In such cases, it seems clear that the municipality should consider long-term management and conservation of existing vegetation as an attractive alternative for these underutilized areas (Fortin Faubert et al., 2022). One potential solution that was considered early on to address zoning constraints is the conversion of some of the many former golf courses in Laval into public parks or green spaces (Courrier Laval, 2024; Ducas, 2022). Although such an intervention would greatly assist CMM in achieving the goal of conserving 30 per cent of the metropolitan territory by 2030 (CMM, 2022b), the results of the Bivariate Local Moran's I analyses make it clear that the areas surrounding these vacant courses are not the ones requiring priority interventions in terms of equity.

Vacant and underutilized land presents a significant challenge for many Canadian municipalities, often remaining abandoned for decades due to soil contamination (FCM, 2015). Beyond remediation needs, these lands offer a unique opportunity to integrate vegetated infrastructures that provide a multitude of ecosystem services that contribute

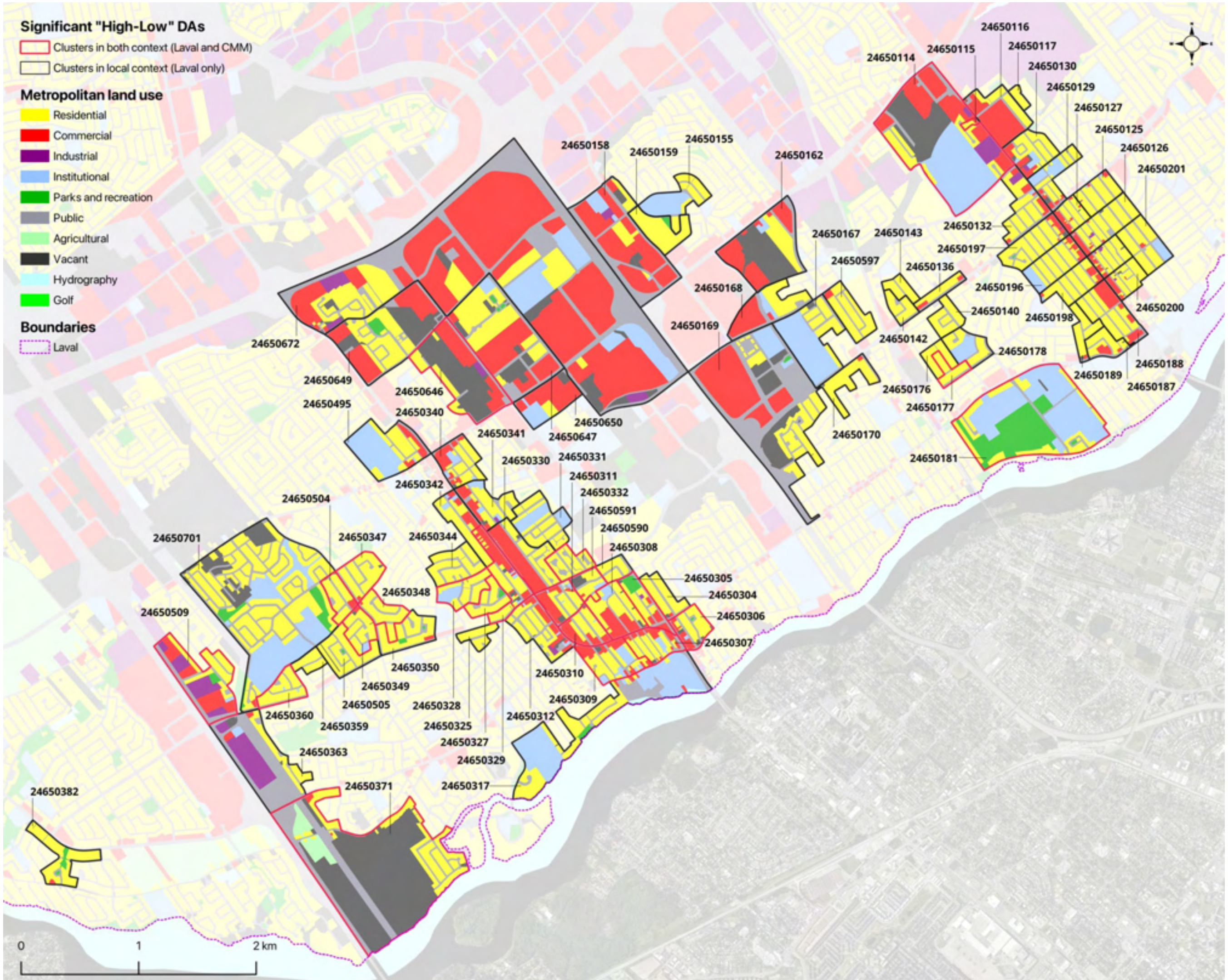

Figure 9. Significant "High-Low" DAs Overlaid on the Metropolitan Land Use.

Labels show the 2021 Census DAs codes. Spatial reference: NAD 1983 (CSRS) MTM Zone 8. Data sourced from the Metropolitan Land Use (CMM, 2022a); Administrative Boundaries (MRNF, 2024); Dissemination Area (Statistics Canada, 2021a). Basemap credited to GrayLight, EsriCanada.

to a more resilient and adaptive urban landscape. Phytoremediation and phytomanagement are nature-based solutions that not only contribute to soil remediation but also improve risk management (Fortin Faubert, Desjardins, et al., 2021; Fortin Faubert, Hijri, et al., 2021). By reducing surface runoff, vegetation cover limits contaminant leaching and mitigates pollution transfer to groundwater and adjacent aquatic ecosystems. Despite the ecological potential, converting contaminated vacant lots into public green spaces remains a complex process, often requiring extensive remediation efforts. Nevertheless, strategic investments for the management of these spaces could yield significant long-term benefits, including environmental sustainability, public health improvements and greater social equity.

Several institutional lands and public parks within the significant "High-Low" DAs already contribute to the sustainability of green spaces in Laval's marginalized neighbourhoods. However, the growing trend of installing playgrounds with synthetic surfaces, as observed in DAs 24650169, 24650167, 24650114, 24650201, 24650178 and 24650317, raises concerns about their long-term environmental and ecological impacts (Barnes et Watkins, 2022; Ignatieva et al., 2024). While synthetic surfaces offer durability and require minimal maintenance, they fail to provide critical ecosystem services, including carbon sequestration, air purification and water infiltration. Moreover, their heat-absorbing properties exacerbate urban heat islands, particularly in areas with limited natural vegetation. Replacing natural green spaces with synthetic alternatives also reduces habitat availability for local biodiversity, further fragmenting ecosystems (Monteiro, 2017). Therefore, careful consideration is needed to weigh the functional advantages of synthetic surfaces against their environmental drawbacks, especially in neighbourhoods already facing ecological pressures due to limited vegetation cover.

IMPLICATIONS FOR GREEN INFRASTRUCTURE PLANNING

Although protection of natural areas, greening and demineralization of living environments are already part of or in the process of being integrated into Laval's practices, the city's most recent climate plan does not address issues of equity and climate justice (Ville de Laval, 2023). Based on the results of this study, Laval's policy-makers should strongly consider implementing additional vegetated infrastructures or prioritizing the conservation and expansion of existing ones, particularly in the significant "High-Low" regions identified through the Bivariate Local Moran's I analysis, in order to improve the equitable distribution of vegetation.

If the municipality decides to act on any or all of these suggestions, it should account for certain considerations to ensure the project's effectiveness. Urbanization impacts on green land cover are not exclusive to built-up environments, but also include the replacement of natural landscapes with designed green spaces (Wu et al., 2023). Results from previous studies indicate that residents obtain greater benefit from natural "wildness" of urban green spaces (Colley et al., 2016; Wu et al., 2023). As such, it may be subsequently beneficial to open the vacant lots for public access and clean them up without over-intervening (Éco-pivot, 2024). The concept of "naturalness" is very easily pointed out and differentiated by people with numerous backgrounds. People can easily identify landscapes including "biotic and hydrological components (or green/blue features)" to be natural, whereas buildings and parking lots are not (Colley et al., 2016). However, the observers were also able to differentiate "artificial" naturalness from true nature as well, and many reported an affinity to the "wildness" of the true nature rather than the "neat and tidy aesthetic in open spaces" (Colley et al., 2016).

LIMITATIONS

As with all spatial analyses, there are limitations to this study that should be considered. Firstly, with the use of statistical boundaries (in this case, DAs) comes the consideration of the modifiable areal unit problem (MAUP) or Openshaw Effect, where results of aggregated data are highly dependent on the zonation scheme and scale of zonation. The results of this analysis will change if the scale is changed from dissemination area to the larger census tract. Of particular concern is the zone problem of the MAUP. Statistical boundaries are not uniform, designed to maintain a consistent range of population size and are enacted without consideration of natural features. The zonation scheme designed to organize population can artificially subdivide patches of green spaces that span the boundaries of two or more zones. Another limitation to consider is that this study focuses solely on the percentage of total vegetation cover within neighbourhoods. It therefore does not account for the percentage of high or low canopy cover, nor does it address access to green spaces in terms of walkability or workplace greenery, which can also significantly influence mental health and overall wellness among residents. Further research is needed to explore if these variables are equitably distributed across the city of Laval.

CONCLUSION

This study highlights the environmental inequities in the distribution of total vegetation cover within the city of Laval. The results show a significant correlation between total vegetation cover and marginalization scores, underscoring marked environmental inequities. The most marginalized neighbourhoods, often located near the city centre, have less vegetation cover, while less densely populated and less marginalized areas, particularly in northern Laval, benefit from greater vegetation cover.

Recognizing the importance of environmental equity in urban planning and the need for targeted strategies to improve vegetation distribution in marginalized neighbourhoods is crucial. To address these inequities and improve environmental equity, it is essential to implement targeted interventions aimed at increasing vegetation cover in marginalized areas. This intervention includes implementation of new green infrastructures and conservation and expansion of existing ones. This can be achieved by prioritizing nature-based solutions, notably through demineralization projects and phytotechnologies. Decision-makers should also promote natural green spaces over artificial alternatives to maximize ecological and social benefits. By adopting these recommendations, the city of Laval and the CMM can move toward a more equitable distribution of vegetation, thereby enhancing urban resilience and the wellbeing of all its residents.

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ANNEX

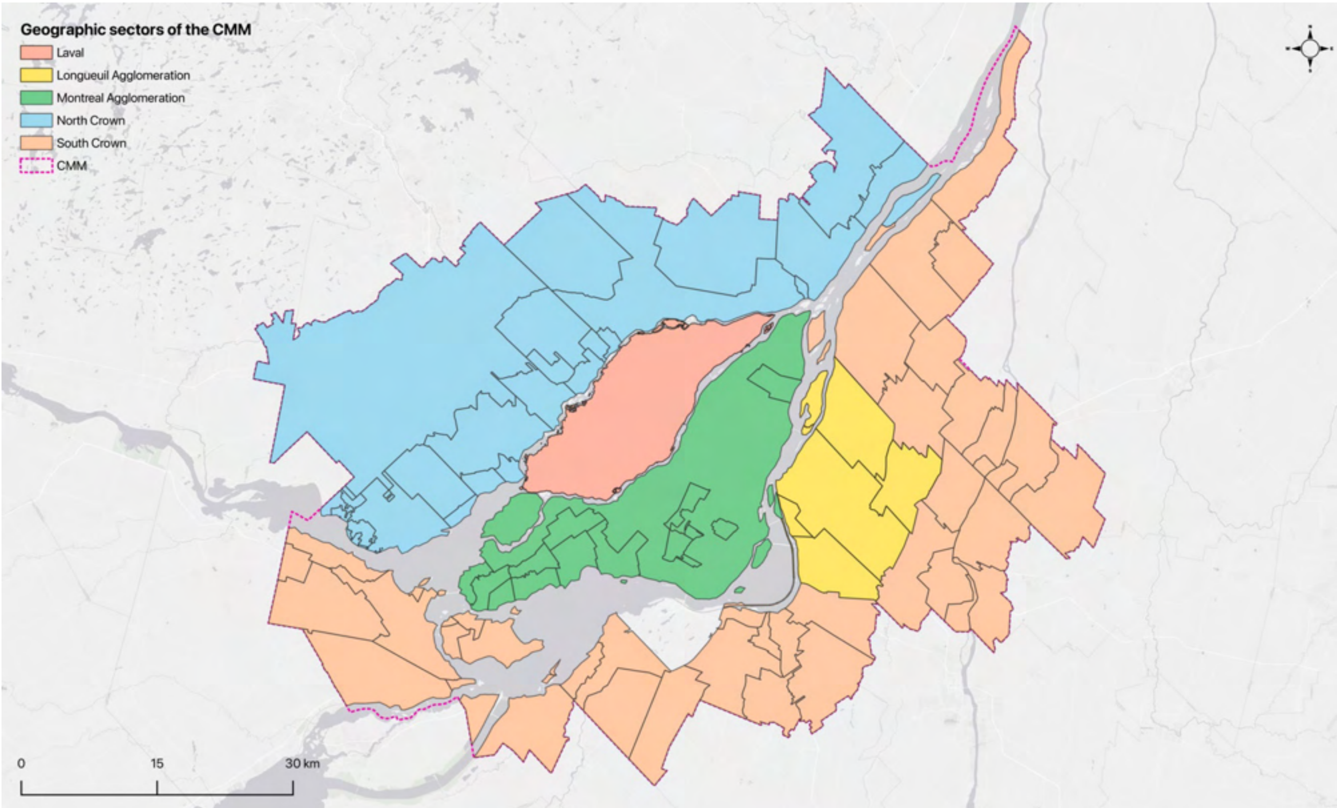

Figure S1. Geographic sectors of the CMM.

Spatial reference: NAD 1983 (CSRS) MTM Zone 8. Data sourced from the Administrative Boundaries (MRNF, 2024). Basemap credited to GrayLight, EsriCanada.

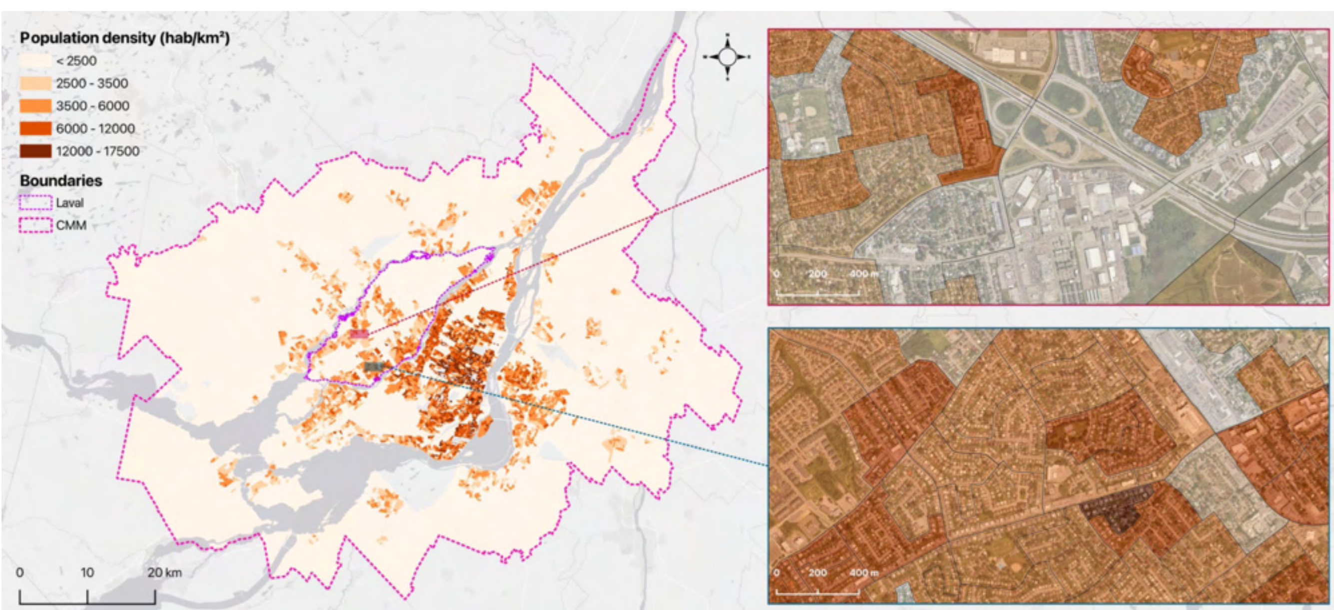

Figure S2. Population Density, with two zoomed-in samples across Laval.

Spatial reference: NAD 1983 (CSRS) MTM Zone 8. Data sourced from the Canadian Marginalization Index (Statistics Canada, 2021b); Dissemination Area (Statistics Canada, 2021a). Basemap credited to GrayLight, EsriCanada.

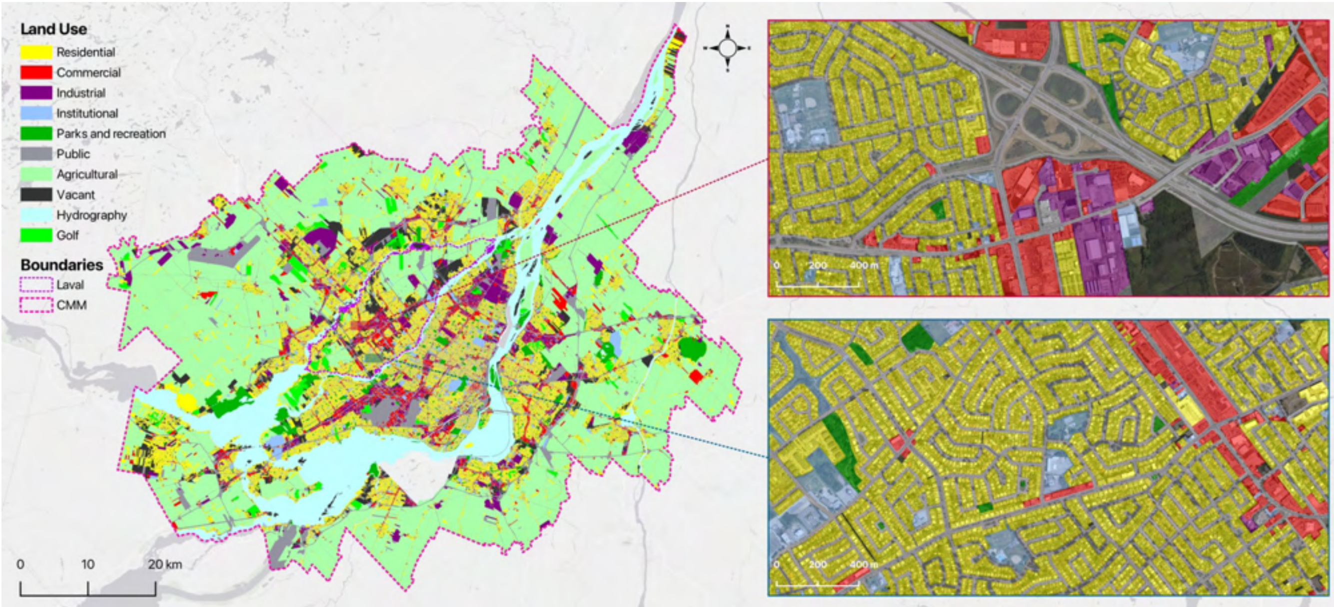

Figure S3. Metropolitan Land Use, with two zoomed-in samples across Laval.

Spatial reference: NAD 1983 (CSRS) MTM Zone 8. Data sourced from the Metropolitan Land Use (CMM, 2022a). Basemap credited to GrayLight, EsriCanada.

Equitable distribution of vegetation cover across Laval

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