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SPATIAL PATTERN OF SUSTAINABLE URBAN DEVELOPMENT INDICATOR FOR THE MONTREAL URBAN COMMUNITY

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Abstract. The City of Montreal initiated a First Strategic Plan for Sustainable Development in 2005 followed by a Community and Corporate Sustainable Development Plan in 2010–2015. This study proposes a sustainable urban development indicator (SUDI) for each Montreal Urban Community (MUC) to evaluate the achievements of sustainable development plans. This study identifies thirty-two variables as the attributes of sustainable urban development. The multivariate technique and Exploratory Spatial Data Analysis are applied to determine the spatial pattern of SUDI for each MUC. The spatial pattern of SUDI identifies that Ville Marie, Verdun, Sud-Ouest, Mercier-Hochelaga-Maisonneuve and Plateau Mont-Royal have strong sustainable development. The findings of this study help the City of Montreal to understand the improvement of the sustainable development plans for Montreal city and to distribute the municipal budget for the community benefits accordingly.

Keywords: community development, spatial data analysis, Moran's I, multivariate technique, sustainability, GIS.

Introduction

The city is a dynamic mechanism of urban system. This urban system not only supports the economic activities and development but also contains cultural, social and environmental characteristics. The cities are essential for creating the development aspirations and demands of national interests (Bentivegna *et al.* 2002). The resulting competition for economic development and indiscriminate urbanisation causes significant consumption of natural resources in cities. In the developed countries, around 6–10 tons of building materials are used per person per day and 75% of total energy is consumed in the use of built environment (BRE 1996, Bentivegna *et al.* 2002). Although many cities are attaining targeted economic development, they become unsustainable because of degrading and inefficient infrastructures, dysfunctional social environments and a wealth-oriented urban economy (Ekins, Cooper 1993). A growing concern on environmental degradation has urged urban planners and policy makers to think carefully about sustainable urban development.

The urban municipalities require an indicator of sustainable urban development (SUD) for managing their urban systems and supporting development in a sustainable manner. A significant barrier to determine whether or not different parts (e.g. urban communities or districts) of a city are achieving sustainable development is the absence of an effective methodology for measuring sustainable urban development (Maclaren 1996). The failure to develop an effective methodology for sustainable urban development indicator (SUDI) aggravates urban sprawl and propagates 'sustainability' problems of inner and outer regions of a city.

The traditional efforts, to attain the sustainable urban life, priorly focused on the protection of environmentally sensitive areas and on the construction of waste treatment facilities (Huang *et al.* 1998). Several researches defined the SUDI (Shen, Guo 2014; Huang *et al.* 1998; Roseland 1991). Shen and Guo (2014) estimated the spatial distribution of urban sustainability for the city of Saskatoon and identified the spatial disparity in economic and environmental factors. Shen and Guo (2014) spatially analysed the cluster patterns in inner-city neighbourhoods and sub-urban areas with respect to environmental, house, socio-political, household, mixed land use, quality of life, urbanization and urban sustainability indices. Shen and Guo (2014) ignored the several significant characteristics of urban system such as transportation, social and community development and waste management system. Huang *et al.* (1998) identified several urban sustainability indicators with respect to natural system, agricultural system, water resources, urban system, life-support services, import resources, urban production, waste treatment, resource recycling and environmental management. They mathematically aggregated the standardised value of indicators to estimate the urban sustainability index, however different indicators have different units of measurement. Huang *et al.* (1998) proposed a signal lighting system for displaying the current situation and trend of the above-mentioned urban development indicators. These indicators are mainly associated with the environmental system and focus little attention on the urban system. Huang *et al.* (1998) also failed to define a unique SUDI and a target value for each indicator. Vega-Azamar *et al.* (2013) estimated the energy consumption as the sole indicator of environmental sustainability of Montreal Island, Canada and compare the Montreal Island with nine cities. Moreover, they didn't explain the criteria of selecting nine cities and the reason to compare these nine cities with the Montreal Island on the basis of energy consumption. Braat (1991) defined two types of sustainability indicators such as predictive and retrospective. The predictive indictor provides direct information on the future state and development of relevant socio-economic and environmental variables. The retrospective indicator provides information on the effectiveness of existing policies.

A measure of SUDI should include other urban characteristics such as economic characteristics, demographic characteristics, social and community characteristics, accessibility to different facilities and urban amenities and affordable urban housing.

The City of Montreal initiated its First Strategic Plan for Sustainable Development 2005–2009, followed by a Community and Corporate Sustainable Development Plan (CCSDP) 2010–2015. The CCSDP 2010–2015 aims to improve air quality and reduce greenhouse gas emissions; ensure a better quality of life; manage resources; build the economy in a sustainable manner; and protect the biodiversity, natural environments and green spaces. Beyond the principles of CCSDP 2010–2015, the City of Montreal is implementing different environmental actions such as compensation system for zero-carbon business travel, reduce heat islands, organise the environmentally responsible events and so on. These community-level strategies that are very effective to attain SUD are not capable of accommodating the big and comparative picture of the Montreal urban community (MUC). A comprehensive structure of SUDI is required to evaluate the performance of the strategies undertaken by the City of Montreal and to coordinate the implementation of SUD initiatives at the MUC level.

This study calculates a SUDI for each MUC to evaluate the achievement of sustainable development of MUC in terms of its existing urban and development policies. This study applies retrospective variables of SUD (Huang *et al.* 1998) considering the complex interaction between the living environment, life-styles and standard urban development.

Methodology

Variables of sustainable urban development indicator

The SUD is defined not only by the improvement of environmental quality and the construction of waste treatment facilities but also by the integration of economy, society, urban facilities and urban environment. Roseland (1991) identified the transportation management, land use planning and housing, energy conservation, waste reduction and recycling, community liveability and sustainable administration as the significant factors of sustainable development for North American cities. The Sustainable Seattle (1993) has been operated as a voluntary network and civic forum to (1) assess the progress of Seattle toward long term sustainability; (2) identify the key steps to improve their progress; and (3) make those changes practical. The Sustainable Seattle (1993) selected forty indicators defining sustainability as a long term cultural, economic, environmental health and vitality. Maclaren (1996) developed urban sustainability indicators assuming sustainability as the specified level of social objectives such as environmental pressure, urban productivity, and services of natural capitals, etc. The BEQUEST (Hamilton *et al.* 2002) attempted to provide easy access to relevant and structured generic information of SUD by framing four main dimensions of urban development such as development activity, environmental and social issues, spatial level and timescale into a single frame (Hamilton *et al.* 2002, Hamilton *et al.* 2002). The development activities are planning initiatives, property development and urban infrastructure maintenance. The environmental and social issues are environmental pollution, depletion of natural resources, loss of biodiversity, lack of access to urban facilities, inadequate safety and security, poor health and well-being of urban dwellers, lack of social and community participation (Hamilton *et al.* 2002, Bentivegna *et al.* 2010).

This study categorises the variables of SUDI into three components such as driving forces, effect and response (Fig. 1). The 'driving forces' are the amounts and rates of inflow sources both from life support environments and the external economic system to the urban economic system. The 'effect' attributes of SUDI are population, urban facilities, housing, environmental quality changes, etc. The 'response' variables are public and community organisations. This study considers thirty-two variables of urban development criteria to estimate the SUDI of MUC (Fig. 1).

The demographic parameter includes the population density (persons/sq. km), percentage of 15–24 years aged population having a high school diploma degree and percentage of 25–64 years aged population having a high school diploma degree.

The economic parameter includes the percentage of employment concentration, percentage of employment establishment concentration, annual average household income (CAD) and proportion of low income people (annual average household income less than CAD $20,000).

The social and community parameter includes the percentage of annual public expenditure on leisure and culture, total number of community and social organizations per 1000 population, total number of organizations for disabled people per 1000 population and crime rate per 1000 population.

The transportation parameter mainly focuses on the mass transit and non-motorized modes. Transportation facilities are represented by the mobility status of Montreal commuters 5 years ago; percentage of labour force (15 years and above age) commuting by public transport, walking and bicycle; percentage of road network with bicycling provision; percentage of total population within 400 meters of a metro or bus station; and percentage of annual public expenditure on transportation and road maintenance.

Urban services and facilities include the number of housing and/or apartments per 1000 population; total

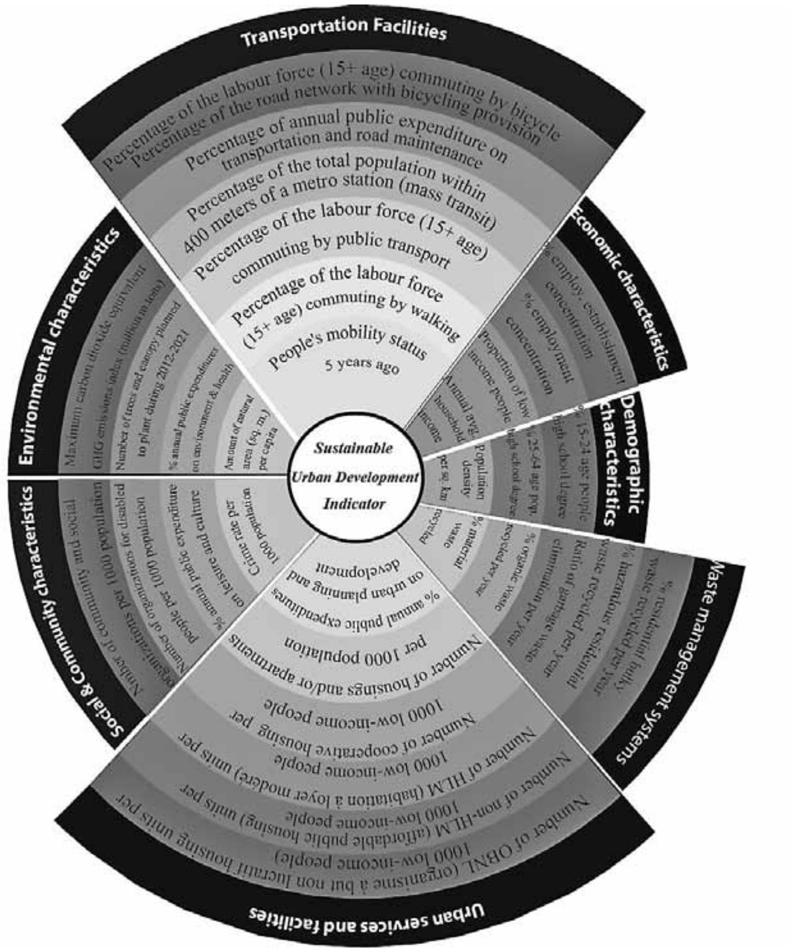


Fig. 1. Variables of sustainable urban development indicator

number of habitation à loyer modéré (HLM) units per 1000 low-income people; total number of organisme à but non lucratif (OBNL) housing units per 1000 low-income people; total number of cooperative housing units per 1000 low-income people; total number of non-HLM (affordable public housing) units per 1000 low-income people; percentage of annual public expenditures on urban planning and development; and percentage of total population within 400 meter of a primary school, medical centre, and emergency shelter.

The environmental parameter includes the total amount of natural area (sq. m.) per capita; percentage of annual public expenditures on environment and health; total number of trees and canopy planned to plant during 2012–2021; and maximum carbon dioxide equivalent (CO2 e) greenhouse gas (GHG) emissions index (million metric tons).

The waste management criteria includes the percentage of material waste recycled per year, percentage of hazardous residential waste recycled per year, percentage of residential bulky waste recycled per year, percentage of organic waste recycled per year and the ratio of garbage waste elimination per year (kg/person/year)

Data collection and manipulation

Data on the selected variables for each MUC were collected from its administration. Data on emergency shelters, medical centres and primary schools were taken from Tamima and Chouinard (2012). Data on Carbon oxide, Nitrogen oxide and Ozone at different air record stations within the MUC were collected from the Réseau de surveillance de la qualité de l'air of the City of Montreal. Since Methane (CH4) contributes to the growing global background concentration of tropospheric Ozone (O3), data on ozone were assumed to be representative of methane. The 100-year 'Greenhouse Warming Potential (GWP)' of GHGs such as 1 for CO2, 310 for nitrous oxide and 21 for methane was expressed as a CO2e GHG emissions index.

The CO2e GHG emissions index of air record stations was spatially interpolated to determine the CO2e GHG emissions index for each MUC. This study applied geo-statistics extension tool of ArcGIS for spatial interpolation of the CO2e GHG emissions index assuming that emission data are purely spatial (Szentimrey *et al.* 2007). The spatial data interpolation of CO2e GHG emissions index was performed by calculating an experimental variogram. The variogram describes the spatial relationship between the sample values using a function that relates the variance to the distance of sample separations (Ciotoli *et al.* 2007).

There are various deterministic (e.g. inverse distance weighting, splines and different trend surface analyses) and stochastic (e.g. simple kriging, ordinary kriging, modified residual kriging, co-kriging, universal kriging and residual kriging) approaches of spatial interpolation (Dyras, Ustrnul 2007). The inverse distance weighting (IDW) gives more weight to the closest samples and less weight to samples located farther away. The weight for each estimate is inversely proportional to the power of the distance between the sample points (Erxleben *et al.* 2002; Isaaks, Srivastava 1989). The Kriging uses spatial dependencies of the measured values. In contrast to ordinary kriging, co-kriging considers multiple secondary variables to estimate values at un-sampled locations (Erxleben *et al.* 2002). The small-scale (local) variation or the residuals from the trend surface are modelled by using kriging and co-kriging techniques, while large scale (local) spatial variability is modelled by modified residual kriging (Erxleben *et al.* 2002). This study cross-validated the IDW and Kriging models to find the best model for the spatial interpolation of CO2e GHG emissions index.

To determine the best fitting model for the spatial interpolation of CO2e GHG emissions index, the residuals from the cross-validation procedure were used. The cross-validation procedure involved the computation of mean error (ME), root mean-squared error (RMSE), mean absolute error (MAE) and goodness-of-prediction (G-value). The smallest MAE identifies the model having the most accurate local or small-scale estimates. The RMSE determines the model's accuracy for global or large scale estimation (Schloeder *et al.* 2001). The G-value is a measure of the effectiveness of results generated from the model relative to an estimate using only the sample mean. The negative values indicate that the mean would have provided a more accurate estimate.

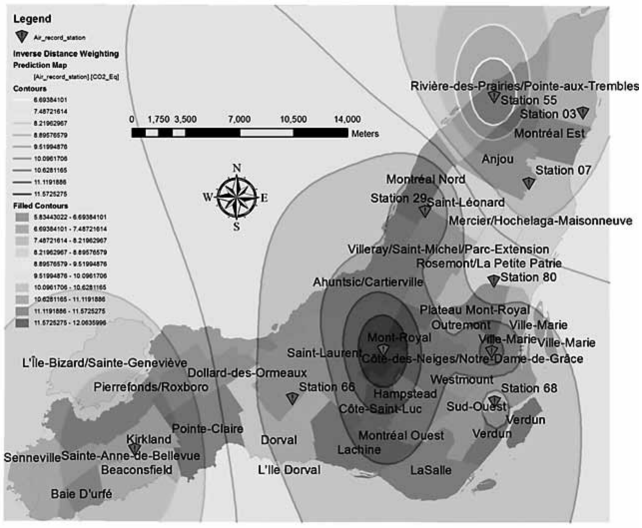


Fig. 2. Geo-statistical analysis of CO2e GHG emissions index (million metric tons)

This study identifies that the IDW is the best fitted spatial interpolation model for the CO2e GHG emissions index based on the RMSE (i.e. 1.761 for IDW and 2.611 for Kriging), MAE (i.e. 0.2924 for IDW and 0.0048 for Kriging) and R-square (i.e. 0.12 for IDW and 0.02 for Kriging). The spatial interpolated CO2e GHG emissions index for MUC is shown in Figure 2.

Calculation of Sustainable Urban Development Indicator (SUDI)

The principal component analysis (PCA) of multivariate analysis techniques was applied to estimate the SUDI for each MUC. The PCA analyses the interrelationships among a large number of variables and to explain these variables in terms of their common underlying dimensions (Hair 1992). The PCA transforms the data to a new set of coordinates that are a linear combination of the original variables.

The SUDI for each MUC was calculated by multiplying the categorical value of each variable, proportion of variance explained by each variables and proportion of variance explained by each factor. The categorical value of each variable was estimated because the unit of each variable was different and that might create the complexity for calculating the SUDI. The value of each variable was equally categorised into five categories – very low (0.2), low (0.4), medium (0.6), high (0.8) and very high (1).

The sustainability of urban development for a particular MUC is not only determined by its SUDI but also is influenced by the sustainable development of the neighbouring communities. For example, a particular urban community may stabilise its population through growth management although there may be a tendency toward increasing population at the city level. The exploratory spatial data analysis (ESDA) was used to investigate the spatial pattern of SUDI for MUC. The general objective behind these techniques is to examine the spatial variation (spatial auto-correlation) among SUDI of different spatial locations (neighbourhood observations). An n-by-n binary geographic connectivity/weights matrix can identify these neighbouring values. The positive spatial autocorrelation means that geographically proximal values of SUDI are suitable to be analogous on map, for example urban communities with high-value of SUDI tend to be located near to similar communities.

The spatial autocorrelation was estimated by applying the Pearson correlation coefficient (Eq. (1)). The left-hand expression of Equation (1) converts to the right-hand one by substituting y for x, computing the numerator term only when a 1 appears in matrix **C** and averaging the numerator cross-product terms over the total number of pairs denoted by a 1 in matrix **C**. The denominator of the revised expression (Eq. (1)) is the sample variance of Y e.g. s_Y^2.

$$\frac{\sum_{i=1}^{n}\left(x_i-\bar{x}\right)\left(y_i-\bar{y}\right)/n}{\sqrt{\sum_{i=1}^{n}\left(x_i-\bar{x}\right)^2/n}\sqrt{\sum_{i=1}^{n}\left(y_i-\bar{y}\right)^2/n}} \text{ becomes}$$

$$\left[\frac{\sum_{i=1}^{n}\sum_{j=1}^{n}c_{ij}\left(y_i-\bar{y}\right)\left(y_j-\bar{y}\right)/\sum_{i=1}^{n}\sum_{j=1}^{n}c_{ij}}{\sqrt{\sum_{i=1}^{n}\left(x_i-\bar{x}\right)^2/n}\sqrt{\sum_{i=1}^{n}\left(y_i-\bar{y}\right)^2/n}}\right]. \quad (1)$$

The right hand part of Equation (1) is known as the Moran's *I*. Similar to a correlation coefficient, the values of Moran's *I* range from +1 (meaning strongly positive spatial autocorrelation) to 0 (meaning a random pattern) and to –1 (indicating strongly negative spatial autocorrelation). Moran's *I* for a spatial proximity matrix w_{ij} for a variable y at location i is defined by Equation (2) (Anselin 1998). Usually, the proximity matrix w_{ij} is everywhere 0 except for contiguous locations i and j, where it takes the value 1.

$$I=\frac{n\sum_{i=1}^{n}\sum_{j=1}^{n}w_{ij}(y_i-\bar{y})(y_j-\bar{y})}{\left(\sum_{i=1}^{n}(y_i-\bar{y})^2\right)\left(\sum\sum_{i\neq j}w_{ij}\right)}. \quad (2)$$

Multivariate analysis of variables of sustainable urban development indicator

The first step of performing PCA was to assess the data suitability. The pattern of relationships among variables was identified from the correlation matrix, determinant of correlation, total variance (before and after rotation) and the component matrix (before and after rotation).

Based on the correlation matrix of the final iteration process, this study identified that all variables of SUDI are strongly correlated except in the case of 'annual average household income', 'percentage of total population within 400 meters of an emergency shelter' and 'natural area (sq. m) per capital'.

The 'Eigenvalues' associated with linear components (factor) before extraction, after extraction and after rotation were evaluated. The 'Eigenvalues' represent the variance explained by the linear component. If the total variance of each test is unity, the 'Eigenvalues' of the first factors have the theoretical maximum equal to the number of tests (Kinnear, Gray 2009). The first factors have the greatest sums and thus account for the greatest part of the total variance. Table 1 illustrates that the first seven factors explain 83.53% of variance and have eigenvalues greater than 1. The rotated sum of squared loading, representing the effects of optimising the factor structure, was examined to equalise the relative importance of the seven factors. The rotation sums of squared loadings indicate that 23.92% of the total variance is explained by first factor, followed by 14.79% of the variance by second factor, 14.19% of the variance by third factor and 13.54% of the variance by fourth factor (Table 1).

The communality of each variable, which is the total proportion of variance accounted for the extracted factors, was calculated by the squared multiple correlations among the test and the factors emerging from the PCA (Kinnear, Gray 2009). The extracted column represents the common variance shared by the variables. For example, 82.8% of the variance associated with 'population density' is common or shared (Appendix). The resulting communalities suggest that these thirty-two variables describe the main characteristics of the SUDI for the MUC (Appendix).

After factor extraction, it was difficult to interpret the factors on the basis of their factor loadings.

Table 1. Total variance explained by factors

	Initial Eigenvalues		Extraction Sums of Squared Loadings		Rotation Sums of Squared Loadings	
Factors	**Total**	**% of Variance**	**Total**	**% of Variance**	**Total**	**% of Variance**
1	13.97	38.79	13.97	38.79	8.61	23.92
2	5.55	15.42	5.55	15.42	5.32	14.79
3	4.23	11.75	4.23	11.75	5.11	14.19
4	2.1	5.83	2.1	5.83	4.88	13.54
5	1.61	4.49	1.61	4.49	3.02	8.39
6	1.52	4.22	1.52	4.22	1.77	4.92
7	1.09	3.03	1.09	3.03	1.36	3.79

Table 2. Extracted variables within the four groups of factors

Factors	Variables
1st factor (F_1)	Percentage of employment concentration, percentage of employment establishment concentration, crime rate per 1000 population, percentage of labour force (15 years and above age) commuting by walking, number of housing and apartments per 1000 population, total number of HLM housing per 1000 low-income people, total number of OBNL housing per 1000 low-income people, total number of cooperative housing per 1000 low-income people, total number of non-HLM per 1000 low-income people, percentage of total population within 400 meters of a medical centre and percentage of annual public expenditure on urban planning and development
2nd factor (F_2)	Percentage of 15-24 years age population having high school diploma degree, proportion of low income people, maximum CO2e GHG emissions index, percentage of material waste recycled per year, percentage of hazardous residential waste recycled per year, percentage of residential bulky waste recycled per year and percentage of garbage waste elimination per year
3rd factor (F_3)	Annual average household income, total number of community and social organizations per 1000 population, total number of organizations for disabled people per 1000 population, percentage of road network with bicycling provision, percentage of total population within 400 meters of an emergency shelter and natural area per capital
4th factor (F_4)	Population density, percentage of person's mobility status 5 years ago, percentage of labour force (15 years and above age) commuting by public transport, percentage of labour force (15 years and above age) commuting by bicycle, percentage of annual public expenditure on transportation and road maintenance and percentage of total population within 400 meters of a primary school
5th factor (F_5)	Percentage of 25–64 years age population having high school diploma degree, percentage of annual public expenditure on leisure and culture and total trees and canopy planned to plant during 2012-2021
6th factor (F_6)	Percentage of annual public expenditure on environment and health and percentage of organic waste recycled per year
7th factor (F_7)	Percentage of total population within 400 meters of a metro or bus station (mass transit)

The criterion used for the PCA indicates that the first factor accounts for the maximum part of the variance. This often ensures that most variables have high loadings on the most important factor and small loadings on all other factors (Habing 2003). Thus, the interpretation of the factors was very difficult. The 'factor rotation' was performed to alter the pattern of the factor loadings and to improve the interpretation. The process of rotation changes the 'Eigenvalues' of the factors that have been extracted so that the common factor variance explained by the extraction is more evenly distributed among the rotation factors. It is possible to make clusters of variables load optimally by orthogonal rotation along the axes. The communalities of the variables are unchanged by rotation because their values depend only upon the number of factors and the correlations among the tests (Kinnear, Gray 2009). The variable 'population density' is highly correlated (0.74) with the first factor before the rotation but it is highly correlated (0.8) with the forth factor after the rotation (Appendix). Moreover, most of the variables are loaded quite strongly (above 0.5) on the first factor for the unrotated factor matrix but seven of them are quite equally loaded in the rotated factor matrix since the variables are clustered optimally (Appendix).

Thus the rotation of the factor structure clarified the relationships considerably. Seven factors of SUDI were extracted from thirty-two variables based on the multivariate analysis. These seven factors explain 83.53% of the initial information (Table 2).

Spatial pattern of sustainable urban development indicator

The urban communities such as Ville Marie, Verdun, Sud-Ouest, Mercier/Hochelaga-Maisonneuve, Plateau Mont-Royal, and Rosemont/La Petite Patrie have the highest values of SUDI (Fig. 3). This implies that these MUCs have development with strong sustainability that means these communities put emphasis on environmental scale over economic gains. The urban communities such as Pierrefonds/Roxboro, Lachine, LaSalle, Côte-des-Neiges/Notre-Dame-de-Grâce, Outremont, Ahuntsic/Cartierville, and Villeray/Saint-Michel/Parc-Extension are good enough to ensure SUD (Fig. 3). On the other hand, Sainte-Anne-de-Bellevue, Senneville, Saint-Laurent, Montréal Nord, Saint-Léonard, Anjou, and Rivière-des-Prairies/Pointe-aux-Trembles are performing moderately well with respect to SUD. These urban communities can likely improve their situation by using the SUD plans of the City of Montreal.

On the other hand, the SUDI values for Dollard-des-Ormeaux, Kirkland, Côte-Saint-Luc, Hampstead and Montreal-East urban communities is within the range of 0–1.78 implying weak sustainability with the idea that natural capital can be used up as long as it is converted into manufactured capital of equal value (Fig. 3). The urban communities with low values of SUDI have not yet attained the goals of the SUD plans of City of Montreal. These communities are forming a spatial cluster that geographically defines their spatial relationship. The SUDI of an urban community has

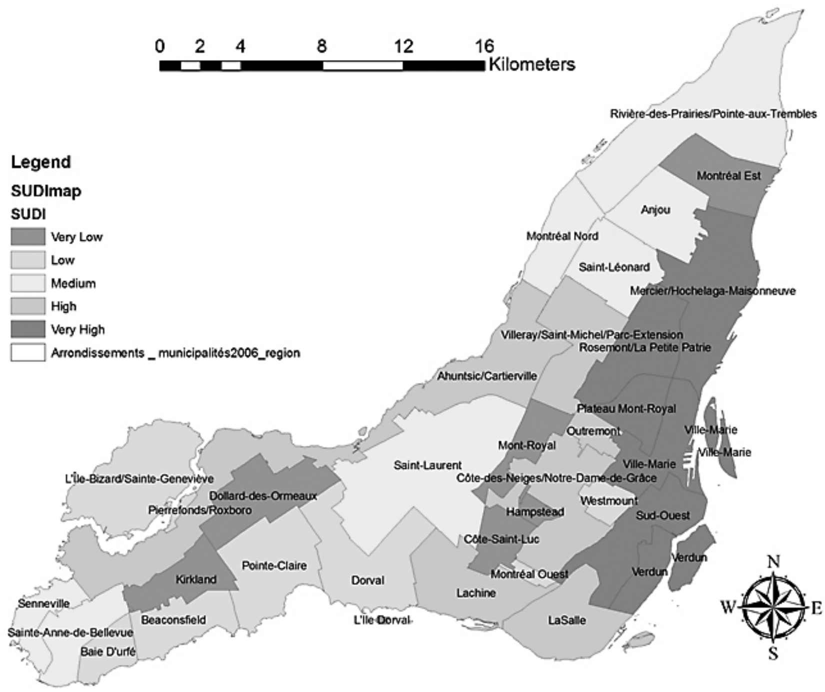


Fig. 3. Sustainable urban development indicators for the Montreal urban community

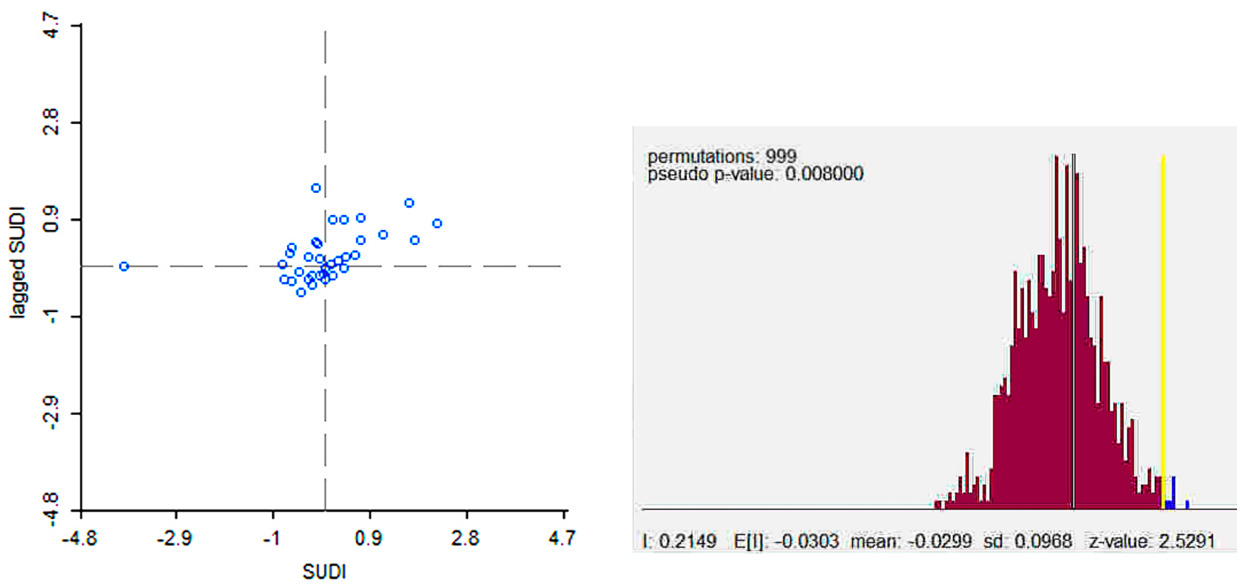
significant neighbourhood impact on that of other urban communities. The urban planners, policy makers and city councillors need to take necessary actions to ensure SUD at the MUC. The city councillors and urban planners can undertake some strategic plans to improve these weak sustainability regions.

The Moran's *I* was calculated using GeoDa software by means of the global spatial autocorrelation statistic. The four quadrants in the 'Moran scatter plot' provide a classification of four types of spatial autocorrelations within two broader categories such as positive and negative spatial autocorrelations. The positive spatial autocorrelation consists of high-high (upper right) and low-low (lower left) correlations; and the negative spatial autocorrelation consists of high-low (lower right) and low-high (upper left) correlations of the 'Moran scatter plot' (Fig. 4a).

The spatial weights are essential for the computation of spatial autocorrelation statistics. In GeoDa, they are also used to implement spatial rate smoothing. The weights were constructed based on contiguity from polygon boundary files (original layout or a set of Thiessen polygons). The Rook Contiguity based spatial weights that only use common boundaries to define the neighbours were created.

The Moran's *I* of the SUDI for the MUC shows that there is a positive spatial autocorrelation (0.22) among the urban communities (Fig. 4a). The Inference for Moran's *I* is based on a permutation approach, in which a reference distribution is calculated for spatially random layouts with the same data (values) as observed. The randomisation uses an algorithm to generate spatially random simulated data sets (Anselin 1986). This study uses 999 times permutations and the pseudo significance level is 0.008 (Fig. 4b). The pseudo significance level is computed as the ratio of the number of statistics for the randomly generated data sets that were equal to or exceeded the observed statistic + 1 over the number of permutations used + 1.

The positive spatial autocorrelation reveals that each MUC has positive influence on its neighbours and the urban communities with good sustainable records are clustering together. The adaptation of sustainable urban development plan by a MUC encourages the near-by urban communities to adapt the plan. These spatial patterns help the City of Montreal to understand the level of sustainability achieved by each MUC and the neighbourhood effects of a community on others. City of Montreal can invest in the development of a MUC with an intention not only to improve the scale of sustainability of that particular MUC but also to make significant contribution to the neighbouring communities achieving strong sustainability. Moreover, the City of Montreal can include SUDI in the investment decisions on urban infrastructure. For example, road infrastructure budget can be prepared for maximizing not only the infrastructure condition but also the SUDI of urban communities under the budget constraints.



4(a) Moran's *I* of SUDI

4(b) Randomization of Moran's *I*

Fig. 4. Spatial autocorrelation and pseudo significance level

Conclusions

The sustainable urban development (SUD) is a major challenge for every city including all sub-systems of urban organisation. The City of Montreal is committed to ensure sustainable development by implementing the Montreal Community Sustainable Development Plans. The City of Montreal initiated its' First Strategic Plan for Sustainable Development in 2005 followed by a Community and Corporate Sustainable Development Plan in 2010. The Community and Corporate Sustainable Development Plan 2010–2015 aims to improve air quality and reduce greenhouse gas emissions, ensure a better quality of life, manage resources, build the economy in a sustainable manner, and protect the biodiversity, natural environments and green spaces. The City of Montreal considers these plans as success to deal with the environmental, social and economic problems. But, the Green Cities Index by the Economist Intelligence Unit shows that Montreal is performing poor regarding sustainable development. The problems are serious enough and current rates of emissions and energy use are rising fast enough. The SUDI gives an integrated approach to urban sustainability. To evaluate the achievement of the sustainable development plans of the MUC or the effectiveness of the existing urban policies and development, this study applies retrospective sustainable urban development criteria to develop SUD indicator considering the complex interaction among the living environment, life style and urban development. This study identifies thirty-two variables reflecting demographic, economic, social and community services, transportation, urban services and facilities, environmental and waste management characteristics as the attributes of sustainable urban development. The multivariate techniques were applied to explain the associations among indicators in terms of the underlying factors not directly observable.

The urban communities such as Ville Marie, Verdun, Sud-Ouest, Mercier/Hochelaga-Maisonneuve, Plateau Mont-Royal, and Rosemont/La Petite Patrie urban communities have the highest values of SUDI and can be considered the best performing urban communities ensuring the SUD. On the other hand, Dollard-des-Ormeaux, Kirkland, Côte-Saint-Luc, Hampstead and Montreal East have the lowest values of SUDI and can be considered the lowest performing urban communities for ensuring SUD.

The SUDI of MUC differs spatially. The exploratory spatial data analysis (Moran's I) of the SUDI for the MUC was employed to identify clusters of low orhigh SUDI and neighbourhood structures of the MUC. The spatial pattern of SUDI identified positive correlation among urban communities. This reveals that each urban community has influence on its neighbours; and the urban communities with good sustainable records are clustering together. The adaptation of sustainable urban development plan by an urban community encourages the near-by urban communities to adapt the plan.

The findings of this study help the City of Montreal to understand the improvement of the sustainable development plans for the MUC. The inclusion of SUDI in the municipal budget allocation decisions for MUC will persuade the communities to develop themselves ensuring strong sustainability and community benefits. This study includes social and community characteristics, urban services and facilities along with environmental, economic, land use and transportation attributes of urban community. This study addresses three significant factors of sustainable development, such as: (a) neighbourhood effects of sustainable development of different communities, (b) unit values of the factors of sustainable development rather than categorical values and (c) define and prioritize factors of sustainable development into different categories based on their statistical importance and interaction rather than individual identity and importance.

This study applies the exploratory spatial data analysis to detect the spatial pattern of SUDI for different urban communities in Montreal but is relatively limited in providing further explanation to the causes or factors related to this association. Further analysis is required to address this issue and provide valuable information that can impact policy. This study explores the global spatial autocorrelation by using Moran's *I* that does not capture variations at the local level. Future studies require exploring the Local indicators of spatial association (LISA). This will yield a better explanation as to why there appears to be an eastwards increasing pattern in SUDI value across MUC. This study should expand to assess the performance of ongoing effort of the municipality toward achieving sustainable development.

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Appendix

Communalities and Factor matrix of variables for sustainable urban development indicator

Variables	Communalities	Factors 1		2		3		4		5		6		7	
		Unrotated	Rotated	Unrotated	Rotated	Unrotated	Rotated	Unrotated	Rotated	Unrotated	Rotated	Unrotated	Rotated	Unrotated	Rotated
Population density	.828	.74	.42	-.19	.10	-.17	.02	-.09	.80	.42	.03	.06	.06	.16	-.01
Percentage of 15-24 years age population having high school diploma degree	.835	.47	.13	-.19	.85	.70	.00	-.06	.03	-.14	.19	.05	.08	-.27	-.24
Percentage of 25-64 years age population having high school diploma degree	.901	.43	.04	-.29	.56	.50	-.04	.49	.00	-.38	.76	.03	.00	.07	.06
Ratio of low income people	.876	.79	.41	-.40	.58	.27	-.14	.08	.44	-.06	.40	-.08	-.06	.04	.01
Percentage of employment concentration	.893	.77	.90	.25	.08	-.30	.24	-.08	.05	-.28	.11	-.18	-.07	-.18	.04
Percentage of employment establishment concentration	.871	.84	.87	.06	.09	-.31	.12	-.07	.24	-.17	.15	-.13	-.07	-.13	.01
Annual average household income	.830	.08	.00	.82	.17	.31	.79	-.01	-.22	.07	-.19	.19	.30	-.14	-.05
Percentage of annual public expenditure on leisure and culture	.884	.66	.28	-.46	.15	-.05	-.09	.41	.57	.15	.58	.16	-.10	-.14	-.33
Total community and social organizations per 1000 population	.900	.27	.12	.83	.00	.10	.94	.29	-.02	.18	.02	.05	.07	-.14	-.03
Total organizations for disabled people per 1000 population	.650	.48	.28	.42	-.04	-.07	.61	.49	.13	.01	.41	-.03	-.07	-.01	.05
Crime rate per 1000 population	.883	.76	.84	.27	.20	-.17	.25	-.10	.03	-.31	.09	-.30	-.11	-.05	.22

Continued of Table

Variables	Communalities	Factors 1		2		3		4		5		6		7	
		Unrotated	Rotated	Unrotated	Rotated	Unrotated	Rotated	Unrotated	Rotated	Unrotated	Rotated	Unrotated	Rotated	Unrotated	Rotated
Percentage of person's mobility status 5 years ago	.858	.82	.47	-.30	.50	.16	-.07	.00	.52	.04	.25	-.25	-.17	.12	.15
Percentage of labour force (15+ age) commuting by public transport	.876	.82	.45	-.37	.27	-.03	-.11	.04	.71	.20	.29	.06	.03	.12	-.03
Percentage of labour force (15+ age) commuting by walking	.958	.80	.82	.25	.14	-.26	.26	-.24	.31	.03	-.15	-.36	-.17	-.02	.20
Percentage of labour force (15+ age) commuting by bicycle	.700	.60	.38	.26	.03	-.14	.32	-.21	.58	.37	-.19	.02	.18	.27	.21
Percentage of road network with bicycling provision	.727	.47	.23	.58	.03	.03	.76	.24	.24	.27	.09	.15	.11	-.13	-.13
Percentage of total population within 400 meter buffer zone of metro station (mass transit)	.841	.35	.29	.50	.05	.01	.40	.12	-.04	-.29	.19	-.23	.10	.56	.74
Percentage of annual public expenditure on transportation and road maintenance	.789	.68	.32	-.33	.17	-.06	.04	.34	.60	.27	.41	-.06	-.26	-.16	-.25
Total housing and apartments per 1000 population	.927	.89	.59	-.15	.59	.21	.04	-.15	.46	.05	.09	-.21	-.09	-.04	.03
Total HLM housing per 1000 low-income people	.867	.82	.80	.06	.01	-.32	.09	-.08	.29	-.18	.23	.22	.27	.01	-.02
Total OBNL housing per 1000 low-income people	.903	.80	.89	.08	.05	-.32	.08	-.08	.11	-.32	.23	.10	.15	-.17	-.09
Total cooperative housing per 1000 low-income people	.823	.77	.70	.01	.00	-.28	.07	-.02	.32	-.14	.29	.36	.35	-.02	-.13
Total non-HLM per 1000 low-income people	.885	.80	.85	.06	.03	-.34	.01	-.30	.31	-.14	.01	.11	.24	.03	.05
Percentage of total population within 400 meter buffer zone of a primary school	.898	.72	.24	-.35	.23	.02	-.05	.03	.86	.45	.18	.14	.08	.18	-.07
Percentage of total population within 400 meter buffer zone of a medical center	.935	.83	.82	.00	.05	-.36	.04	-.31	.49	.12	-.11	-.04	.04	-.06	-.04
Percentage of total population within 400 meter buffer zone of an emergency shelter	.784	.25	.11	.72	.07	.10	.81	.17	.07	.25	-.12	-.31	-.18	.04	.25
Percentage of annual public expenditure on urban planning and development	.635	.66	.50	-.12	.18	-.07	.11	.12	.30	.05	.26	.16	-.01	-.38	-.43
Natural area (sq. m) per capital	.948	.24	.14	.90	-.03	.08	.93	.25	-.10	.06	.01	-.03	.09	.03	.19
Percentage of annual public expenditure on environment and health	.704	.59	.42	.23	.11	-.01	.21	-.14	.25	-.10	.14	.47	.62	.24	.09
Total trees and canopy planned to plant during the period o 2012-2021	.784	.55	.25	-.19	.08	-.02	.04	.57	.24	-.24	.80	.15	.06	.20	.09
Max. CO2e GHG emissions index	.818	.51	.14	-.22	.83	.62	-.07	-.15	.21	-.05	.06	-.30	-.10	.10	.21
Percentage of material waste recycled per year	.907	.32	.06	.24	.80	.71	.30	-.42	.06	.16	-.39	-.07	.12	-.20	-.10
Percentage of hazardous residential waste recycled per year	.819	.38	.07	-.07	.72	.65	-.04	-.32	.07	-.14	.01	.37	.53	.03	-.08
Percentage of residential bulky waste recycled per year	.802	.53	.02	-.28	.77	.64	-.05	-.03	.37	.06	.20	.02	.12	.15	.07
Percentage of organic waste recycled per year	.832	.01	-.05	.69	.19	.35	.52	-.24	-.24	-.09	-.23	.38	.63	.14	.13
Ratio of garbage waste elimination per year	.700	.31	-.05	.22	.72	.71	.40	.12	-.06	-.05	.13	-.14	-.03	-.09	.03

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