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Article

Sustainability Assessment of the Residential Land Use in Seven Boroughs of the Island of Montreal, Canada

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Abstract: High resource utilization in the residential sector, and the associated environmental impacts, are central issues in the growth of urban regions. Land-use urban planning is a primary instrument for the proper development of cities; an important point is the consideration of the urban form's influence on resource utilization intensity. Emergy synthesis, an energy-based methodological approach that allows the quantification and integration of both natural and human-generated flows interacting in urban environments, was used to assess sustainability of the residential land use of seven boroughs on the Island of Montreal. Natural resources, food, water, acquired goods and services, electricity and fuels were the main flows considered in the analysis. Results suggest that income, household size and distance to downtown are the variables affecting resource utilization intensity more noticeably and that allocation of green area coverage is an important parameter for controlling land use intensity. With the procedure used for calculating resource use intensity in the seven boroughs, it is possible to generate a tool to support urban planning decision-making for assessing sustainable development scenarios. Future research should consider urban green space potential for accommodating local waste treatment systems, acting as a greenhouse gas emissions sink and promoting human health.

Keywords: emergy evaluation; residential land use; domestic consumption; resource utilization intensity; urban form; urban planning

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1. Introduction

1.1. Domestic Resource Utilization and Urban Planning

Since 2007, one out of two persons in the world lives in a city and current trends point out that urban population will continue to rise to about 5 billion by 2030 [1]; more than 75% of this population lives in settlements of five million residents or less, and, for a long time, this kind of urban region will continue to absorb the majority of the urban population in the world [2]. Given that urban regions are among the main originators of local, regional and global scale environmental problems, many of which are directly or indirectly associated to poor planning [3], the proper development of cities is at the center of current concerns.

High resource use is a common feature of modern day cities that must be addressed. A major contributor to this utilization rate is the residential, or domestic, sector. Around 30% of energy use in the world goes to housing [4], operation of buildings reaches up to 50%, 41% and 36% of total energy consumption in the United Kingdom, the European Union and the United States, respectively, on a national basis [5]. In countries like Canada, household water utilization accounts for around 30% of all the used water [6]. Likewise, domestic consumption from households is a major source of carbon emissions in urban areas [7]. Several works have found food, mobility of people, housing and energy-using products, among the main domestic related aspects affecting sustainability, accounting, aggregately, for almost 80% of the environmental impacts in industrialized nations [8].

On the other hand, land-use planning is the primary policy intervention influencing the form of urban settlements [9] that continues to be among the most powerful management instruments for design and control used by urban planners; one of its main objectives is to look for simultaneous territorial integrity for both the human and the natural subsystems [10]. One key point for this is the knowledge of the interrelationships between the socio-economic drivers and the environmental performance at the land use level [11]. Hence, an important aspect to better inform planning decisions for future development of urban areas with less environmental burden is the influence of the nature and the intensity of occupation of the city's territory [12]. For instance, it is widely acknowledged that densely populated cities use less per capita energy from transport than cities with low density, even though the debate continues on the causal mechanisms involved [13]. For the residential sector, the concept of urban form involves, besides density, spatial distribution of dwellings, housing typology [9,12] and other aspects related to the urban macro structure, such as distance to central business districts [14].

1.2. Emergy Evaluation in Urban Regions

Material flow accounting [15,16], ecological footprint [17,18], and energetic life cycle assessment [12,19,20] are widely used methods to account for the flows interacting in urban environments. Emergy synthesis is part of the energy 'family' of methodologies: "emergy is the total amount of available energy of one kind (usually solar) that is directly and indirectly required to make a given product or to support a given flow" [21]. The method takes into account the 'free' work that the environment carries out and the quality of the used resources and provides a way to incorporate in the same base of comparison both natural and human-generated flows, such as currency and labor, through a common unit of measure, the solar emergy joule (seJ).

At the city level, emergy analysis has been applied to urban areas since more than two decades ago, being one of the seminal works reported by Huang for the Taipei metropolitan region in Taiwan [22]. Since then, several emergy papers related to urban environments have been published; in most of the cases, the overall objective was to carry out sustainability assessments, whether for a given year of study or for a time period in which evolution of the environmental and emergetic trends were observed and evaluated. Lei and colleagues evaluated Macao in 2004, remarking the prominent role played by tourism [23]. Ascione and collaborators studied Rome in 2002, including imported labour and certain specific sectors such as tourism and government support [24,25]. Vega-Azamar and colleagues assessed the environmental sustainability in Montreal in 2005 and compared it to that of other selected cities [26]. Zhang and collaborators examined Beijing from 1990–2004; they found that Beijing relies heavily on resources purchased from abroad (similarly to what was observed for Macao, Rome and Montreal) and that this dependence increased during the studied period [27].

With respect to the residential land use, few emergy evaluations, with a rather accentuated building materials or energy performance-based approach, have been conducted at the scale of single buildings, while other studies have been carried out in 'housing units' so large that might be considered small cities by their own. Brown and Buranakarn evaluated emergy consumption in the life cycles of the main building materials used in a 1012 m^2 building located in Florida [28]. Pulselli and colleagues used emergy analysis for calculating material and energy inputs during the construction and operation (including maintenance) phases of a 2700 m^2 multi-storey building in central Italy to gain insights for the evaluation and selection of building materials and technologies [4]. For their part, Li and Wang used a mixed life-cycle assessment and emergy analysis approach to evaluate a large-scale suburban residential area of more than 152 thousand people and almost 62 thousand households in Beijing, focusing mainly on building materials use [29].

The aforementioned emergy evaluations are related to urban planning domains to a certain extent; however, studies directly related to land use planning are scarce. In this regard, the most thoroughly studied urban agglomeration is the Taipei metropolitan region; Huang and collaborators have worked on this aspect, aiming mostly at the exploration of the spatial energetic hierarchy in urban landscape systems, through the follow-up of urban growth and land use change at a municipal disaggregation level [30]. This work resorted to emergy synthesis as the analysis was intended from a deep sustainability perspective [31], emphasizing the environmental support that provides the resource flows [32] sustaining, in this case, the daily activities in a borough.

In this context, sustainability of the residential land use of seven boroughs in the Island of Montreal, located in the southeastern part of Canada (45°30′N, 73°30′W), from the perspective of the environmental support required for their daily activities, was evaluated. In 2011, the Island had more than 1.9 million inhabitants in its 499 km^2 area, implying a population density of around 3900 persons by square kilometer [33]. The city has a diversified economy based on a consolidated industrial sector and on the growing services, technology and knowledge sectors, being an important part of the industrial and commercial region of eastern North America [34]. The Island has an average gross residential density of 48.1 dwellings per hectare (dw/ha), rising to more than 150 dw/ha in some boroughs of the city center, while in the suburbs, the boroughs present values of less than 20 dw/ha [35]. The main objective of the present work was to assess the environmental sustainability of the residential land use, at the borough level in the Island of Montreal, through the quantification and analysis of the material, energetic and economic flows by means of the emergy synthesis method to explore the response of emergy-based indicators to the variation of urban parameters and their usefulness in urban planning regarding their ability to account for the ‘free’ environmental work supporting long-term sustainability.

2. Methods and Data

According to Odum’s idea of energy hierarchy, in which all energy transformations can be arranged in a hierarchy from sunlight to electrical power (requiring many joules of the former to obtain one joule of the latter), a central concept is the unit emergy value, the amount of emergy needed to produce one unit of output [36]. Transformity, defined as the amount of seJ required to produce one joule of available energy at the output, is the most widely used unit emergy value, but other values such as specific emergy (expressed in seJ/g) and emergy per unit of currency (seJ/$) are also frequently used [37]. From the unit emergy values of rain, wind, fossil fuels, minerals and so on, other natural and human-made products have been analyzed and many more unit values have been estimated, which in turn have been used in more detailed analyses of different kinds [24,38,39].

An emergy evaluation begins with the definition of the system under the analysis diagram (Figure 1), including the main input and output flows of materials, energy, money, *etc.* For the analysis of the boroughs, the main flows considered were sunlight, kinetic energy from wind, evapotranspiration from rain, surface heat flux, local topsoil loss, food, water, acquired goods and services, and electricity and fuels, for both the operation of the dwellings and the transport of the residents.

After the formulation of the diagram, a table is integrated with the raw data to calculate the corresponding emergy flows (Table 1), which are obtained through a multiplication by the appropriate unit emergy values [37].

Total emergy used (*U*) was calculated as the sum of emergy from items 5–20 and the highest emergy input among items 1–4 in Table 1 to avoid double counting [27,40]. The global emergy budget (15.83×10^{24} seJ/year) used in this study was calculated from solar insolation, deep earth heat and tidal energy [37,39].

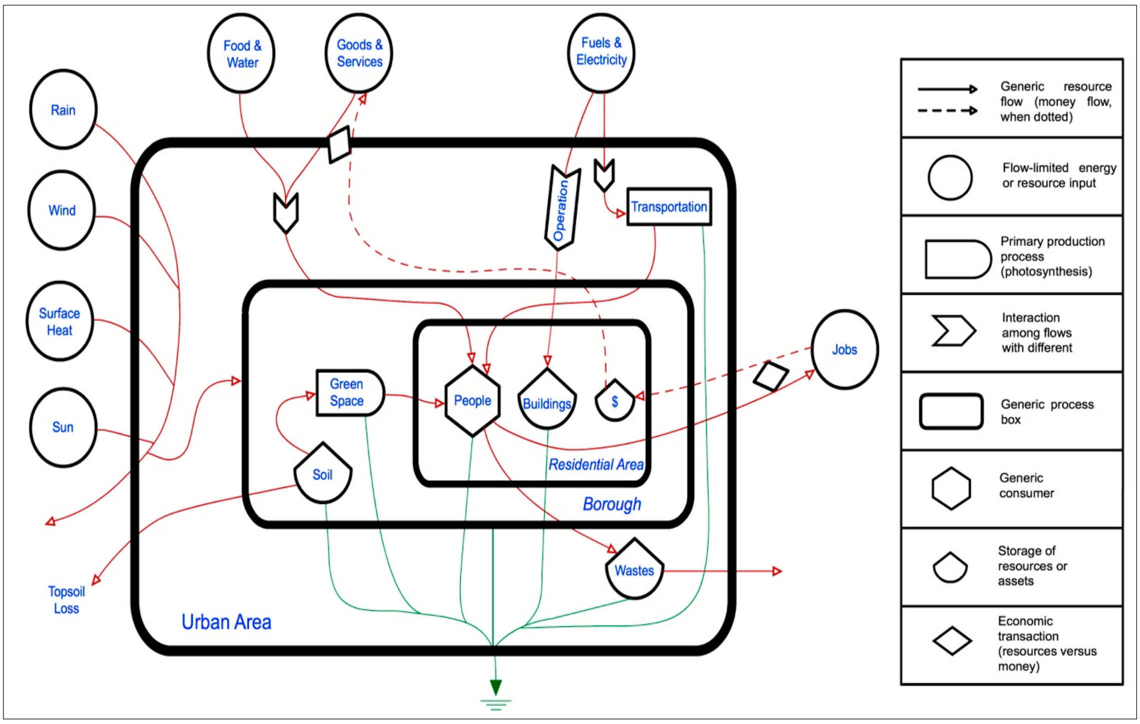

Figure 1. Diagram of the main flows considered in the analysis of the boroughs.

Table 1. Emergy synthesis of material, energy and economic flows in the boroughs (Ville-Marie).

	Item	**Quantity**	**Unit**	**Transformity (seJ/J, g, $)**	**Reference (Transformity)**	**Emergy (seJ/Year)**
	Renewable resources (R)					
1	Solar radiation	7.31×10^{16}	J/year	1.00	[21]	7.31×10^{16}
2	Wind	1.96×10^{14}	J/year	2.45×10^{3}	[39]	4.81×10^{17}
3	Rain (evapotranspiration)	1.76×10^{13}	J/year	3.10×10^{4}	[39]	5.45×10^{17}
4	Surface heat flux	2.34×10^{13}	J/year	1.07×10^{4}	After [39]	2.51×10^{17}
	Local non-renewable resources (N)					
5	Topsoil loss	9.60×10^{7}	g/year	2.29×10^{9}	[39,41]	2.20×10^{17}
	Purchased (imported) resources (F)					
6	Cereals	6.44×10^{9}	g/year	9.82×10^{8}	[21,42]	6.32×10^{18}
7	Fruits	5.76×10^{9}	g/year	1.23×10^{9}	[21,42]	7.05×10^{18}
8	Vegetables	1.11×10^{10}	g/year	5.96×10^{9}	[21,38]	6.60×10^{19}
9	Meat	6.76×10^{9}	g/year	3.17×10^{10}	[38,43]	2.15×10^{20}
10	Fish	6.72×10^{8}	g/year	1.53×10^{11}	[21,43]	1.03×10^{20}
11	Milk and other diaries	9.58×10^{9}	g/year	2.41×10^{10}	[21,38]	2.30×10^{20}
12	Eggs	7.58×10^{8}	g/year	1.07×10^{11}	[38]	8.11×10^{19}
13	Sugars and syrups	2.42×10^{9}	g/year	1.55×10^{8}	[37,38]	3.75×10^{17}
14	Potable water	8.84×10^{12}	g/year	3.00×10^{6}	[42]	2.65×10^{19}
15	Natural gas	2.42×10^{15}	J/year	4.00×10^{4}	[44]	9.66×10^{19}
16	Electricity	6.04×10^{14}	J/year	6.23×10^{4}	[45]	3.76×10^{19}
17	Gasoline	8.02×10^{9}	g/year	2.92×10^{9}	[44]	2.34×10^{19}
18	Diesel	7.66×10^{8}	g/year	2.83×10^{9}	[44]	2.17×10^{18}
19	Electricity (transport)	1.85×10^{13}	J/year	6.23×10^{4}	[45]	1.15×10^{18}
20	Acquired goods and services (spending)	3.94×10^{8}	$/year	1.54×10^{12}	[26]	6.09×10^{20}

Finally, from the aggregate emergy flows estimated (renewable resources, *R*; local non-renewable resources, *N*; and purchased or imported resources, *F*), performance indices and indicators, which are dealt with in the results and discussion sections, are calculated for their interpretation as a support in decision-making processes [46], in this case, in urban planning contexts.

Emergy-based indicators (Table 2) help to compare the environmental performance of the boroughs stressing the support needed for the dwellers activities, estimated through the emergy from the used resources' emergy. Based on the requirements for the estimation of these indicators, the appropriated data were selected and elaborated on.

Table 2. Emergy-based indicators considered in the study cases.

Indicator	Calculation	Unit	Indication
Empower per household (*EH*)	*U/borough's number of households (occupied dwellings)*	seJ/household year	Living quality and intensity of resource utilization
Per capita emergy (U_{cap})	*U/borough's number of dwellers*	seJ/person year	Standard of living and intensity of resource utilization
Empower density of the habitable area (ED_{Hab})	*U/borough's total residential floor area*	seJ/m^2 year	Intensity of resource utilization
Emergy to money ratio (*EMR*)	*U/total income of borough's households*	seJ/USD	Ecological-economic efficiency
Per capita support area (SA_{cap})	$([N+F]_{borough}/[(N+F)/area]_{Montreal})/$ *borough's number of dwellers*	m^2/person	Emergy-based ecological footprint
Emergy sustainability index (*ESI*)	*[U/F]/[(N+F)/R]*	-	Long term sustainability

Seven boroughs of the City of Montreal (Le Plateau-Mont-Royal, Le Sud-Ouest, Pierrefonds-Roxboro, Rivière-des-Prairies-Pointe-aux-Trembles, Rosemont-La Petite-Patrie, Ville-Marie and Villeray-Saint-Michel-Parc-Extension), with different characteristics, such as housing types, green area coverage, per household income, number of residents per dwelling and distance to downtown, were analyzed.

One of the most important aspects defining urban form is density of occupation, expressed through the number of dwellings per unit area [9]. Accordingly, the gross residential density of the boroughs ranged around three values: above 150, about 100 and below 35 dwellings per hectare. Table 3 shows the main attributes used in the analysis of the boroughs, presented in descending order of gross residential density.

Table 3. Main characteristics of the boroughs.

Case	Gross Density (dw/ha)	Area (ha)	Per household Income (USD/year)	Total Households	Floor Area (ha)	Total Dwellers	Dist. to DT (km)	Green Area (%)
Ville-Marie	161.1	1652	46,511	43,250	859	74,265	0.84	30.8
Plateau M-R	151.1	813	40,684	56,045	890	98,275	2.93	9.4
Villeray	103.2	1649	33,138	62,865	975	141,765	7.31	12.4
Rosemont	99.3	1585	37,501	70,085	1129	130,570	5.85	15.3
Sud-Ouest	94.4	1568	35,715	33,005	559	68,080	3.73	17.7
Riv. Prairies	30.3	4228	49,004	40,635	885	102,470	17.42	12.7
Pierrefonds	18.5	2706	57,415	23,730	821	64,285	23.31	16.4

Residential floor area in each borough was calculated, with the help of ArcView GIS software, through the reported gross residential density [35] and the weighted mean of the floor area ratio, *i.e.*, floor space/plot area, established in the Master Plan of Montreal [47]. Distance to downtown was considered as that of the straight line between the centroid of each borough and the corner of two of the most significant streets in the business and commercial heart of the city (it was estimated also with the afore-mentioned GIS software). Similarly, distance to two of the major employment areas (one located to the east and the other to the west of the island) was examined. Green area coverage was also compiled from the reported in the Island of Montreal's Master Plan [47].

Two of the main sources of statistical data were the City of Montreal's socio-demographic profiles of boroughs [48] and economic profiles of boroughs [49]. It is important to note that the calculations in this paper were made taking into account only the population housed in private homes (total dwellers in Table 3), which means around 95% of total population in the boroughs, and the occupied dwellings (total households in Table 3). Unavailable data at the borough level were scaled down, as in the case of food consumption, for which national averages for urban regions were adjusted through the expenditure on food in each borough. For the estimation of emergy from natural resources, data coming from long periods were used; owing to the fact that environmental inputs of regional systems are frequently calculated using long-term averages [40]. Also, data corresponding to monetary flows (currency values are expressed in US dollars) were brought to present value by applying price indexes when needed [19,50]. Table 4 shows the way in which data were processed and the main information sources.

Table 4. Data elaboration and sources.

Item	Elaboration	Sources
Natural resources	Long period averages	[51–53]
Food	Per capita averages for urban regions adjusted by food spending in the boroughs	[49,54]
Water	Consumption by house type	[55,56]
Electricity and natural gas from house operations	Average of energy consumption by house type and by number of residents	[57]
Fuels and electricity from transport	Split mode, average trip length, vehicle and public transport performance	[58–61]
Goods and services	Household expenditure in the boroughs	[49]

3. Results

In the analyzed boroughs, U varied depending on the number of residents, household size, income, distance to downtown and mixing of house types, among other aspects. As expected, F was the dominant flow sustaining the day-by-day activities in each borough with an average of 99.94% of U, while R and N averaged about 0.04% and 0.02%, respectively. Figure 2 shows the main aggregated emergy flows, as a percentage of U, calculated for the seven cases; they are presented in descending order of gross residential density.

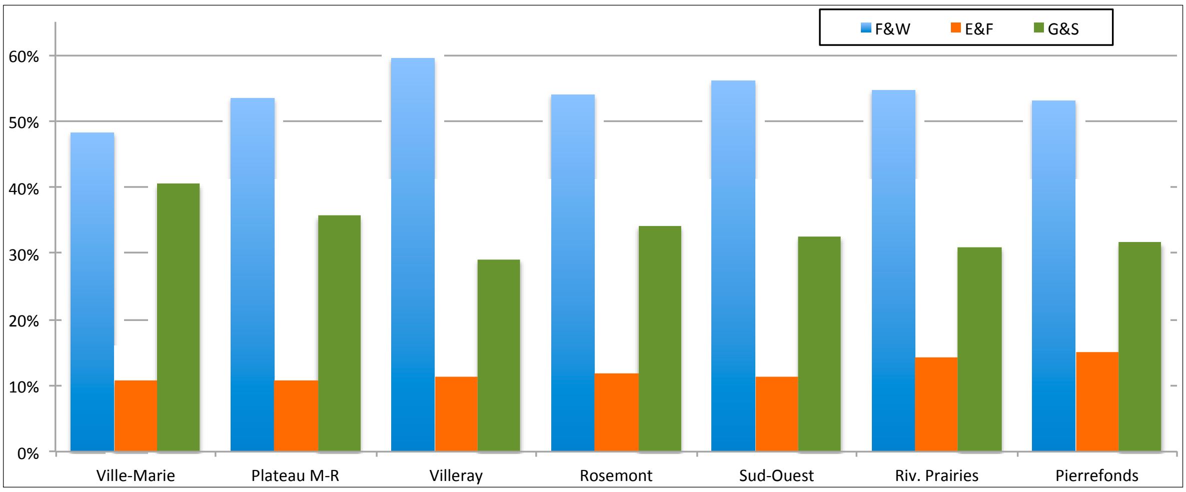

Figure 2. Purchased emergy as a percentage of the total emergy used in the seven boroughs (F&W: food and water; E&F: electricity and fuels; G&S: goods and services).

Comparisons among cases with different characteristics are usually carried out favoring the utilization of intensity indicators instead of total quantities to attenuate such differences [24]. In this work, the emergy requirements were considered mainly on a per occupant basis, on a per household basis, and on a per unit area of habitable space basis, in all cases, higher values of U_{cap}, EH and ED_{Hab} indicating higher resource utilization intensity (Table 2).

Emergy from food and water averaged 54% of U in the boroughs. Plateau M-R and Ville-Marie presented the highest and the lowest per resident uses (9.88×10^{15} and 9.70×10^{15} seJ/person year, respectively) and Villeray and Pierrefonds showed the highest and the lowest per square meter of floor area utilization values (1.43×10^{14} and 7.69×10^{13} seJ/m^2 year, respectively). Emergy from acquired goods and services averaged 33%, with Ville-Marie exhibiting the highest per capita use (8.20×10^{15} seJ/person year) and Villeray the lowest (4.80×10^{15} seJ/person year), and Plateau M-R and Pierrefonds showing the largest and the smallest per square meter uses (7.25×10^{13} and 4.57×10^{13} seJ/m^2 year, respectively). For its part, emergy from total electricity and fuels consumption ranged around 12% of U in the boroughs; Pierrefonds presented the highest per occupant use (2.80×10^{15} seJ/person year) and Villeray the lowest (1.86×10^{15} seJ/person year), while, Rivière Prairies and Ville-Marie exhibited the largest and the smallest per square meter uses (2.95×10^{13} and 1.87×10^{13} seJ/m^2 year, respectively). Table 5 summarizes the main indicators estimated from the analysis of the emergy flows.

Table 5. Emergy-based indicators calculated for the seven boroughs.

Case	U_{cap}	EH	ED_{Hab}	EMR	SA_{cap}	ESI
Ville-Marie	2.01×10^{16}	3.45×10^{16}	1.74×10^{14}	7.41×10^{11}	89.76	0.00037
Plateau M-R	1.84×10^{16}	3.23×10^{16}	2.04×10^{14}	7.95×10^{11}	82.42	0.00013
Villeray	1.65×10^{16}	3.72×10^{16}	2.40×10^{14}	1.12×10^{12}	73.66	0.00021
Rosemont	1.82×10^{16}	3.40×10^{16}	2.11×10^{14}	9.06×10^{11}	81.53	0.00019
Sud-Ouest	1.75×10^{16}	3.62×10^{16}	2.13×10^{14}	1.01×10^{12}	78.37	0.00038
Riv. Prairies	1.79×10^{16}	4.52×10^{16}	2.08×10^{14}	9.23×10^{11}	80.14	0.00067
Pierrefonds	1.85×10^{16}	5.01×10^{16}	1.45×10^{14}	8.72×10^{11}	82.58	0.00066

4. Discussion

This section presents an exploratory search for trends that must be viewed with caution, given the peculiarities of the Island of Montreal, such as location, socioeconomic structure, relationships with the rest of the metropolitan region, among other factors, in addition to the limited number of boroughs analyzed.

4.1. Per Capita and Per Household Emergy Utilization

Empower per household may be an indicator of quality of living in residential areas [29] and, similarly, per capita emergy may also be an indirect indicator of standard of living [26]. For this reason, it was explored if per household income, an economic measure of well-being, could be related to per capita emergy consumption and to empower per household, expecting that higher household incomes corresponded to higher U_{cap} and EH (see Figures 3 and 4).

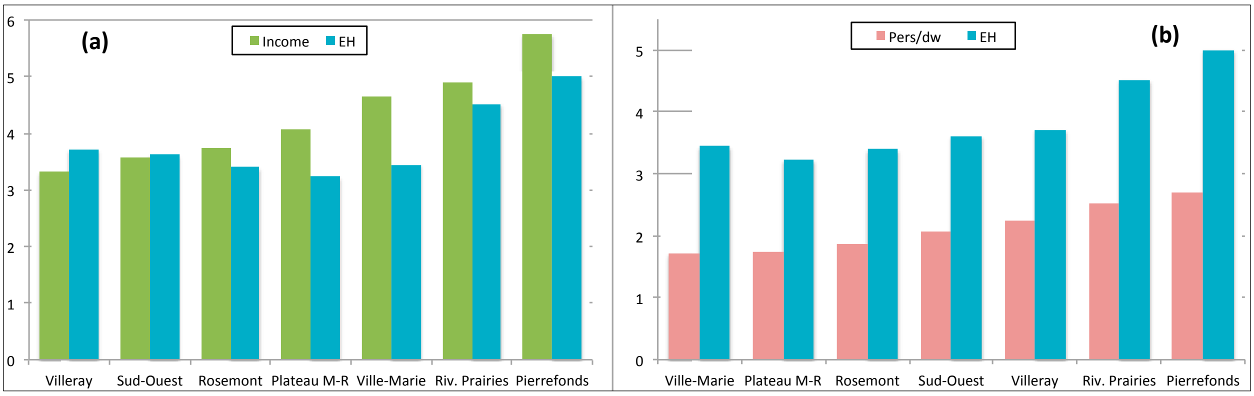

Figure 3. (**a**) Per household emergy (×10^{16} seJ/dw year) and per household income (×10^4 USD/year); (**b**) Per household emergy and household size (persons/dw).

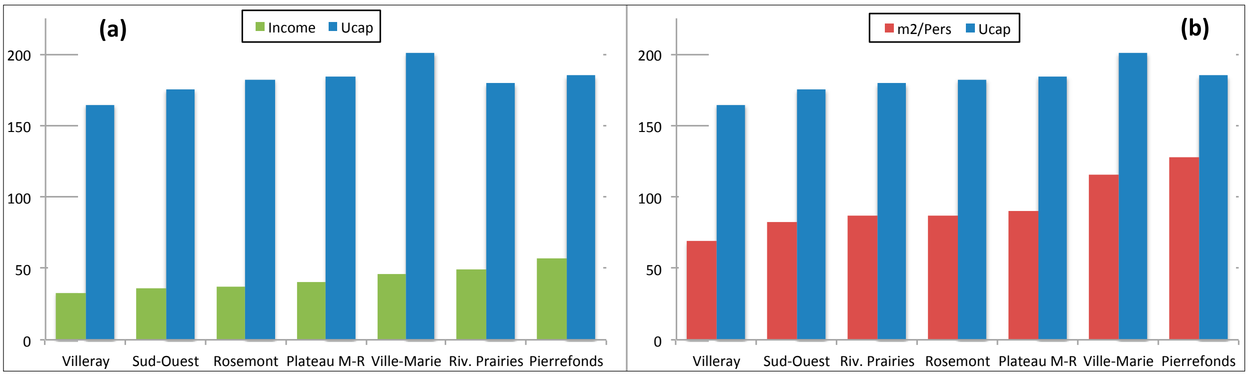

Figure 4. (**a**) Per capita emergy (×10^{14} seJ/person year) and per household income (×10^3 USD/year); (**b**) Per capita emergy and available living space per person (m^2/person).

A nonlinear trend of *EH* variation with respect to household income was noted, presenting a minimum *EH* for the borough of Plateau M-R, which has a medium income level and the second lowest household size (number of occupants per dwelling), with 1.75 residents (Figure 3a).

Also, a strong positive linear correlation between per dwelling occupancy and empower per household was confirmed (Figure 3b); the coefficient of determination value (R^2) estimated for the seven cases was 0.904. The central borough of Ville-Marie, which matches the smallest household size with the highest per capita emergy consumption (associated to its considerable rate of acquisition of goods and services, see Figure 2), breaks the trend. The highest per household emergy utilizations corresponded to Rivière Prairies and Pierrefonds, the boroughs combining the highest incomes and the highest resident occupancies.

For its part, although the range of variation of U_{cap} was not broad, a gradual increment was detected when per household income increased, with a peak for Ville-Marie and a small drop for the two boroughs with the highest incomes (Figure 4a). The highest per capita emergy utilization value, registered in Ville-Marie, is associated with the aforementioned emergy from goods and services, while, in turn, Rivière Prairies and Pierrefonds presented the highest household sizes (2.52 and 2.71 persons per dwelling, respectively), which slightly attenuates the parameters estimated on a per capita basis.

A certain influence of per resident habitable space on per capita emergy consumption was also observed. In general, a greater availability of per person floor area corresponded to a higher U_{cap} (Figure 4b), which may be partly explained by the positive linear correlation between income level and living space availability ($R^2 = 0.731$, estimated for the seven cases).

4.2. Emergy from Electricity and Fuels

As mentioned above, one of the main aspects defining urban form is density [9]. Results suggest that density by itself does not appear to significantly affect the behavior of U_{cap}, although it was correlated to *ED* and ED_{Hab} and to per capita emergy from the use of fuels and electricity used for both the operation of dwellings and the transport of residents (*E&F*) estimated for the seven boroughs. However, this has to do more with issues indirectly related to density: longer distances to the city center correspond to low-density boroughs, where houses are sought after by larger families with higher incomes that frequently use cars, which can give low density the appearance of causing greater fuel consumption.

As expected, emergy from fuels and electricity for the transport of residents was highly influenced by distance to downtown, similarly to other studies suggesting that distance to central districts is more important than variables such as housing typology and density and road layout [14]. Distance to downtown and gross residential density were strongly correlated to per capita emergy from *E&F* for the transport of residents ($R^2 = 0.963$), while correlation between these two variables and per capita emergy from *E&F* for the operation of dwellings was virtually nil. For its part, geometric mean of distance to downtown and to major employment areas was also correlated to per capita emergy from *E&F* for the transport of residents, but to a lesser extent ($R^2 = 0.693$). The boroughs of Pierrefonds and Rivière Prairies exhibited the highest values of emergy from total *E&F* on a per capita basis; both are the furthest away from downtown and have the highest percentage of car use, 76.3% and 68.9%, respectively [58].

With regard to the emergy required for the operation of dwellings, outcomes on a per capita basis contrast with findings of life cycle energy consumption studies in which energy utilization for buildings operations in low-density areas are approximately from 1.5–2 times of that of high-density areas [12,19], while here no differences were observed, which may be attributed to the particularities of the present study (data disaggregation, selected densities, house typology, weather conditions).

4.3. Ecological-Economic Efficiency, Emergy-Based Ecological Footprint and Long-Term Sustainability

As mentioned in Table 2, *EMR* is the ratio of total emergy used to total income in boroughs which, besides indicating the capacity to buy emergy [27], may be an indicator of ecological-economic efficiency when regions are compared, with lower values of *EMR* corresponding to higher levels of emergy use efficiency [62]. For its part, carrying capacity may be estimated by means of the support area of land (*SA*) required to obtain enough inputs to fulfill the emergy requirements of a given population (here, that of the dwellers in the studied boroughs), within a local economic and environmental system (in this case, the Island of Montreal), based on the intensity of development of the region [63], see Table 2.

With respect to these two indicators, a general trend was observed: higher per capita support land areas corresponded to lower emergy to money ratios. In addition to their individual values, the combined performance may be observed by considering the accumulated area of the two bars for the boroughs (Figure 5), given that lower values correspond to better performances for each indicator. Ville-Marie presented the lowest *EMR*, because its income level results in a high emergy use rate, which in turn translates into the highest SA_{cap} needed. In this central high-density borough, high-income childless couples and singles live in apartment buildings, which mistakenly can give high density the appearance of producing high ecological-economic efficiencies. The low per capita and the medium per household emergy consumption of Villeray are reflected in the smallest need of support land per resident, but its lowest per household income brings along the highest *EMR*. The best-combined performance corresponded to Plateau M-R.

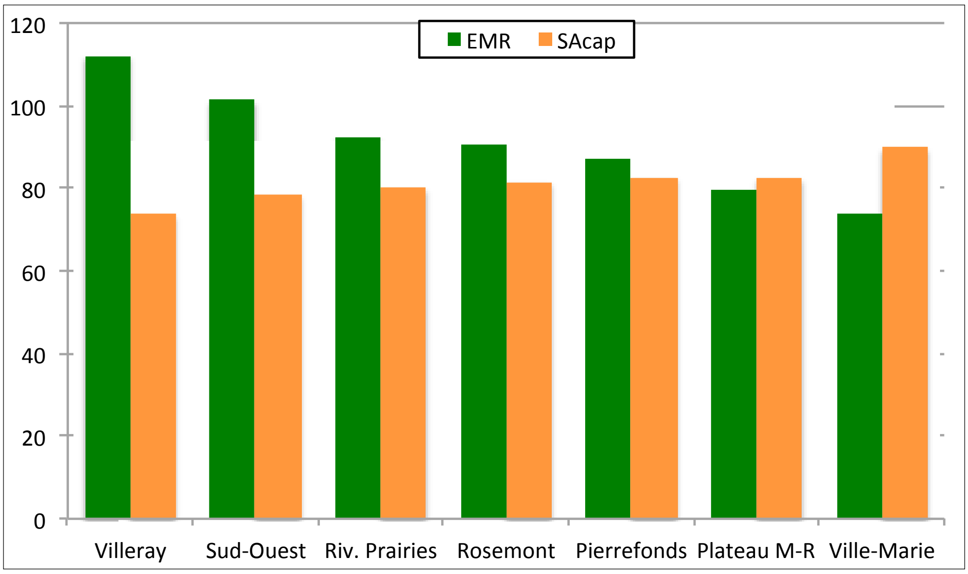

Figure 5. Emergy to money ratio ($\times 10^{10}$ seJ/USD year) and per capita support area (m^2/person) for the seven boroughs.

Figure 6 presents a ternary diagram of sustainability in which the curved lines designate constant values of the *ESI*, these lines divide the triangle into sustainability areas, which are helpful to classify products or processes; the resource flow lines (dotted) represent the relative proportions of *R*, *N* and *F* (in this case, the average of the seven boroughs), given by the lengths of the perpendiculars from the vertex to the opposite side of the triangle [64]. *ESI* can inform about the possible degree of contribution of the boroughs to the regional system (the Island of Montreal) with respect to the environmental burden inflicted [24]. *ESI* gives an appraisal of long-term sustainability, in general, the higher its value the higher the dependence on renewable resources and the lower the environmental burden [46].

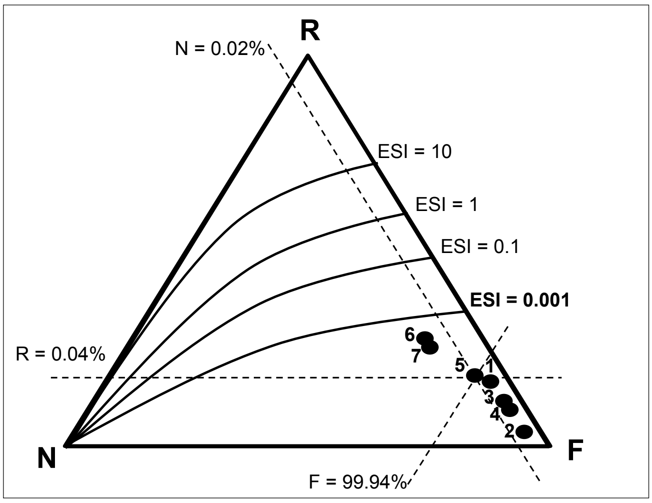

Figure 6. Ternary diagram of sustainability lines for the seven boroughs (1: Ville-Marie; 2: Plateau M-R; 3: Villeray; 4: Rosemont; 5: Sud-Ouest; 6: Rivière Prairies; 7: Pierrefonds).

By the nature of the present analysis, the estimated values of *ESI* for the boroughs were well below 1, however, they would not fail to provide insights about the performance of the boroughs. The best performances corresponded to boroughs with important green area coverage (low residential land use area to total area ratio and low habitable area to lot area ratio), while the worst performance corresponded to the borough with the poorest green area coverage (Figure 6 and Table 2). It is important to note that the best-combined ecological-economic efficiency-ecological footprint performance corresponded to the borough with the worst long-term sustainability performance (Figures 5 and 6), which could be enhanced by renewable emergy inputs from higher provisions of green areas.

4.4. Urban Planning Implications

When the empower density variation in function of the distance to city center is reviewed, it is confirmed that empower density decreases as the borough 'moves' away from the center, which is similar to that reported by some authors for other equivalent geographical scales [30], although in a less marked way, in part, probably because of the unusual characteristic of the most central borough analyzed of having a significant amount of green area (Figure 7a). Clearly, when the area covered by the residential land use is the only one considered, the variation becomes more pronounced ($R^2 = 0.919$). The correlation holds, with slightly less strength, when mixed land use (multiple uses) is included, that is, if areas from stores, office buildings, light industrial and/or institutional and community facilities are added to the residential area ($R^2 = 0.830$).

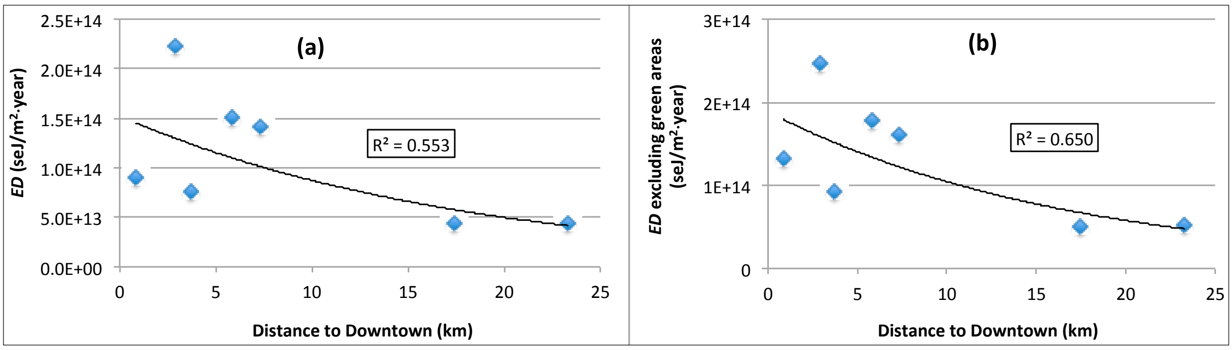

Figure 7. (**a**) Empower density and distance to the city center; (**b**) Empower density, excluding green area surface, and distance to the city center.

For its part, area occupied by parks and other green areas do not necessarily have a direct relationship with the residential density (one of the main parameters for allocating intensities of occupation in urban planning). If the surface occupied by parks and other green areas is subtracted from the borough's total area, its influence on empower density can be observed (Figure 7b). Boroughs like Ville-Marie and Sud-Ouest, with a significant percentage of green areas, present an empower density closer to those of suburban boroughs (for the estimation of the empower densities in this section, data from Montreal's Master Plan were used).

Thus, allocation of green area coverage (including guidelines for its spatial distribution) is an important parameter for the reduction and control of land use intensity, which also gives the opportunity to influence urban form and the configuration of the transport system structure. In future work, it will be imperative that the assessment take into account urban green space potential for accommodating local systems of solid waste and wastewater treatment and for acting as a greenhouse gas emissions sink, in addition to its inherent renewable flow supplier function, so that their environmental relevance may be increased. The inclusion of the determinants of human health related to urban green area should be considered as well. The question of how exactly urban green space promotes health is starting to be more closely examined, helping to introduce and consolidate the idea that green space is not limited to beautifying urban landscapes, but also helps to improve the health of those around it [65].

With the elements and procedures used for calculating resource utilization intensity, through the emergy analysis in the seven boroughs, it will be possible to generate a dynamic tool for the estimation of hypothetical residential zonings' main indicators, so that future scenarios of urban development, and their associated consequences, may be compared. Ideally, at the urban zoning scale, hypothetical residential intensities might be weighted, which would be useful as a basis for the comparison of development alternatives in urban physical planning. The tool could estimate the indicators considering population, number of dwellings and projected surface, based on combinations of house types, number of occupants per dwelling (household size), income, average daily distance to travel by residents and modal split and results can be exported and mapped with the help of geographic information system tools to explore possible suitable locations (according to U_{cap}, ED, ED_{Hab}, EMR and EH). Of course, the procedure may also be performed in the reverse order, that is, if possible locations available for real-state development (or re-development) projects are known, from such locations, occupation intensities intervals can be determined (U_{cap}, ED, *etc.*) for defining the appropriate characteristics for the projects. Planners might use the tool at early stages of urban planning processes, which would help to set potential development scenarios for better urban planning interventions. Table 6 presents a summary of the key parameters and indicators arising from the research work and their potential use in urban planning.

Table 6. Key parameters and emergy-based indicators for sustainable urban planning.

Parameter	Indicator	Potential use
Per capita available living space	Per capita emergy (U_{cap})	Urban master plans: criteria for the allocation and distribution of land use intensity of the land use mix (zoning by-laws)
Household income and size	Per household emergy (*EH*), emergy-to-money ratio (*EMR*)	
Distance to downtown	Emergy used for transport ($E\&F_{Transport}$)	
Green area coverage (%)	Emergy sustainability index (*ESI*) and empower density (*ED*)	Urban master plans: guidelines for green area coverage and *in-situ* remediation infrastructure

5. Conclusions

Residential land use of seven boroughs in Montreal was evaluated, stressing the “free” environmental work supporting long-term sustainability of the daily activities through the quantification and analysis of the material, energetic and economic flows and the calculation of indicators using the emergy synthesis method to examine their response with respect to the variation of urban planning parameters.

As expected, total emergy used varied principally according to household size, income level, distance to downtown and mixing of house types, while imported emergy was by far the dominant flow sustaining each borough’s activities. The highest proportions of emergy from food and water, from electricity and fuels and from acquired goods and services, with respect to total emergy used, were obtained for the borough with the lowest per household income, for the borough the furthest away from downtown and for the most centrally located borough, respectively. The overall contribution of these flows to total emergy use, in descending order, was: food and water, goods and services, and electricity and fuels. Also, regarding resource utilization per unit floor area, the lowest rate corresponded to the borough with the largest available space per person, for the cases of food and water and of goods and services, and to the borough with the second largest available space per person, for the case of electricity and fuels.

A strong positive linear correlation between household size and per household empower was confirmed: the highest per household emergy utilisations corresponded to the boroughs combining the highest incomes and the largest household sizes. For its part, the per capita emergy range of variation was not broad, however, a gradual increment was observed when income increased, with a maximum for the borough with the highest per resident utilization rate of emergy from goods and services. In addition, some influence of per resident habitable space on per capita emergy was noted; in general, a greater amount of the former corresponded to a higher value of the latter. In turn, emergy from fuels and electricity for the transport of dwellers was highly influenced by distance to downtown, while gross residential density did not appear to be correlated neither to per capita emergy from total energy use nor to per capita emergy from electricity and fuels used for the operation of dwellings.

With respect to the emergy-based ecological footprint and the emergy to money ratio, a general trend was observed: higher per capita land areas needed to support the activities in the boroughs corresponded to lower ecological economic efficiencies. In the long-term sustainability assessment through the emergy sustainability index, the best performances corresponded to the two boroughs the furthest away from downtown, which may be explained by their green area coverage, the low residential land use area to total area rate and the low habitable area to lot area ratio. Results suggest that allocation of green area coverage is an important parameter for the control of land use intensity, which in turn would influence urban form and the configuration of the transport system structure. Urban green space potential for accommodating local waste treatment systems, for acting as a greenhouse gas emissions sink and for promoting human health should be considered in future work.

With the procedure used for calculating resource use intensity in the seven boroughs, it is possible to generate a tool to support decision-making in urban planning for assessing future development scenarios. Hypothetical residential intensities might be weighted for the comparison of development alternatives or, inversely, occupation intensities intervals may be determined for particular projects, if their possible locations are known. Finally, it will be very important to examine more cases to confirm or discard the results obtained in this work. From a wider perspective, future research should consider emergy modeling at urban planning zoning scales, based on the variables that were found to more significantly affect the intensity of resource utilization.

Author Contributions

Ricardo Vega-Azamar applied the environmental accounting methodology of emergy synthesis, quantified the analyzed flows, managed the data and wrote the manuscript draft. Rabindranarth Romero-López contributed to the analysis of the urban environmental system dynamics and helped with the writing of the manuscript draft. Mathias Glaus contributed to the energetic life cycle analysis and the review of the transport system and its relationship to urban land use and revised the drafting of the manuscript. Norma Oropeza-García contributed to the quantification of material flow, mass balance, and energetic life cycle analysis and helped with the writing of the manuscript draft. Robert Hausler contributed to the idea of quantifying resource utilization intensity of dense urban and suburban areas to contrast them, held the management of the environmental information, reviewed the urban environmental system dynamics and revised the drafting of the manuscript. All of the authors contributed to the work in this manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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