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Article

The Potential of Urban Agriculture in Montréal: A Quantitative Assessment

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Abstract: Growing food in urban areas could solve a multitude of social and environmental problems. These potential benefits have resulted in an increased demand for urban agriculture (UA), though quantitative data is lacking on the feasibility of conversion to large-scale practices. This study uses multiple land use scenarios to determine different spaces that could be allocated to vegetable production in Montréal, including residential gardens, industrial rooftops and vacant space. Considering a range of both soil-bound and hydroponic yields, the ability of these scenarios to render Montréal self-sufficient in terms of vegetable production is assessed. The results show that the island could easily satisfy its vegetable demand if hydroponics are implemented on industrial rooftops, though these operations are generally costly. Using only vacant space, however, also has the potential to meet the city's demand and requires lower operating costs. A performance index was developed to evaluate the potential of each borough to meet its own vegetable demand while still maintaining an elevated population density. Most boroughs outside of the downtown core are able to satisfy their vegetable demand efficiently due to their land use composition, though results vary greatly depending on the farming methods used, indicating the importance of farm management.

Keywords: urban agriculture; land use design; Montréal; sustainable communities; food security; urban planning; resilience; urban development; food systems

1. Introduction

In the face of a growing global population, food security has become a pressing concern [1]. Urban sprawl is continuously expanding onto natural landscapes [2,3] and is often located in the vicinity of very rich and fertile soil that could be useful for agriculture [4]. This worrying trend has been observed in several different parts of the world [5–8]. By 2025, two thirds of the world's population will be concentrated in urban areas, increasing the importance of a resilient food system for city dwellers [9]. One of the proposed solutions to make cities more sustainable is to implement local urban agriculture (UA) systems. UA is commonly referred to as the practice of growing, processing and distributing food in towns, cities and peri-urban areas [1]. Diversifying food sources and becoming at least partially self-sufficient through UA is one way to increase the resiliency of food systems, as well as to ensure food security in urban areas [10,11].

UA can be implemented in many forms, by people with varying levels of expertise and with a variety of farm management techniques [10–12]. Gardening techniques range from organic agriculture, in which no pesticides or herbicides are used, to hydroponics, in which crops are fed nutrients through water, eliminating the need for soil [13,14]. Geographic location plays a key role in determining the crop varieties and quantities that can be grown using soil-bound methods [11,15]. With UA, the variety of crops grown can also depend on the economic state of the country in question. In Western countries, UA practices are mainly devoted to vegetable production, as this practice tends to be more productive and profitable than other crops, such as cereals [16–18]. In developing countries, however, it has been reported that UA is also used to grow staple crops, even with the diminished returns [11,17–19].

While hydroponic systems generally result in extremely high yields and benefit from a limitless growing season, they are also associated with increased energy and manpower requirements, as well as higher infrastructure costs [14]. Some cohorts speculate about pollution and harmful chemicals that may be transferred to humans by UA products [20,21]. These contrasting benefits and drawbacks have resulted in a debate on the applicability of hydroponics in UA [14].

UA provides many social and environmental benefits for both urban and rural populations [11]. Duchemin *et al.* [12] underline numerous improvements in urban lifestyle, such as the creation of united, self-sufficient communities and access to fresher, healthier, local food. In addition to its social benefits, UA can also: create green areas and reduce the urban heat island effect [11,22]; provide urban residents with ecosystem services, such as water and air purification [1,23]; reduce poverty and hunger by recycling urban food waste [24]; create new jobs [12,25]; and reduce food miles and cities' carbon footprint [12]. Given that many of these benefits are in alignment with the goals for achieving sustainable development, it is unsurprising that many North American cities have implemented UA programs, though most operate on a relatively small scale [9,25]. More quantitative research is needed to assess the viability of scaling up UA practices.

The island of Montréal is a typical mid-sized North American metropolis, with a densely packed downtown core that is surrounded by neighborhoods of varying incomes and suburbs along the city limits in the east, west and north. Known as a green city, its inhabitants have been practicing UA for the past 30 years, through collective gardens, city-organized community garden programs and personal gardens [12]. Currently undergoing a surge in popularity, multiple local food projects have emerged, ranging from industrial hydroponics to community gardens. Following a petition with over 22,000 residents' signatures, the Office de Consultation Publique de Montréal (OCPM) recently published a report on the state of UA in Montréal [15]. This report confirms that UA can increase social wellbeing and environmental quality in Montréal, but failed to provide any quantitative data on Montréal's UA potential. As a case study, Montréal serves as a prototype for a typical post-industrial North American city and, with its relatively northern latitude, can complement case studies performed in other climates [11].

The goals of this study are threefold:

(1) To investigate how difficult it would be for the island of Montréal to meet its domestic vegetable demand according to several assumptions. We crafted and based our investigation on a variety of urban agricultural systems, such as conventional or high-intensity gardening methods. (For the purpose of this paper, conventional urban agriculture will be referred to as low intensity. Low-intensity UA can be performed by citizens with average gardening experience, usually as part of a collective garden, whereas high-intensity UA refers to a farm management with increased inputs, such as better farmer training and more care per plant, either in an individual or community garden. See Duchemin *et al.* [6] for more information). Multiple land use scenarios simulate how the city might change its land use composition if forced to be self-sufficient in its vegetable production.

(2) To examine the issue on another scale and comment on the ability of Montréal's 33 boroughs to provide the recommended vegetable diet to their respective inhabitants through UA, while minimizing the use of hydroponics, due to the increased energy and financial requirements associated with the practice [14].

(3) To create a performance index to evaluate the ability of each borough to support a high population density while still producing enough vegetables for its inhabitants based on its land use availability. Boroughs that are able to sustain high population densities without having to resort to the use of hydroponics are considered to have the most desirable land use composition for efficient implementation of UA.

2. Methods

In order to assess Montréal's UA potential, both consumption and production patterns were considered. Assigning a fixed vegetable demand target allowed for the creation of different land use simulations with varying production capabilities. This methodology, inspired by Martellozzo *et al.*'s [26] global approach, was tailored to the specifics of the Montréal case study. The vegetable consumption of each inhabitant was defined based on recommendations for an active, healthy lifestyle from several international organizations [1,27,28]. The proportions and variety of vegetables consumed in Montréal were assessed based on the contents of a popular local community supported agriculture (CSA) (community supported agriculture is a food production and distribution system wherein consumers pre-order crop baskets and receive seasonally ripe weekly harvests, securing the farmer's livelihood and reducing food waste) basket. These vegetables were then assigned a yield (g/m^2) for each farming system based on actual agricultural yields in the province of Québec, as well as yield ratios found in several referred studies. Multiple production scenarios were simulated by applying a range of vegetable yields to portions of vacant and residential land that were designated for UA under each scenario. Industrial rooftop space was used for greenhouse hydroponics and was assumed to produce vegetables all year long. The ability of each borough to produce enough vegetables to meet its inhabitants' demand was then evaluated. All spatial analyses were conducted using ArcMap 10.1 and Google Earth 6.2 [29,30].

2.1. Vegetable Demand

A combination of data from the United Nations Food and Agriculture Organization (UN FAO), Statistics Canada (StatsCan), United States Department of Agriculture (USDA), the World Health Organization (WHO) and Institut National de Prévention et d'Éducation pour la Santé (INPES) was used to define recommended vegetable consumption per person [1,28,31–33]. The average recommended daily intake of vegetables and fruit is 500 g per person, per day, according to these organizations. Canada's Food Guide [34] suggests that fresh vegetables should represent two thirds of this amount, resulting in a recommended daily intake 330 g of fresh vegetables per person. Vegetable demand per borough was calculated using population data from the 2011 Statistics Canada census [35,36]. The following formula was used to determine yearly vegetable demand for a given population:

$$YVD_{(g)} = \sum RVI_{v\,(g/day)} * Pop_b * 365_{days/year} \quad (1)$$

where *YVD* is the yearly vegetable demand, Pop_b is the total population of a single borough in 2011 and RVI_v is the recommended daily intake of a single variety of vegetable, which, when summed, represents 330 grams of fresh vegetables daily per person.

2.2. Vegetable Yields and Varieties

A popular CSA basket designed and distributed by Santropol Roulant [37] (Santropol Roulant is a community organisation based in downtown Montréal. Founded in 1995, it is a pioneer of urban agriculture in the area. Some of their produce comes from a partnership with McGill University's "Edible Campus" project) was used as a representative sample of the proportions and varieties of vegetables present in the average Montréaler's diet. Their production choices reflect not only the variety of vegetables that can be grown in Montréal's climate, but also the preferences of their customers, a group that was used as a proxy for the vegetable preferences of Montréal's population as a whole. Vegetables that are not commonly grown hydroponically, such as potato, were not considered, so that a consistent vegetable mix could be selected for all farm management systems.

As yields can vary greatly depending on the type and intensity of farming, a range of yield estimates were investigated [12]. Five agricultural management systems were considered:

high-intensity vacant space, low-intensity vacant space, high-intensity residential space, low-intensity residential space and rooftop hydroponics. High-intensity farming is defined as closely monitored plots that receive more care and can produce much higher yields than either conventional or basic organic agriculture, and it is usually practiced in individual or community gardens, where plot sizes are smaller than in traditional agriculture [12]. Conversely, low-intensity UA is a production practice that requires a less intensive management system, is generally practiced in areas with poorer soil quality, produces relatively lower yields and is usually practiced in a collective garden [12]. High- and low-intensity vacant space yields are derived from yield ratios representing a range of community and collective gardens, which are more likely to be practiced on a large parcel of publicly owned land, such as vacant space. Both residential yields are derived from yield ratios that represent individual farmers with a varying degree of technical knowledge, farming experience and labour input.

Hydroponic yields were compiled and averaged from a variety of sources, including several international studies [14,38], as well as Montréal's Lufa Farms [39] (Lufa Farms is a commercial hydroponic rooftop farm that provides CSA baskets, as well as hosts its own farmers market). All low- and high-intensity yields were estimated by applying yield ratios to Statistics Canada [31] data for conventional vegetable yields in Québec. Low- and high-intensity vacant space yields per vegetable are estimated as a ratio of 0.53 and 1.12 of the corresponding conventional yield for that vegetable, respectively [12]. Low- and high-intensity residential space yields per vegetable were calculated using a ratio of 2.03 and 3.50 of the conventional yields [11,12,40]. The sources for the yields and yield ratios can be seen in Table 1. Since yields for individual gardens are more variable, two sources were averaged to provide the yield ratio for high-intensity residential space. These four yield values were applied as if production were happening year round, ignoring seasonality in the city. Table 2 shows the proportion that each vegetable represents in an average Montréaler's diet and the associated yield for each type of potential growing space. The resulting wide range of yield values in these different farm management strategies are important in determining what proportion of the population could be fed in alternate scenarios.

Table 1. Sources of yield and yield ratio data for various farm management systems.

	Low-Intensity Vacant Space	**High-Intensity Vacant Space**	**Low-Intensity Residential**	**High-Intensity Residential**	**Hydroponic**
Yield Source	Statistics Canada, 2012 [31]	Statistics Canada, 2012 [31]	Statistics Canada, 2012 [31]	Statistics Canada, 2012 [31]	Jenson, 1997 [14] Resh, 2004 [38] Lufa Farms, 2012 [39]
Yield Ratio Source	Duchemin *et al.*, 2008 [12]	Duchemin *et al.*, 2008 [12]	Duchemin *et al.*, 2008 [12]	Grewal and Grewal, 2012 [11] and Columbia Urban Design Lab, 2012 [40]	N/A
Yield Ratio	0.53	1.12	2.03	3.50	N/A

Table 2. Vegetable types and their associated yields using various farm management systems.

Vegetable Type	Proportion of Diet	Low-Intensity Vacant Space (g/m²/y)	High-Intensity Vacant Space (g/m²/y)	Low-Intensity Residential Space (g/m²/y)	High-Intensity Residential Space (g/m²/y)	Industrial Rooftop Hydroponics (g/m²/y)
Tomato	30%	707.02	1494.08	2708.02	4669	42,860
Bush Beans	1%	169.9816	359.2064	651.0616	1122.52	4550
Cabbage	12%	2006.7019	4240.5776	7686.0469	13,251.805	26,922
Cucumber	19%	985.8	2083.2	3775.8	6510	63,030
Radish	8%	715.5954	1512.2016	2740.8654	4725.63	17,790
Lettuce	11%	819.274	1731.296	3137.974	5410.3	43,025
Turnip	8%	1920.826	4059.104	7357.126	12,684.7	87,600
Pepper	11%	1437.572	3037.888	5506.172	9493.4	23,333

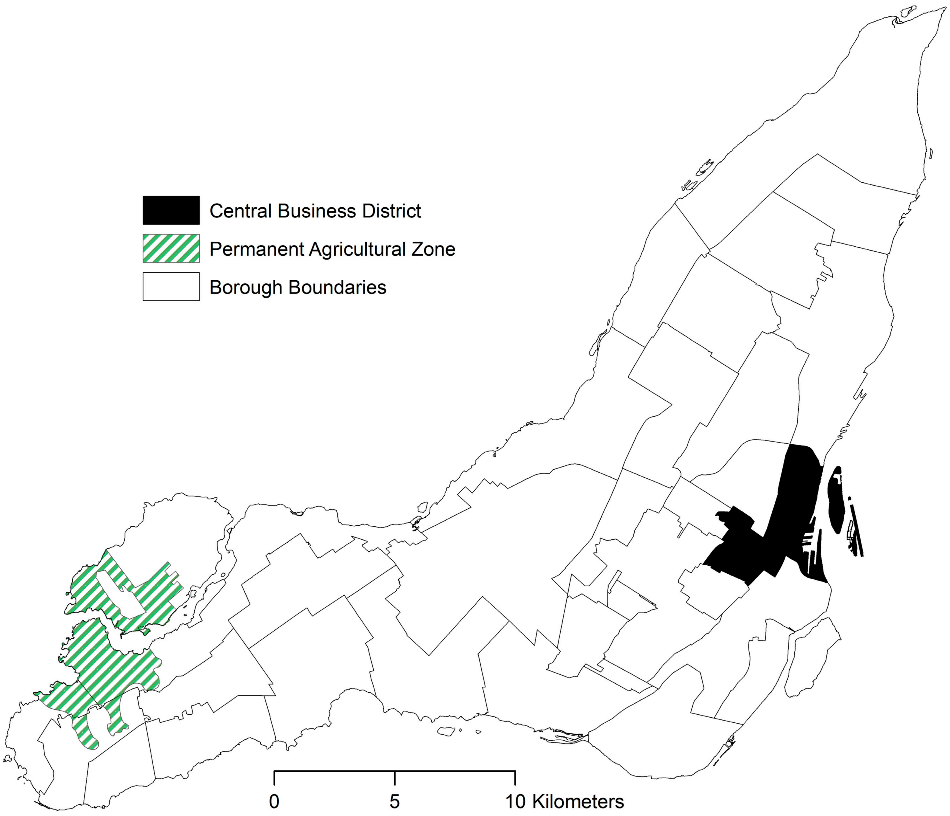
2.3. Land Use and Population

To conduct a spatial analysis, we obtained a land use map from the Communauté Urbaine de Montréal [41], as well as a map outlining the 33 boroughs of Montréal [42]. In order to avoid overestimating the potential space available for agriculture, roads were removed from all land uses on the map using an average width of 8 m per two-lane road (Lanes have an official width of 3.5 m, with an additional 1 m per road; a two-lane road is therefore 8 m wide) [43]. The population of each borough was obtained from the most recent Canadian census [35].

The land uses that were considered available for UA in the study are: vacant space, residential yard space and industrial rooftop space. Vacant space was defined as all unused space in a borough, including officially unexploited space and parking lots [41]. Though parking lots serve an important purpose, the land use map did not distinguish between these and other vacant spaces, therefore making them a limitation in the dataset. Industrial rooftop space was calculated by overlaying building footprints [42] on the land use map and calculating the area of all rooftops that fell within industrial land use. Residential yard space was calculated by sketching the yards from randomly sampled residential land parcels. In Google Earth, ten land parcel samples from each of low-, medium- and high-density residential housing were selected from across the island. During the digitization process, historical imagery from the closest possible date to that of the land use map was used. The proportion of lawn space relative to the size of the parcel was calculated and averaged for the three housing densities. In low-density housing areas (including semi-detached row housing), 27.68% of each land parcel was considered a potential area to implement UA. In medium-density (townhouses) and high-density (condominiums or apartments) residential areas, 20.13% and 21.27% of each parcel were allocated to UA space, respectively. High- and low-intensity UA yields were applied to these vacant and residential areas, while hydroponic yields were applied exclusively to industrial rooftops.

The Permanent Agricultural Zone in Montréal extends over five peri-urban boroughs. This agricultural zone was left intact in the analysis. All production in this zone was assumed to be vegetable production with the conventional agriculture yields of Québec farmers, gathered from Statistics Canada [31]. The area of the Permanent Agricultural Zone is minor (~4% of the island's area) when compared to the amount of space that could potentially be devoted to UA and, so, does not have a major impact on the results of this study.

Figure 1. The island of Montréal.



2.4. Island Simulation Scenarios

Simulations were conducted on two different scales: the island as a whole and for each borough independently. The island and its boroughs are shown in Figure 1. The island-wide analysis was carried out in order to estimate the percentage of vegetable demand that could be met by allocating agriculture to the previously described land use areas. We calculated and compared the following four scenarios:

Island Scenario 1: Vegetable production is allocated to all vacant space on the island. This could be considered a low-risk plan that requires a relatively small financial investment. Public administration aims to convert and devote all vacant space available to agriculture, either as community or collective gardens. Presumably in this scenario, the aim would not be to solely produce food, but would also be to foster social and environmental benefits. For Scenario 1, two results were produced: one using low-intensity UA yields and a second one applying high-intensity UA yields, as described in Section 2.1.

Island Scenario 2: Vegetable production is allocated to all industrial rooftop space using hydroponic yields. Scenario 2 can be characterized as an intensive investment into commercial UA in which a greenhouse is built on top of every industrial building. This would undoubtedly require a significant investment in both finances and labour. Scenario 2 produces one result, whereby all industrial rooftops are used to grow vegetables hydroponically.

Island Scenario 3: Vegetable production is allocated to residential yard space. Scenario 3 envisions a future where the UA movement expands and is practiced by every household. This scenario can be characterized as a mass action plan whereby everyone uses their available land for UA. In this case, two results were produced, one in which practitioners garden casually and do not have advanced farming techniques and a second one with high-intensity yields.

Island Scenario 4: Combination of Scenarios 1, 2, and 3. In Scenario 4, a food production system in which the public converts vacant space into UA and residents grow personal gardens on their home lots is envisioned. Hydroponics would also be implemented on industrial rooftops. The goal of this scenario is to examine how easily the population could be fed given an idealistic and comprehensive UA system involving both the public and private sectors. This simulation produces 2 results: one in which low-intensity yields are applied to residential yard and vacant space and one in which high-intensity yields are applied to these areas. Both results utilize the same hydroponic yields on industrial rooftops.

2.5. Borough Simulation

The analysis at the borough level was conducted using a scenario in which the ability of each borough to produce its own food requirement was assessed. Use of residential and vacant space was maximized, and hydroponics use was minimized due to the increased financial and labour costs associated with the practice. Residential yard space and vacant space were used to produce both low- and high-intensity yields, as in Island Scenarios 1 and 3. The amount of hydroponics required to supplement this production in order to meet the vegetable demand per borough was calculated according to the following formula:

$$HD_{b(\%)} = 100 - \left(\frac{Rv_{b(g)} + Vv_{b(g)}}{YVD_{b(g)}} \times 100\right) \tag{2}$$

where HD_b is the percentage of the vegetable demand that would need to come from hydroponics to meet the vegetable demand for a borough, Rv_b is the yearly amount of vegetables grown in residential yards, Vv_b is the yearly amount of vegetables grown in vacant space and YVD_b is the yearly vegetable demand in a borough. Boroughs where HD_b is zero can produce sufficient vegetables to meet their population's demand without requiring hydroponics, while boroughs with an HD_b of 100 would theoretically have no residential or vacant space and would require all of their vegetable diet to come from hydroponics. The following formula was then applied to determine the percentage of each borough's total industrial rooftop space that would be necessary to produce the required amount of vegetables hydroponically:

$$IR_{b(\%)} = \frac{\sum\left(\left(YVD_{vb(g)} - \left(Rv_{vb(g)} + Vv_{vb(g)}\right)\right)/Y_v\right)}{TIR_{b(km^2)}} \times 100 \tag{3}$$

where IR_b is the percentage of total industrial rooftop space needed to meet the annual vegetable demand, YVD_{vb} is the yearly vegetable demand of a single variety of vegetable in a borough, Rv_{vb} is the amount of that vegetable grown in residential areas in the borough, Vv_{vb} is the potential amount of that vegetable grown in vacant space in the borough, Yv is the low- or high-intensity yield for that vegetable and TIR_b is the total available industrial rooftop space in the borough. Boroughs where IR_b is

100 or greater would not be able to meet their vegetable demand, even if they utilized all of the industrial rooftop space for hydroponics.

A performance index was created to measure the ability of each borough to support a high population density without resorting to hydroponic production to meet its vegetable demand. An ideal borough would support a high population density and would grow all of its vegetables using vacant or lawn space, eliminating the need for hydroponics. Assuming each borough implements average-yielding urban agriculture in its vacant and residential space, the need for hydroponic vegetable supplements per borough was plotted against the relative population density in order to assess which boroughs fit into this category.

3. Results

The results of the four island-wide simulations are listed in Table 3. The use of high- *versus* low-intensity urban agriculture had a large impact on the percentage of the population that can be fed, suggesting that the intensity of farming in vacant and residential space is important. Hydroponic use on industrial rooftops (Scenario 2) would produce an excessive amount of vegetables alone; however, this would require a much greater commitment, both socially and financially. By combining residential and vacant space for UA use (Scenario 1 and 3), 136.5% of the vegetable diet could be produced using the conservative low-intensity yield estimates. In this case, the vegetable demand could be met without major financial costs, even if practitioners were not experienced farmers. If practitioners were more experienced and committed to farming, the vegetable demand could be met using only a percentage of residential lawns alone (Scenario 3). Moreover, in the somewhat less realistic Scenario 4, where all vacant and residential space grows produce using low-intensity yields in combination with all industrial rooftops implementing hydroponics, Montréal's vegetable demand can be met four-times over.

Table 3. Four simulation scenarios expressing the percentage of vegetable demand met on the entire island of Montréal using either a low or a high estimate for urban agriculture (UA) yields.

Island Scenario	Low-Intensity Yields	High-Intensity Yields
1. All vacant space	44.8%	75.5%
2. All industrial rooftops	276.7%	
3. Residential yard space	91.7%	128.4%
4. Vacant space, residential yard space and industrial rooftops	378.7%	446.1%

The analysis conducted at the borough level assessed the amount of supplementary hydroponics required for each borough. Considering low-intensity yields (Figure 2), the borough with the highest hydroponic demand was Plateau-Mont Royal, where 74.8% of the vegetable demand had to be provided with hydroponics. Conversely, no hydroponics use is necessary to meet the vegetable demand in 19 of the 33 boroughs, accounting for 30.5% of Montréal's population. When the same analysis was conducted with high-intensity yield estimates, 28 boroughs do not require hydroponics to meet their food demand. This accounts for 66.8% of Montréal's population. The populations of each borough are listed in Table 4.

Figure 2. Percentage of hydroponics needed to reach vegetable demand after maximizing the use of vacant and residential yard space for low-intensity or high-intensity vegetable production. See Table 4 for the borough key.

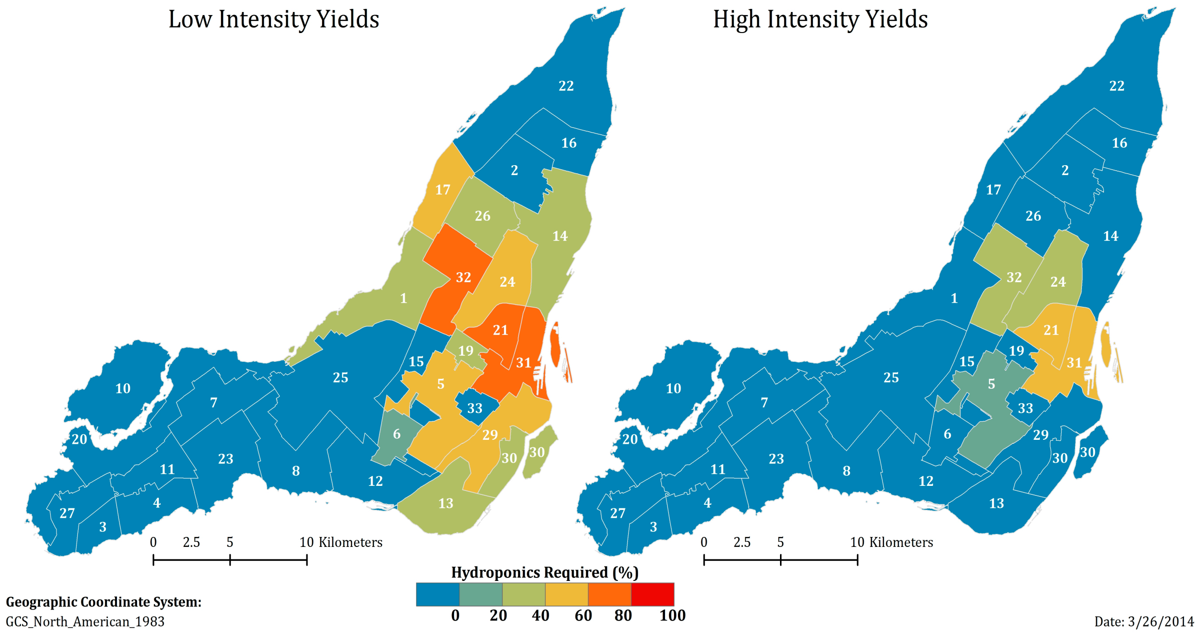


Table 4. Montréal boroughs and their associated population.

ID	Borough	Population	ID	Borough	Population
1	Ahuntsic-Cartierville	126,891	**18**	Montréal-Ouest	5085
2	Anjou	41,928	**19**	Outremont	23,566
3	Baie-D'Urfé	3850	**20**	Pierrefonds-Roxboro	68,410
4	Beaconsfield	19,505	**21**	Plateau-Mont-Royal	100,390
5	Cote-des-Neiges-NDG	165,031	**22**	Point Trembles	106,437
6	Cote-Saint-Luc	32,321	**23**	Pointe-Claire	30,790
7	Dollard-Des Ormeaux	49,637	**24**	Rosemont-La Petite-Patrie	134,038
8	Dorval	18,208	**25**	Saint-Laurent	93,842
9	Hampstead	7153	**26**	Saint-Léonard	75,707
10	L'ile-Bizard-Sainte-Geneviève	21,253	**27**	Sainte-Anne-de-Bellevue	5073
11	Kirkland	18,097	**28**	Senneville	920
12	Lachine	41,616	**29**	Sud-Ouest	71,546
13	LaSalle	74,276	**30**	Verdun	66,158
14	Mercier-Hochelaga-Maisonneuve	131,483	**31**	Ville-Marie	84,013
15	Mont-Royal	19,503	**32**	Villeray-Saint-Michel-Parc-Extension	142,222
16	Montréal-Est	3728	**33**	Westmount	19,931
17	Montréal-Nord	83,868		**Total**	1,886,476

In order to determine the infrastructural feasibility of these plans, the percentage of industrial rooftop space required to meet the demand for each borough was calculated. For example, some boroughs may require 50% of their vegetable demand to be produced through hydroponics, but do not have enough rooftop space to facilitate this. With low-intensity farming (Figure 3), seven boroughs did not have the required rooftop space. However, with high-intensity estimates, only one borough was unable to grow enough vegetables with industrial rooftops: Plateau-Mont Royal.

Figure 3. The percentage of industrial rooftop space needed to produce hydroponics after maximizing the use of vacant and residential yard space for low-intensity or high-intensity vegetable production. See Table 4 for the borough key.

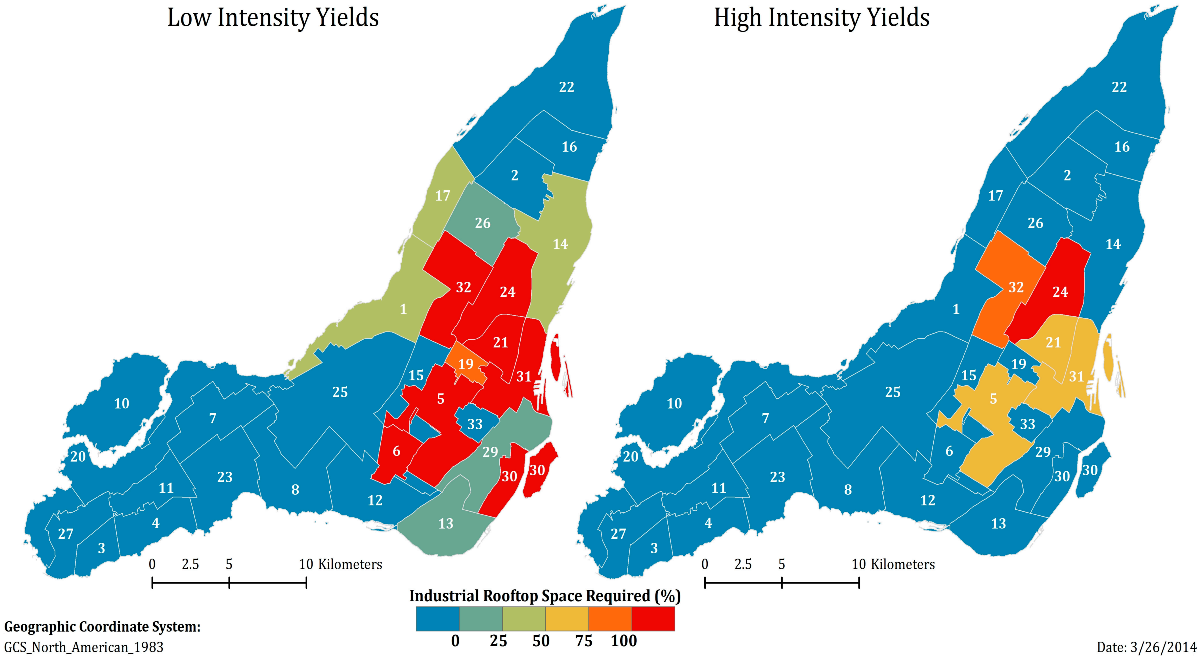
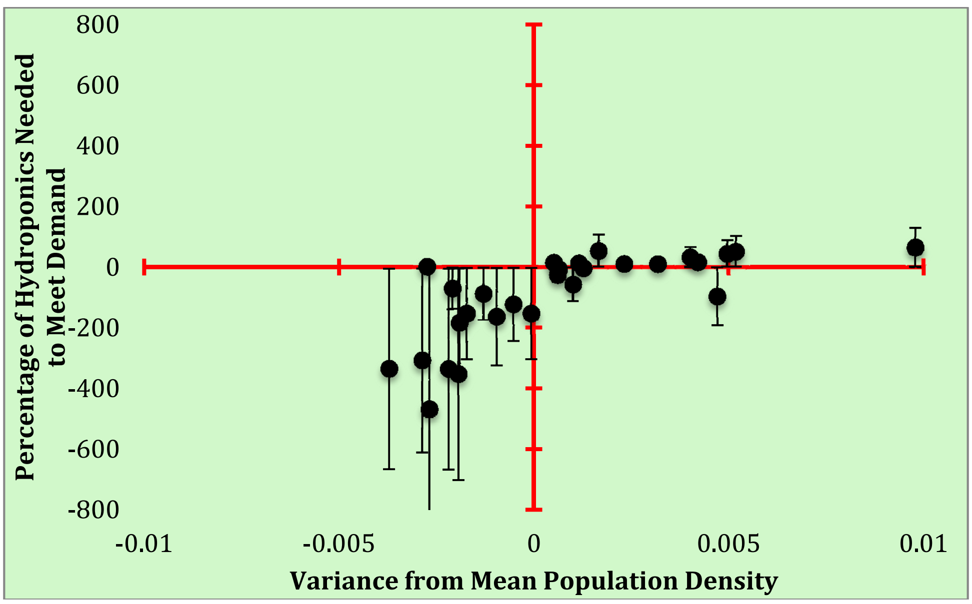


Figure 4. Performance indicator of each borough comparing hydroponic needs against relative population density, assuming average yield values (mean of high- and low-intensity yield estimates). Error bars show the variance in the need for hydroponics as farm management and yield values becomes more or less intense. Five outlier boroughs were excluded for visual clarity.



When comparing the performance of the boroughs, an ideal borough is considered to be able to support a high population density while farming in vacant and residential areas, without the need for hydroponics (Figure 4). Higher population density in a borough implies that there would be less space available for UA, since more land would be devoted to high-density residential housing. In these boroughs, supplementary hydroponics would likely be needed unless the boroughs have a surplus of vacant land available, as is the case with boroughs located in the bottom right quadrant of Figure 4. Only five boroughs are situated in the ideal quadrant; however, the error bars highlight the importance of farm management: with low-intensity yields, only four boroughs perform in the ideal quadrant compared to a potential of ten boroughs with high-intensity yield estimates.

4. Discussion

Despite being recognized as a green city, there is a surprising lack of quantitative data available on urban agriculture in Montréal. Given the assumptions made in this study, the results show that satisfying the vegetable demand of Montréal's population is within reach. In Island Scenario 4, albeit a very idealistic scenario, the vegetable demand could easily be met if all vacant space, industrial rooftops and specified residential garden space were utilized for UA. These results appear to be attainable, even when using low-intensity yield estimates that could typically be obtained by an average household gardener. Alternatively, in a more realistic scenario, where vacant and residential yard spaces are used for UA with low-intensity yield estimates, the vegetable demand of the entire island could also be met. This result, while not immediately achievable, is encouraging for the UA enthusiasts in Montréal, as it shows that significant amounts of our diet could be produced on the island in the near future without the need of a significant financial buy-in. It is important to note, however, that there were some limitations and assumptions that were made during the course of the analysis. Given the high variability of UA yields due to weather patterns, growing season, air and water quality, fertilizer usage, crop sabotage and other external factors, these results may be overestimated. Conversely, some potential areas for UA, such as balcony space, were not considered due to data limitations. Nevertheless, the results support the same conclusions drawn in the Grewal and Grewal [11] study: UA can be a substantial tool for increasing food security and resilience in cities.

Currently, most of the vegetables consumed on the island arrive from off-island sources [10], requiring each borough to import their respective vegetable requirement. If food were produced according to the island scenarios outlined in this paper, the boroughs with large amounts of vacant space would become producers for the more consumptive boroughs. They would be relied upon to fill the demand of the more residential boroughs that do not have adequate rooftop or vacant space to feed their own residents. This could create inequalities in food access and availability between boroughs, as prices and supply may vary by location. These inequalities negate one of the main advantages of UA: increased food security [9,11,22,44]. Generally, UA reduces some of the risks associated with a modern food production system by minimizing food miles, eliminating the middleman and increasing stability through food sovereignty [9,22,44]. Importing from a neighbouring borough, however, is still preferable to importing from distant rural areas, since it would be less costly and would reduce food waste.

The ability of each borough to meet its own vegetable demand is a more relevant metric than absolute production potential when determining where UA should take place. Using a multi-scale analysis and examining UA in this regard can help to devise sustainable methods of co-existing where we grow food. The boroughs examined in this study each contain different amounts of residents and proportions of land uses. Boroughs that require large amounts of rooftop space to meet their vegetable demand either have an extremely high population or an extensive amount of land that is dedicated to another land use type, such as commercial or industrial, making it difficult to implement effective UA in these areas. An ideal borough, within the framework of this study, is one where its land use composition supports both its population density and allows adequate food production space to meet its demand.

The few boroughs that fell in the fourth quadrant of Figure 4 were able to accomplish this; although, the land use layouts of most boroughs were not ideally suited to perform well on this index. An ideal borough in this case could easily feed its population with its current land use, without needing hydroponics. Admittedly, urban planning policies should not necessarily force the under-performing boroughs to have similar infrastructure and land use configuration as those in Quadrant 4. There are many other factors that influence the planning of space in a borough, and this figure only captures one aspect. For example, land competition may emerge between the transportation, housing, industrial and agricultural sectors. If developers incorporate the applicability of UA in city layout and composition design, these results have implications for zoning and planning and should be investigated in more detail. Currently, disparities exist in access to fresh vegetables in Montréal [12,15,45]; however, these results show that this does not always have to be the case. Creating an urban layout in each borough where it is possible for production to meet or exceed the demands of its respective inhabitants would aid in eliminating some of the inequalities previously discussed.

With regards to seasonality, the shortened growing season at this latitude would make it difficult to produce enough fresh earth-bound crops. However, in a Cleveland case study on UA [11] that considered both fresh and processed vegetable demand separately, considerable self-reliance was achieved, further strengthening the results of this study. In Montréal's northern climate, meeting the year-round fresh vegetable demand would necessitate the use of hydroponics. While the exact effects of the shortened growing season are difficult to quantify, the excess of industrial rooftop space available island-wide suggests that meeting vegetable demand throughout the winter would not be a problem. The boroughs without enough useable rooftop space, however, will find themselves lacking in fresh vegetables in the winter, adding a temporal element to the issue of spatial inequality.

Pundits of UA may argue that the implementation of large-scale operations would have resounding economic consequences for rural farmers. However, rural farmers are able to grow more extensive crops, like cereals, which carry a much higher production value than vegetables [23,46], thus preserving their livelihoods.

5. Conclusions

This research provides a starting point for further investigations on the potential of urban agriculture in Montréal. The analysis reveals that a strong potential exists for UA to play a significant role in meeting Montréal's vegetable needs. In a broader sense, the results support the conclusions of other case studies, confirming that implementing UA on a large scale, even at relatively high latitudes, can substantially increase the self-reliance and resilience of food systems in North American cities. Though these results are promising, they also raise many questions regarding the implications for zoning and redistricting plans, as well as the spatial-temporal patterns of inequality in food access and availability that may arise given the implementation of a large-scale UA operation. Examining this issue on multiple scales may reveal some of the intricacies of these interactions; however, there is a genuine need for indicators of food self-reliance that consider impacts of land use in addition to food demand.

Further research is required in order to determine socio-economic and ecological trade-offs involved in the large-scale production of food in an urban environment and the development of an indicator of food self-reliance that considers these trade-offs. Only when all of the trade-offs are understood can we implement adequate policies. This study serves as a stepping-stone in that process by providing a range of potential vegetable produce available to a typical North American city and a multi-scale analysis that examines which land use compositions are conducive to UA. Hopefully, this data will be a useful element in the crafting of policy on land use planning with regards to urban sustainability and the looming food crisis [47].

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Author Contributions

This study was based on research conducted in the course "Research in Sustainability" at McGill University in fall, 2012, taught and supervised by Federico Martellozzo. All authors conceived of and designed the study together. Daniel Haberman conducted all GIS and Google Earth analyses. All authors aided in the rest of the implementation of the study, as well as the revision of the manuscript. All authors read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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