Measuring and monitoring urban sprawl in Canada from 1991 to 2011

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ABSTRACT

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Mehrdokht Pourali Rahdari

Urban population growth and the expansion of urban areas has resulted in numerous negative environmental impacts. In Canada, built-up areas increased by more than 150% between 1971 and 2011, significantly faster than the number of inhabitants. Much of this increase took the form of dispersed, low-density urban development commonly referred to as *urban sprawl*. However, serious attempts to rigorously quantify and compare urban sprawl across Canada are lacking. This thesis measures the degree of sprawl for all 34 Canadian Census Metropolitan area (CMA) and the 469 Census Subdivisions (CSD) located within the boundaries of the CMAs and assesses temporal changes in urban sprawl between 1991 and 2011. This thesis uses the metrics of Weighted Urban Proliferation (*WUP*) and Weighted Sprawl per Capita (*WSPC*) to quantitatively assess the degree of urban sprawl. The value of *WUP* answers the question of how strongly the landscape within each reporting unit is sprawled per km^2. *WSPC* quantifies the amount that, on average, each inhabitant or workplace contributes to urban sprawl in a reporting unit. The results demonstrate that urban sprawl increased considerably in all CMAs between 1991 and 2011. Montreal scored highest in 2011 among the CMAs (18.24 UPU/m^2), followed by Victoria (17.93 UPU/m^2), Kitchener-Cambridge-Waterloo (17.70 UPU/m^2), Vancouver (17.24 UPU/m^2), and Toronto (16.75 UPU/m^2). Between 1991 and 2011, the Victoria CMA experienced the highest increase in *WUP* among all the CMAs. In the first decade between 1991 and 2001, urban sprawl increased in all CMAs. CMAs also showed a clear, continuous increase in urban sprawl in the second decade (2001-2011), except for Guelph and Ottawa-Gatineau-ON, where it decreased. *WSPC* also increased in more than half (59%) of the CMAs between 1991 and 2011. Saint John

CMA (NB) obtained the highest value in 2011, followed by Thunder Bay and Greater Sudbury. The lowest *WSPC* values were observed in Toronto, due to the lowest land uptake per inhabitant or job, followed by Montreal, Vancouver, and Calgary. The period 1991-2001 witnessed an increase in *WSPC* in most of the CMAs (76%). In contrast, the value of *WSPC* decreased from 2001 to 2011 in most (76%) of the CMAs. The results presented here are especially useful for environmental monitoring and sustainability monitoring and to guide future planning seeking to reduce urban sprawl and its negative impacts. Although some sustainable development policies and Transit-Oriented Development (TOD) plans have been established to control urban sprawl in several cities (e.g., Vancouver, Toronto, and Montreal), progress towards controlling urban sprawl in the Canadian CMAs overall has been weak and sprawl continues to be a major threat to sustainable land use in Canada. Increased efforts are needed to more consistently and more effectively monitor and control urban sprawl and to transition to more sustainable forms of development e.g., smart growth. The insights from this study are particularly relevant to urban, regional, and land-use planning, and to the planning of future transport infrastructure.

Keywords: Built-up area, Dispersion, Land up-take, Monitoring, Urban development, Urban growth, Urban permeation (*UP*), Urban Sprawl, Utilization density (*UD*), Weighted urban proliferation (*WUP*), Weighted Sprawl per Capita (*WSPC*)

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Contribution of Authors

As first author, I was responsible for the conception of the paper, acquisition of data, correcting the shapefiles using GIS for the years 1991, 2001 and 2011, data analysis and quantitative calculations for the CMAs and CSDs, interpretation of data and results, and the writing of the manuscript related to this thesis. The manuscript was co-authored by Dr. Craig Townsend, who contributed to conception and design, data analysis and quantitative calculations. The third author, Alex Guindon assisted with data collection for inhabitants and jobs, historic maps and shapefiles. Dr. Jochen Jaeger advised on experimental design, data analysis, quantitative calculations, editing, and overall revisions to the manuscript.

Table of Contents

List of Figures

List of Tables

To my parents, Iraj and Iran, for their love.

1. Introduction

According to Statistics Canada, the proportion of agricultural land in Canada is 7.3%, while this figure in Ontario is 5.2% and 2.6% in Quebec. Unfortunately, cities in Canada are growing rapidly into agricultural lands. For instance, "by 2001, about one-half of Canada's urbanized land was located on dependable agricultural land (i.e. Class 1-2-3 land as classified by the Canada Land Inventory)." (Hofmann et al. 2005, p.1). The authors define "dependable" agricultural land as "land designated as Class 1, Class 2 and Class 3, these classes include all land areas that are not hampered by severe constraints for crop production" (Hofmann et al. 2005, p.1). In other words, dependable agricultural land is the endowment of quality land suitable for farming (Hofmann et al. 2005). Planners and decision makers must consider the loss of agricultural land in Canada and how it can be prevented more carefully in their plans and decisions regarding urban development.

The standard pattern of urban growth in North America is suburban sprawl (Duany et al. 2001). The term "urban sprawl" was coined by urban planners in Europe following the end of World War II. However, the corresponding German term "Zersiedelung" was already used earlier in the 1920s (Akademie für Raumforschung und Landesplanung 1970). By increasing the manufacturing output and federal loan programs, many American citizens were able to buy single-family houses and use their own automobiles. In addition, road-building projects continued and other infrastructure developments made it easier to build houses in new suburban areas. These areas were much cheaper than land in the cities. Citizens moved to the suburbs for many reasons: a better lifestyle and more open spaces providing escape from metropolitan congestion, pollution and crime, etc. These factors increased sprawl patterns of urban growth (Rafferty, 2019).

Urban sprawl contributes to many environmental problems. For example, it has negative impacts on the infrastructure and air quality (Brunner, 2012). The many detrimental effects of urban sprawl on the environment include increased energy consumption, increased water pollution and consumption, reduced amount of farmlands, open spaces, and natural habitats, fragmentation of wildlife habitats, increased traffic congestion and higher expenditures for infrastructure.

The global human population will further increase by 30–70% in this century, which will lead to a population shift from rural to urban areas and to significant land-uptake for urban expansion (Montgomery, 2008; Gerland et al., 2014). This urban sprawl will be a major challenge to implementing sustainable land-use plans. Spreading awareness and creating mitigation measures will thus be paramount in controlling it.

Hennig et al. (2015) accomplished a multi-scale analysis of urban sprawl in Europe. Their results showed that large parts of Europe are affected by urban sprawl (Figure 1), and the value of weighted urban proliferation (*WUP*) (a measure of the degree of urban sprawl) for all of Europe (32 countries considered) was 1.56 UPU/m^2 in 2006. In addition, Hennig et al. (2015) proposed a European de-sprawling strategy, which included the implementation of targets and limits, and a set of concrete measures to control urban sprawl and to use land in a more efficient way.

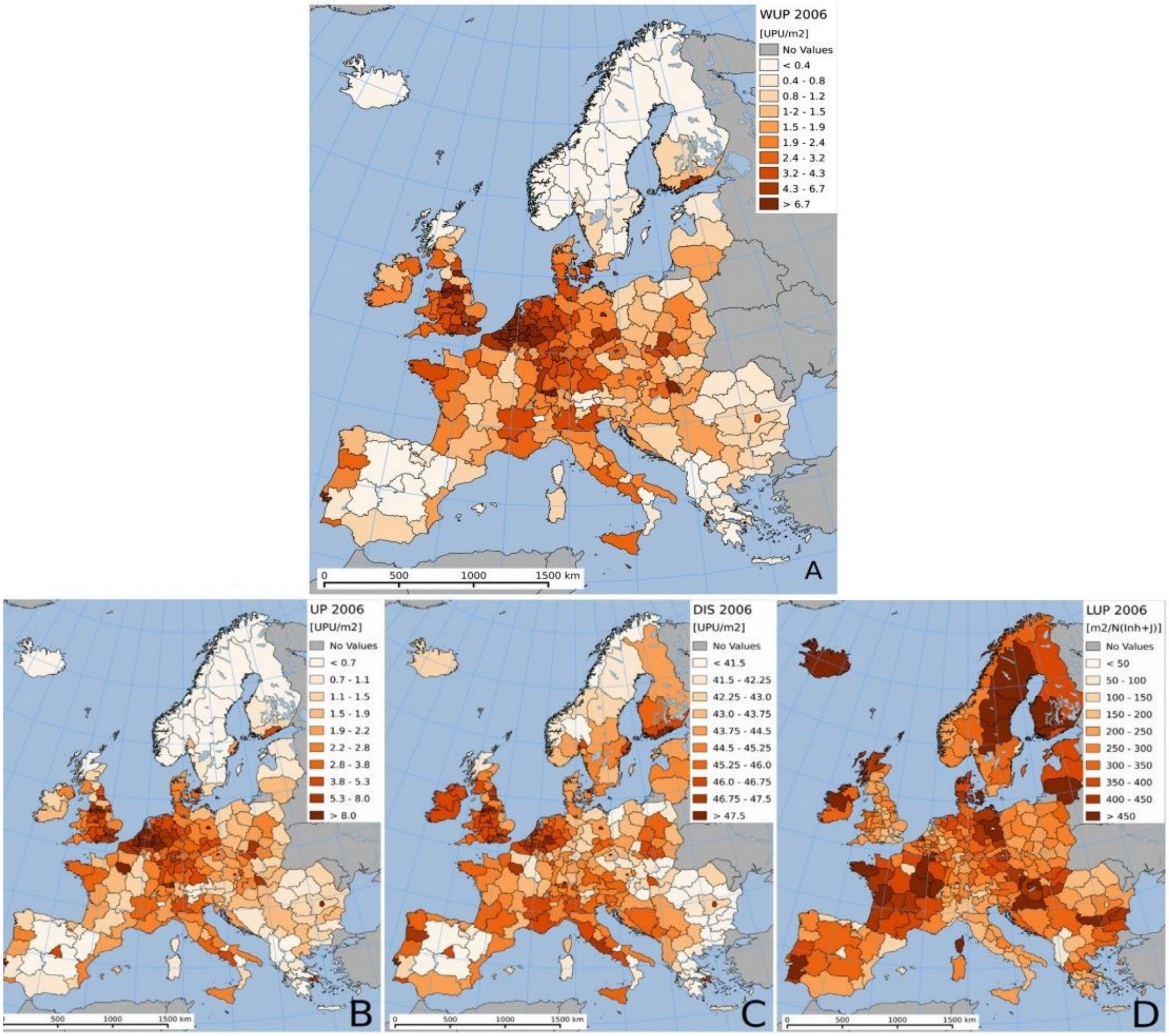


Figure 1. Map of Weighted Urban proliferation *WUP* (A), Urban Permeation UP (B), Dispersion *DIS* (C) and Land Up-take Per person *LUP* (D) in NUTS-2 regions. (Hennig et al. 2015)(See chapter3 for more detailed information)

Many scientists believe that urban planners must explore various dimensions and characteristics of the metropolitan-level built environment to ensure policies will lead to smart growth and improvements in public transit ridership through the entire metropolitan area (Nasri et al. 2017). Nasri et al. (2017) presented a multi-dimensional method of measuring form and development patterns for urban areas in the United States. This methodology utilized specific variables and indices that enable the characterization and quantification of the overall physical form of a metropolitan area. These multi-level, multi-dimensional measures explore the urban structure at various hierarchical levels (Nasri et al. 2017).

In general, different measure were used for measuring urban sprawl around the world, however, most of the existing measurement methods are not accurate and reliable, e.g., entropy (Nazarnia et al. 2019). In this study, the most accurate and reliable metric will be used, which considers 13 suitability criteria for measuring urban sprawl (Jaeger et al. 2010a).

The objective of this project, is to quantify the degree of urban sprawl in 34 census metropolitan areas that Statistic Canada provided land cover details for the years: 1991, 2001 and 2011. Therefore, the rate of increase can be compared for two periods of time (1991-2001 and 2001-2011). In this thesis, I will produce maps of urban sprawl and maps of the changes of urban sprawl (absolute and relevant changes e.g. EEA 2016).

The following reporting units will be considered: 1. Census Metropolitan Areas and 2. Census Subdivisions.

The thesis will address two main research questions:

1. **Which reporting units in Canada exhibit higher or lower degrees of urban sprawl?**
2. **How quickly has the degree of urban sprawl increased between 1991 and 2011 in the various reporting units in Canada? When did the strongest increases of sprawl occur?**

Considering the combination of the three components of urban sprawl (dispersion, percentage of built-up areas, and land-up take per person), I hypothesised that **urban sprawl increased faster than the population and faster than the built-up areas in all parts of Canada.**

This thesis first provides an overview of the literature about urban sprawl, focusing on its definitions, causes, and consequences, as well as the various methods for measuring it and existing studies of urban sprawl in Canada and elsewhere. The third chapter explains the methods and data that were used for measuring urban sprawl in this study. Chapters 4 and 5 present the manuscript for peer-reviewed journal as the output of this study. Chapter 6 provides the results of historical analysis of urban sprawl in Canada over 20 years. Finally, chapters 7 and 8 present the overall discussion and conclusion of the whole thesis.

2. Literature Review

For understanding the necessity of this research it is essential to explore different aspects of urban sprawl such as definitions, causes and consequences, different methods for measuring urban sprawl and existing studies about urban sprawl in Canada and elsewhere.

2.1. Definitions of urban sprawl

The definition of urban sprawl has been the subject of much discussion in the literature. Currently, there is no generally agreed upon definition for urban sprawl. The approaches are different from each other, and some definitions include causes and drivers of urban sprawl. Conversely, there are even some incorrect definitions of urban sprawl which define it as urban development at high density. Therefore, urban sprawl has been defined depending on the perspective of the author of the definition (Barnes et al. 2001).

The corresponding German term ‘‘Zersiedelung’’ was presented for the first time in the 1920s. It was commonly used in German-speaking countries after the Second World War (Akademie für Raumforschung und Landesplanung, 1970).

This diversity of approaches has been summarized by Pamela Blais (2011) in her book "Perverse Cities": "Sprawl could be viewed as an aesthetic judgment, as the cause of an externality (e.g., auto dependence), as the consequence of an action or condition (e.g., exclusionary zoning), as a pattern of development, or as a process of development" (p. 18). She continues by presenting that "most commonly sprawl is defined as an urban landscape having certain characteristic physical elements. Definitions based on physical elements are especially attractive to planners, urban designers, and citizens as they are readily understood. There is little consistency with regards to what these elements are, however. Often cited are: leapfrog development, commercial strip development on or near the urban fringe" (Blais, 2011, p. 18).

Low population density is also an important dimension of urban sprawl that Schwick et al. (2012) used in their definition: "Sprawl is a phenomenon that can be visually perceived in the landscape. The more heavily permeated a landscape by buildings, the more sprawled the landscape. Urban sprawl therefore denotes the extent of the area that is build up and its dispersion in the landscape in relation to the utilization of build-up land for living and work. The more area built over and the more dispersed the buildings, and the less the utilization, the higher the degree of urban sprawl" (p. 115).

In general, I have chosen to define urban sprawl in a basic and objective way as dispersed, low-density development, which is ultimately unsustainable, and occurs usually at the expense of high-quality agricultural land and natural areas. This definition of urban sprawl is similar to those given by Schwick et al. (2012) and EEA & FOEN (2016), which focus on the low density feature of urban sprawl and does not include its causes and effects. The most common definitions from the literature are collected in Table 1.

Table 1. Common definitions of urban sprawl

Definition	Source
"Landscape sprawl has four dimensions: a population that is widely dispersed in low density development; rigidly separated homes, shops, and workplaces; a network of roads marked by huge blocks and poor access; and a lack of well-defined, thriving activity centers , such as down-town and town centers".	(Smart Growth Amercia (SGA) report, Ewing et al 2002) – as cited in Pamela Blais (2011:32)
Sprawl is identified as the combination of three characteristics = ''(1) leapfrog or scattered development; (2) commercial strip development; and (3) large expanses of low-density or single-use developments—as well as by such indicators as low accessibility and lack of functional open space''.	Ewing (1997: 32)
"Urban sprawl is visually perceptible. A landscape suffers from urban sprawl if it is permeated by urban development or solitary buildings. For a given total amount of build-up area, the degree of urban sprawl will depend on how strongly clumped or dispersed the patches of urban area and buildings are; the lowest degree of sprawl corresponds to the situation when all urban area is clumped together into the shape of a circle. The highest possible degree of sprawl is assumed in an area that is completely built over. Therefore, the more urban area present in a landscape and the more dispersed the urban patches, the higher the degree of urban sprawl".	Jaeger et al. (2010a: 400)
"Urban sprawl is commonly used to describe physically expanding urban areas. The European Environment Agency (EEA) has described sprawl as the physical pattern of low-density expansion of large urban areas, under market conditions, mainly into the surrounding agricultural areas. Sprawl is the leading edge of urban growth and implies little planning control of land subdivision. Development is patchy, scattered and strung out, with a tendency for discontinuity. It leap-frogs over areas, leaving agricultural enclaves. Sprawling cities are the opposite of compact cities — full of empty spaces that indicate the inefficiencies in development and highlight the consequences of uncontrolled growth".	EEA (2006: 6)
"Sprawl is characterized by unplanned and uneven pattern of growth driven by a multitude of processes and leading to inefficient resource utilization".	Bhatta et al. (2010: 9)

"Sprawl is low density, auto-dependent land development taking place on the edges of urban centers, often "leapfrogging" away from current denser development nodes, to transform open, undeveloped land into single-family residential subdivision and campus-style commercial office parks and diffuse retail uses".	Soule (2006: 3)
"Low density, Scattered, urban development without systematic large-scale or regional public land-use planning".	Bruegmann (2005: 18)
''Sprawl is an unplanned, unsystematic, area-intensive outward growth mainly of city-type settlements into the rural space and is a consequence of progressive urbanization. The wish for living in green places, for weekend houses, quickly accessible shopping centers, cheap industrial areas, and transportation infrastructure occupies much space, and if there are no conditions posed by regional planning and environmental protection, then construction will happen at places where it is cheapest. In this way, open spaces, recreational areas, and ecological compensation areas are lost, become dissected or downsized and lose their ecological and socio-economic functions''.	Landscape Gesellschaft für Geo-Kommunikation (2000–2002: 469)
''A particular type of suburban development characterized by very low-density settlements, both residential and non-residential; dominance of movement by use of private automobiles, unlimited outward expansion of new subdivisions and leap-frog development of these subdivisions; and segregation of land uses by activity''.	USHUD (1999: 33)
"The unchecked growth of settlements. The danger of sprawl in a landscape is particularly high in the fringe of larger cities, not only through expansive residential building activities, but also through economic institutions that are extensive in area (industrial businesses, airports, etc.). In recent time, sprawl particularly threatens attractive nearby recreational areas through increased building of weekend houses".	Leser and Huber-Fröhli (1997), as cited in Jaeger et al. (2010a)
''The process in which the spread of development across the landscape far outpaces population growth. Landscape sprawl has four dimensions: a population that is widely dispersed in low-density development; rigidly separated homes, shops, and workplaces; a network of roads marked by large blocks and poor access; and a lack of well-defined, thriving activity centers, such as downtowns and town centers. Most of the other features usually associated with sprawl – the lack of transportation choices, relative uniformity of housing options or the difficulty of walking – are a result of these conditions".	Ewing et al. (2002), as cited in Jaeger et al. (2010a: 399)

2.2. Drivers of urban sprawl

The drivers of growth in urban areas that are responsible for undesirable patterns or processes of urban development are also principally important for the analysis of urban sprawl since urban planners need to identify the causes and drivers of different sprawled areas to find suitable solutions for this issue (Bhatta, 2010). According to the European report about urban sprawl (EEA & FOEN, 2016), some important drivers of urban sprawl include:

Demographic drivers

It is undeniable that larger human populations need more space to accommodate them. Population size has effects on the extent of build-up areas (EEA & FOEN, 2016).

Socio-economic drivers

Desired lifestyles and high incomes are often associated with detached housing in the suburbs rather than apartments in a city’s downtown core (EEA & FOEN, 2016). The increase of gross domestic product per capita (GDPc) often leads to an increase in urban sprawl (Bresson et al., 2004; Barbero-Sierra et al., 2013). Because people with higher incomes can more easily afford a single-family house and a car. Despite proliferation of high-rise condos, policy supportive of ownership within a culture that values detached houses has incentivized sprawl in North America.

Political drivers

One factor that has an effect on urban sprawl is unsustainable decision-making in politics. For example, many decisions in planning, zoning, road infrastructure, lawmaking, pro-home ownership policies, and the lowering of taxes greatly impact the extent of urban sprawl (EEA & FOEN, 2016). Inter-municipal competition between suburban jurisdictions can also play an important role. For instance, when government applies lower taxes in the suburbs than in the city core, this way encourage people to move to the rural areas to pay less.

Technological drivers

As technological development continues, for instance, modern communication technologies, people can work at home more easily than ever (Hardill and Green, 2003; Kurz and Rieger, 2013). The result of this technology might decrease the frequency of travel to and from work in an office building, but it can lead to a higher dispersion of settlements and increased urban sprawl (EEA & FOEN, 2016).

Geophysical drivers

Some geophysical factors have direct effects on urban sprawl such as topography and the presence of areas that are not suitable for the construction of buildings, such as steep slopes, mountains and lakes. These limitations to space available for construction limits urban sprawl (EEA & FOEN, 2016).

2.3 Effects of urban sprawl

It is necessary to first understand the effects of urban sprawl before it is possible to evaluate its extent and to plan for sustainable urbanization. These effects include economic, social, and environmental impacts. In this thesis, I focus on the economic, social and environmental effects of urban sprawl, which are summarized as follows.

2.3.1 Economic impacts

According to Nivola (1999), one of the key consequences of the expansion of urban areas is significant economic growth. Urban sprawl is considered as advantageous economically due to the buildings being constructed on inexpensive land, so in this perspective, there is no need to use the land sparingly. The dispersed city leads to new jobs due to more services, infrastructure, and maintenance construction (EEA & FOEN, 2016). However, urban sprawl increases the distances between homes, shopping and workplaces, which leads to high car dependency and low service levels of the public transport system. Increasing numbers of automobiles increase accidents, air pollution, and mental health issues due to traffic congestion and noise (Costal et al., 1988). All of these consequences have impacts on human health and result in higher costs for health insurance and health services, which increase the gross domestic product (GDP), but does not increase human well-being.

Urban sprawl requires significantly larger amounts of infrastructure, since it takes more roads, pipes, cables, and wires to service these low-density areas compared to more compact developments with the same number of households. Moreover, inefficiency of urban sprawl also relates to the operation and maintenance of these infrastructures and to the provision of public services. Since people are more dispersed instead of residing in centralised cities, the costs of community infrastructure and public services in suburban areas is considerably higher. Quebec is likely to experience more ice storms and other extreme weather events in the future as a consequence of climate change, which cause extensive damage to hydroelectric infrastructure (e.g., in the ice storm of 1998, many power lines were broken and over 1,000 transmission towers collapsed in chain reactions under the weight of the ice, leaving more than 4 million people without electricity, most of them in southern Quebec, western New Brunswick and Eastern Ontario, some for an entire month).

Densification is one of the most important sustainable solutions to this problem because it will limit the expenditures for construction, operation, repair, and maintenance of infrastructures. In Europe, researchers are now considering this issue by measuring urban sprawl in the past and present as a basis to set targets, limits, and benchmarks for sprawl in the future (EEA & FOEN, 2016, Schwick et al. 2018).

2.3.2 Social impacts

People who live in the suburbs spend a lot of time commuting between their homes and workplaces. Due to weak connection to public transport, they are forced to use their own car. This increase in car dependency is a cause of many diseases such as obesity due to an increased the level of inactivity (EEA & FOEN, 2016).

The loss of agricultural land to urban sprawl means the loss of fresh local food sources and higher dependence on imported food. Urban sprawl also has effects on the perception of the landscape. Built-up areas change natural landscapes and agricultural landscapes into anthropogenic sites. The open areas between the built-up parts often disappear. Recent surveys indicate higher social segregation in the populations of sprawled regions, with a lower level of participation in activities in the community (Kienast et al., 2015).

There are two opposing processes that may contribute to the spatial separation of the high and low economic classes. In the first process, the financial sector or citizens of the high economic class may move into the city core which can cause surrounding residential prices to increase gentrification, thus displacing the less wealthy. However, in the second process, the movement of the financial sector and wealthy citizens away from the city core may cause these areas to become more economically unattractive (EEA & FOEN, 2016).

Some drivers such as potential increase in crime rate, low education rate, the lack of recreational centers, and unsuitable appearance of the neighborhood, can lead more people to move away from these parts of the city core to achieve a higher quality of social life in the suburbs (EEA & FOEN, 2016). The formation of gated communities is known to be another extreme type of urban development that is linked to urban sprawl. The development of these communities has become common in North America and some developing countries (Atkinson and Blandy, 2005; Le Goix, 2005).

2.3.3. Environmental impacts

Energy inefficiency

Urban Sprawl also causes an increase in fuel consumption as people travel more between suburbia and the central city (Newman et al. 1989). It is also likely to result in traffic gridlock which again leads to more fuel consumption (Bhatta, 2010).

Impacts on wildlife and ecosystems

Urban sprawl changes ecosystem patterns and processes as it decreases the amount of forest areas, farmlands, wildlife habitats, and open spaces. These changes have negative effects on the remaining ecosystems and lead to habitat fragmentation. Roads and infrastructure (e.g. power lines, subdivisions and pipelines) associated with built-up areas often disrupt natural areas and alter wildlife movement patterns. These alterations of ecosystems reduce the availability of habitat for many species (Bhatta, 2010).

Increase in temperature

Urban areas are usually warmer than the rural areas surrounding them (Figure 2). This is called the urban heat island (UHI) effect (Frumkin, 2002), shown by the positive correlation between land surface temperature and the amount of impervious surface (Klinenberg, 2002; Weng et al. 2003; Wang et al. 2007). The UHI effect is triggered by two determinants. The first factor is solar radiation heat absorbed by dark surfaces like asphalt, roads, and tar rooftops and emitted as thermal infrared radiation. Secondly, less vegetation in urban areas results in reduced evapotranspiration, a natural process through which the air is cooled. In addition, life in metropolitan areas requires ownership of vehicles which results in increased fuel combustion and more carbon dioxide emissions that exacerbates global climate change (Bhatta, 2010).

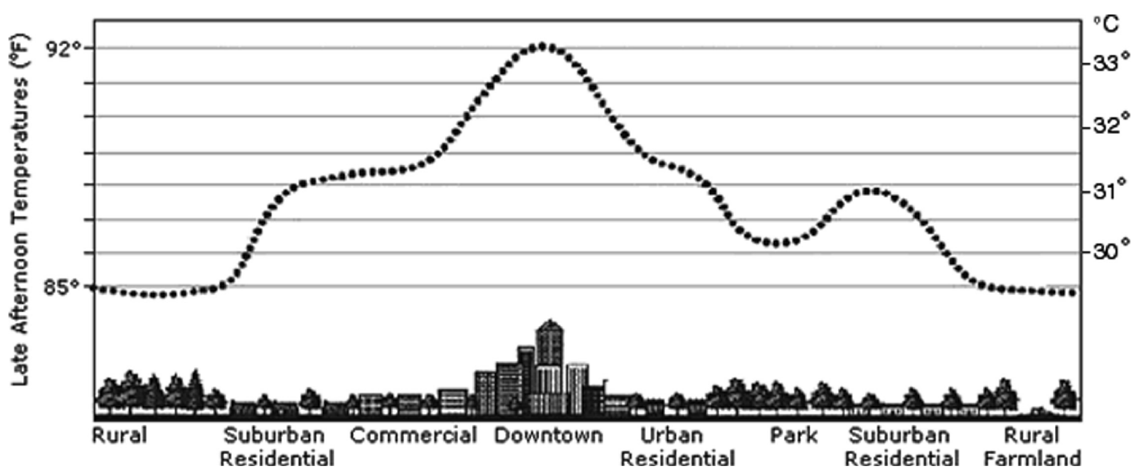


Figure 2. An urban heat island profile (Klinenberg, 2002)

The trade-off for having higher density development includes an increased heat island effect in the high-density areas, while surrounding areas are kept free of built-up areas. The potential increase in temperature overall, including in low-density areas shown in Figure 2 and the destructive impacts of sprawl on the landscape (agricultural and natural areas) result in more wide-spread negative impacts than a few degrees of temperature increase in the high-density areas, at least for the surrounding ecosystems. There are also ways to decrease the heat-island effects in cities that have not been applied (green space, use of alternative materials, etc).

Poor air quality

Car-dependent lifestyles are major drivers of air pollution due to the increase in fossil fuel consumption and emissions of greenhouse gases from vehicles (Stoel, 1999). Air pollutants such as carbon monoxide, ground-level ozone, sulphur dioxide, nitrogen oxides, volatile organic carbons, and microscopic particles increase when more automobiles are used due to urban sprawl (Frumkin, 2002). These pollutants are disturbing plant growth, creating acid rain, contribute to global warming, and cause serious human health problems. While it may seem that better air conditions are associated with low density, Kahn and Schwartz (2008) argue that air pollution is higher in sprawled, low density areas. There is an indirect relationship between increased temperature in urban areas and air pollution (Klinenberg, 2002). By increasing the temperature in summer, the demand for energy to power fans, air and water coolers and air conditioners will increase, resulting in higher energy demand from power plants (Bhatta, 2010). Power plants burn fossil fuels and due to seasonal high demand of power, the emissions of the pollutants increase. Furthermore, heat further enhances ozone formation, leading to a positive feedback loop of continuous ozone creation (Frumkin, 2002).

Impacts on water quality and quantity

Sprawl has serious impacts on water quality and quantity. Rain water and snow melt are unable to soak into the ground due to the impermeability of the built-up areas (e.g. houses, parking lots, roads, etc.). Therefore, urban development associated with sprawl leads to increases in total runoff volume, and intensifies the potential for flooding and erosion (Jacquin et al. 2008). As new development continues in suburbs of the city, citizens, urban planners, the government and insurance sectors are becoming increasingly concerned about the risk of flood disasters and damage associated with them (Wisner et al. 2004; Jacquin et al. 2008). In urban areas, water runs off into sewers and finally into the rivers and lakes. Heavy downpour leads to increases in the flowrate through rivers and lakes, eroding green spaces and destroying habitats close to the river. This leads to flood damage downstream and increased water pollution from the runoff of oils and chemicals from roads and gardens into the rivers (Lassila, 1999; Wasserman, 2000). Humans are also affected by these pollutants when they drink the water or eat contaminated fish from polluted water sources. Moreover, rainstorms in cities with weak water management systems can cause untreated human sewage to enter waterways (Bhatta, 2010).

As presented in this literature review, urban sprawl has serious environmental, economic and social consequences. It increases the costs of infrastructure and provisioning services like public transportation and leads to lower social cohesion. Therefore, urban planners and decision makers should apply efficient solutions such as densification to reduce urban sprawl.

2.4. Existing studies of urban sprawl in Canada

Many studies indicate that Canada has experienced urban development in a low density/urban sprawl pattern in the past. Murshid (2002) examined the process of urbanization in the former County of Laprairie, part of the urban-rural fringe of Metropolitan Montreal. She used Geographic Information Systems (GIS) to create a land-use database with spatial information using data from 2000 to compare the process of urbanization for several years (1964, 1976, and 1988). The results showed that 72% of the remaining open lands of the former county of

Laprairie were developed from 1988 to 2000 (Murshid, 2002). According to Murshid (2002), the increases in urbanization and land consumption rates were caused by factors such as low-density suburban development that were non-residential activities such as strip malls and conventional malls with large parking areas, large industrial and manufacturing districts, hobby farms, and golf courses.

In 2007, Sun et al. (2007) accomplished a quantitative measurement of urban sprawl for the City of Calgary, Alberta by using Shannon's Entropy method. This research has demonstrated a process for creating land use classification from Landsat images using the object-oriented methodologies contained in the eCognition software. Sun et al. (2007) proved that it is possible to produce a satisfactory classification result by using an object-oriented approach. This study demonstrated that urban sprawl continued to grow in Calgary with the value of 0.850 to 0.905 during the years 1985 and 2001. However, the results need to be interpreted with great caution because entropy is not a suitable measure of urban sprawl (Nazarnia et al. 2019), as explained on page 23.

A year later, Behan et al. (2008) in their research on smart growth strategies, transportation and urban sprawl, demonstrated that "the nature of recent development in the Hamilton CMA has been low-density suburban sprawl, with detached homes existing on suburban tracts only" (p. 299-300). This study predicted that the city of Hamilton will experience household growth in the magnitude of approximately 80,000 households during the years 2001 and 2031. It means there should be some specific policies to control urban sprawl in the city of Hamilton. Behan et al. (2008) focused on smart growth policies as a solution to urban sprawl. They mentioned that the purpose of smart growth policies like urban residential intensification (URI) is to increase population densities in the urban core. The aim of their research was to estimate the benefits of smart growth policies in a transportation perspective.

Additionally, Eidelman's 2010 study describes in detail the management of urban sprawl in Ontario. According to this study, The Ontario Places to Grow Plan, finalized in 2006, indicates the strongest measures that have been used to address the urban sprawl issue in Canada and possibly North America. The project included the creation of a permanent greenbelt covering almost 728,000 hectares of environmentally sensitive land. Eidelman argued that "the Plan was partially devised to garner support in key suburban ridings (electoral districts) across the Greater Toronto Area in the 2003 provincial election" (p. 1211). The Ontario case underlines the utility of adaptive models of policy making to the study of environmental policy, but suggests that these models perhaps underemphasize the desire of politicians and political parties to pursue policies in their electoral interest.

Filion et al. (2010) investigated the balance between forces of standardization and differentiation in the evolution of residential density in Ottawa-Hull, Montreal, Toronto, and Vancouver (Canada's four largest metropolitan areas) over the period 1991–2006. The results showed that each metropolitan area has a particular density pattern. As an example, in Ottawa-Hall the pattern merged decentralization and consistency. Montreal and Toronto appeared as decentralizing metropolitan areas, while Vancouver is experiencing heightened density, which is not the same as a density distribution affiliated with traditional high-density North American metropolitan areas. The results of this study presented "the need to adapt intensification strategies to the specific circumstances of each metropolitan region, and thus question reliance on template approaches" (Filion et al. 2010, p. 564).

According to Nazarnia et al. (2016a), the degree of urban sprawl increased exponentially in Montreal in the last 30 years, and the strikingly high value of sprawl in Montreal is mainly due to the low level of utilization density and the high level of dispersion of built-up areas in this metropolitan area. The study presents a quantitative assessment of urban sprawl in Montreal and Quebec City. The changes demonstrate the need for further research regarding trends of urban sprawl in the past, and how it may continue or change in the future.

Townsend et al. (2018) measured population densities and freeways in 57 North American metropolitan regions with at least one million residents. They used both metropolitan region and central core as spatial scales to measure overall density, population-weighted average census tract density, and density of the top 5% of the population. Moreover, these spatial scales were also used to measure the absolute and per capita quantities of lanes of freeways. The results showed that while Canada's metropolitan regions are commonly represented as more dense and auto-oriented to a lesser degree than the United States, the six largest of Canada's metropolitan regions do not have higher population densities and fewer freeways than all of the 51 largest United States metropolitan regions. Townsend et al. (2018) suggested that future studies include data that covers a greater time-span, using the same data, comparing cities that have similar populations at a point in the past, and continued to grow at similar rates.

At a time of rising concern about urban sprawl and its negative consequences in Canada, some scientists have focused their research on efficient strategies and policies to prevent urban sprawl. One of the most efficient ways to reduce urban sprawl is the application of greenbelts because it leads to the containment of urban growth in existing and planned communities and the protection of both agricultural land and the environment. Due to these potential benefits, the province of Ontario adopted a greenbelt policy in 2005. Amal (2008) applied content policy analysis to review Ontario's plans, reports and greenbelt regulations. He assessed Ontario's greenbelt initiative by examining four factors including: political will, public support, greenbelt planning, and enabling legislation. The results show that Ontario's greenbelt initiative demonstrated strong political will, valuable planning, and legislation enforcing greenbelt plans. However, Ontario's greenbelt initiative does not consider public support as one of the most important factors to help keep the greenbelt permanent. The author believed that the provincial government should apply some strategies to include the public in greenbelt planning. Moreover, planners must consider the dangers of leapfrog development. "Leapfrog development is considered as a manifestation of urban sprawl that also incorporates low density development, strip and ribbon development and dispersed development" (Akhter et al. 2015, p. 283). Therefore, Amal (2008) emphasized that the whole province should be covered by the greenbelt policies to prevent the possibility of leapfrog development beyond the greenbelt. In addition, it is necessary to attract businesses into designated growth centers and redistribute people and investments across communities by integrating decentralization and economic policies into the greenbelt planning. All of these actions are required for successful applications of Ontario's greenbelt initiative.

Another study about efficient strategies and policies as the solution to urban sprawl explored the limited capacity of using nodes among planning agencies to attract new office and retail development, and difficulties in launching new nodes by using Toronto's experiences as a case study (Filion, 2009). Nodes were defined as "high-density multifunctional developments featuring a pedestrian-conducive environment and good public-transit accessibility" (Filion ,2009, p. 505). His research proposed four means of enhancing the smart growth performance of nodes: (1) improved planning coordination; (2) reliance on both incentives and coercion; (3) investment in public transit systems; (4) merging nodal and corridor approaches.

Vancouver is regarded as a region with some of the strongest growth management plans and policies to control unsustainable development like urban sprawl (Tomalty 2002). However, an assessment of the actual performance of these plans and policies is needed. Tomalty (2002) addressed some quantitative growth management goals that have been (officially and unofficially) adopted by urban planners in the region, and measured against actual trends. Some key growth management goals adopted by the region are not ambitious compared with existing trends, and yet are not being met. For instance, the supposedly compact scenario adopted by the region rarely deviates from existing growth trends, which regional planners had clearly identified as untenable and requiring drastic change. However, the policy's goal of preserving substantial green areas has been achieved "without being watered down during goal formulation or implementation" (Tomalty, 2002, p. 431).

However, there is not enough information available about the degree of urban sprawl for all metropolitan areas within Canada. Most of the existing studies consider the causes or effects of urban sprawl (Dupras et al. 2016; Johnson, 2001). Obtaining data and information on the degree of urban sprawl will help urban planners develop the cities in a more sustainable fashion. The results of measuring urban sprawl will be useful for environmental monitoring, sustainability monitoring, landscape-quality monitoring and biodiversity monitoring, to observe temporal changes in urban sprawl (for example, how fast have the changes been?), and to compare different regions. Therefore, this research is relevant to urban, regional and land use planning, and planning of various transportation infrastructure.

To find these publications, I used Google Scholar and the Concordia library website to search for publications containing the following keywords: Urban Sprawl, Urban growth, Urban development, Built-up areas, Density. There was another option in the Concordia library website named “databases by subject”, and I chose the “Geography planning and environment” category. In the Geography Canadian Sources category I could use more advanced databases to find the sources of mentioned keywords and Canadian studies.

2.5. Methods for measuring urban sprawl

In this section, the most common methods for measuring urban sprawl are reviewed.

The Sierra Club (1998) used four metrics for measuring urban sprawl, including: population moving from the inner city to suburbs; ratio of land use and population growth; the time spent in traffic; and decrease of open space, to rank major metropolitans in the US. Smart Growth America (2002) also used four metrics (residential density; mixture of residence, employment and service facilities; vitalization of inner city; and accessibility of road network) for the measurement of urban sprawl to study the impacts of sprawl on quality of life.

Jiang et al. (2007) used 13 geospatial indicators to quantify urban sprawl: 1) Area index, 2) Shape index, 3) Discontinuous development index, 4) Strip development index, 5) Leapfrog development index, 6) Planning consistency index, 7) Horizontal density index, 8) Vertical density index, 9) Population density index, 10) GDP density index, 11) Agriculture impact index, 12) Open space impact index and 13) Traffic impact index. They applied these indices in three groups (urban growth efficiency, spatial configuration, and external impacts) (Figure 3). The datasets for calculating these indicators were different. The datasets include: former land use maps, land price maps, floor area maps, land use planning maps, and population datasets.

According to Jiang et al. (2007), some indices on external impacts are useful to quantify the impacts on agricultural land loss, open area loss and traffic congestion. However, there are still other impacts of sprawl, such as energy consumption, that are not included in their set of indices because of data limitations. For more information about the strengths and weaknesses of this method, please refer to Jiang et al. (2007).

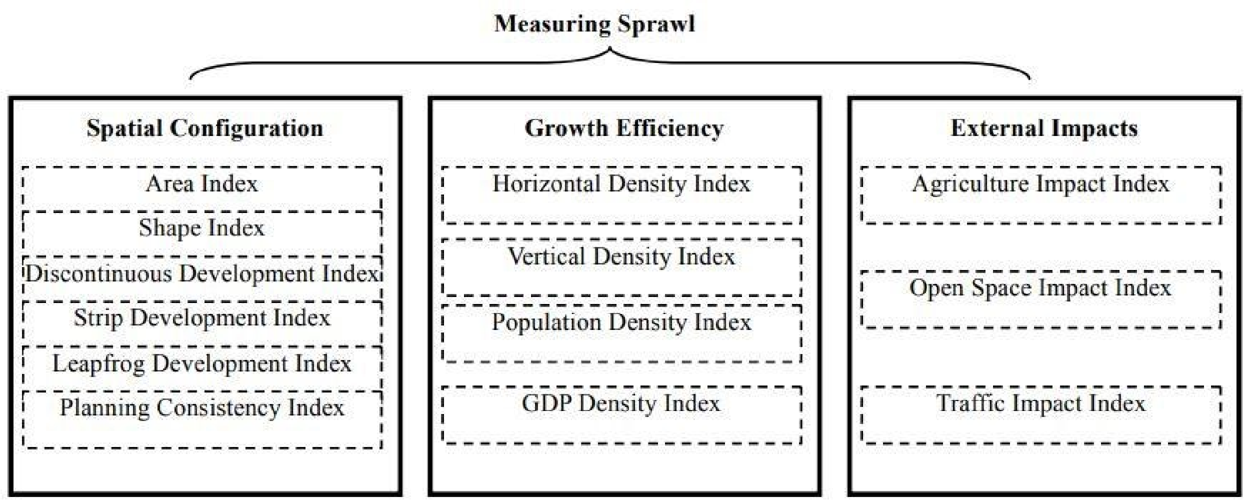


Figure 3. Geo-spatial indices for measuring urban sprawl, applied to Beijing by Jiang et al. (2007)

One of the measures commonly used for urban sprawl measurement is Shannon's entropy (Yeh and Li, 2001). This method is supposed to measure the patterns of built-up area as either dispersed or concentrated over time (Yeh and Li, 2001). The entropy method is based on the spatial distribution of built-up area (Singh 2014), e.g., based on a combination of remote sensing (RS), geographic information system (GIS), and photogrammetric techniques (Sudhira et al., 2004). The value of entropy is always between 0 and log(n). The entropy (H_n) value can be calculated using the following formula (Nazarnia et al. 2019):

$$H_n = \sum_i^n p_i \log {}^{1}/_{p_i} ,$$

where p_i indicates the proportion of urban area that is located in the i^{th} zone. The zones are chosen by the researchers. There is no right or wrong choice of zones and different researchers usually would choose different zones (different numbers and shapes of the zones, e.g., concentric rings with different locations of the center and different widths), which makes the results different and not comparable (Nazarnia et al. 2019). The value of entropy depends on the size and locations of the zones used, and by parting the zones into smaller ones, the value of the entropy and consequently urban sprawl increases:

$$H_n = \sum_{i=1}^{m} p_i \log\left(1/p_i\right) + \sum_{j=1}^{m}\left[p_i \sum_{\text{i}=1}^{n_j}\left(p_{i(i)}/p_i\right)\log\left(p_i/p_{i(j)}\right)\right]$$

where *j* is the *j*th zone at the region scale, the total number of zones at the region scale is displayed by *m*, and p_j is the proportion of urban areas in the *j*th zone at the region scale.

However, Nazarnia et al. (2019) examined the entropy method in three different ways to assess the suitability of this method as a measure of urban sprawl. First, they applied the entropy method to six real-world case studies. They also used the entropy method in seven spatial scenarios in a hypothetical landscape model of spatial distribution of urban areas. Finally, they systematically examined entropy with regard to 13 suitability criteria for measures of urban sprawl presented by Jaeger et al. (2010a). The results showed that the entropy method is not sensitive to important differences between spatial forms of built-up areas that demonstrate different degrees of urban sprawl, e.g., detached vs. dense spatial patterns of built-up areas. According to Nazarnia et al. (2019), the entropy method does not achieve meaningful results in relation to the selection of the city center in the case of concentric zones since the value of entropy is highly affected by changes in the choice of zones within a landscape. The results also indicated that entropy does not meet several important suitability criteria for measuring urban sprawl (in fact, the entropy method only meets 5 out of 13 suitability criteria). Nazarnia et al. (2019) concluded that entropy is not suitable for measuring urban sprawl. They suggest the metrics of “Weighted Urban Proliferation” and “Urban Permeation” by Jaeger et al. (2014) and Jaeger et al. (2010b) as two suitable alternatives. These metrics will be used to measure urban sprawl in this thesis (see below and ch. 3).

Angel et al. (2007) used five metrics for measuring manifestations of sprawl (metrics of main urban core, secondary urban core, urban fringe, ribbon development, and scatter development) (Table 2). They used these five metrics for the measurement of sprawl in Bangkok and Minneapolis case studies. They “define and measure sprawl both as a pattern of urban land-use that is, a spatial configuration of a metropolitan area at a point in time and as a process, namely as the change in the spatial structure of cities over time” (Angel et al. 2007). They measured the changes in sprawl over time, and they also considered sprawl as a geographic pattern. The disadvantage of this method is that it provides complicated results despite the limited number of metrics.

Table 2. Metrics for measuring manifestations of sprawl according to Angel et al. (2007)

Metric	Definition
Main urban core	the largest contiguous group of built-up pixels in which at least 50% of the surrounding neighborhood[2] is built-up
Secondary urban core	built-up pixels not belonging to the main urban core that have neighborhoods that are at least 50% built-up.
Urban fringe	built-up pixels that have neighborhoods that are 30 -50% built-up
Ribbon development	semi-contiguous strands of built-up pixels that are less than 100 meters wide and have neighborhoods that are less than 30% built-up
Scatter development	built-up pixels that have neighborhoods that are less than 30% built-up and not belonging to ribbon development

Jaeger et al. (2010b) presented a new method for measuring urban sprawl that includes four metrics, including: urban permeation (*UP*), urban dispersion (*DIS*), total sprawl (*TS*), and sprawl per capita (*SPC*). Schwick et al. (2012) suggested the Weighted Urban Proliferation *(WUP)* metric for the measurement of urban sprawl. The *WUP* method includes three components: 1) Percentage of built-up areas (*PBA*), 2) Dispersion of the built-up areas *(DIS)*, and 3) Land uptake per person *(LUP),* see chapter 3 for more detailed information.

Examples of studies using the *WUP* method

Hayek et al. (2010) used settlement development scenarios for Switzerland to explore the causes of urban sprawl in order to avoid undesired future settlement developments. The results showed that overall urban permeation and the dispersion of settlement areas are likely to increase, in varying degrees, in all scenarios by 2030. In addition, Jaeger et al. (2014) analysed historical changes as well as future scenarios for urban sprawl in Switzerland. They concluded that the degree of urban sprawl increased by 155% between 1935 and 2002 and that, within the framework of modelling future scenarios, urban sprawl is likely to further increase by more than 50% by 2050 without strong anti-sprawl measures. Moreover, Weilenmann et al. (2017) analysed the major socio-economic determinants of change in urban patterns in Switzerland. Their analysis covered the years 1980–2010 and was conducted on all 2495 Swiss municipalities. On the larger scale, Hennig et al. (2015) analysed the degree of urban sprawl for 32 countries in Europe. Large parts of Europe are affected by urban sprawl, and significant increases took place between 2006 and 2009. However, the values of the individual countries differ greatly.

Nazarnia et al. (2016a) compared patterns of urban sprawl between 1951 and 2011, in the metropolitan areas of Montreal and Quebec City, Canada, and Zurich, Switzerland. In Montreal, the degree of urban sprawl increased 26-fold in 1971 to 2011, while in Quebec City, it increased 9-fold in the same period of time, and in the Inner Zurich metropolitan area, urban sprawl increased almost 3-fold from 1960 to 2010.

The *WUP* method was also used by Torres et al. (2016) to quantify spatial patterns of urban sprawl for mainland Spain at multiple scales. They tested the stability, non-stationarity, and scale-dependency of the relationship between landscape fragmentation patterns and urban sprawl. More recently, Vermeiren et al. (2018) applied the *WUP* method to Flanders (Belgium).

3. Paper manuscript: Historical analysis of urban sprawl in Canada over 20 years

3.1. Introduction

In many countries worldwide, the rapid increase of urban development, often studied under the broad concept of urban sprawl, has become a controversial issue largely due to a variety of adverse environmental effects such as loss of environmentally fragile lands, greater air pollution, higher energy consumption, loss of farmland, reduced diversity of species, and increased runoff of stormwater (Bhatta, 2010; Johnson, 2001).

Several factors contribute to urban sprawl, e.g., increased road construction projects and other infrastructure developments allowing people to build single detached houses in new suburban areas. Relatedly, increased global population has led to a population shift from rural to urban areas and to significant land-uptake for urban expansion (Montgomery, 2008; Gerland et al., 2014).

Another major factor contributing to urban sprawl is unsustainable decision-making in politics, with related short-sighted decisions in planning, zoning, road infrastructure, lawmaking, and the lowering of taxes greatly impacting the extent of urban sprawl (EEA & FOEN, 2016). In contrast, urban planners and decision makers should use the information about the dispersion and proportion of built-up areas and land up take per person in each region to compare the trends in different regions and to apply sustainable policies to prevent urban sprawl.

Urban sprawl has been a major challenge to implementing sustainable land-use plans. Particularly, in Canadian metropolitan areas (CMAs), built-up areas have increased by 157% in just 40 years, between 1971 and 2011, i.e., more than doubled in four decades, while the CMA population increased in Canada by only 74% in the same period of time, i.e., built-up areas increased much more than the population in Canadian CMAs (Statistics Canada. 2016, Soulard et al. 2016). This observation clearly calls for a systematic investigation of the development of urban sprawl in Canadian metropolitan areas, allowing planners to more accurately predict how it is likely to evolve in years to come.

Taking up this challenge, this work provides a systematic analysis of how fast the increase in urban sprawl occurred in Canadian metropolitan areas between 1991 and 2011.

3.1.1. Definition of urban sprawl

The definition of urban sprawl has been the subject of much discussion in the literature, with currently no generally accepted definition at hand. Several definitions have been suggested in the literature, with some incorporating causes and effects of urban sprawl, and yet some largely mischaracterizing it by defining it in terms of urban development at high density. According to the United States Environmental Protection Agency (USEPA, 2001), "at a metropolitan scale, sprawl may be said to occur when the rate at which land is converted to non-agricultural or non-natural uses exceeds the rate of population growth" (cited in Bhatta 2010, p. 9). In this work, we define urban sprawl as dispersed, low-density development. It occurs usually at the expense of high-quality agricultural land and natural areas and is ultimately unsustainable. Our definition of urban sprawl is consistent with those given by Schwick et al. (2012) and EEA & FOEN (2016), which particularly focus on the two features of low-density and dispersion of urban sprawl, and distinguish it from its causes and effects.

3.1.2. Past studies of urban sprawl in Canada

Several studies have focused on changes in density at large scales, e.g., country level or sizeable regions. For example, Townsend et al. (2018) revealed that the six largest Canadian metropolitan regions do not have higher population densities or fewer freeways than any of the 51 largest United States metropolitan regions. On the other hand, according to the 2018 OECD report about urban sprawl in Canada between 1990 and 2014, the percentage of urban land with a population density in the range of 150-3500 inhabitants/km^2 has continuously decreased.

Several past studies indicates that many parts of Canada have experienced urban development in a low-density pattern in the past (Filion et al. 2010; Nazarnia et al. 2016a; Sun et al. 2007; Murshid. 2002). Notably, these studies have focused on a smaller extent at sub-country level, e.g., census metropolitan areas. According to Filion et al. (2010), Toronto showed a pattern that can be qualified as recentralized between 1971 and 2011, while Montreal appeared as a decentralizing CMA and Vancouver exhibited clear signs of intensification. In Ottawa-Hull, the pattern was an amalgamation of decentralization.

Nazarnia et al. (2016a) presented a quantitative assessment of urban sprawl in Montreal and Quebec City. This research shows the degree of urban sprawl has increased exponentially in Montreal over the past 30 years. Similarly, Sun et al. (2007) demonstrated that urban sprawl continued to grow in Calgary between the years 1985 and 2001, using Shannon's Entropy method. For a smaller study area, Murshid (2002) examined the process of urbanization in the former County of Laprairie, part of the urban-rural fringe of Metropolitan Montreal, showing that 72% of the remaining open lands of the former county of Laprairie were developed between 1988 and 2000.

Past research has also leveraged available datasets to identify current trends and predict future trends of urban sprawl, investigating likely scenarios for decision-makers to consider. For example, Behan et al. (2008) predicted that the city of Hamilton will experience household growth in the magnitude of approximately 80,000 households during the years 2001 and 2031. This clearly indicates the need for effective policies to control urban sprawl in the city of Hamilton.

Several recent studies have also focused on efficient strategies and policies to avoid sprawl in Canada. For example, Tomalty (2002) addressed a range of quantitative growth management goals that have been adopted by urban planners in Vancouver and compared them to actual trends. These results demonstrate that some objectives, e.g., preserving substantial green areas, have been adequately achieved, but some key growth management goals adopted by the region are not ambitious compared to existing trends. As another example, Filion (2009) used Toronto's experiences to study several efficient urban sprawl reduction strategies by exploring the effectiveness of "nodes", which are defined as "high-density multifunctional developments featuring a pedestrian-conducive environment and good public-transit accessibility" (p. 505). This was chiefly done by evaluating the limited capacity of using such nodes among planning agencies to attract new office and retail development, and difficulties in launching new nodes.

Adopting greenbelts is one of the main solutions to protect the environment and agricultural lands. This is also an effective strategy to control urban growth in existing and planned communities. Pursuing this mindset, Amal (2008) evaluated Ontario's greenbelt initiative by examining four factors (political motive, public support, greenbelt planning, and enabling legislation) revealing that Ontario's greenbelt initiative exhibits a strong political motive, effective planning, and legislation enforcing greenbelt plans. Nonetheless, the provincial government should implement strategies to include the public in greenbelt planning, to ensure that the greenbelt remains permanently. Additionally, it is crucial to apply decentralization and economic policies to redistribute people and attract businesses into designated growth centers.

Eidelman (2010) outlined in detail the management of urban sprawl in Ontario. The project assumed the creation of a permanent greenbelt encompassing nearly 728,000 hectares of environmentally sensitive land. This project underscores the usefulness of the models of policy making, particularly in the context of environmental policies. Eidelman (2010) explains that researchers theorized two models of policy development: “normal” and “atypical” (Howlett et al. 2003, 234). The “normal” pattern is defined by incrementalism, which means “once the policies are established, they tend to persist over time, as every decision taken in the same direction inevitably makes it more costly to switch course” (Eidelman, 2010, p.1215). In contrast, “atypical” policy happens when policy processes (or policy contents) experience considerable changes.

Currently, information available on the degree of urban sprawl across the metropolitan areas within Canada is patchy and has many gaps. In this work, we analyze and report the degree of weighted urban proliferation and weighted sprawl per capita for all of the CMAs in Canada from 1991 to 2011. To our knowledge, our work is the first to report these.

3.1.3. Research questions

The objective of this project is to systematically quantify the degree of urban sprawl for all 34 census metropolitan areas for which Statistic Canada has provided land cover information for the years 1991, 2001 and 2011. This allows comparing the rate of increase in sprawl between two time periods (1991-2001 and 2001-2011). The following reporting units will be considered: (1) Census Metropolitan Areas and (2) Census Subdivisions. The analysis will address two main research questions:

1. Which reporting units in Canada exhibit higher or lower degrees of urban sprawl?
2. How quickly has the degree of urban sprawl increased between 1991 and 2011 in the various reporting units in Canada? When did the strongest increases of sprawl occur?

One key hypothesis will be tested in this work: Urban sprawl increased faster than the population and faster than the built-up areas in all parts of Canada.

3.2. Methods

3.2.1. Metrics used for measuring of urban sprawl

Weighted Urban Proliferation (*WUP*)

WUP was first introduced by Schwick et al. (2012) and is now a well-established measure of the degree of urban sprawl. The method is based on the following definition: The degree of urban sprawl increases with (1) the size of the built-up areas in a given landscape (i.e., the percentage of built-up area), (2) the dispersion of the built-up area (spatial configuration), and (3) the uptake of built-up area per inhabitant or job. The *WUP* metric measures urban sprawl by integrating these three dimensions into a single metric. *WUP* is computed by multiplying *PBA*, *DIS*, the weighting of the *DIS* ($w_1(DIS)$), and the weighting of the *LUP* ($w_2(LUP)$):

$$WUP = (PBA * DIS) * w_1(DIS) * w_2(LUP),$$

where *PBA* = Percentage of built-up areas,

DIS = Dispersion of built-up areas,

$w_1(DIS)$ = weighting function$_1$ (Dispersion), and

$w_2(LUP)$ = weighting function$_2$ (Land uptake per inhabitant or job).

The term Weighted Urban Proliferation is that land uptake per person and dispersion are, respectively, weighted by the weighting functions $w_2(LUP)$ and $w_1(DIS)$.

The three components of the *WUP* method:

The Proportion of Built-up Area (*PBA*) is the ratio of the size of the built-up area divided by the size of the landscape (reporting unit): *PBA* = Size of built-up area / Reporting unit.

Dispersion: The second component of the *WUP* method is dispersion (*DIS*). The dispersion metric analyzes the spatial pattern of built-up area in a landscape from a geometric perspective, by calculating distance measurements between all pairs of points (locations) within the built-up area and subsequently weighting them by the effort function. The integral over all point pairs can be approximated by a sum over pairs of small cells of built-up areas. The average of the effort values is then computed using the measurements of all possible pairs of points. The farther apart a pair of points are, the higher their contribution to dispersion. The horizon of perception (*HP*) is the maximum distance between two built-up areas considered in the calculation, and defines the scale of analysis (Jaeger et al. 2010b). The weighting function w_1 *(DIS)* gives sections of the landscape in which built-up areas are more dispersed a higher weight ─ hence, a lower weight is assigned to more compact built-up areas (more detailed explanation is given by Jaeger et al. 2010b). *DIS* is defined in urban permeation units per square meter of built-up area (UPU/m^2) (Jaeger et al. 2010b).

Land Uptake per Person *(LUP)* is expressed as the amount of built-up areas divided by the number of inhabitants and jobs (unit: m^2/(inh. or job)).The more space used per inhabitant and per workplace, the higher the *LUP* value. This component posits that the higher the number of people and jobs located in the built-up area, the higher the efficiency of the utilization of the land.

The number of jobs is included in the calculation of *LUP,* emphasizing the fact that many downtown areas are dominated by office buildings that have very few residents, and yet, each building ─ and thus the land they occupy ─ is densely utilized and should not be considered sprawl. The weighting function w_2 *(LUP)* assigns a value between 0-1 to sections of the built-up area. The lower the land uptake per inhabitant or job, the lower the weighting value (more detailed explanation is provided by Jaeger and Schwick 2014). This lower weight reflects the understanding that dense subsections of the reporting unit, like inner cities, are not considered as urban sprawl. In addition, there are two different types for job data, full-time and part-time. Part-time workers spend less time in the built-up areas than full-time employees. In order to consider this difference in *LUP*, full-time equivalents can be used. The conversion factor for full-time equivalents can be found for different countries and regions based on available national data sets (EEA & FOEN, 2016).

The value of Total Sprawl (*TS*) is computed by multiplying *DIS* and the total amount of built-up areas (i.e., *TS* = *DIS* * Area of built-up area). Total Sprawl (*TS*) is the average sum of weighted distances between all points in the urban area and the second points which are not farther away from the first point than the *HP*. Suitable choices for *HP* are distances between 1 km and 5 km. This study used an *HP* of 2 km to be consistent with the studies by Nazarnia et al. (2016), Hennig et al. (2015), and Schwick et al. (2012). More detailed explanation for *HP* is provided by EEA & FOEN (2016) in Annex A2.2

Among these metrics, **Weighted Urban Proliferation *(WUP)*** is the main metric used to quantify urban sprawl. It combines the three components ─ *UP*, *DIS*, and *LUP* ─ into a single metric, which is an important advantage compared to other measures of urban sprawl (Figure 4) (EEA and FOEN, 2016). Importantly, the *WUP* method can be applied at any scale (EEA and FOEN, 2016).

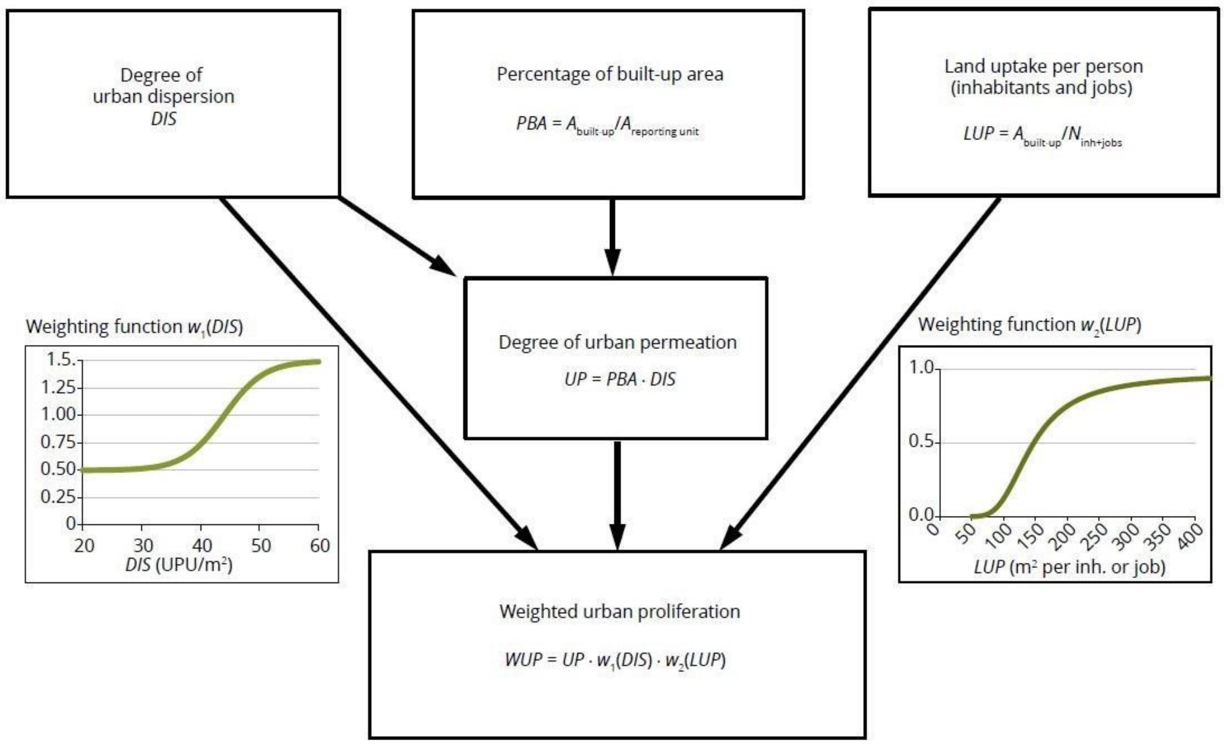


Figure 4. The relationships between the *WUP* metric and its components *DIS*, *PBA* and *LUP*. Adapted from EEA & FOEN (2016).

Weighted Sprawl per Capita (*WSPC*)

While the value of *WUP* indicates how strongly the landscape within each CMA's boundary is sprawled per km^2, we also use **Weighted Sprawl per Capita (*WSPC*)**, which quantifies how much on average each inhabitant or workplace contributes to urban sprawl in a reporting unit. *WSPC* is the result of the combination of *LUP*, the weighting of the *LUP* (w_2

(LUP)), *DIS*, and the weighting of *DIS* ($w_1(DIS)$): $WSPC = w_2(LUP)*DIS*LUP*w_1(DIS)$ (Figure 5).

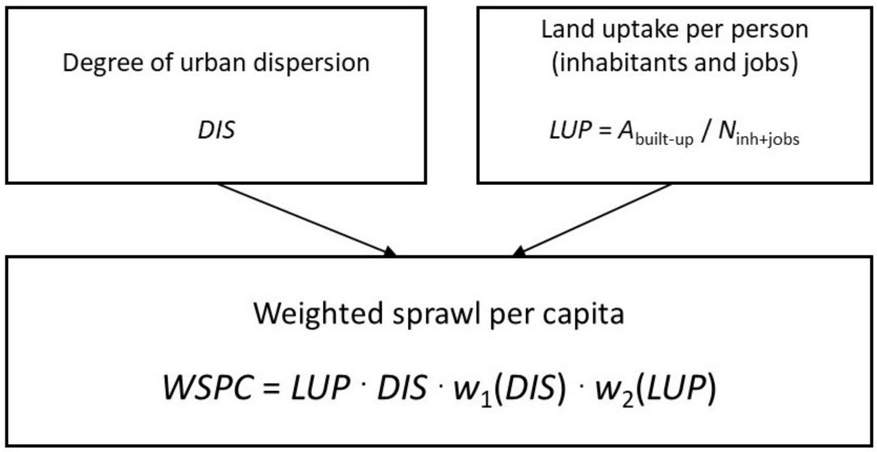


Figure 5. The relationships between the *WSPC* metric and its components *LUP* and *DIS*.

The CMA boundaries can be much larger than the built-up area. For example, the CMA border in Kelowna is much larger for reasons they have little to do with the area and population of the built up area. We can report urban sprawl in relation to the inhabitants and jobs rather than the total area, while *WUP* is used to compare the degree of urban sprawl of the landscapes of different CMAs. For more detailed explanations using Kelowna and Victoria as an example, please see Appendix C.

3.2.2. Definition of built-up areas

EEA & FOEN (2016) define built-up area as various types of settlement and buildings, ranging from places with urban character to villages to separate single buildings in the open landscape. In general, a built-up area is defined as a surface covered by man-made structures. Railways and roads outside cities and towns are not included in this definition of built-up areas since they are not considered a part of the urban sprawl (EEA and FOEN, 2016). The definition of built-up areas used in any particular study depends on data availability and can differ between studies (see below).

3.2.3. The Urban Sprawl Metrics (USM) toolset

The Urban Sprawl Metrics (USM) toolset was used to measure the degree of urban sprawl. The USM toolset was recently developed for the calculation of the *WUP* metric (Nazarnia et al. 2016b). This geographic information system (GIS) toolset is freely available on the website of the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) website (https://www.wsl.ch/de/services-und-produkte/software-websites-und-apps/urban-sprawl-metrics-toolusm.html).

The Toolset requires three input data: (1) The binary map of built-up areas (settlements areas and solitary buildings) in the ESRI raster format; (2) the map of the reporting unit(s) of interest (e.g., municipalities, districts, or a grid of a certain cell size) in geodatabase feature class or shapefile format, and (3) the number of inhabitants and jobs for the reporting unit(s) (this information has to be stored by the user in the attribute table of the reporting unit(s) shapefile) (Nazarnia et al. 2016b).

3.2.4. Data sources

Reporting units and built-up areas

In this thesis, two nested sets of reporting units were used: the metropolitan areas (CMAs) and the Census subdivisions located within the boundaries of each CMA. I retrieved all the shapefiles of built-up areas and reporting units from the Statistics Canada database (2016). I used the built-up area data for Canada for the years 1991, 2001, and 2011 (Soulard et al. 2016). In this dataset, built-up area is considered as “land that is predominantly built-up or developed, including the vegetation associated with these land covers, such as gardens and parks. It is characterized by a high percentage of impervious surfaces including roadways, parking lots, and roof tops. Low-density dwellings and small structures or buildings in rural areas outside core built-up areas may not be captured due to the resolution of the data and overlying tree canopy” (Soulard et al. 2016, p. 331). To create these datasets, remote sensing imagery data were used from Agriculture and Agri-food Canada's Land Use for the years 1990, 2000 and 2010. These land use maps cover all of Canada south of 60°N at a spatial resolution of 30 m.

In the built-up area shapefiles, most of the parks and green spaces were identified as built-up areas, such as Mount Royal park, La Fontaine park, and Jean Drapeau park in the Montreal CMA. Some small water bodies were also included in the built-up area shapefiles. To increase the accuracy of the built-up area shapefiles and exclude the green spaces, parks, and water bodies from them, I applied some corrections.

First, the shapefiles of all the rivers of each province were collected from Government of Canada; Natural Resources Canada; Earth Sciences Sector, 2017, to be able to exclude all waterbodies from being counted as built-up areas. Subsequently, the Canadian park layer was used (Concordia Library, CanMap 2018) to remove all parks from built-up area layers. We particularly excluded botanical gardens, campgrounds, ecological reserves, golf courses, national parks, national wildlife areas, natural areas, park reserves, park/sort fields, protected areas, provincial parks, recreation areas, sanctuaries, territorial parks, wilderness areas, wilderness parks, and wildland parks from the built-up areas layer since they could be confused with built-up areas that contribute to urban sprawl (Table 3).

Table 3. Types of parks that were excluded or not excluded from the built-up areas, respectively.

Types of parks	Excluded	Not excluded
AMUSEMENT PARK		✓
BOTANICAL GARDEN	✓	
CAMPGROUND	✓	
CEMETERY		✓
DRIVE-IN THEATRE		✓
ECOLOGICAL RESERVE	✓	
EXHIBITION GROUND		✓
GOLF	✓	
HISTORIC SITE		✓
LOOKOUT		✓
NATIONAL PARK	✓	
NATIONAL WILDLIFE AREA	✓	
NATURAL AREA	✓	
PARK RESERVE	✓	
PARK/SPORTS FIELD	✓	
PROTECTED AREA	✓	
PROVINCIAL PARK	✓	
RECREATION AREA	✓	
SANCTUARY	✓	
SPORTS/RACE TRACK		✓

SWIMMING POOL		✓
TERRITORIAL PARK	✓	
WILDERNESS AREA	✓	
WILDERNESS PARK	✓	
WILDLAND PARK	✓	
ZOO		✓

For example, in the Montreal CMA, Mount Royal park, La Fontaine park, and Jean Drapeau park were all considered as PARK/SPORTS FIELD type. Although there are some buildings and parking lots in Mount Royal park, we excluded them from the built-up area shapefile because the scale of the built-up areas in these parks were insignificant and the error of excluding them is smaller than the error caused by considering the entire park as built-up area (Figure 6).

The built-up area data that we used in this study includes all the roads inside and outside the CMAs. The road information was recorded in a single field, it would have been difficult and time consuming to identify and tease apart all the roads inside and outside each of the CMAs for each year, therefore all the roads remained as parts of the built-up area's shapefiles.

Figure 6. Mount Royal Park, La Fontaine Park, and Jean Drapeau Park in Montreal (in green) and built-up areas (in gray).

For the projected coordinate system, we adopted NAD_1983_Albers to conform to that of the corresponding data within ArcGIS. Subsequently, the data were entered into the USM toolset. To use this toolset, first, the polygon layers of built-up areas were converted to 15 m raster cells in accordance with Nazarnia et al. (2016a). Upon completion of these steps of the USM-toolset, the results appeared in an attribute table of a new layer created by the toolset. Finally, the results were exported into Excel files. The USM toolset provides the information about the degree of *PBA*, *DIS*, *TS*, *UP*, *UD*, *LUP* and *WUP*. The degree of *WSPC* can be calculated from these values, indicating how much on average each inhabitant or workplace is contributing to urban sprawl in a CMA or CSD, in UPU/(inhab. or job). An important advantage of this metric is that the *WSPC* does not depend on the size of the CMA.

Population (inhabitants)

Information about inhabitants for all CMAs in 1991, 2001, and 2011 was used from Statistics Canada (The changing landscape of Canadian metropolitan areas, 2019). The information about inhabitants for all CSDs within the CMAs boundaries in 1991, 2001, and 2011 were compiled from the Canadian Census Analyzer (2014). When we compared the Canadian Census Analyzer population data for the CMAs with the Human Activity and the Environment (2016), we found that the datasets were identical.

Jobs/ workplaces

We obtained job data from Statistics Canada (Special tabulation, based on the 1991, 2001 censuses of population and the 2011 National Household Survey). The data provide information of the numbers of total type of work (the sum of the number of employees who worked full time and those who worked part time and the number of total employees who did not work during the reference week of the census, across all professions), the numbers of total employees who did not work during the reference week of the census and those who worked during the reference week separately, and finally the number of employees who worked full time and those who worked part time for all Census Subdivisions in Canada in 1991, 2001 and 2011. Reference week is defined as "the entire calendar week (from Sunday to Saturday) covered by the Labour Force Survey each month. It is usually the week containing the 15th day of the month. The interviews are conducted during the following week, called the Survey Week, and the labour force status determined is that of the reference week." (Statistics Canada, Guide to the Labour Force Survey, 2012 p. 16).

However, the numbers of the part-time and full-time employees, respectively, who did not work during the reference week were missing. To calculate the numbers of part-time employees who did not work during the reference week, we assumed that the proportion of part-time employees among the employees who did not work during the reference week was the same as for those who worked during the reference week. Based on this assumption, we applied the following equation:

> (The number of employees who worked part time / (The number of employees who worked full-time **+** The number of employees who worked part-time)) ***** The number of total employees who did not work during the reference week = The number of part-time employees who did not work during the reference week

Accordingly, we estimated the numbers of full-time employees who did not work during the reference week by calculating the difference of the numbers of total employees who did not work during the reference week and the numbers of part time employees who did not work during the reference week.

Finally, we summed the numbers of part time employees who did not work during the reference week to the number of employees who worked part time to find the best possible estimate for part time jobs. To discover the best estimate for full-time jobs, we summed the numbers of full-time employees who did not work during the reference week to the numbers of employees who worked full time.

We used the number of full-time equivalents (FTEs) in order to better reflect the true situation of land uptake per person (*LUP*). Information about full- and part-time jobs was used to calculate FTEs. The information of the hours for FTEs was derived from Statistics Canada (2020). The conversion factors were found by dividing the hours of part-time employment (all jobs, both sexes, and 15 years and over) by the hours of full-time employment (all jobs, both sexes, and 15 years and over) (Hennig et al. 2015). We applied the same steps separately for the years 2011, 2001, 1991 for Canada, and also separately for the provinces to get the most accurate results of *LUP*, *WUP* and *WSPC*. Finally, we multiplied the numbers of the part-time jobs by the conversion factors and summed the results to the numbers of full-time jobs to discover the best estimate for the numbers of total jobs:

The number of total jobs = (The number of part-time jobs * the conversion factor) + The number of full-time jobs

Due to the changes in the boundaries of the CSDs over the years, the layers of the CSDs for 2001 and 1991 were used to find the correct number or closest estimate of inhabitants and jobs for each CSD for these years. The boundaries of the CMAs of 2011 were used for all three points in time (1991, 2001, and 2011). Therefore, there were no increases in the size of CMAs and the values of *WUP* can be directly compared. For example, for Ottawa–Gatineau, Ontario in 1991, we combined all the values of the CSDs that were within the boundaries of a new CSD in 2011. The CMA included these CSDs in 2011, but combined 14 CSDs in 1991. Only CSD Russell did not change its code (3502048). As presented in figure 7 and table 4, the census subdivisions with the codes 3506004, 3506006, 3506001, 3506014, 3506009, 3506011, 3506012, 3506018, 3506027, 3506030, and 3506042 in 1991 are within the boundaries of a CSD (3506008) in 2011, by adding the numbers of inhabitants and jobs of those 11 CSDs in 1991, we were able to find the value of inhabitant and jobs for CSD 3506008. Similarly, to find the value for 3502036 CSD in 2011, the values of CSDs 3502037 and 3502039 were added. 1991 and

2001 spatial units are constructed by merging CSDs to match the 2011 CSD reporting units. For more information please refer to the shapefiles of each year.

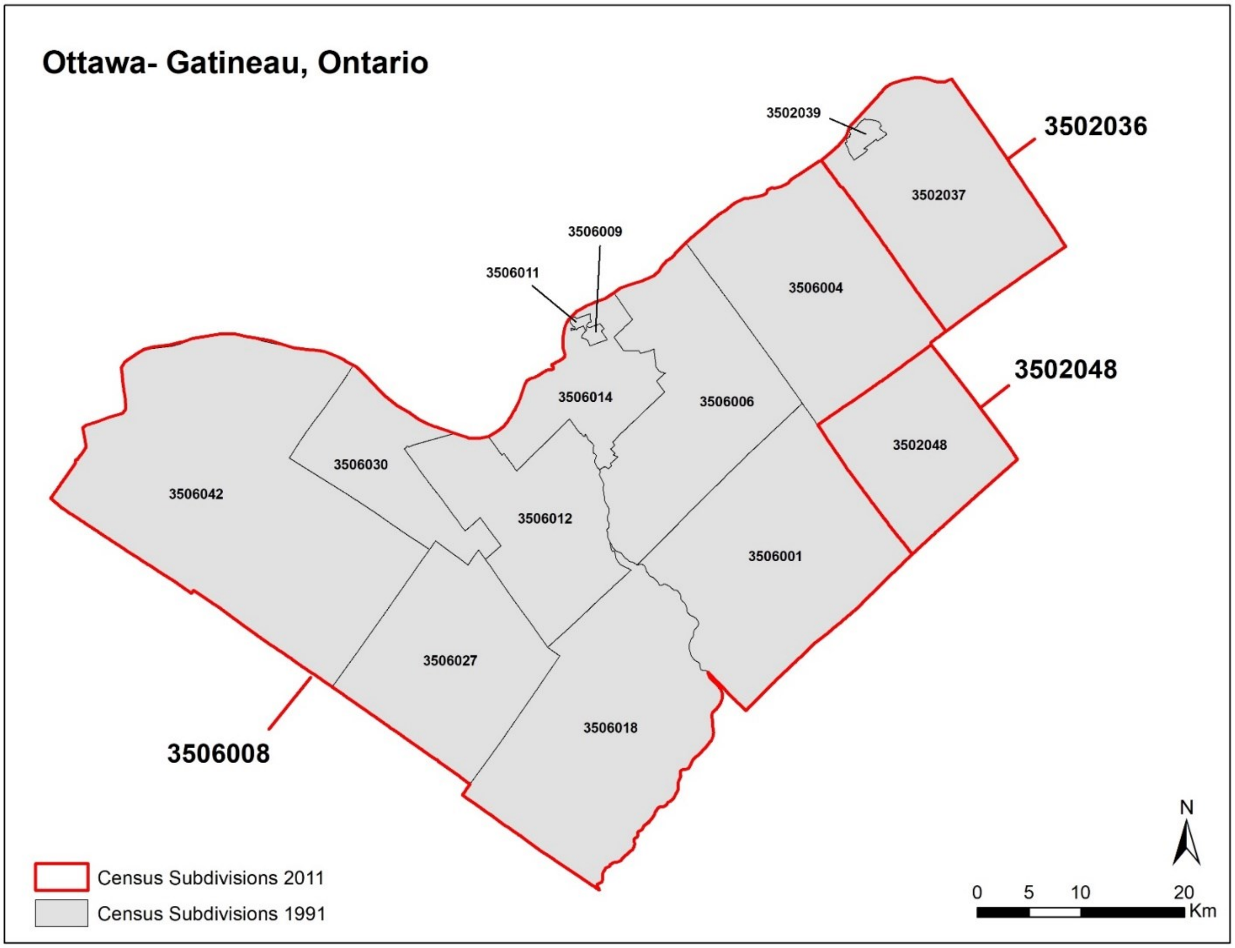


Figure 7. The differences between the census subdivions in Ottawa-Gatineau (Ontario part) in 1991 and 2011.

Table 4. Census Subdivisions and their codes and names in Ottawa-Gatineau, Ontario, in 1991 and 2011

Note: For more information about the abbreviations (e.g., TP, T, C) please refer to section 3.3.4.

CSD Code 1991	CSD Name 1991
3502037	Clarence, TP
3502039	Rockland, T
3502048	Russell, TP
3506004	Cumberland, TP
3506006	Gloucester, C
3506001	Osgoode, TP
3506014	Ottawa, C
3506009	Vanier, C
3506011	Rockcliffe Park, VL
3506012	Nepean, C
3506018	Rideau, TP
3506027	Goulbourn, TP
3506030	Kanata, C
3506042	West Carleton, TP

CSD Code 2011	CSD Name 2011
3506008	Ottawa, CV
3502036	Clarence-Rockland, CY
3502048	Russell, TP

For some of the CMAs that had new CSDs (as a part of the old/ bigger CSD), first we applied the clip toolset on the 1991 and 2001 shapefiles, using the 2011 CSDs reporting unit layer as the features used to clip and built-up areas (1991 and 2001) as the features to be clipped to find the percentage of built-up areas in 1991 and 2001 for the new CSD reporting unit in 2011. Then by using the percentage of built-up areas, we assumed that the percentage of built-up areas for the new CSD was the same percentage as the number of inhabitants and jobs.

3.3. Results

3.3.1. Level of urban sprawl in 2011

The values of *WUP* ranged between 3 and 19 UPU/m^2 indicating large differences between the CMAs. Montreal scored highest on *WUP* in 2011 among the CMAs (18.24 UPU/m^2), followed by Victoria (17.93 UPU/m^2), Kitchener-Cambridge-Waterloo (17.70 UPU/m^2), Vancouver (17.24 UPU/m^2), and Toronto (16.75 UPU/m^2) (Figure 8). Notably, although Montreal experiences a low *LUP* (272 m^2/(inh. or job)), its *DIS* value is fairly high (48.24 UPU/m^2). Additionally, the highest value of *PBA* among all CMAs was observed in Montreal (34%). The Toronto CMA has a *PBA* of 31.21% and a *DIS* of 48.72 UPU/m^2, larger than the Montreal CMA. The value of *WUP* in Montreal is clearly higher than Toronto's due to Montreal's lower *LUP*, while *LUP* in Toronto is 250.34 m^2/(inh. or job). Nonetheless, the fact that Toronto CMA is much larger (6269 km^2) than the Montreal CMA (4293 km^2) should not be neglected (see Figure 8).

In contrast, the lowest levels of *WUP* are found in the CMAs of Kelowna (3.01 UPU/m^2), Saskatoon (3.24 UPU/m^2), Saguenay (3.31 UPU/m^2), Saint John (3.49 UPU/m^2), and Regina (3.50 UPU/m^2) which have sizably less built-up area compared to the other CMAs. Some other CMAs such as Quebec, Sherbrooke, Calgary, Edmonton, and Winnipeg obtain average *WUP* values (between 5 to 7.5 UPU/m^2). The results for the three dimensions of *WUP* (*PBA*, *DIS* and *LUP*) are provided below for further clarifications.

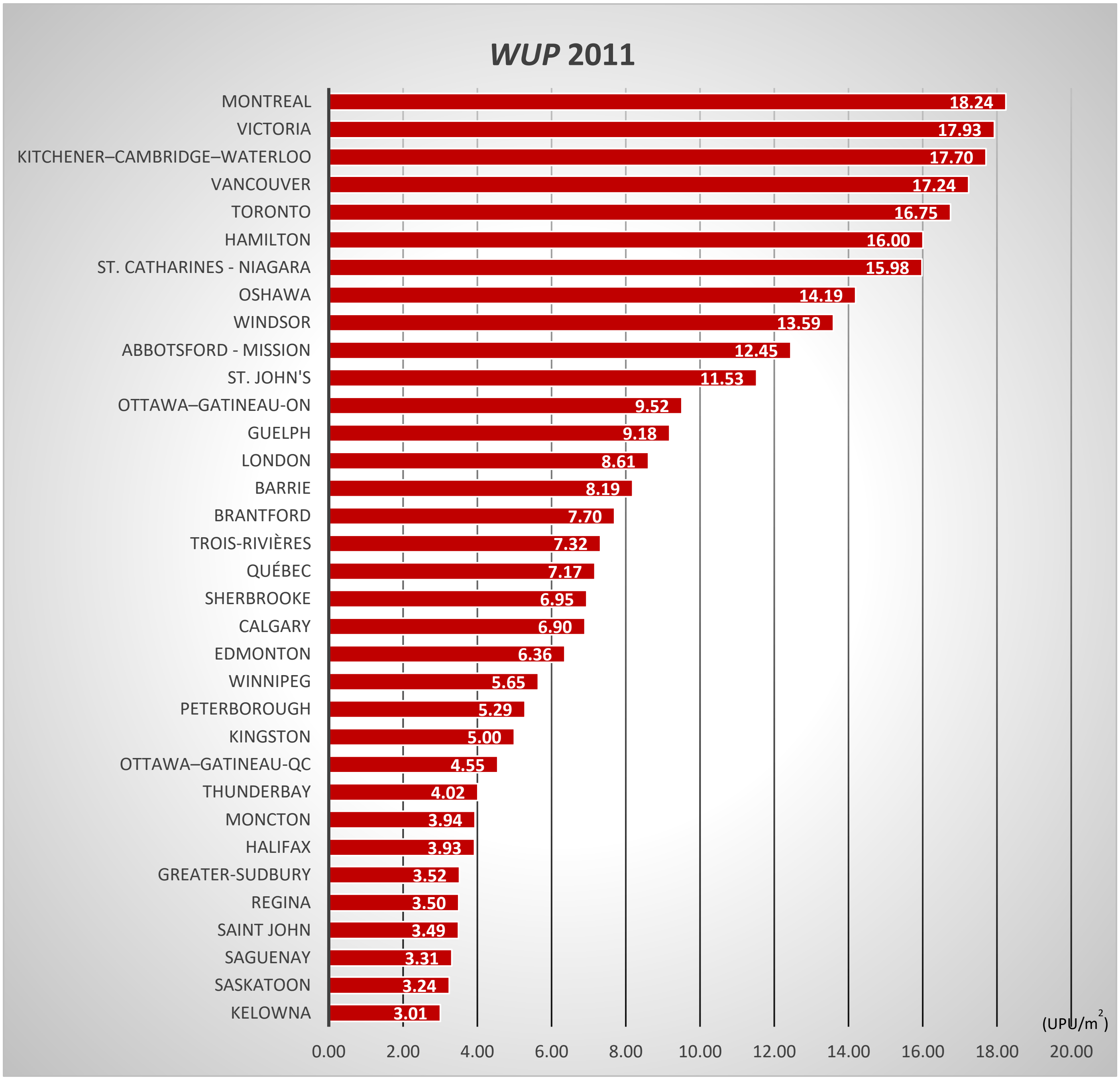


Figure 8. Values of weighted urban proliferation (*WUP*) in all 34 CMAs in Canada in 2011 (in UPU/m^2).

3.3.2. The values of the components of *WUP* in Canada in 2011

In this section, I systematically analyze various components of *WUP*.

3.3.2.1. The proportion of built-up areas (*PBA*)

As a key component of *WUP*, *PBA* measures the ratio of the size of built-up areas to the size of the reporting unit. Montreal obtained the highest *PBA* in 2011 (34.01%), followed by Toronto (31.21%), Victoria (31.15%), Vancouver (30.72%), and Kitchener-Cambridge-Waterloo (30.57%). There are many CMAs in which the value of percentage of built-up areas is intermediate such as Quebec (13.09%), Sherbrooke (12.33%), Calgary (12.05%), Edmonton (10.67%), and Winnipeg (9.65%). The lowest *PBA* scores were noted in Kelowna and Saskatoon with 5.57% and 5.65%, respectively (Figure 9).

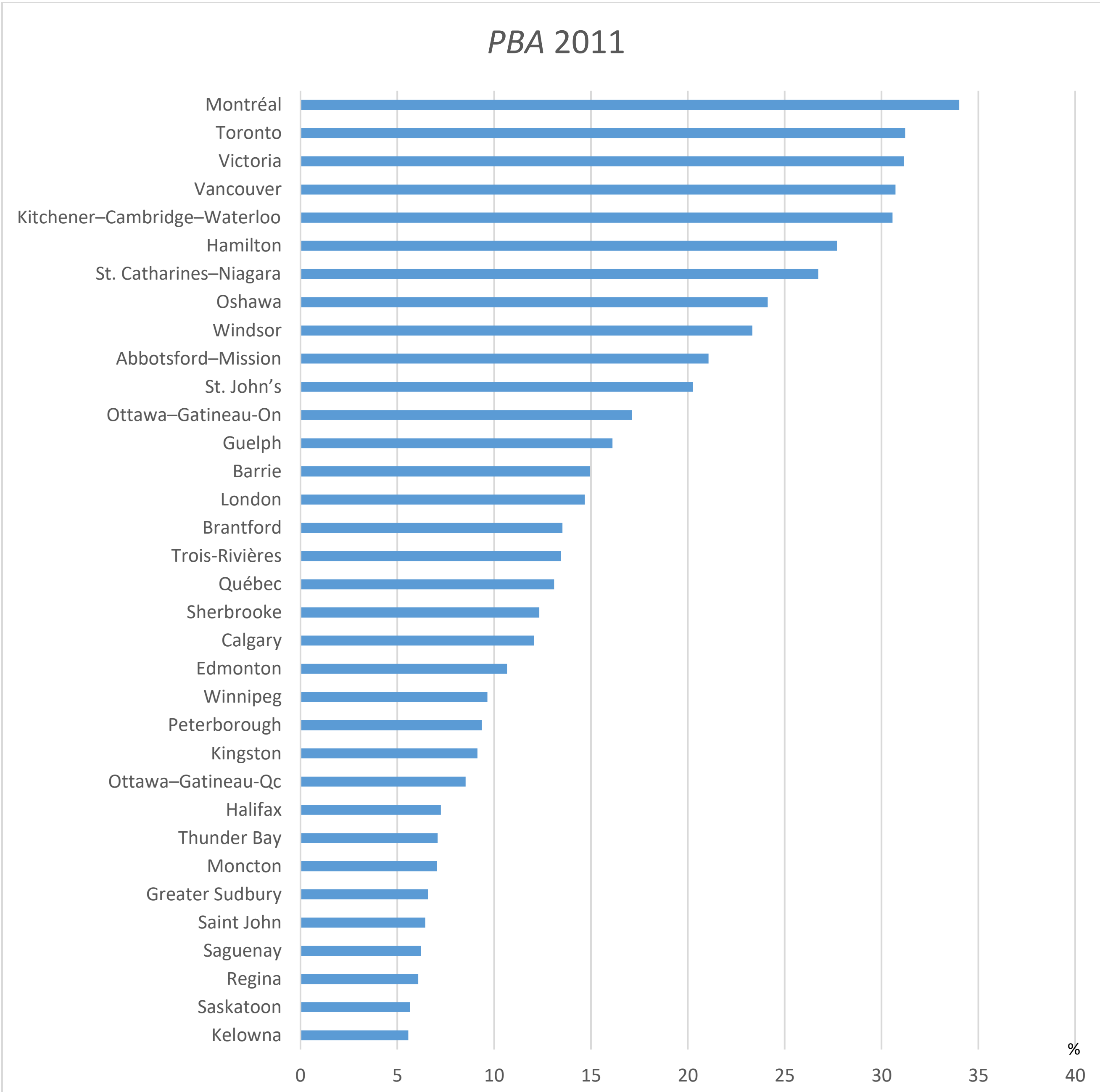


Figure 9. The proportion of built-up areas (*PBA*) in all 34 CMAs in Canada in 2011 (in %).

3.3.2.2. Degree of urban dispersion (*DIS*)

The results on the degree of urban dispersion (*DIS*) reveal a different ranking of CMAs. Toronto experienced the highest *DIS* (48.72 UPU/m^2), followed by Vancouver, Kitchener-Cambridge-Waterloo, Edmonton, and Calgary; Montreal, however, ranked 10^{th} (48.24 UPU/m^2) (Figure 10). The lowest *DIS* values were exhibited by Greater Sudbury (46.57UPU/m^2), Saguenay (46.59 UPU/m^2), and Ottawa- Gatineau (46.68 UPU/m^2) (Figure 10).

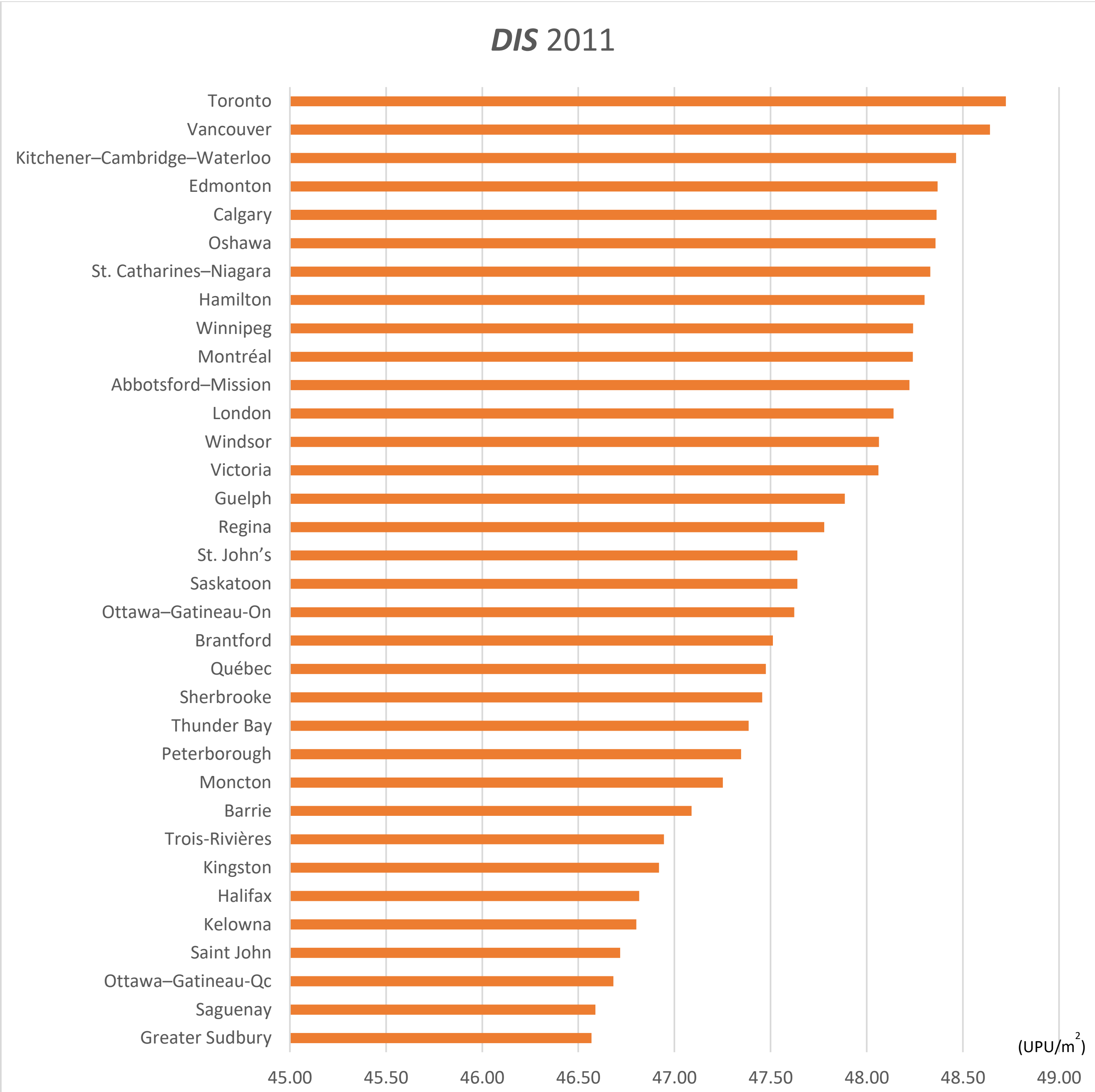


Figure 10. Values of the degree of urban dispersion (*DIS*) in all 34 CMAs in Canada in 2011 (in UPU/m^2).

3.3.2.3. Land up take per person (*LUP*)

The highest *LUP* values of more than 1000 in m^2/(inh. or job) were found in Saint John (1334 m^2/(inh. or job)), Greater Sudbury (1148 m^2/(inh. or job)), and Thunder Bay (1121 m^2/(inh. or job)), indicating a higher space use per inhabitant or workplace compared to areas with lower *LUP* values such as Calgary, Kitchener-Cambridge-Waterloo, Quebec, and Hamilton (between 300 and 450 m^2/(inh. or job)) (Figure 11). The lowest *LUP* values were observed in Toronto (250 m^2/(inh. or job)), Montreal (272 m^2/(inh. or job)), and Vancouver (296 m^2/(inh. or job)) reflecting a higher utilization density in these CMAs (since *LUP* is the reciprocal of utilization density) (Figure 11). Most CMAs have *LUP* values between 400 and 800 m^2/(inh. or job).

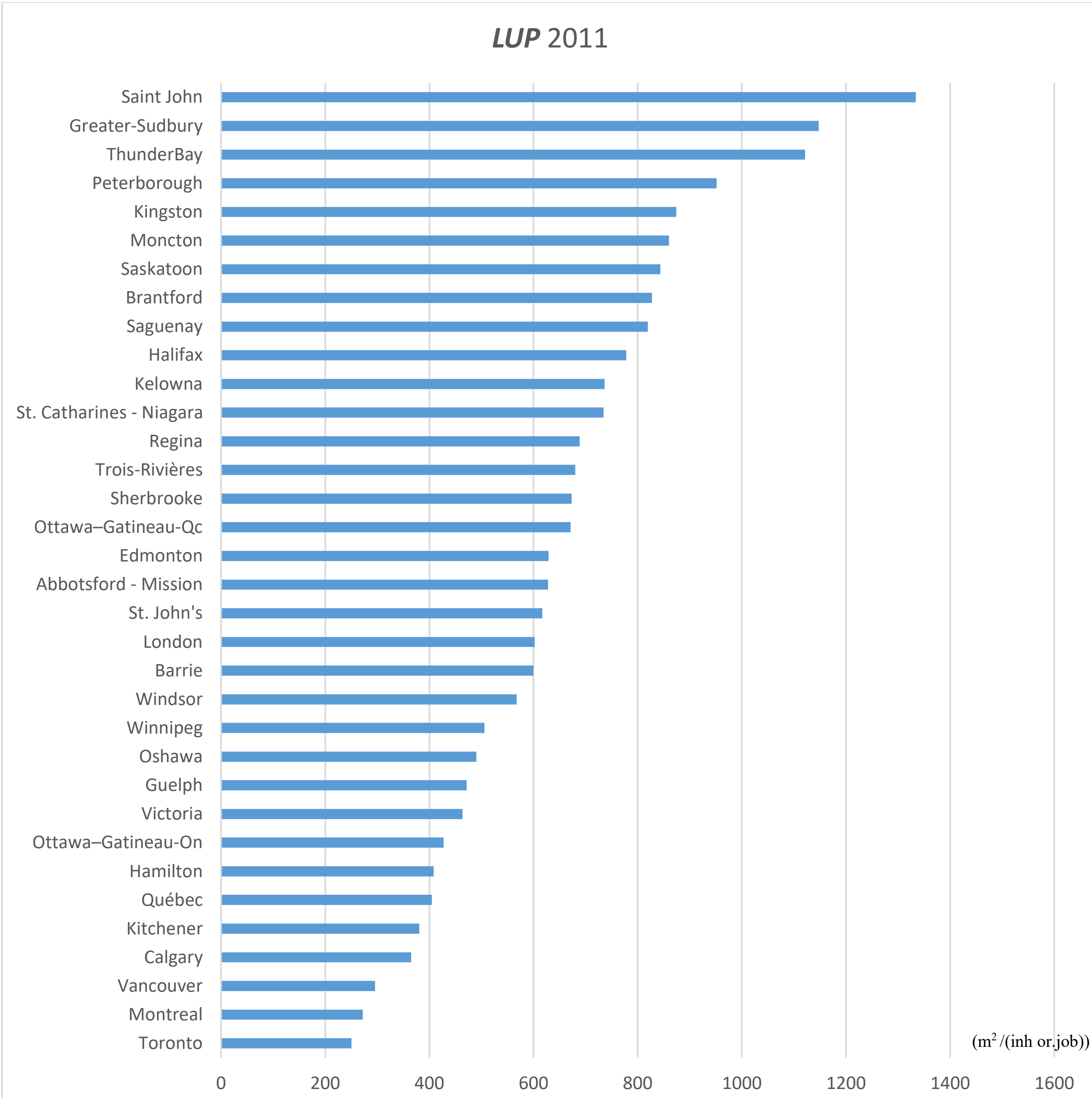


Figure 11. Values of Land Uptake per person (*LUP*) in all 34 CMAs in Canada in 2011- (in m^2 /(inh. or job))

3.3.2.4. Weighted Sprawl per Capita (*WSPC*)

WSPC indicates the average contribution of each inhabitant or workplace to urban sprawl in a CMA. For example, in 2011, Saint John CMA (NB) obtained the highest *WSPC* score (72.39 kUPU/(inh. or job)), followed by Thunder Bay (63.66 kUPU/(inh. or job)), and Greater Sudbury (ON) (61.46 kUPU/(inh. or job)). The lowest *WSPC* values were observed in Toronto (13.44 kUPU/(inh. or job)), Montreal (14.60 kUPU/(inh. or job)), Vancouver (16.58 kUPU/(inh. or job)), and Calgary (20.91 kUPU/(inh. or job)) (Figure 12).

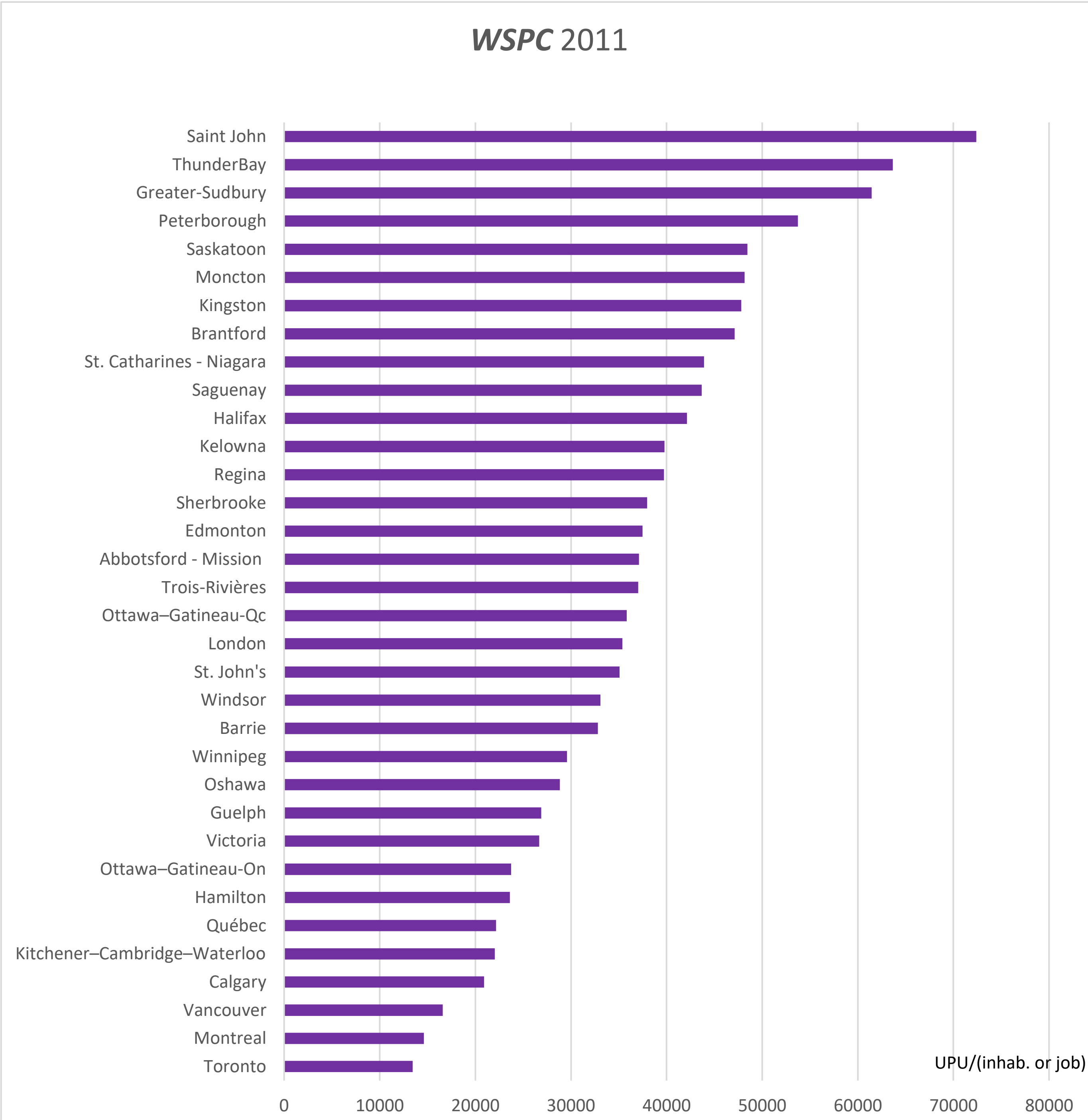


Figure 12. Values of weighted sprawl per capita (*WSPC*) in all 34 CMAs in Canada in 2011 (in UPU/(inh. or job)).

3.3.2.5. Total sprawl (*TS*)

The absolute values of sprawl are expressed by *TS*. As demonstrated by Jaeger et al. (2010b), the value of *TS* increases when new zones are developed anywhere in a CMA. I next present the *TS* values for all the CMAs. In 2011, Toronto experienced the highest *TS* value by a large margin compared to the other CMAs. Montreal showed the second highest *TS* value by a large margin, followed by Edmonton and Vancouver. Notably, most CMAs obtained a *TS* score below 3000 MUPU (Figure 13).

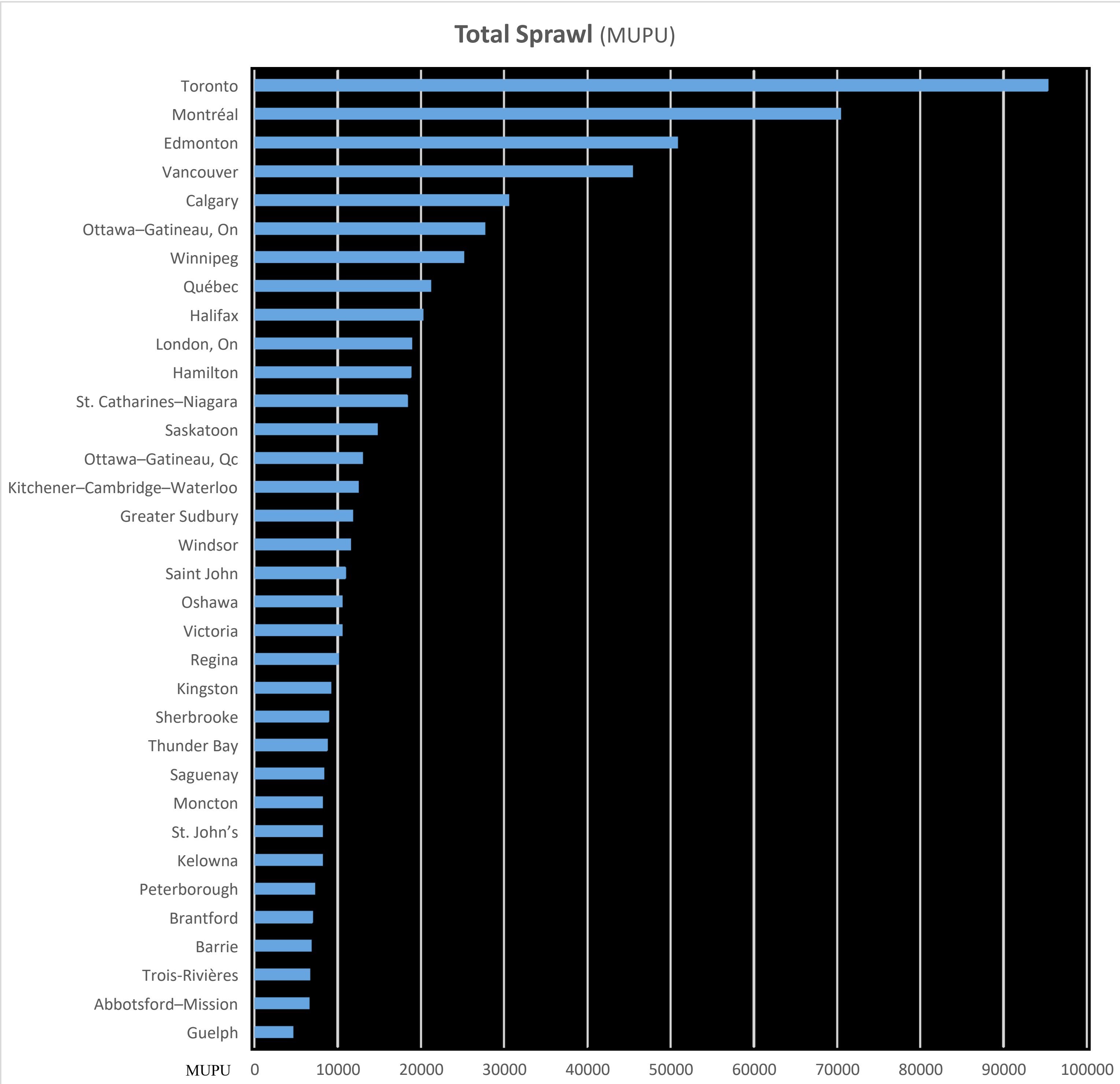


Figure 13. Values of Total Sprawl (*TS*) in all 34 CMAs in Canada in 2011 (in MUPU).

3.3.3. Historic development since 1991

3.3.3.1. Values of *WUP* between 1991 and 2011

Urban sprawl has increased in all CMAs between 1991 and 2011 (Figure 14). Between 1991 and 2011, the Victoria CMA experienced the highest increase in *WUP* among all the CMAs (4.46 UPU/m^2), a trend followed by St. Catharines–Niagara (4.23 UPU/m^2), St. John's (4.20 UPU/m^2), Hamilton (4.12 UPU/m^2), and Kitchener-Cambridge-Waterloo (4.09 UPU/m^2). The increase in *WUP* for Montreal, as the most sprawled CMA in 2011, was 3.69 UPU/m^2, while the increase in Toronto was a little lower (3.34 UPU/m^2). The CMAs experiencing the lowest increases were Saskatoon (0.30 UPU/m^2), Regina (0.31 UPU/m^2), Winnipeg (0.40 UPU/m^2), and Saguenay (0.66 UPU/m^2) (Figure 15).

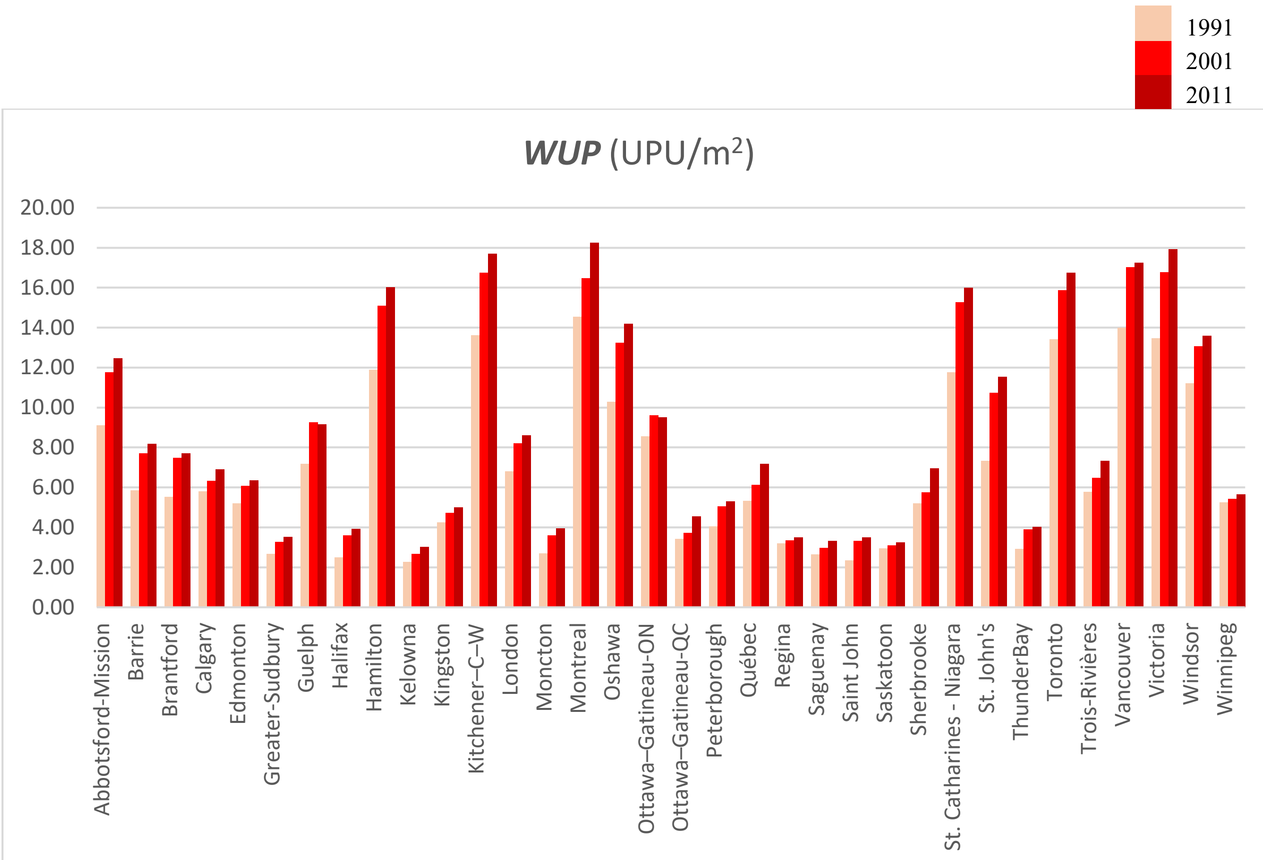


Figure 14. Values of *WUP* in all 34 CMAs in Canada, 1991, 2001, and 2011 (in UPU/m^2), odered alphabetically. (Kitchener-C-W= Kitchener-Cambridge-Waterloo)

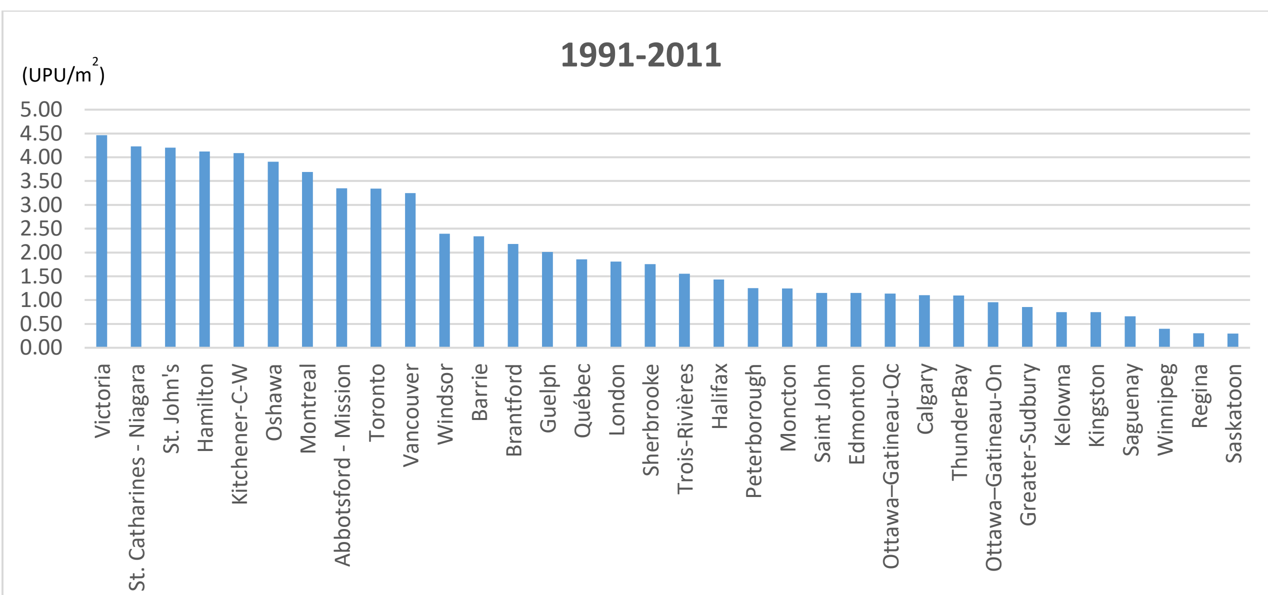


Figure 15. Absolute changes in the values of *WUP* in all 34 CMAs in Canada between 1991and 2011 (in UPU/m^2), ordered by the amount of increase. (Kitchener-C-W= Kitchener-Cambridge-Waterloo)

Changes 2001-2011

To identify changes in trends, I compare the changes of the first and second decade. Interestingly, all the CMAs show a clear, continuous increase of urban sprawl in the 2001-2011 period, except for a decrease in Guelph (from 9.25 to 9.16 UPU/m^2) and Ottawa- Gatineau-ON CMAs (from 9.61 to 9.52 UPU/m^2) (Figure 16). For this time period, Montreal exhibited the highest increase (1.79 UPU/m^2). The second and third highest increases in *WUP* were observed in Sherbrooke (1.19 UPU/m^2) and Victoria (1.16 UPU/m^2). All the other CMAs experienced comparably smaller increases in *WUP* (Figure 16).

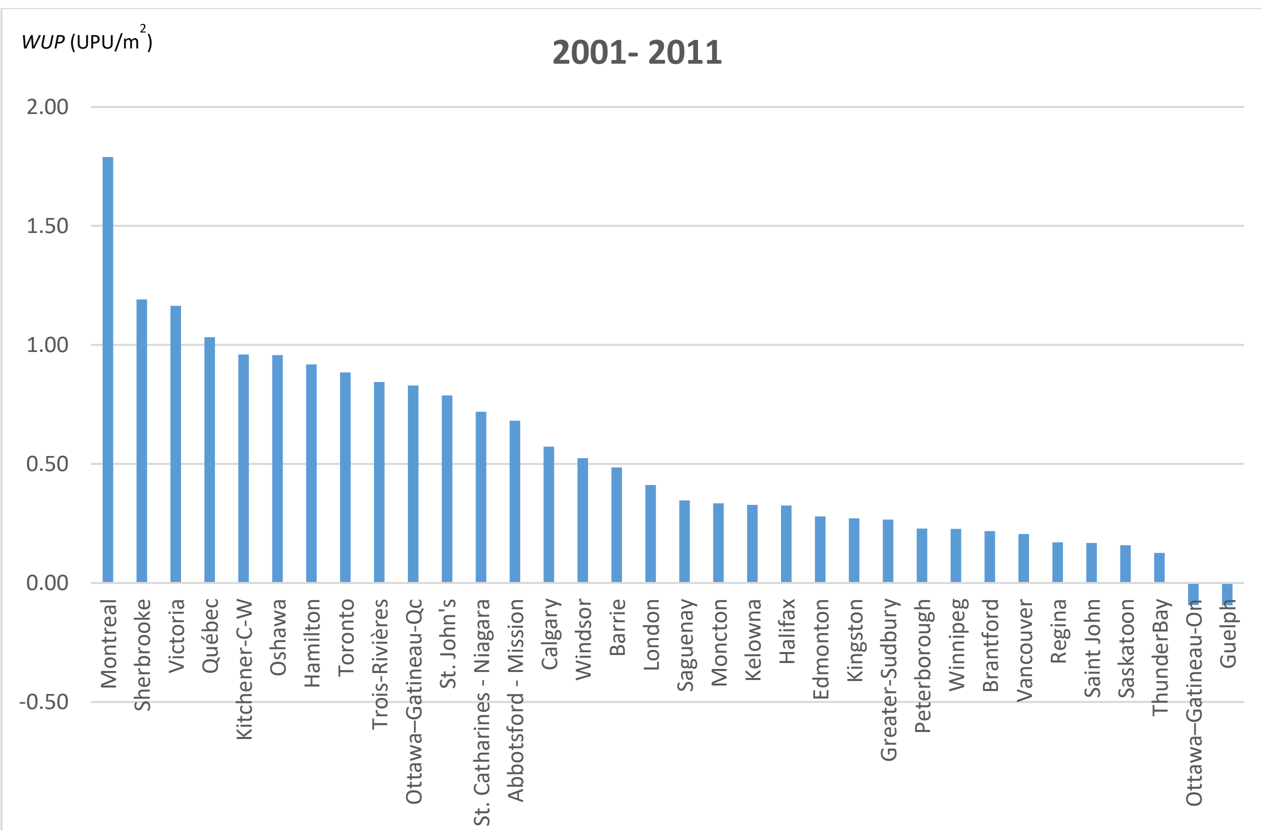


Figure 16. Changes in the values of *WUP* in all 34 CMAs in Canada (in UPU/m^2). (Kitchener-C-W= Kitchener-Cambridge-Waterloo)

Changes 1991-2001

St. Catharines- Niagara experienced the highest increase in *WUP* (3.51 UPU/m^2), followed by St. John's (3.42 UPU/m^2), Victoria (3.30 UPU/m^2), Hamilton (3.20 UPU/m^2), Kitchener-Cambridge-Waterloo (3.13 UPU/m^2), and Vancouver (3.04 UPU/m^2) (Figure 17). The Toronto and Montreal CMAs also experienced a relatively high *WUP* increase (2.46 and 1.90 UPU/m^2, respectively). Regina (0.14 UPU/m^2), Saskatoon (0.14 UPU/m^2), and Winnipeg (0.17 UPU/m^2) experienced a much smaller *WUP* increases in this time period (Figure 17).

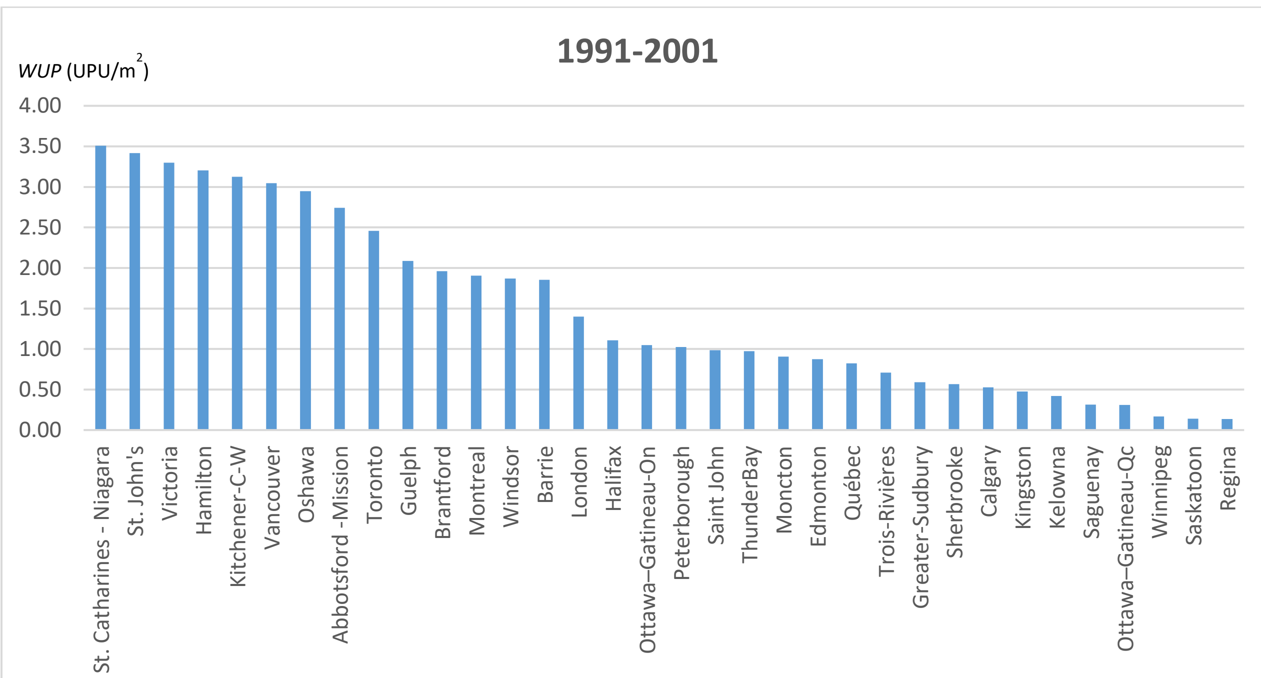


Figure 17. *WUP* values for all 34 CMAs in Canada, for the 1991- 2001 period (in UPU/m^2). (Kitchener-C-W= Kitchener-Cambridge-Waterloo)

The increases in *WUP* in the first decade (1991-2001) were stronger in most of the CMAs (75%) compared to the second decade (2001-2011), with increases of more than 1 UPU/m^2 observed in the St. Catharines – Niagara (+3.51 UPU/m^2), St. John's (+3.42 UPU/m^2), Victoria (+3.30

UPU/m^2), Hamilton (+3.20 UPU/m^2), Kitchener–Cambridge–Waterloo (+3.13 UPU/m^2), Vancouver (+3.04 UPU/m^2), Oshawa (+2.95 UPU/m^2), Abbotsford -Mission (+2.74 UPU/m^2), Toronto (+2.46 UPU/m^2), Guelph (+2.09 UPU/m^2), Brantford (+1.96 UPU/m^2), Montreal (+1.90 UPU/m^2), Windsor (+1.87 UPU/m^2), Barrie (+1.85 UPU/m^2), London (+1.40 UPU/m^2), Halifax (+1.11 UPU/m^2), Ottawa–Gatineau-ON (+1.05 UPU/m^2), Peterborough (+1.02 UPU/m^2) CMAs. The increases in *WUP* in the second decade were stronger in only a few CMAs such as Sherbrooke (+1.19 UPU/m^2) and Québec (+1.03 UPU/m^2).

3.3.3.2. Changes in the components of *WUP* since 1991 to 2011

This section investigates how various components of *WUP* changed between 1991 and 2011 for each CMA. This analysis allows for a deeper understanding of urban sprawl in Canadian CMAs in this time period.

Montreal obtained the highest *PBA* value in 2011 (34.01 %). Further analysis revealed a 2.56% increase in *PBA* for the first decade (between 1991 and 2001) and a slightly higher 3.71% increase in *PBA* for the following decade (from 2001 to 2011). As such, the percentage of built-up area in Montreal has grown by 6.27% between 1991 and 2011, while the value of *DIS* increased by 0.17 UPU/m^2. Montreal's *LUP* value increased by 10 m^2/(inh. or job) and Montreal scored the lowest *LUP*, just below Toronto, in 2011.

The Toronto and Montreal CMAs are the most densely populated CMAs in Canada. The result shows that Toronto CMA experienced a reduction by 23 m^2/(inh. or job) in *LUP* value between 1991 and 2011. Although Toronto experienced the lowest *LUP* among all CMAs in 2011, it had the highest *DIS* value in the same year.

In the Vancouver CMA, the degree of *WUP* markedly increased between 1991 and 2001 (by 3.04 UPU/ m^2), while in the following decade (2001-2011), the increase in *WUP* was much smaller (0.21 UPU/ m^2). While the Vancouver CMA scored the second highest *DIS* value in 2011, it experienced a lower value of *LUP* than the other CMAs, except for Montreal and Toronto. The value of *LUP* in the Vancouver CMA only weakly changed from 1991 to 2011, with a slight decrease in *LUP* between 2001 and 2011 (from 331 to 296 m^2/ (inh. or job)). The following Figures depict how the three components of *WUP* interact in different CMAs. For more detailed results of *WUP*, *WSPC*, and their components for CMAs in 1991, 2001, and 2011 please refer to Appendix D.

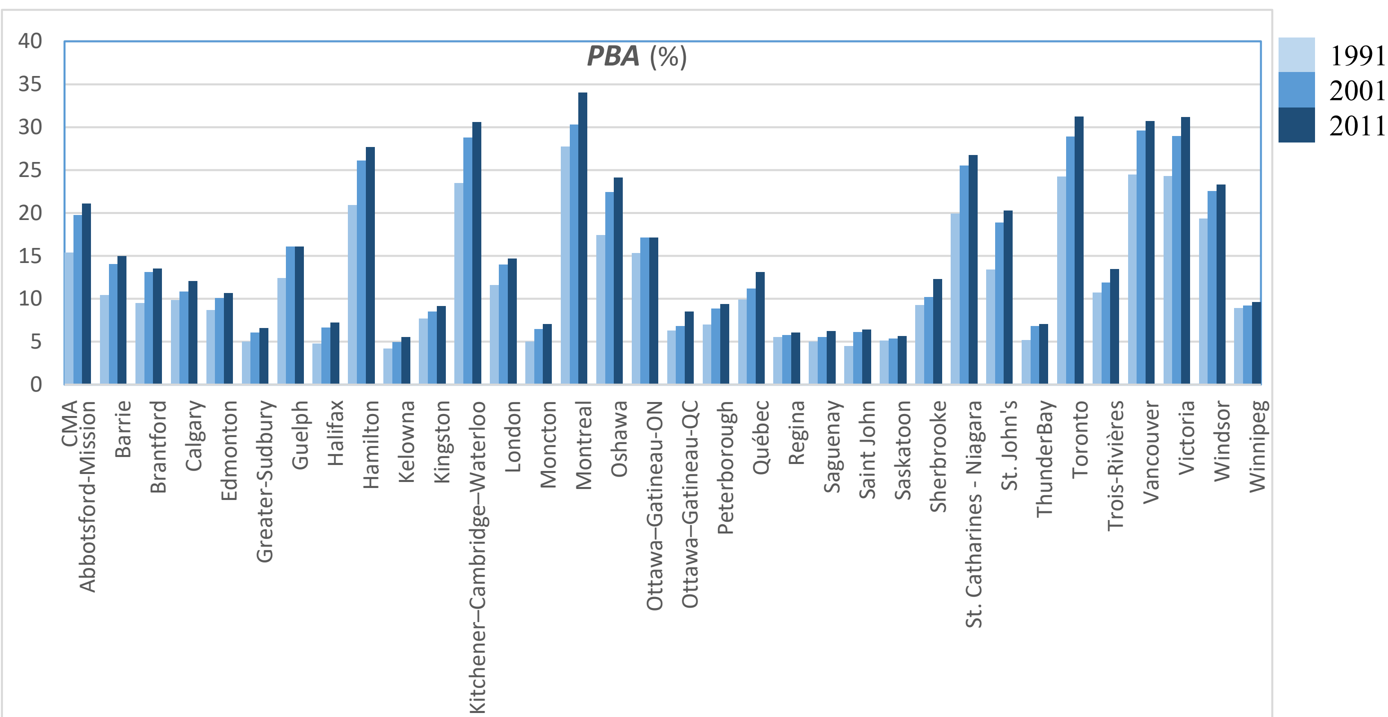


Figure 18. Values of *PBA* in all 34 CMAs in Canada, 1991, 2001, and 2011 (in %).

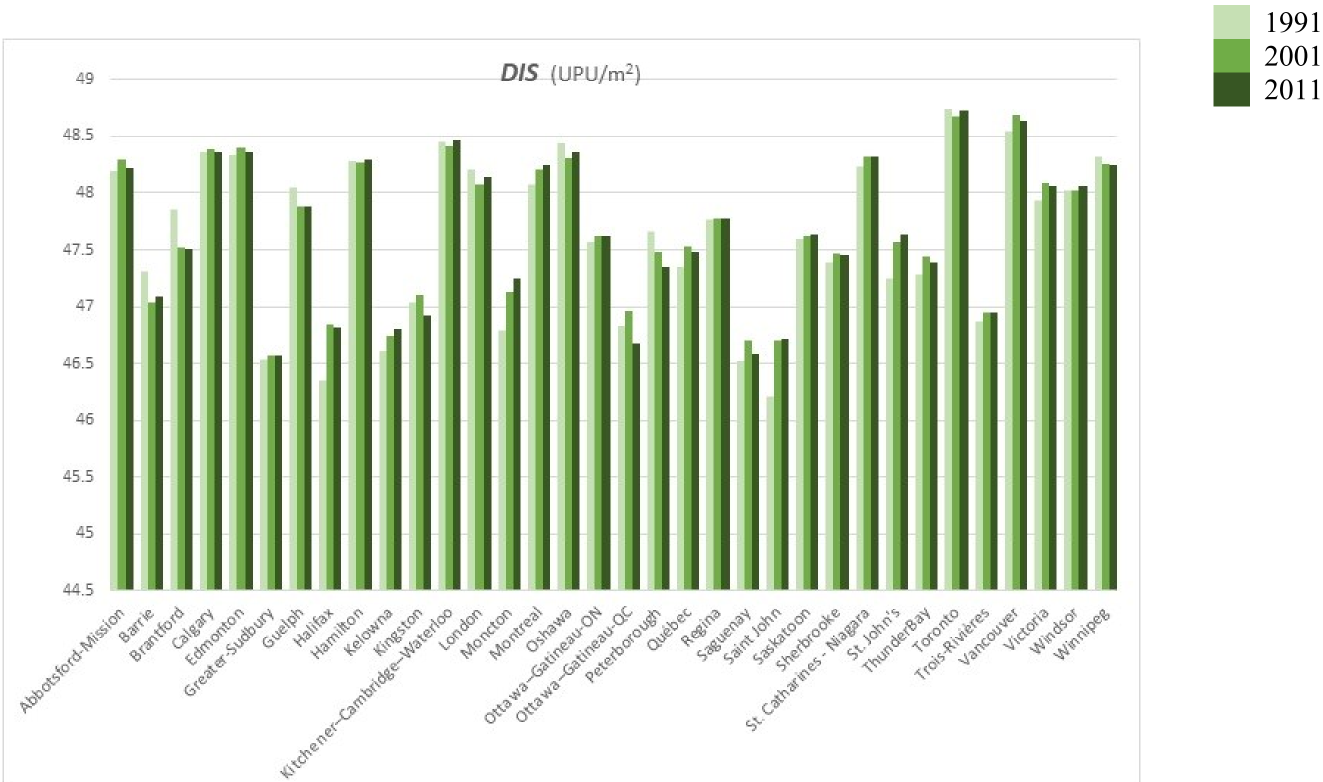


Figure 19. Values of *DIS* in all 34 CMAs in Canada, 1991, 2001 and 2011 (in UPU/m^2).

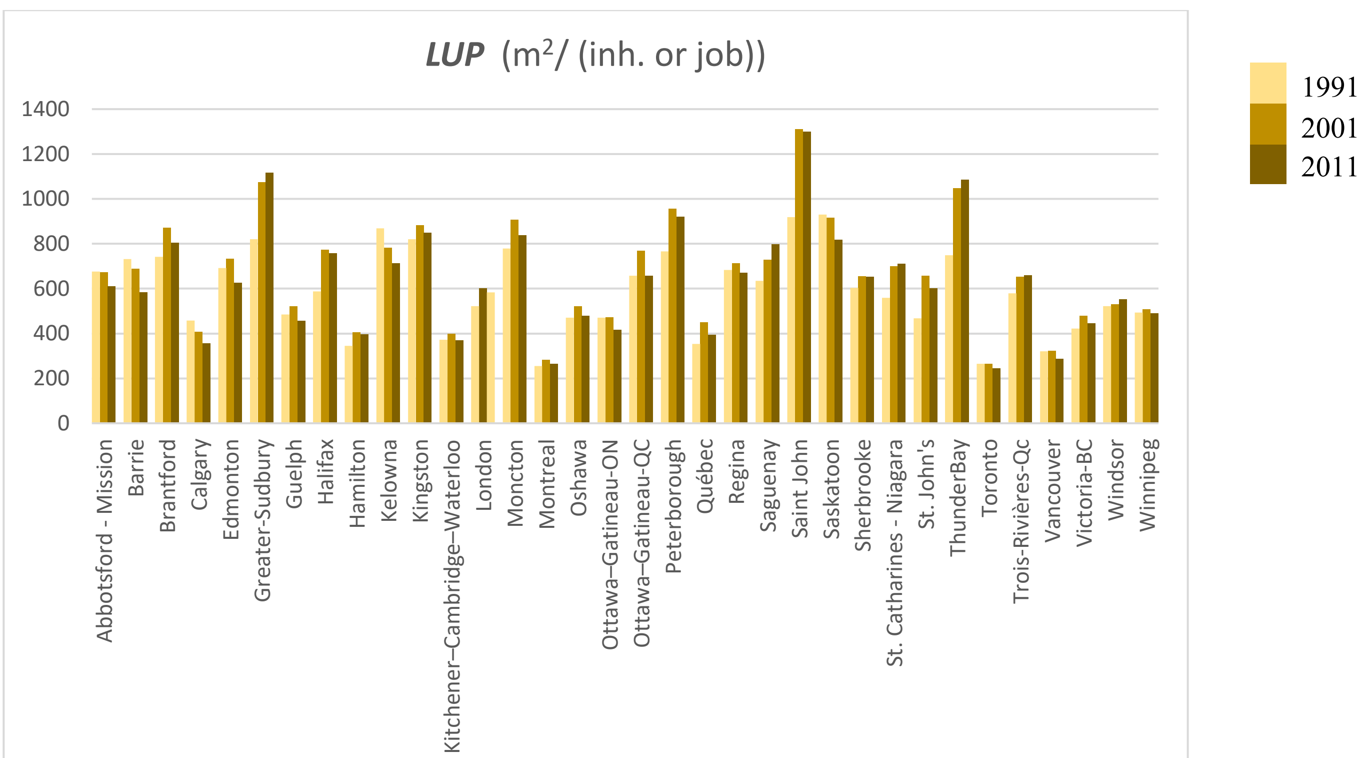


Figure 20. Values of *LUP* in all (34) CMAs in Canada, 1991, 2001 and 2011 (in m^2/ (inh. or job))

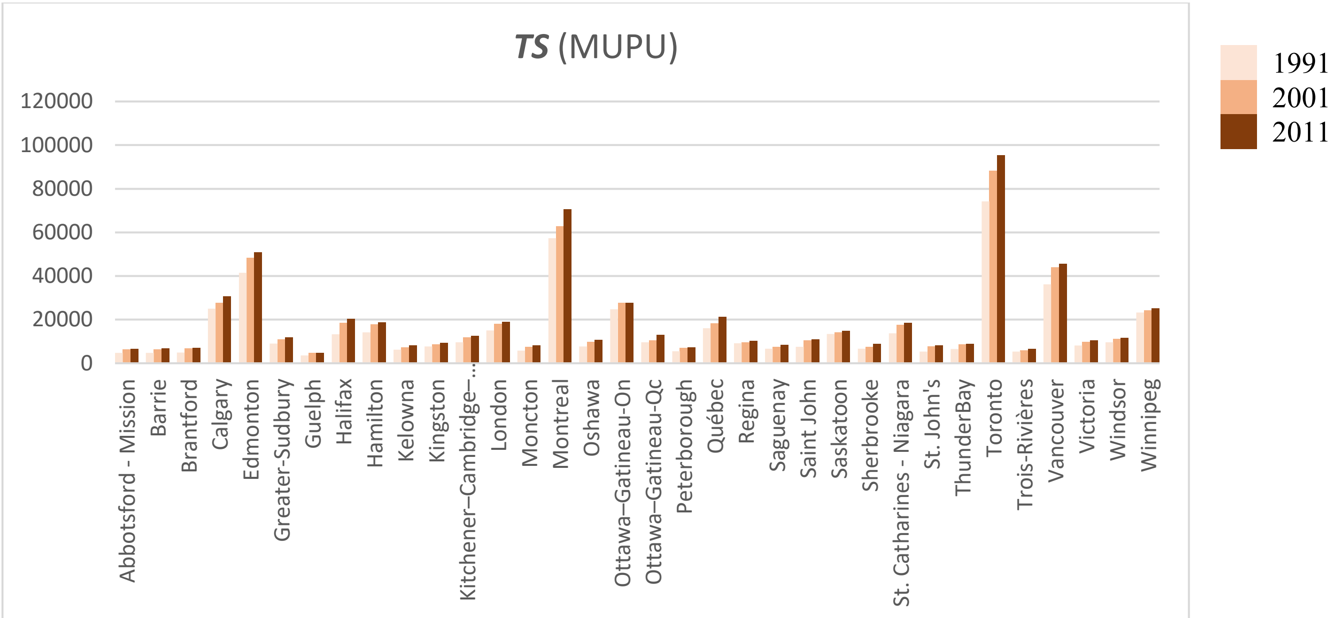


Figure 21. Values of *TS* in all (34) CMAs in Canada, 1991, 2001 and 2011 (in MUPU)

3.3.3.3. Changes in *WSPC* between 1991 and 2011

The value of *WSPC* decreased from 2001 to 2011 in all of the CMAs except for Greater-Sudbury, Quebec, Saguenay, Sherbooke, St. Catharines-Niagara, Thunder Bay, Trois-Rivières, and Windsor (Figure 22). The period 1991-2001 witnessed an increase in *WSPC* in most of the CMAs (76%). In contrast, the value of *WSPC* decreased from 2001 to 2011 in most (76%) of the CMAs. For example, several CMAs (e.g., Barrie, Calgary, Kelowna, Saskatoon, Vancouver, and Toronto) showed a decrease in *WSPC* in the period 1991-2011. On the other hand, the highest *WSPC* values were observed for 2001 in several other CMAs, e.g., Brantford, Edmonton, Guelph, Halifax, Hamilton, Kingston, Kitchener–Cambridge–Waterloo, London, Moncton, Montreal, Oshawa, Ottawa–Gatineau-QC, Peterborough, Regina, Saint John, St. John’s, Victoria, and Winnipeg (Figure 22).

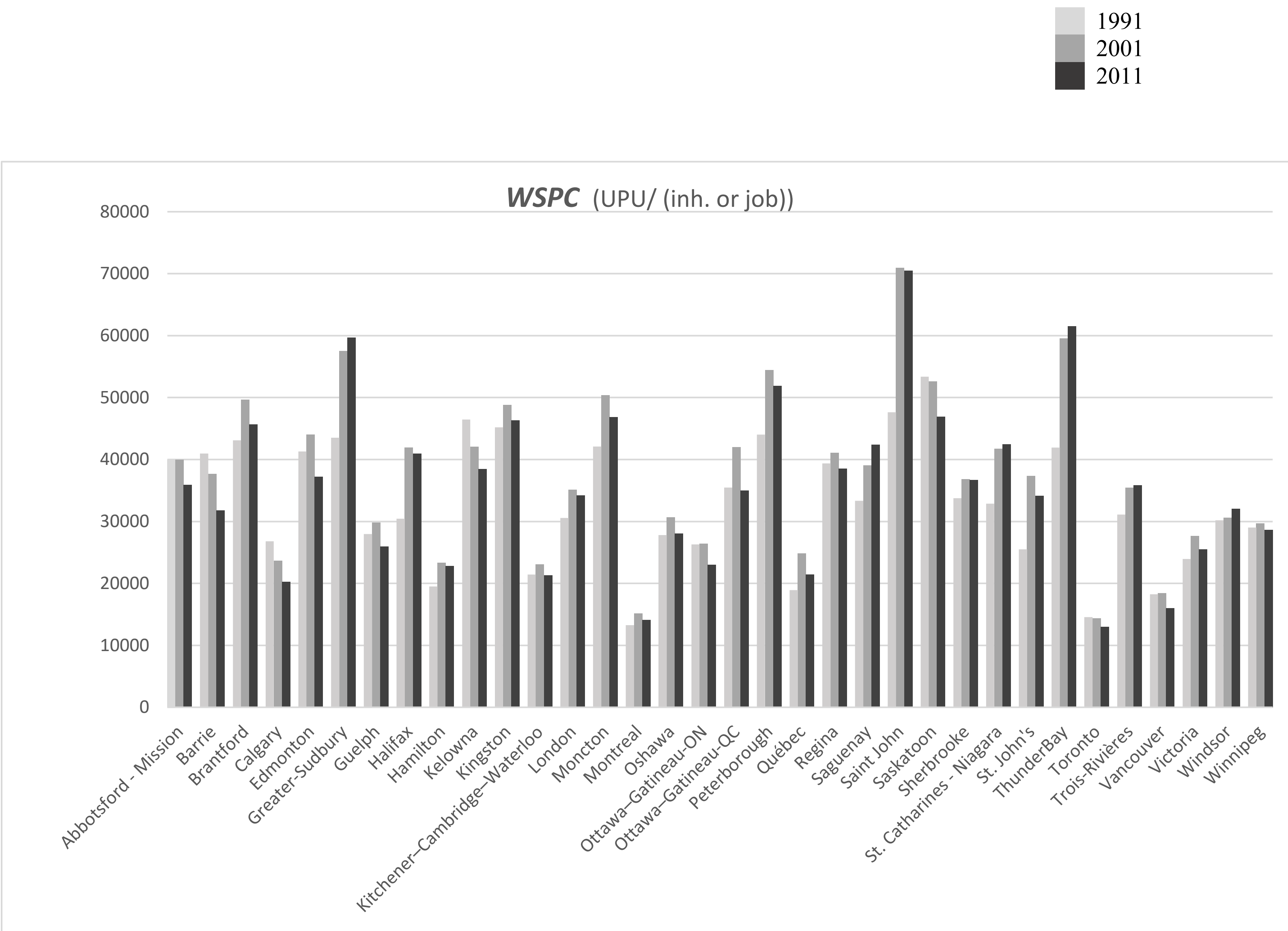


Figure 22. Values of *WSPC* in all 34 CMAs in Canada in 1991, 2001, and 2011 (in UPU/(inh. or job)).

3.3.3.4. Correlation analysis of changes in population and changes in sprawl between 1991 and 2011

The relationships between the values of *WUP*, *PBA*, *WSPC*, and the number of inhabitants, offer insights about the sprawl growth pattern in each CMA to answer our hypothesis.

The *r* value of correlation between the changes in *WUP* and the changes in population in the CMAs from 1991 to 2011 was 0.01 ($p = 0.95$), which indicates a weak positive correlation where the values of the two variables tend to increase together. However, the *r* value is close to zero, which shows that the relationship is weak. This correlation analysis indicates that in some of the CMAs such as Toronto, Vancouver, Abbotsford – Mission, Barrie, Calgary, Edmonton, Guelph, Kelowna, Oshawa, Ottawa–Gatineau-ON, and Saskatoon, urban sprawl has increased less fast than the population (data points below the diagonal in Figure 23a). In several other CMAs, e.g., Kingston, Regina, Kitchener-Cambridge-Waterloo, Ottawa–Gatineau-Qc, Windsor, and Winnipeg, the changes in population and in the values of *WUP* were very close and the changes in population were slightly stronger than the changes in *WUP*. In contrast, in Montreal, Québec, Brantford, Halifax, Hamilton, London, Moncton, Peterborough, Sherbrook, Trois-Rivières, and Victoria, the percentages of the change in *WUP* were higher than the percentages of the population (data points above the diagonal). Moreover, in Saint John, St. John's, and St. Catharines – Niagara, urban sprawl (*WUP*) increased much more than the population. In Greater-Sudbury, Saguenay, and Thunder Bay, the changes in population were negative, while urban sprawl had increased in all of these CMAs by 32%, 25%, and 38%, respectively (Figure 23a).

The diagram of relative change in *PBA* as a function of relative change in population shows that in Brantford, Halifax, Hamilton, London, Moncton, Montreal, Peterborough, Québec, Sherbrooke, Trois-Rivières, Victoria, and Windsor, the increase in *PBA* was higher than the increase in population (Figure 23b). In a few CMAs, the increase in *PBA* was much stronger than the increase in population. For example, *PBA* increased by 41 percentage points more strongly than the population (increase in *PBA* by 43% and increase in population by 2%) in Saint John, 36 percentage points in St. John's, and 25 percentage points in St. Catharines – Niagara. A strong increase in *PBA* was also observed in the CMAs with a negative population change (Greater-Sudbury, Saguenay, and Thunder Bay) (Figure 23b). The r value of the correlation between these two variables for all CMAs was 0.14 ($p = 0.434$).

Relative change in *WSPC* as a function of relative change in population shows that some CMAs experienced a decrease in *WSPC* from 1991 to 2011, although population increased in these CMAs (with an r value of -0.77 and $p = 1.05E\text{-}07$). For example, the change in population in Toronto was 43% while the change in *WPSC* was -11%. The same trend with the different values was detected in Vancouver, Abbotsford – Mission, Barrie, Calgary, Edmonton, Guelph, Ottawa–Gatineau-On, Regina, Saskatoon, and Winnipeg. In contrast, in Greater-Sudbury, Halifax, Peterborough, Saguenay, Saint John, St. Catharines – Niagara, St. John's, Thunder Bay, Trois-Rivières, and Victoria, the values of *WSPC* increased more than population. When the population increased by more than 30%, a reduction in *WSPC* due to densification was observed. For population increases of less than 20%, an increase in *WSPC* occurred in most of the CMAs. In the Regina and Winnipeg CMAs, although the population increased by 10%, these two CMAs experienced a decrease in *WSPC* (Figure 23c).

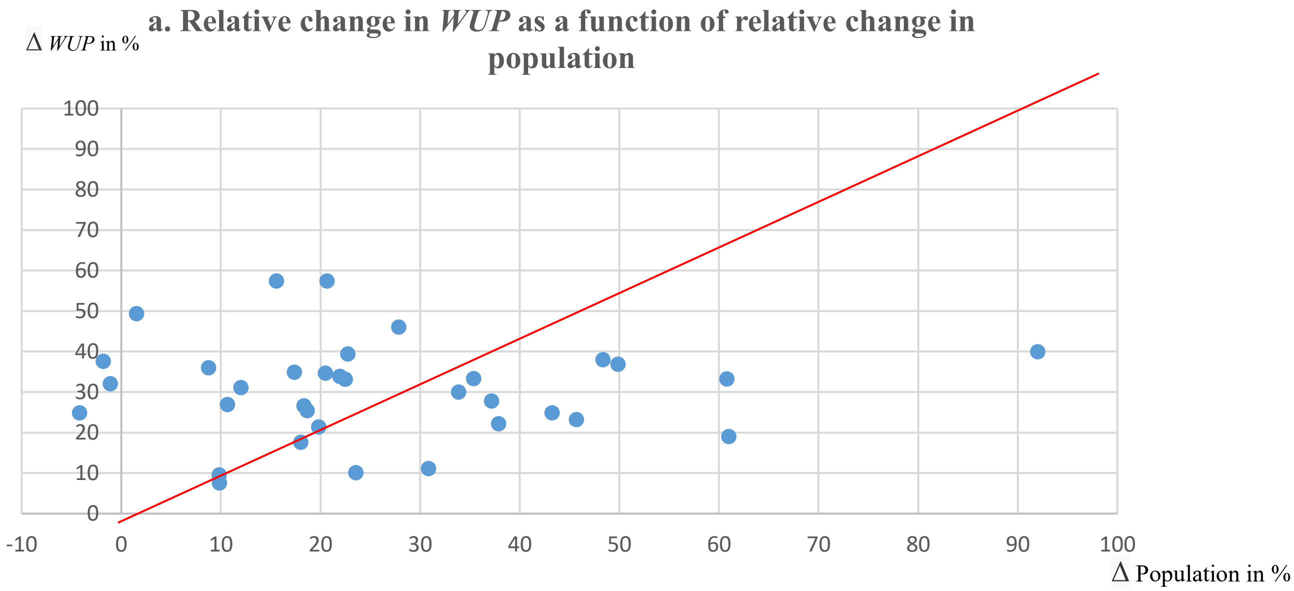


Figure 23a. Relative change in *WUP* as a function of relative change in population between 1991 and 2011. All the CMAs (dots) above the diagonal represent the CMAs in which urban sprawl increased faster than the population. All the CMAs (dots) below the diagonal represent the CMAs in which urban sprawl increased more slowly than the increase in population.

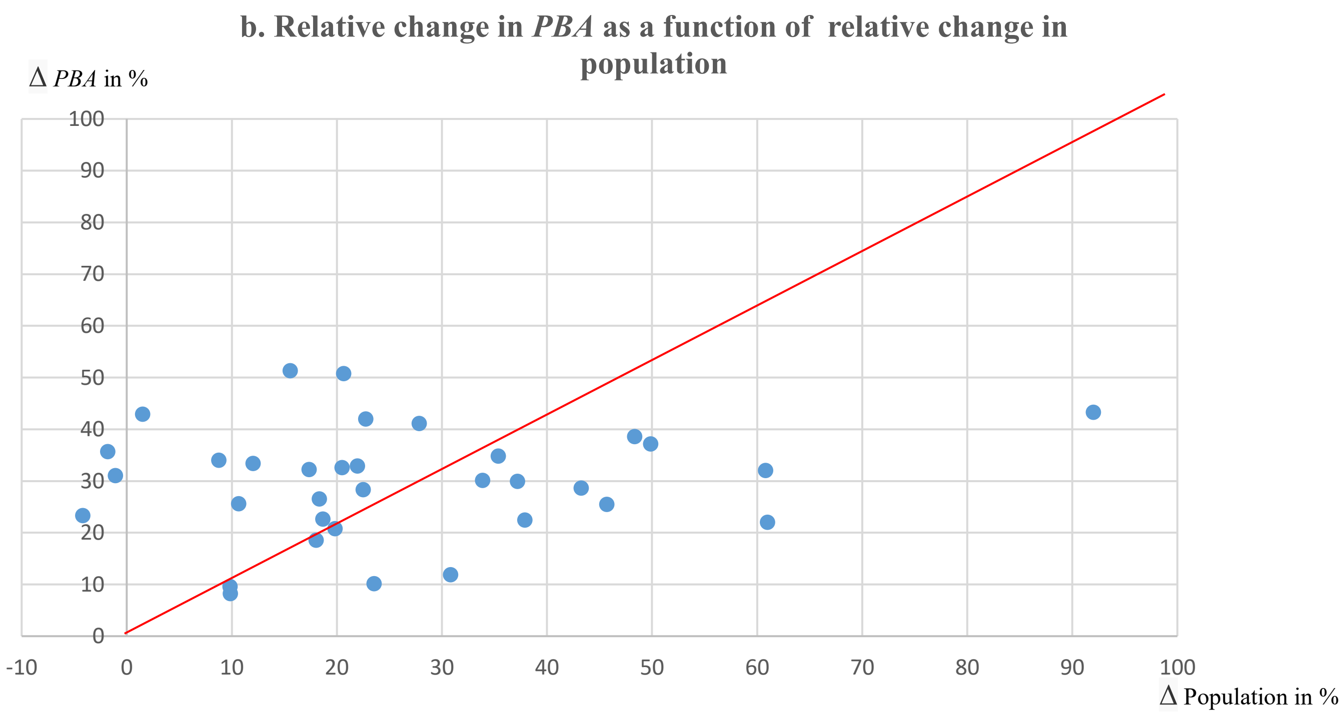


Figure 23b. Relative change in *PBA* as a function of relative change in population between 1991 and 2011. All the CMAs (dots) above the diagonal represent the CMAs in which *PBA* increased faster than the population. All the CMAs (dots) below the diagonal represent the CMAs in which *PBA* increased more slowly than the increase in population.

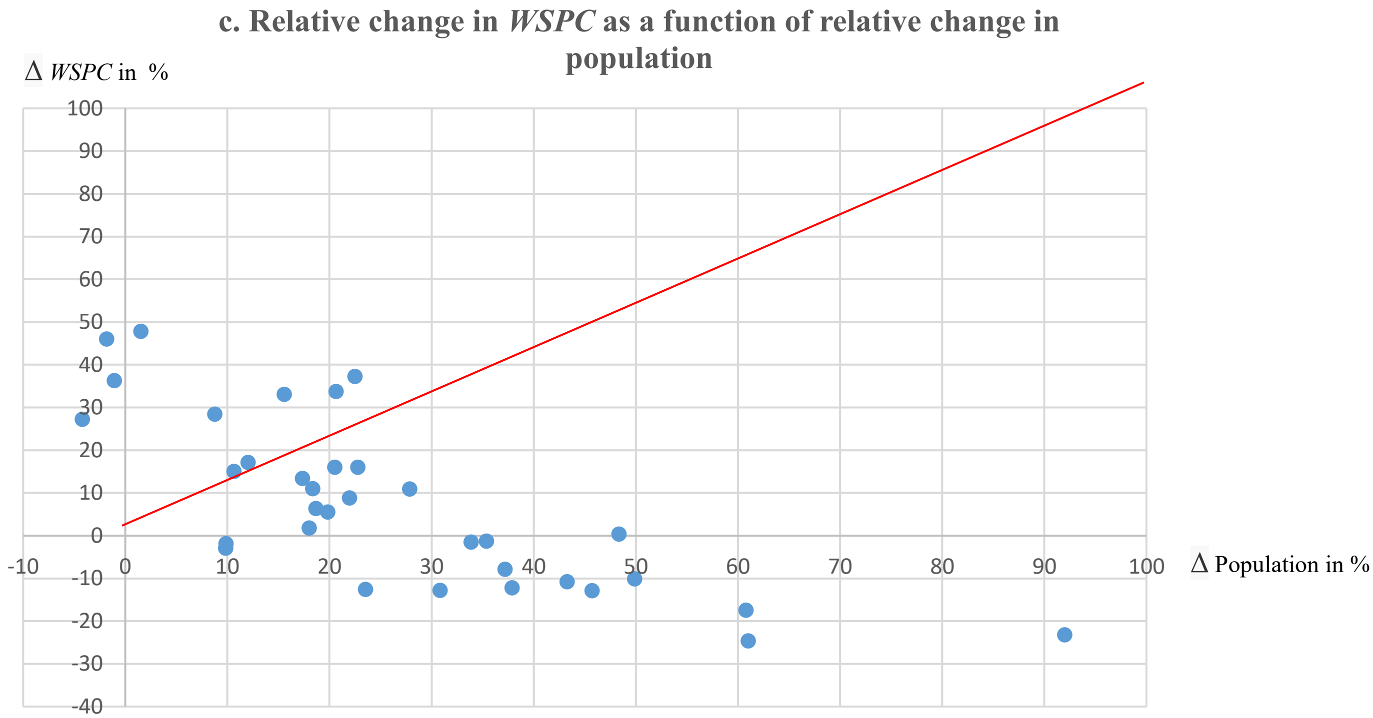


Figure 23c. Relative Change in *WSPC* as a function of relative change in population. All the CMAs (dots) above the diagonal represent the CMAs in which *WSPC* increased faster than the population between 1991 and 2011. All the CMAs (dots) below the diagonal represent the CMAs in which *WSPC* increased more slowly than the increase in population.

3.3.4. Census Subdivisions

The *WUP* and *WSPC* method was applied to the census subdivisions within the boundaries of the CMAs in 1991, 2001, and 2011. “The Census Subdivision Boundary File contains the boundaries of all census subdivisions which combined cover all of Canada. A census subdivision is a municipality or an area treated as an equivalent to a municipality for statistical purposes (for example, Indian reserves and unorganized territories)” (Statistics Canada, 2020, page 101).

According to official designations adopted by provincial/territorial or federal authorities, there are 54 different types of census subdivisions (CSDs). To identify CSDs, the census subdivision type is associated with the census subdivision name. For instance, Balmoral, VL (for the village of Balmoral) and Balmoral, P (for the parish /paroisse (municipalité de) of Balmoral) (Statistics Canada, 2020). Some CSDs have the same geographical name but different CSD types. Thus, to distinguish CSDs from each other, both the census subdivision type and the census subdivision name need to be used (i.e., Moncton, C [for the city of Moncton] and Moncton, P [for the parish of Moncton]). There are two exceptions ('subdivision of unorganized' (SNO) in Newfoundland and Labrador, and the 'subdivision of county municipality' (SC) in Nova Scotia). These two exceptions are "geographic areas created as equivalents for municipalities by Statistics Canada in cooperation with those provinces, for the purpose of disseminating statistical data" (Statistics Canada, 2020 page 101).

This thesis is using the CSD types of 2011. The CSD types have been modified several times in the last two decades. For example, the changes to CSD types made in 2011 include:

1) CSD types added:

- City / Ville (CV) in Ontario;
- Self-government / Autonomie gouvernementale (SG) in Yukon.

2) CSD types deleted:

- Cité (CÉ) in Quebec was replaced by Ville (V);
- County (municipality) (CM) in Alberta was corrected to Municipal district (MD);
- Nisga'a village (NVL) in British Columbia has been included in Nisga'a land (NL).

Census subdivision codes

The CSD code is a three-digit code that is based on the Standard Geographical Classification (SGC). In order to uniquely identify each CSD in Canada, the two-digit province/territory (PR) code and the two-digit census division (CD) code must precede the CSD code (see examples in table 5).

Table 5 - Examples of census subdivision codes	
PR-CD-CSD code	**CSD name and type (and province)**
12 06 008	Mahone Bay, T (N.S.)
35 06 008	Ottawa, CV (ON)

There are two municipalities in Canada that straddle provincial limits: Flin Flon (Manitoba and Saskatchewan) and Lloydminster (Saskatchewan and Alberta). Each of their provincial parts is treated as a separate CSD. Indian reserves are also treated as separate CSDs when they straddle provincial limits (Statistics Canada 2020).

The numbers of the CSDs within the boundaries of the CMAs differ among the CMAs. In 2011, the average number of CSDs inside the boundaries of the CMAs was 14, ranging from 3 to 91. For example, Montreal has the highest number of CSDs within its boundaries (91 CSDs), Toronto has 24, while Barrie, Brantford, Greater-Sudbury, Guelph, Hamilton, Oshawa, and Ottawa-Gatineau-On only have 3 CSDs each. For more information about the distribution of census subdivision types by province and territory please refer to Appendix B.

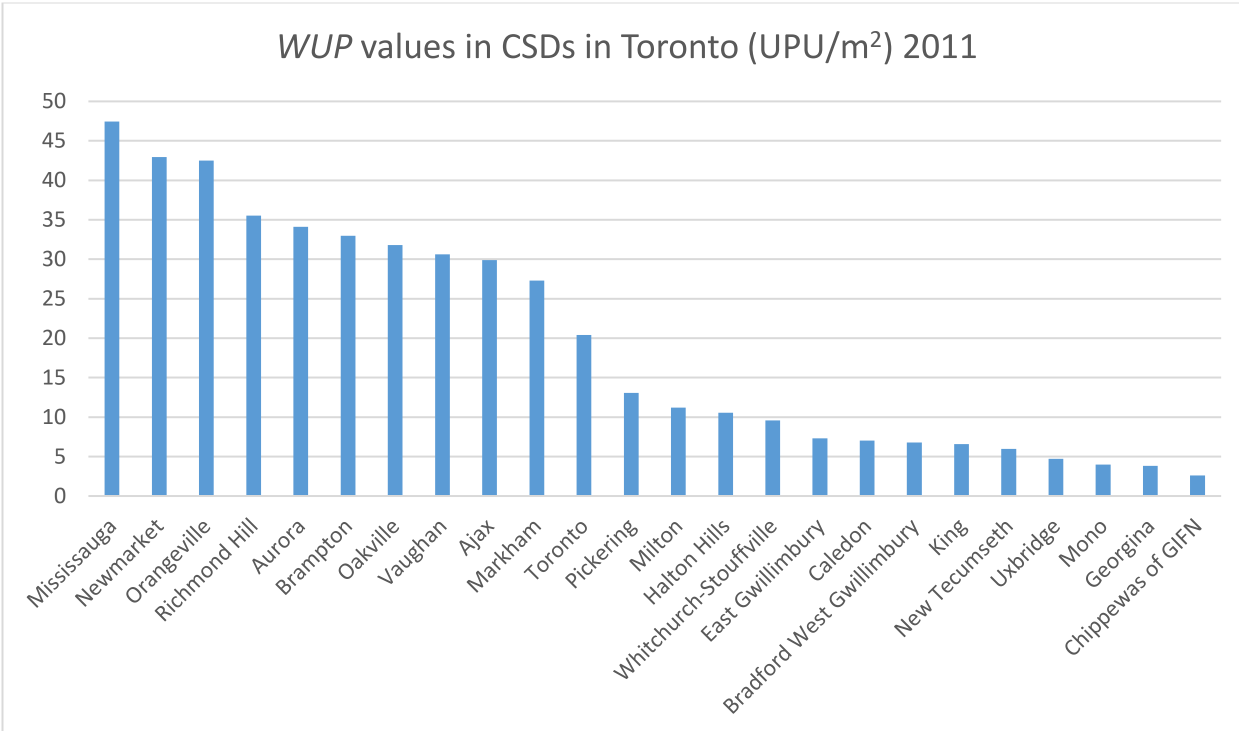
3.3.4.1. The values of *WUP* in the largest CMAs in 2011

Toronto, Montreal, Edmonton, Vancouver, Calgary, and Ottawa-Gatineau-On are the largest CMAs with the highest population and had the largest extent of built-up areas in 2011 (according to Soulard et al. 2016). The following sentences focus on these CMAs (for the CSDs of the other CMAs please refer to the separate Data-in-Brief paper, see Appendix A).

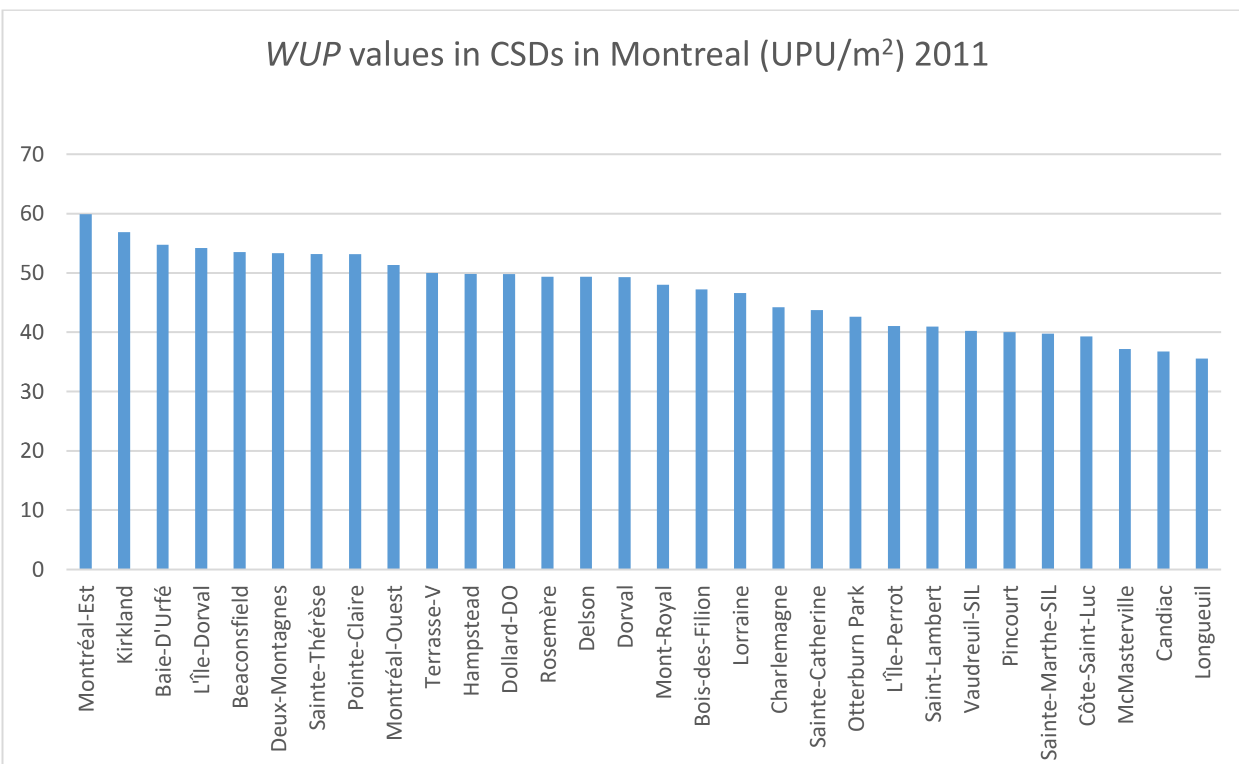
CSD Katzie 1 (5915830) in Vancouver scored highest in *WUP* among all CSDs of the largest CMAs (63.89 UPU/m^2). In contrast, the lowest level of *WUP* was found in Vancouver's CSD Greater Vancouver A (5915020), a value of 0.53 UPU/m^2. The highest *WUP* values in each of the largest CMAs were Montreal's CSD Montréal-Est, V (2466007) (59.89 UPU/m^2), Toronto's CSD Mississauga, CY (3521005) (47.99 UPU/m^2), Edmonton's CSD Edmonton, CY(4811061) (35.06 UPU/m^2), Calgary's CSD Airdrie, CY (4806021) (32.16 UPU/m^2), and Ottawa-Gatineau-On's CSD Ottawa, CV(3506008) (10.19 UPU/m^2).

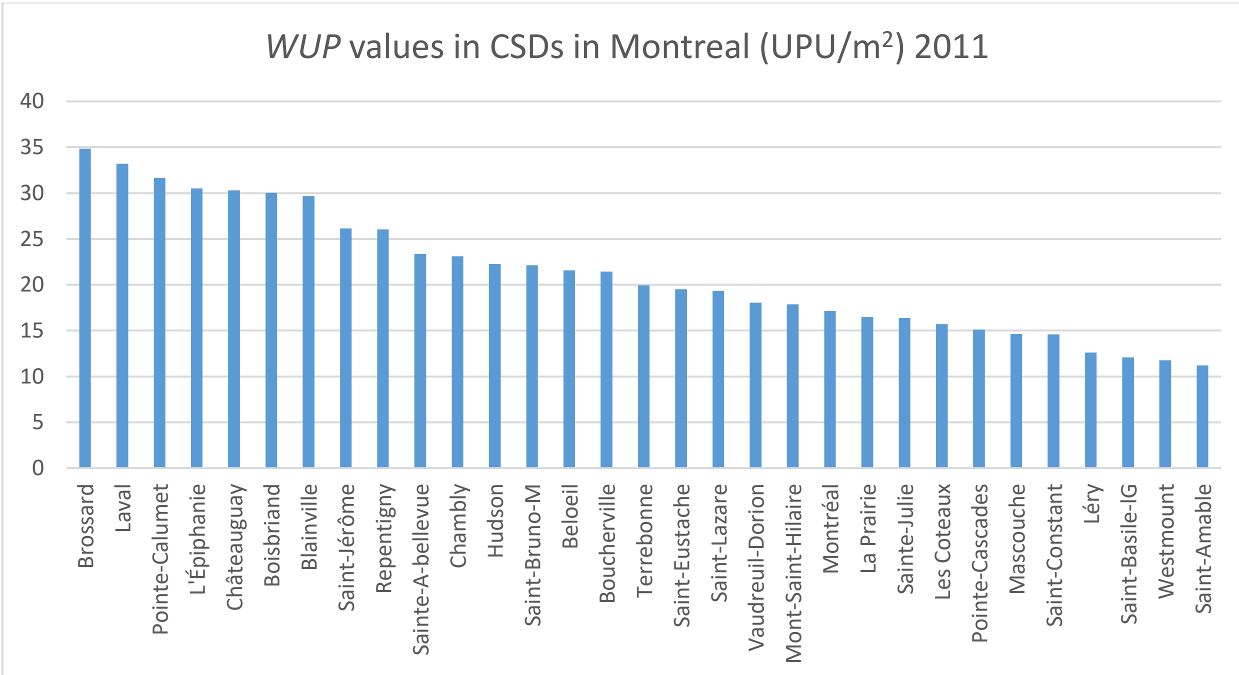
The CSDs showing the lowest values of *WUP* in each CMA respectively are Edmonton's CSD Alexander 134, IRI (4811805) (1.09 UPU/m^2), Calgary's CSD Tsuu T'ina Nation 145 (Sarcee 145), IRI (4806804) (1.33 UPU/m^2), Montreal's CSD Saint-Placide, MÉ (2472043) (2.19 UPU/m^2), Toronto's CSD Chippewas of Georgina Island First Nation (3519076) (2.61 UPU/m^2), and Ottawa-Gatineau-On's CSD Clarence-Rockland CY (3502036) (5.35 UPU/m^2) (Figure 24).

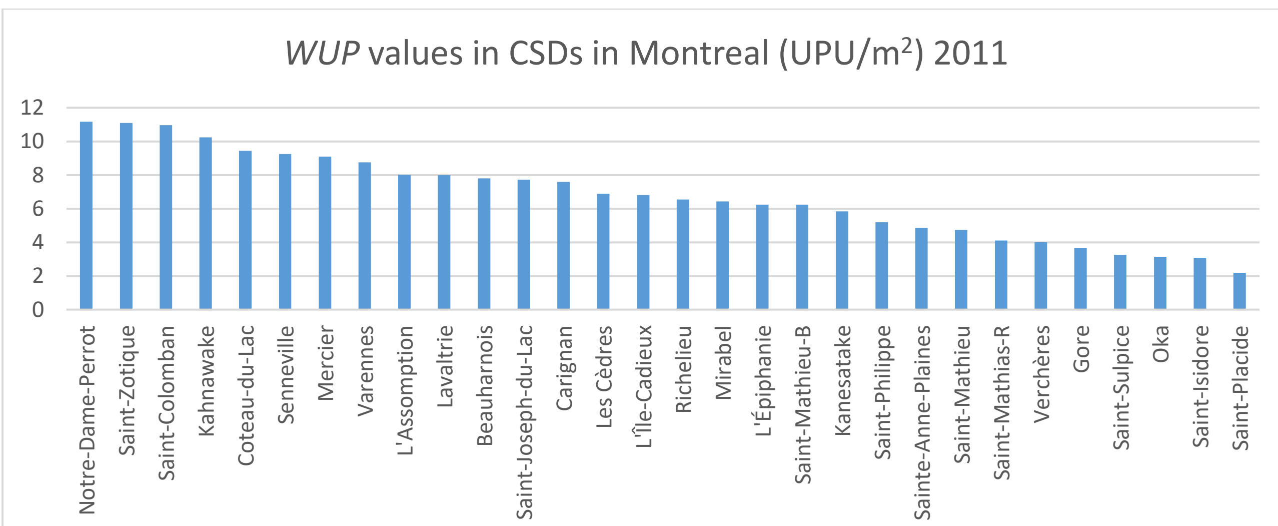
a


WUP values in CSDs in Toronto (UPU/m²) 2011
50
45
40
35
30
25
20
15
10
5
0
Mississauga
Newmarket
Orangeville
Richmond Hill
Aurora
Brampton
Oakville
Vaughan
Ajax
Markham
Toronto
Pickering
Milton
Halton Hills
Whitchurch-Stouffville
East Gwillimbury
Caledon
Bradford West Gwillimbury
King
New Tecumseth
Uxbridge
Mono
Georgina
Chippewas of GIFN

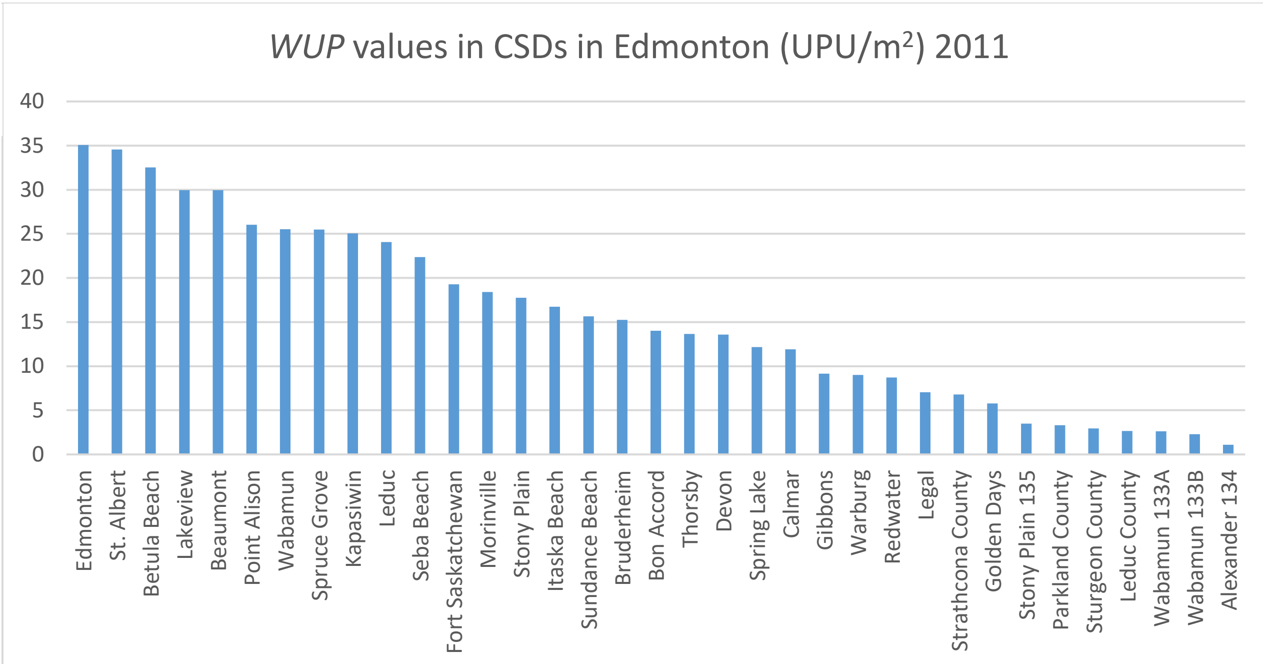
b


WUP values in CSDs in Montreal (UPU/m²) 2011
70
60
50
40
30
20
10
0
Montréal-Est
Kirkland
Baie-D'Urfé
L'Île-Dorval
Beaconsfield
Deux-Montagnes
Sainte-Thérèse
Pointe-Claire
Montréal-Ouest
Terrasse-V
Hampstead
Dollard-DO
Rosemère
Delson
Dorval
Mont-Royal
Bois-des-Filion
Lorraine
Charlemagne
Sainte-Catherine
Otterburn Park
L'Île-Perrot
Saint-Lambert
Vaudreuil-SIL
Pincourt
Sainte-Marthe-SIL
Côte-Saint-Luc
McMasterville
Candiac
Longueuil



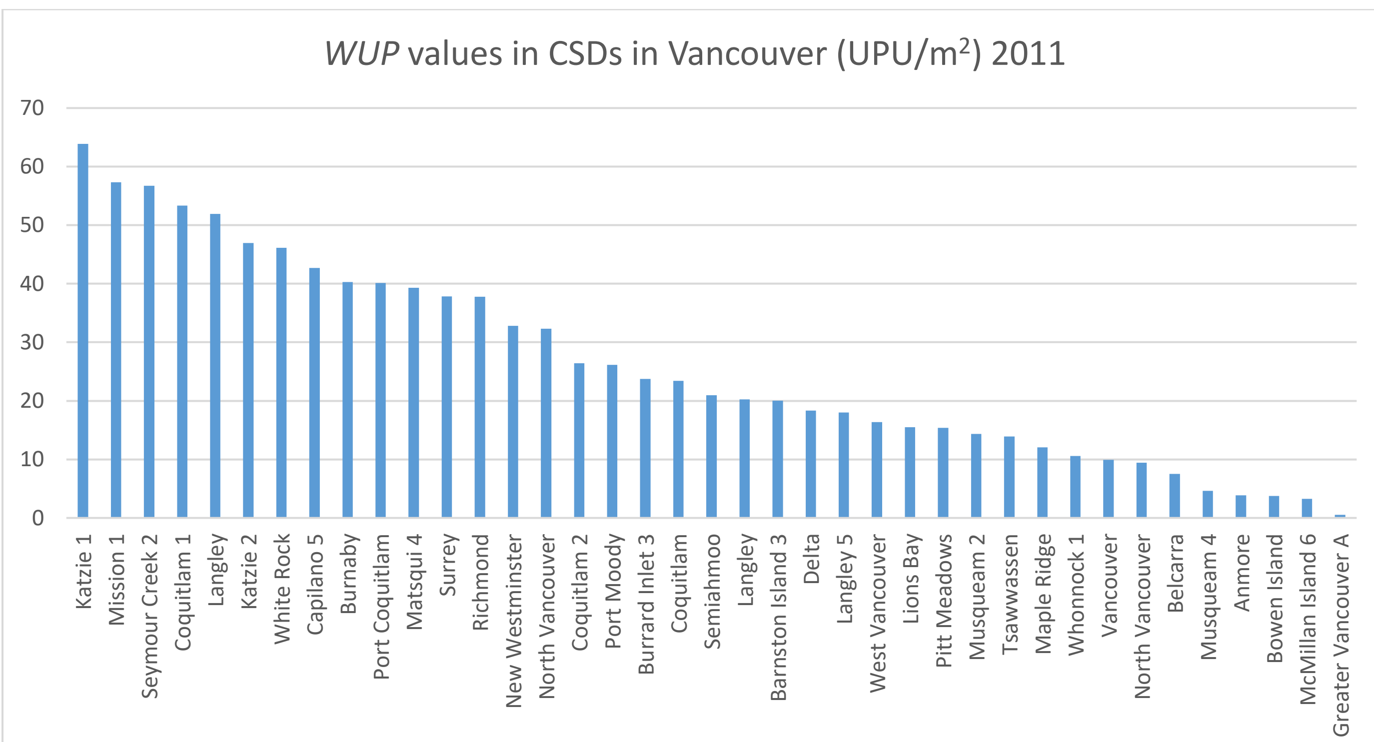


b. (Terrasse-Vaudreuil = Terrasse-V, Dollard-Des Ormeaux = Dollard-DO, Vaudreuil-sur-le-Lac = Vaudreuil-SIL, Sainte-Marthe-sur-le-Lac = Sainte-Marthe-SIL, Sainte-Anne-de-Bellevue = Sainte-A-bellevue, Saint-Bruno-de-Montarville = Saint-Bruno-M, Pointe-des-Cascades = Pointe-Cascades, Saint-Basile-le-Grand = Saint-Basile-lG, Notre-Dame-de-l'Île-Perrot = Notre-Dame-Perrot, Saint-Mathieu-de-Beloeil = Saint-Mathieu-B, Sainte-Anne-des-Plaines = Sainte-Anne-Plaines, Saint-Mathias-sur-Richelieu = Saint-Mathias-R) c



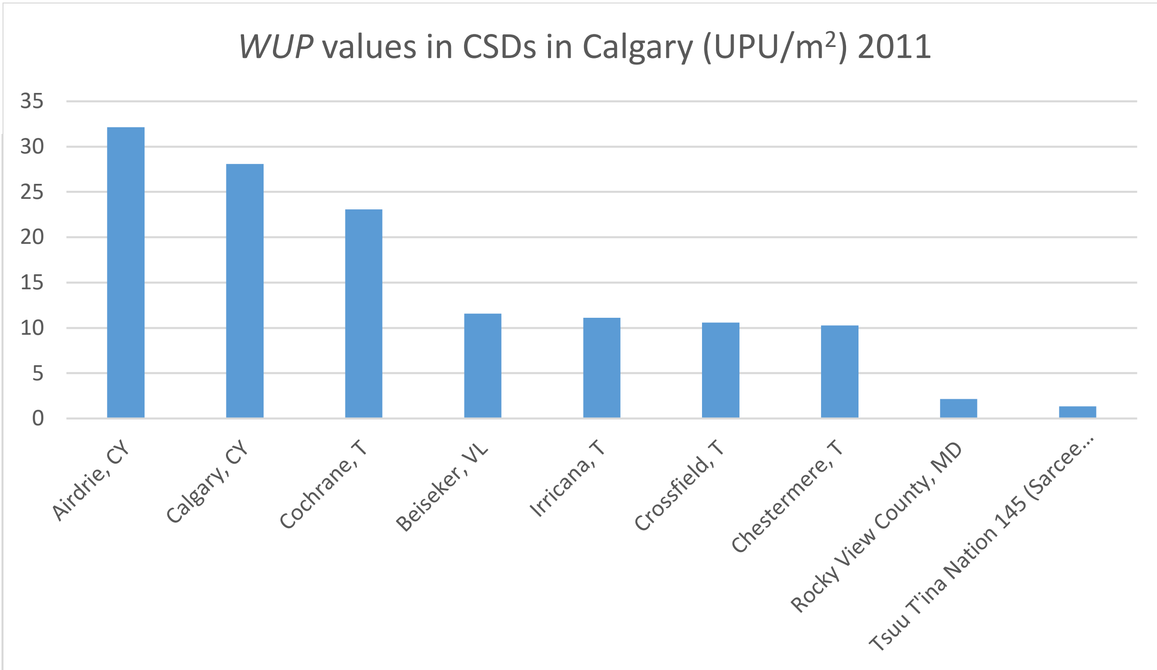
WUP values in CSDs in Edmonton (UPU/m2) 2011
40
35
30
25
20
15
10
5
0
Edmonton
St. Albert
Betula Beach
Lakeview
Beaumont
Point Alison
Wabamun
Spruce Grove
Kapasiwin
Leduc
Seba Beach
Fort Saskatchewan
Morinville
Stony Plain
Itaska Beach
Sundance Beach
Bruderheim
Bon Accord
Thorsby
Devon
Spring Lake
Calmar
Gibbons
Warburg
Redwater
Legal
Strathcona County
Golden Days
Stony Plain 135
Parkland County
Sturgeon County
Leduc County
Wabamun 133A
Wabamun 133B
Alexander 134

d



WUP values in CSDs in Vancouver (UPU/m2) 2011
70
60
50
40
30
20
10
0
Katzie 1
Mission 1
Seymour Creek 2
Coquitlam 1
Langley
Katzie 2
White Rock
Capilano 5
Burnaby
Port Coquitlam
Matsqui 4
Surrey
Richmond
New Westminster
North Vancouver
Coquitlam 2
Port Moody
Burrard Inlet 3
Coquitlam
Semiahmoo
Langley
Barnston Island 3
Delta
Langley 5
West Vancouver
Lions Bay
Pitt Meadows
Musqueam 2
Tsawwassen
Maple Ridge
Whonnock 1
Vancouver
North Vancouver
Belcarra
Musqueam 4
Anmore
Bowen Island
McMillan Island 6
Greater Vancouver A

e



f

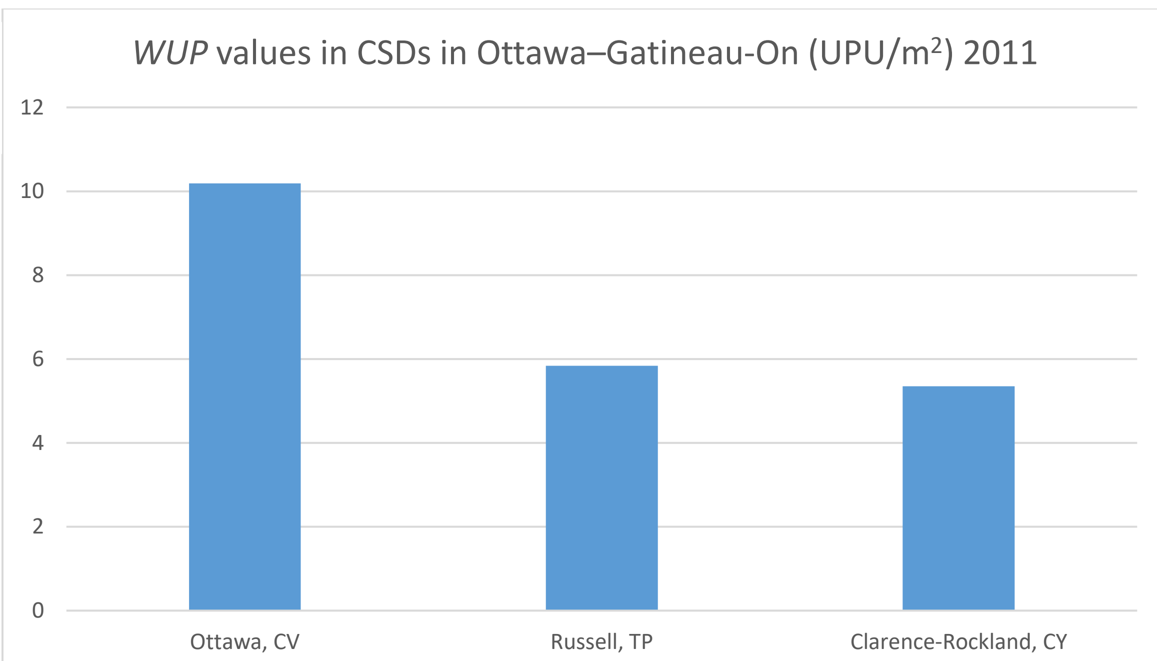


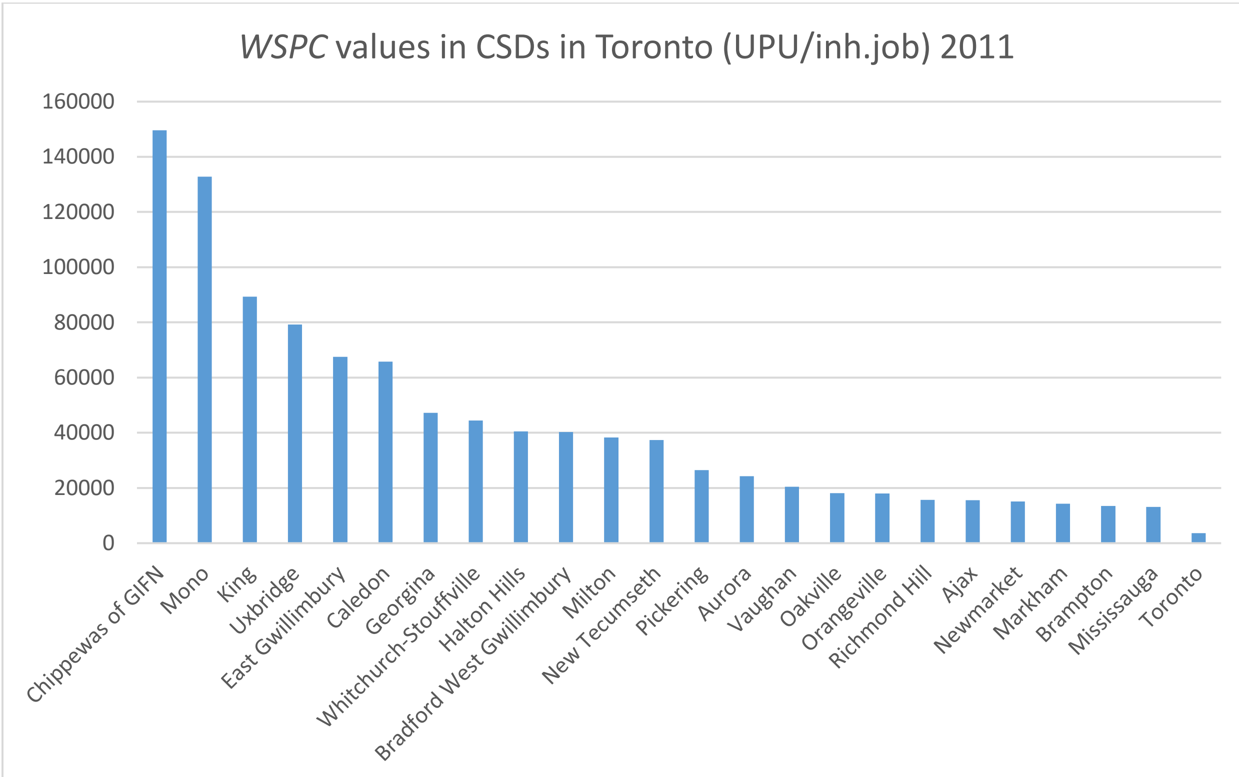
Figure 24. Urban sprawl (*WUP*) at the census subdivision level in 2011 in the Toronto CMA (a), in the Montreal CMA (b), in the Edmonton CMA (c), in the Vancouver CMA (d), in the Calgary CMA (e), and in the Ottawa-Gatineau-On CMA (f), ordered from largest to smallest. (GIFN= Georgina Island First Nation)

3.3.4.2. The values of *WSPC* in the largest CMAs in 2011

CSD Coquitlam 2 (5915804) in Vancouver scored highest in *WSPC* among the CSDs of the largest CMAs (4358750.69 UPU/inh.job). In contrast, the lowest level of *WSPC* was found in Vancouver's CSD Vancouver (5915022), a value of 1277.82 UPU/inh.job. The highest *WSPC* values in each of the largest CMAs, respectively, were Toronto's CSD Chippewas of Georgina Island First Nation (3519076) (149666.85 UPU/m^2), Montreal's CSD L'Île-Dorval (2466092) (1955472.40 UPU/inh.job), Edmonton's CSD Kapasiwin (4811044) (775827.75 UPU/inh.job), Vancouver's CSD Coquitlam 2 (5915804) (4358750.69 UPU/inh.job), Calgary's CSD Rocky View County, MD (4806014) (196351.68 UPU/inh.job), and Ottawa-Gatineau-On's CSD Russell, TP (3502048) (66294.69 UPU/inh.job).

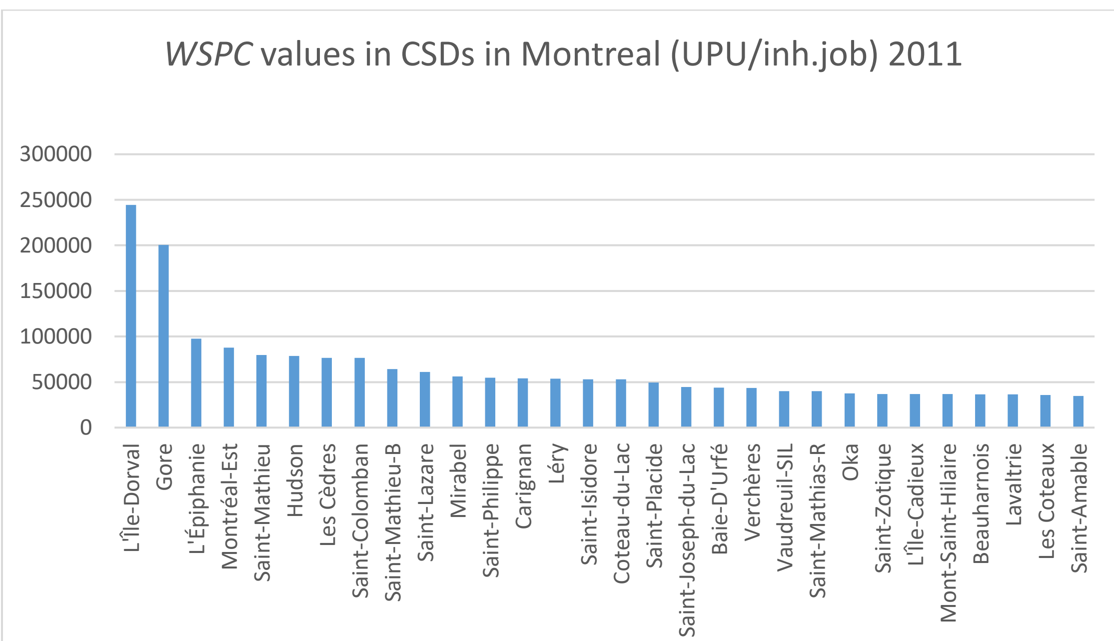
The CSDs exhibiting the lowest *WSPC* values were Montreal's CSDs Westmount (4811805) (1447.87 UPU/inh.job) and Montréal (2466023) (2483.63 UPU/inh.job), Toronto's CSD Toronto (3520005) (3633.65 UPU/inh.job), and Vancouver's CSD Vancouver (5915022) (1277.82 UPU/inh.job), Edmonton's CSD Legal (4811807) (16004.35 UPU/inh.job), Calgary's CSD Calgary, CY (4806016) (15018.53 UPU/inh.job), Ottawa-Gatineau-ON's CSD Ottawa, CV (3506008) (22348.83) (UPU/inh.job) (Figure 25).

a



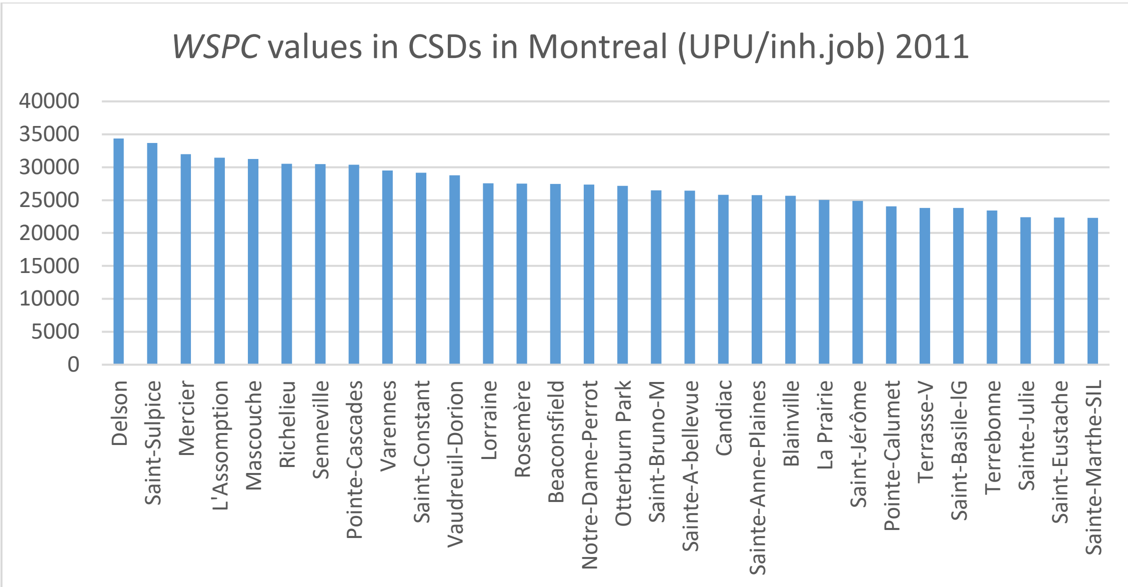
WSPC values in CSDs in Toronto (UPU/inh.job) 2011
160000
140000
120000
100000
80000
60000
40000
20000
0
Chippewas of GIFN
Mono
King
Uxbridge
East Gwillimbury
Caledon
Georgina
Whitchurch-Stouffville
Halton Hills
Bradford West Gwillimbury
Milton
New Tecumseth
Pickering
Aurora
Vaughan
Oakville
Orangeville
Richmond Hill
Ajax
Newmarket
Markham
Brampton
Mississauga
Toronto

b.1



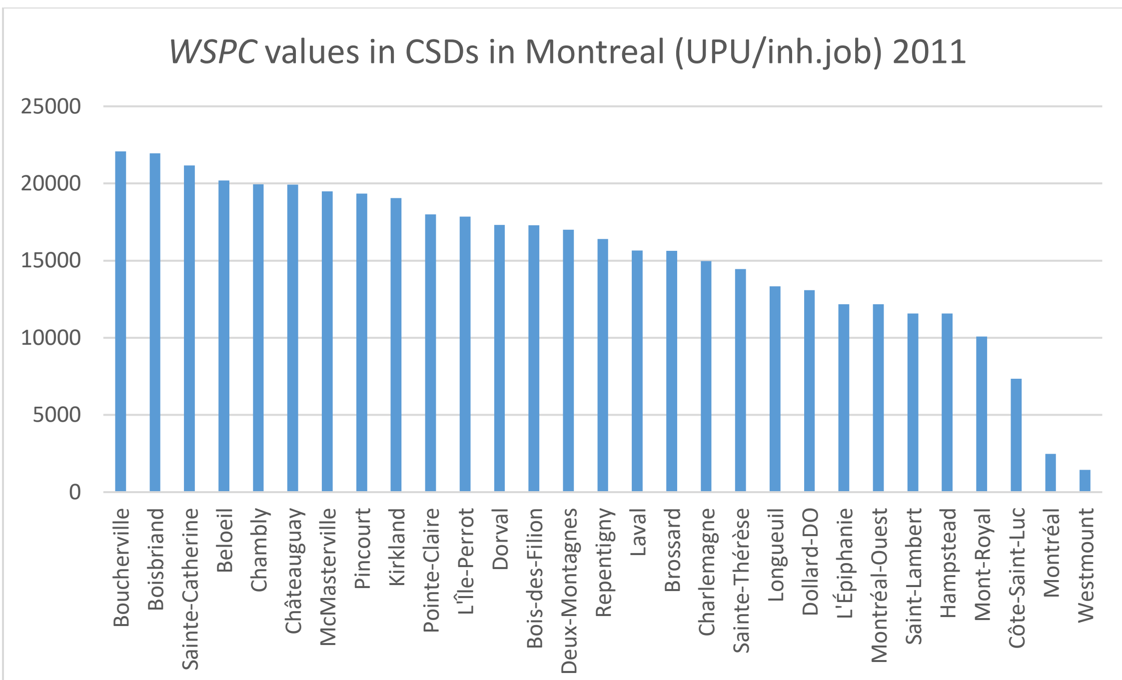
WSPC values in CSDs in Montreal (UPU/inh.job) 2011
300000
250000
200000
150000
100000
50000
0
L'Île-Dorval
Gore
L'Épiphanie
Montréal-Est
Saint-Mathieu
Hudson
Les Cèdres
Saint-Colomban
Saint-Mathieu-B
Saint-Lazare
Mirabel
Saint-Philippe
Carignan
Léry
Saint-Isidore
Coteau-du-Lac
Saint-Placide
Saint-Joseph-du-Lac
Baie-D'Urfé
Verchères
Vaudreuil-SIL
Saint-Mathias-R
Oka
Saint-Zotique
L'Île-Cadieux
Mont-Saint-Hilaire
Beauharnois
Lavaltrie
Les Coteaux
Saint-Amable

b.2



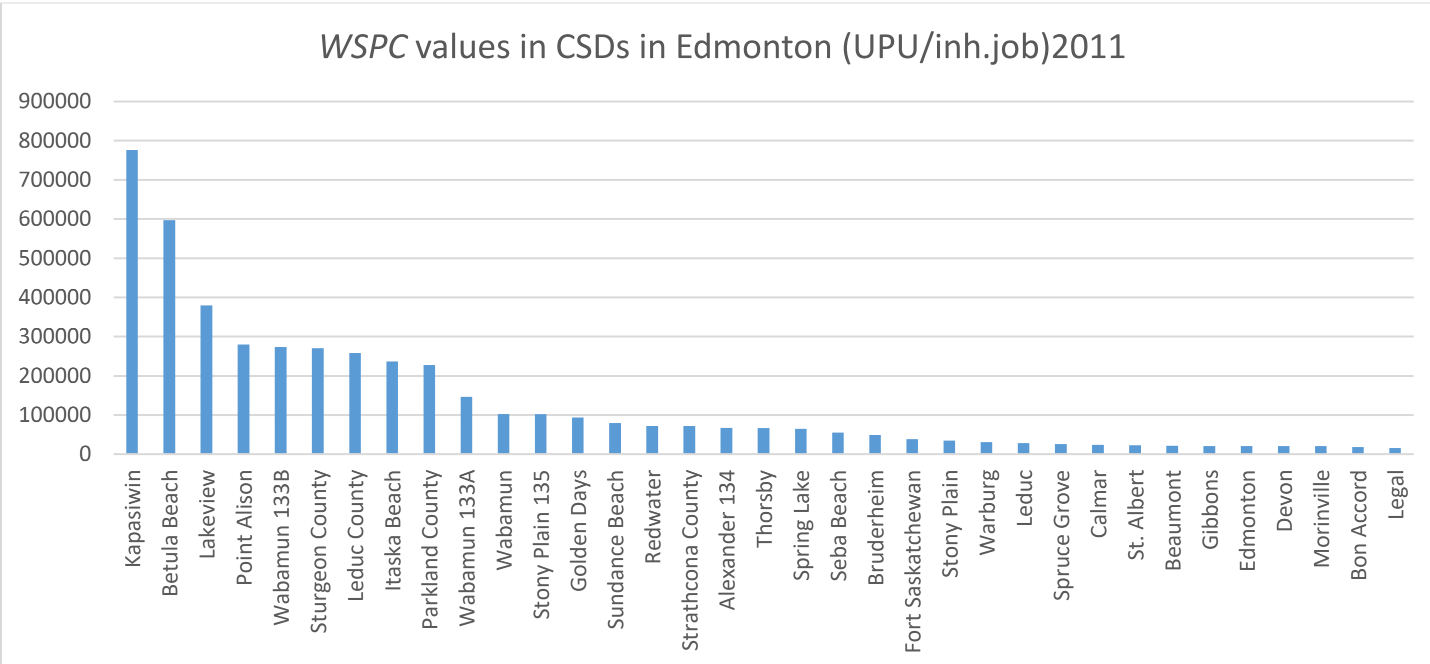
WSPC values in CSDs in Montreal (UPU/inh.job) 2011
40000
35000
30000
25000
20000
15000
10000
5000
0
Delson
Saint-Sulpice
Mercier
L'Assomption
Mascouche
Richelieu
Senneville
Pointe-Cascades
Varennes
Saint-Constant
Vaudreuil-Dorion
Lorraine
Rosemère
Beaconsfield
Notre-Dame-Perrot
Otterburn Park
Saint-Bruno-M
Sainte-A-bellevue
Candiac
Sainte-Anne-Plaines
Blainville
La Prairie
Saint-Jérôme
Pointe-Calumet
Terrasse-V
Saint-Basile-IG
Terrebonne
Sainte-Julie
Saint-Eustache
Sainte-Marthe-SIL

b.3

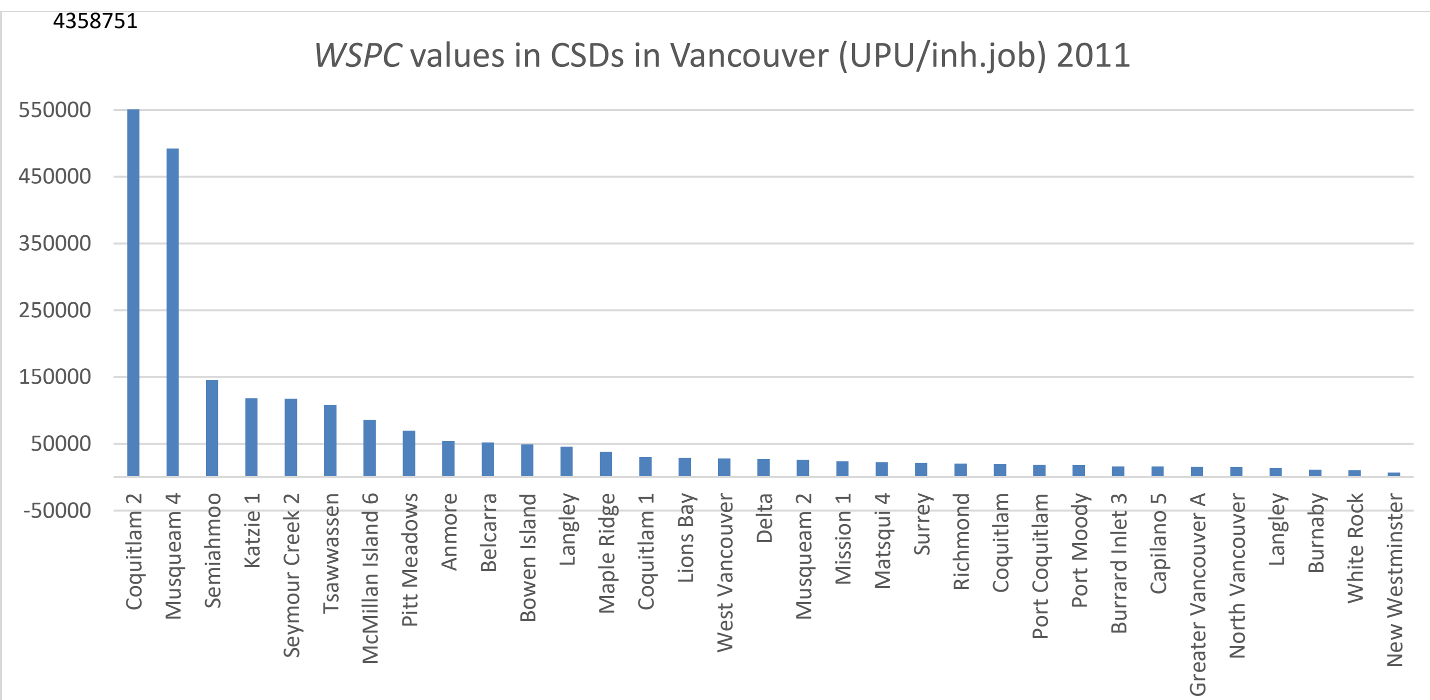


WSPC values in CSDs in Montreal (UPU/inh.job) 2011
25000
20000
15000
10000
5000
0
Boucherville
Boisbriand
Sainte-Catherine
Beloeil
Chambly
Châteauguay
McMasterville
Pincourt
Kirkland
Pointe-Claire
L'Île-Perrot
Dorval
Bois-des-Filion
Deux-Montagnes
Repentigny
Laval
Brossard
Charlemagne
Sainte-Thérèse
Longueuil
Dollard-DO
L'Épiphanie
Montréal-Ouest
Saint-Lambert
Hampstead
Mont-Royal
Côte-Saint-Luc
Montréal
Westmount

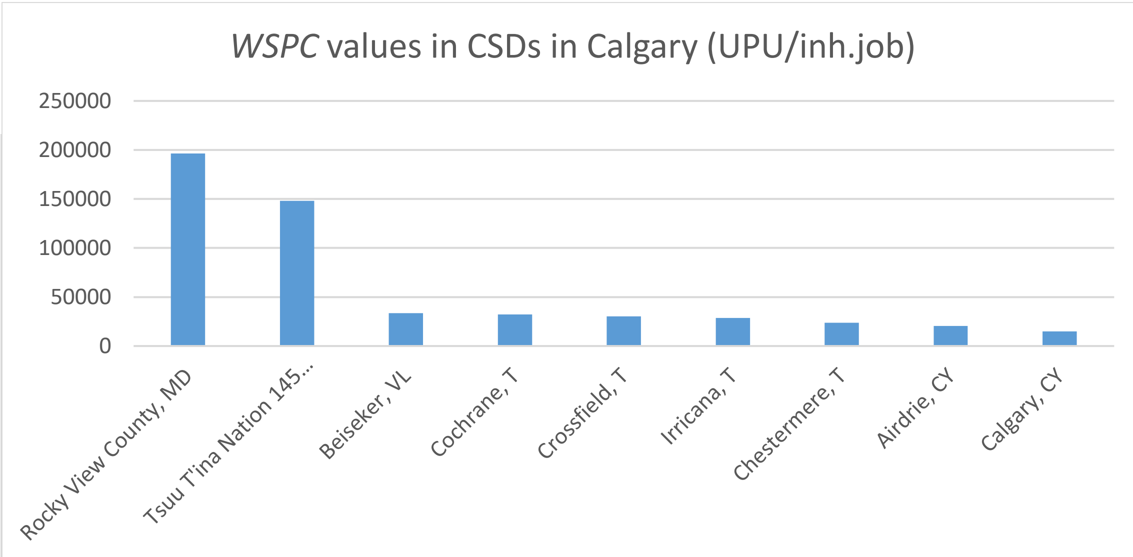
c


WSPC values in CSDs in Edmonton (UPU/inh.job)2011
900000
800000
700000
600000
500000
400000
300000
200000
100000
0
Kapasiwin
Betula Beach
Lakeview
Point Alison
Wabamun 133B
Sturgeon County
Leduc County
Itaska Beach
Parkland County
Wabamun 133A
Wabamun
Stony Plain 135
Golden Days
Sundance Beach
Redwater
Strathcona County
Alexander 134
Thorsby
Spring Lake
Seba Beach
Bruderheim
Fort Saskatchewan
Stony Plain
Warburg
Leduc
Spruce Grove
Calmar
St. Albert
Beaumont
Gibbons
Edmonton
Devon
Morinville
Bon Accord
Legal

d


4358751
WSPC values in CSDs in Vancouver (UPU/inh.job) 2011
550000
450000
350000
250000
150000
50000
-50000
Coquitlam 2
Musqueam 4
Semiahmoo
Katzie 1
Seymour Creek 2
Tsawwassen
McMillan Island 6
Pitt Meadows
Anmore
Belcarra
Bowen Island
Langley
Maple Ridge
Coquitlam 1
Lions Bay
West Vancouver
Delta
Musqueam 2
Mission 1
Matsqui 4
Surrey
Richmond
Coquitlam
Port Coquitlam
Port Moody
Burrard Inlet 3
Capilano 5
Greater Vancouver A
North Vancouver
Langley
Burnaby
White Rock
New Westminster

e



f

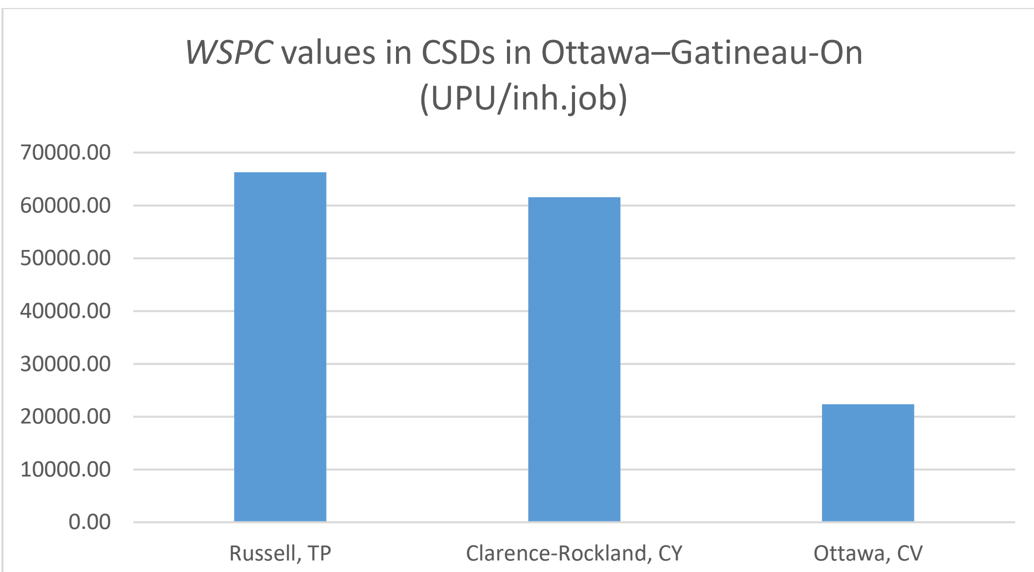


Figure 25. *WSPC* values at the census subdivision level in 2011 in the Toronto CMA (a), in the Montreal CMA (b1,b2, and b3) in the Edmonton CMA (c), in the Vancouver CMA (d), in the Calgary CMA (e), in the Ottawa-Gatineau-On CMA (f), ordered from largest to smallest. (GIFN= Georgina Island First Nation)

3.3.4.3. Historic development

Values of *WUP* between 1991 and 2011

All CSDs in Toronto showed a continuous increase in urban sprawl in the 1991-2011 period except for CSD Toronto, C (3520005) which experienced a decrease by 13.87 UPU/m^2. CSD Toronto, C (3520005) is defined as a separate CDS in 2011 and 2001, but in 1991, it was the combination of several other CSDs: Etobicoke, C (3520019), North York, C (3520008), York, C (3520014), Toronto, C (3520004), East York, BOR (3520006). CSD Toronto, C (352005) is located in the downtown core of Toronto's CMA. This could be a possible reason for the decrease in sprawl within the area; the population has increased in the down-town area, as well as the percentage of built-up areas with high density (which leads to a decrease in the degree of dispersion) from 1991 to 2011 (Figure 26.a).

In Montreal, the values of *WUP* increased in most of the CSDs from 1991 to 2011. Surprisingly, the CSD Montréal, V (2466023) (which covers a considerable part of the island of Montreal) experienced an increase of urban sprawl between 1991 and 2001, and a decrease between 2001 and 2011. The sizes of some of the CSDs like 2466023 are large, and there was not enough information to distinguish the degree of urban sprawl for different parts of these large CSDs (Figure 26.b).

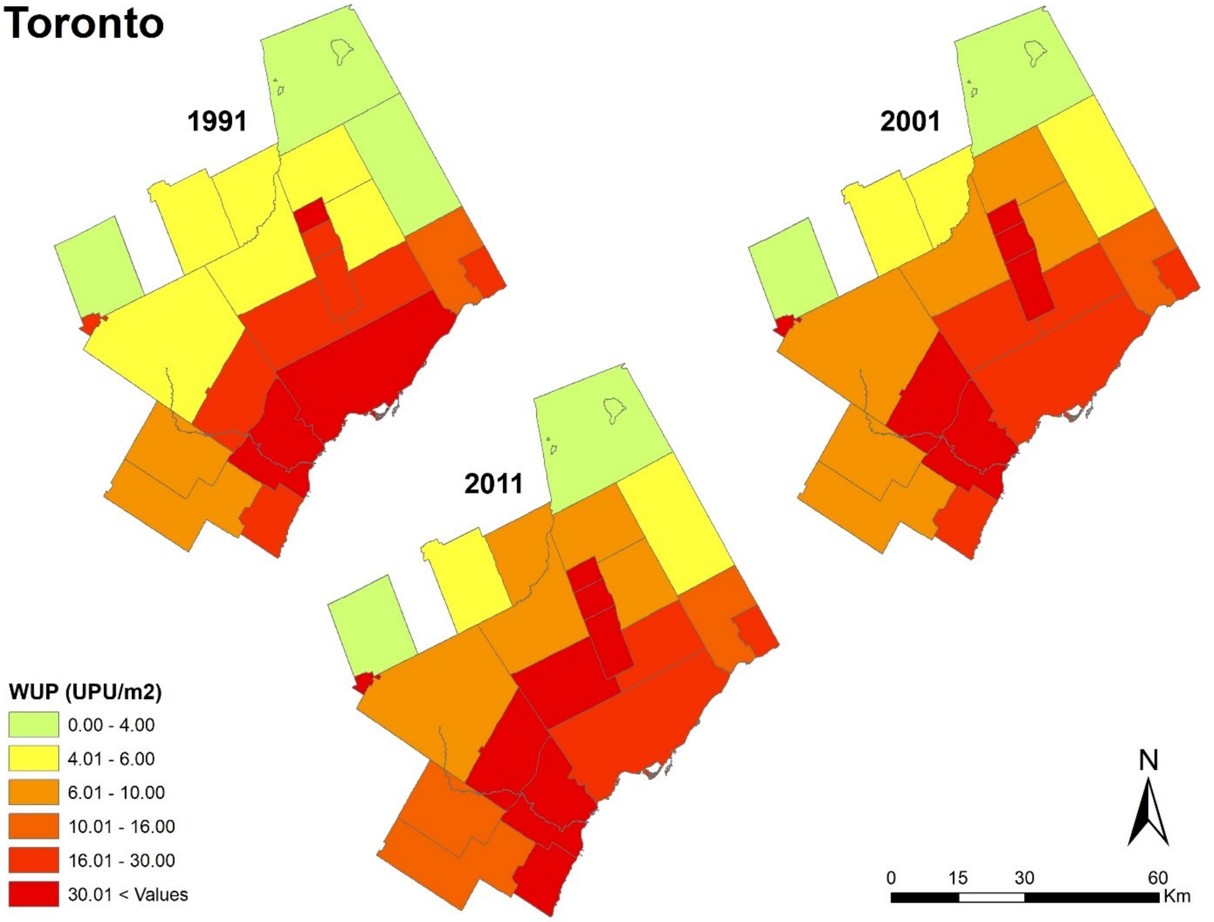
The values of *WUP* increased in all of the CSDs in Edmonton from 1991 to 2011, except in CSD Alexander 134, IRI (4811805) (from 1.10 to 1.09 UPU/m^2). Moreover, CSD Lakeview (4811042) experienced the highest increase in *WUP* (+15.50 UPU/m^2), a trend followed by CSD Beaumont, T (4811013) (+12.40 UPU/m^2), and Betula Beach (4811039) (+8.34 UPU/m^2) between 1991 and 2011 (Figure 26.c).

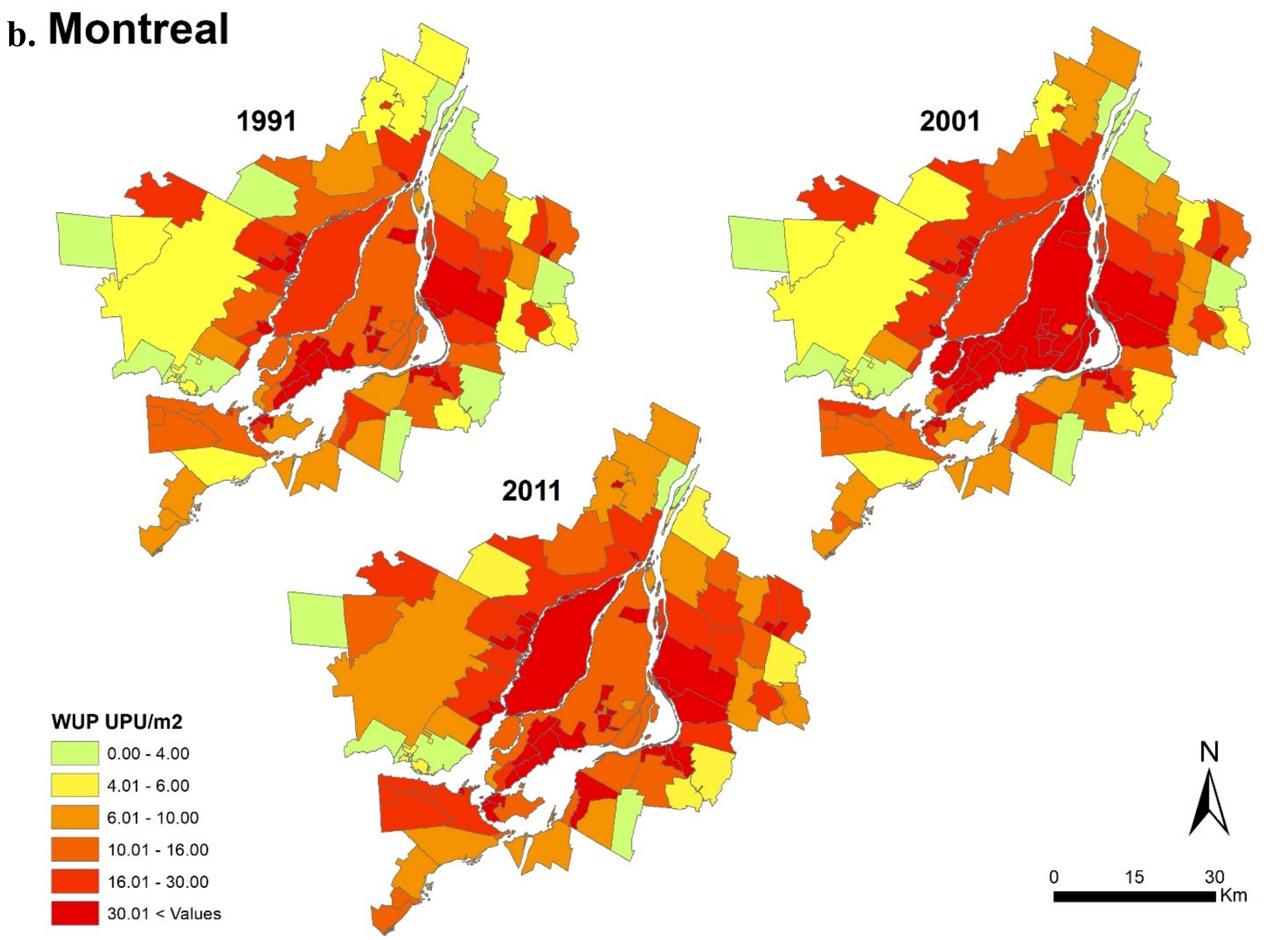
In Vancouver, the values of *WUP* decreased in some CSDs between 1991 and 2011. The highest decreases in *WUP* were observed in CSD Vancouver (5915022) (-9.75 UPU/m^2), followed by CSD North Vancouver (5915051) (-9.64 UPU/m^2) and CSD Mission 1 (5915807) (-2.10 UPU/m^2) (Figure 26.d).

Urban sprawl increased in all CSDs of Calgary in the 1991-2001 period. The highest increases in *WUP* were observed in CSD Airdrie, CY (4806021) (+9.72 UPU/m^2) and CSD Cochrane, T (4806019) (+6.89 UPU/m^2). The CSDs experiencing the lowest increases in *WUP* were CSD Rocky View County, MD (4806014) (+0.23 UPU/m^2) and CSD Tsuu T'ina Nation 145 (Sarcee 145), IRI (4806804) (+0.39 UPU/m^2) (Figure. 26.e).

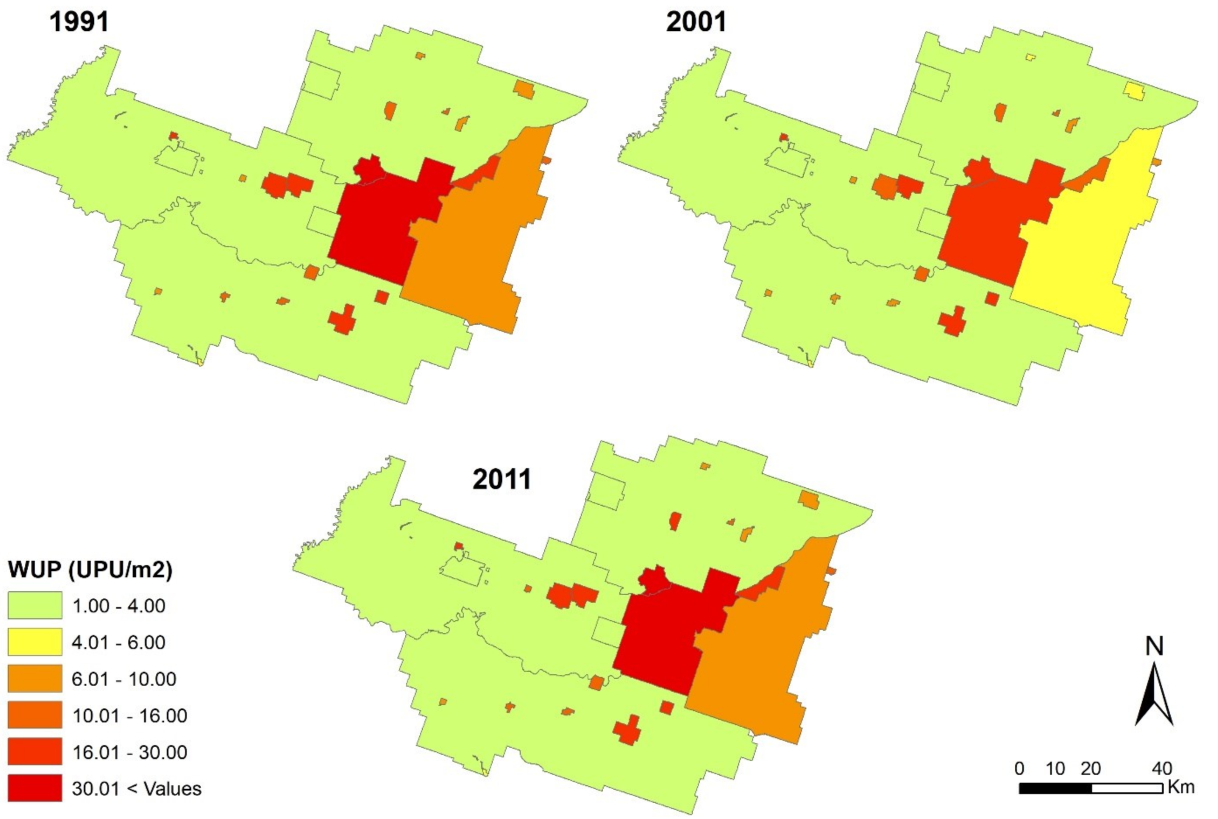
In Ottawa-Gatineau-ON, the value of *WUP* increased in all of the CSDs from 1991 to 2001. CSD Ottawa, CV (3506008) experienced the highest increase (+1.01 UPU/m^2), followed by CSD Clarence-Rockland, CY (3502036) (+0.64 UPU/m^2), and CSD Russell, TP (3502048) (+0.47 UPU/m^2) (Figure 26.f).

a. **Toronto**


1991
2001
2011
WUP (UPU/m2)
0.00 - 4.00
4.01 - 6.00
6.01 - 10.00
10.01 - 16.00
16.01 - 30.00
30.01 < Values
N
0 15 30 60
Km

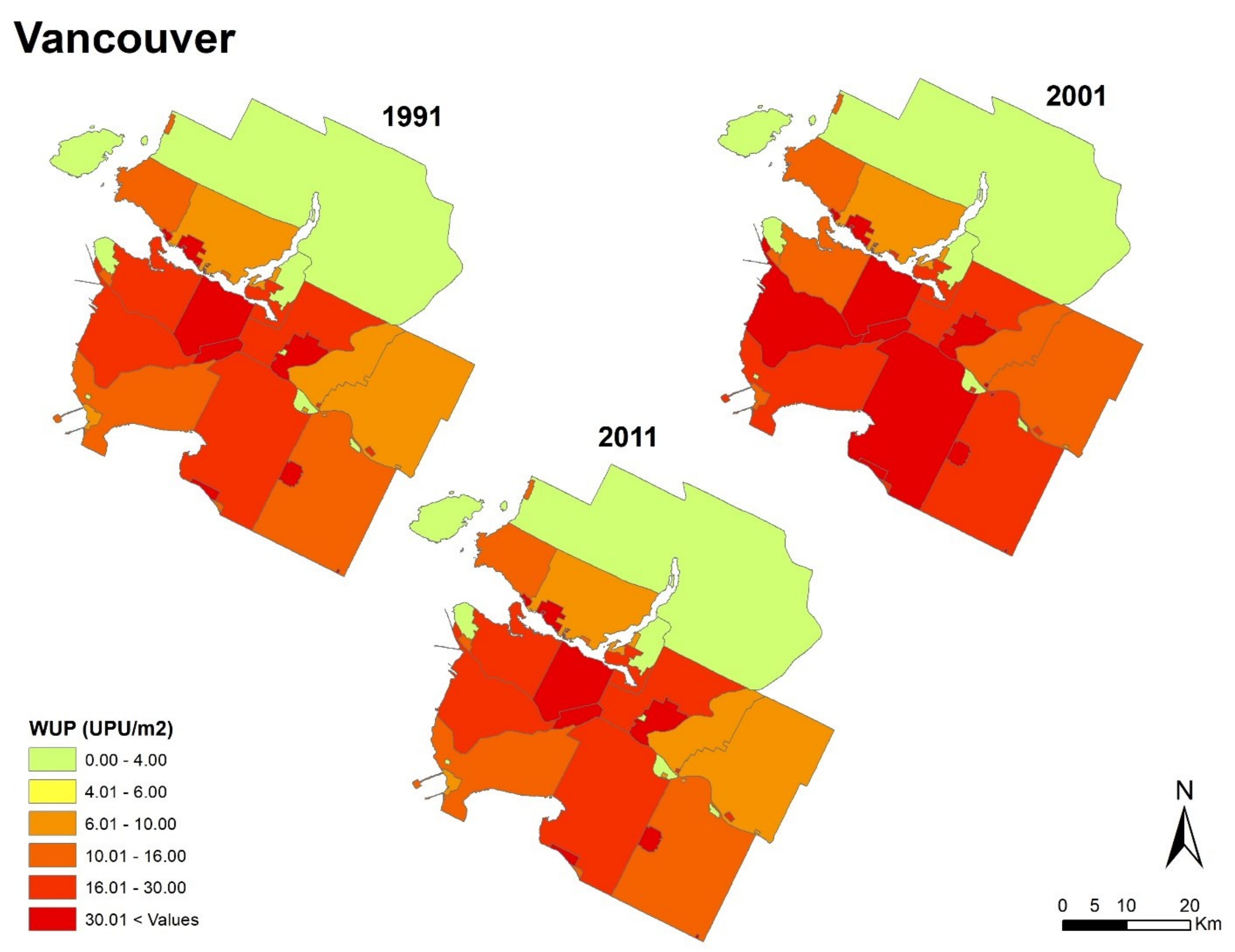

b. Montreal
1991
2001
2011
WUP UPU/m2
0.00 - 4.00
4.01 - 6.00
6.01 - 10.00
10.01 - 16.00
16.01 - 30.00
30.01 < Values
N
0
15
30
Km

c. Edmonton



1991
2001
2011
WUP (UPU/m2)
1.00 - 4.00
4.01 - 6.00
6.01 - 10.00
10.01 - 16.00
16.01 - 30.00
30.01 < Values
N
0 10 20 40
Km

d.


Vancouver
1991
2001
2011
WUP (UPU/m2)
0.00 - 4.00
4.01 - 6.00
6.01 - 10.00
10.01 - 16.00
16.01 - 30.00
30.01 < Values
N
0 5 10 20
Km

e. Calgary

1991
2001
2011
WUP (UPU/m2)
0.00 - 4.00
4.01 - 6.00
6.01 - 10.00
10.01 - 16.00
16.01 - 30.00
30.01 < Values
N
0 10 20 40
Km

f. Ottawa-Gatineau-ON

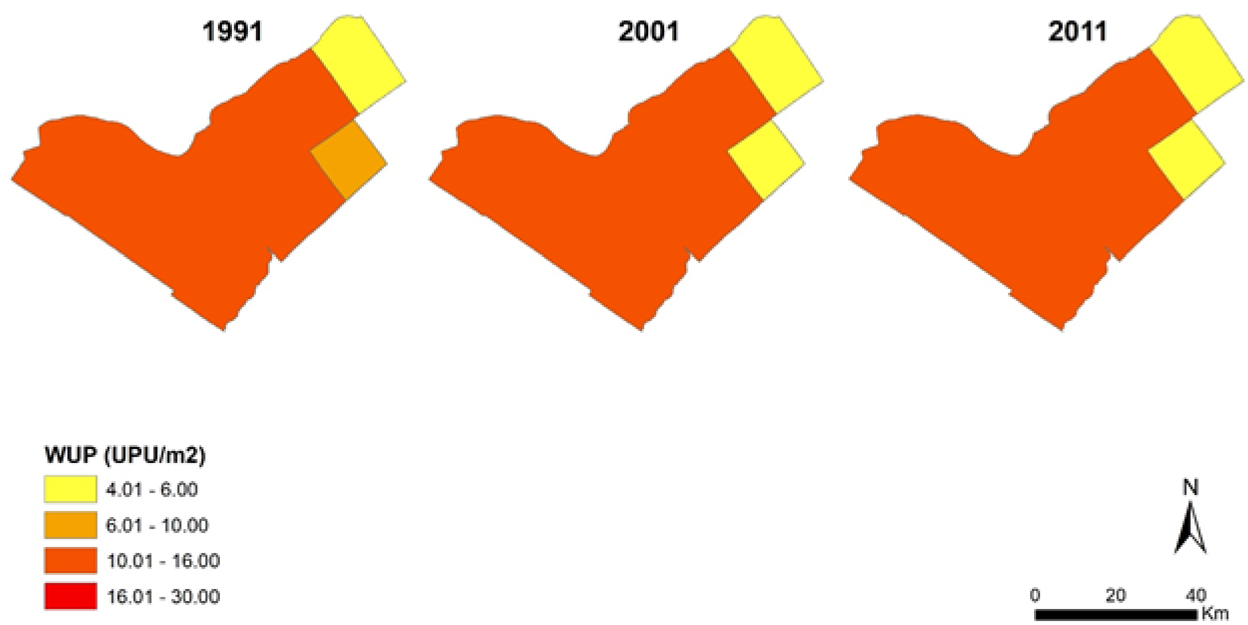


Figure 26. Urban sprawl (*WUP*) at the census subdivision level in 1991-2011 in the Toronto CMA (a), in the Montreal CMA (b), in the Edmonton CMA (c), in the Vancouver CMA (d), in the Calgary CMA (e), and in the Ottawa-Gatineau-ON CMA in (f).

Values of *WSPC* between 1991 and 2011

All CSDs showed a decrease in *WSPC* in Toronto in the 1991-2011 period except for CSD King (3519049), CSD East Gwillimbury (3519054), and CSD Halton Hills (3524015), which experienced an increase by 21738.36 UPU/inh.job, 9763.24 UPU/inh.job, and 1142.77 UPU/inh.job, respectively.

In Montreal, the value of *WSPC* decreased in most of the CSDs between 1991 and 2011. The strongest decreases were observed in CSD Gore (2476025) (-2637388.55 UPU/inh.job), CSD Saint-Placide (2472043) (-2300532.23 UPU/inh.job), CSD Saint-Jérôme, V (2475017) (-197103.87 UPU/inh.job), and CSD Sainte-Anne-des-Plaines (2473035) (-52313.09 UPU/inh.job). Some of the CSDs that experienced a noticeable increase between 1991 and 2011 in Montreal were CSD Saint-Colomban (2475005) (increase by 52699.23 UPU/inh.job), CSD Saint-Lazare (2471105) (+41091.27 UPU/inh.job), CSD Les Cèdres, MÉ (2471050) (+37940.21 UPU/inh.job), and Montréal-Est, V (2466005) (+25149.68 UPU/inh.job).

The values of *WSPC* increased in some of the CSDs in Edmonton from 1991 to 2011. CSD Betula Beach (4811039) experienced the highest increase in *WSPC* (+419629.53 UPU/inh.job), a trend followed by CSD Point Alison (4811041) (+241546.86 UPU/inh.job), and Itaska Beach (4811022) (+127519.08 UPU/inh.job).

In Vancouver, the values of *WSPC* increased in some CSDs between 1991 and 2011. The highest increases in *WSPC* were observed in CSD Coquitlam 2 (5915804) (+4225571.13 UPU/inh.job), followed by CSD Semiahmoo (5915801) (+64212.99 UPU/inh.job), CSD Tsawwassen (5915802) (+54427.81 UPU/inh.job), CSD Bowen Island (5915062) (+27785.87 UPU/inh.job), CSD Coquitlam 1 (5915805) (+11568.78 UPU/inh.job), and, CSD Matsqui 4 (5915825) (+649.54 UPU/inh.job).

The values of *WSPC* decreased in all CSDs of Calgary in the 1991-2011 period except in CSD Beiseker (4806024) which experienced an increase by 1379.56 (UPU/inh.job).

In Ottawa-Gatineau-ON, the value of *WSPC* decreased in all of the CSDs from 1991 to 2011. CSD Clarence-Rockland, CY (3502036) experienced the strongest decrease (-19327.37

UPU/inh.job), followed by CSD Russell (3502048) (-16461.52 UPU/inh.job), and CSD Ottawa, CV (3506008) (-3197.50 UPU/inh.job).

3.4. Discussion

3.4.1. Level of urban sprawl in 2011

All Canadian CMAs experienced urban sprawl in 2011. The highest degrees of urban sprawl were observed in the large CMAs such as Montreal, Vancouver, and Toronto. The high degree of urban sprawl in Montreal as the most sprawled CMA in 2011, is due to the high values of *PBA* and *DIS*. However, Montreal was ranked 2nd to last for the value of *LUP*. Toronto also is affected by high values of the same components. This CMA experienced the highest dispersion among all of the CMAs and ranked 2nd for the value of *PBA* in 2011. The high values of *DIS* and *PBA* in Toronto caused the high value for *WUP* in this CMA (the 5th most sprawled CMA in 2011).

Although population growth is a major driver of urban expansion (EEA and FOEN, 2016), urban sprawl and *PBA* have continued to increase in the CMAs where a population decline was observed (e.g., Greater-Sudbury, Saguenay, and Thunder Bay). The lack of efficient planning was a major reason for the high degree of urban sprawl and *PBA* in these CMAs.

According to the study by Nazarnia et al. (2016), in 2011, the value of *WUP* in the Montreal CMA was 12.6 UPU/m^2; this was because Montreal had a large proportion of built-up area (26.5%) and a high value for *DIS* (47.82 UPU/m^2). Nazarnia et al.'s (2016) values for *WUP* and its components were lower than ours. This discrepancy is due to our use of different datasets and built-up areas shapefiles. The amount of the built-up area in the shapefiles that we used for this study were considerably higher due to the different definitions of built-up areas in each dataset. In Nazarnia et al. (2016) study, all the buildings and structures that were manmade, also the small roads and alleys that were located between settlement areas were included as a part of built-up areas. However, highways and infrastructure that join urban areas within the landscape were not considered in the built-up areas' shapefiles. In contrast, in the present study, all the roads (inside and outside) of the cities were considered in the built-up areas' layers. Also, the numbers of jobs were slightly different. Nazarnia et al. (2016) noted a value of 4.98 UPU/m^2 for the *WUP* of the Quebec CMA, which is substantially lower than what we found in this study (7.16 UPU/m^2).

The highest values of total sprawl were observed in the largest CMAs of Canada (Toronto, Montreal, Edmonton, Vancouver, Calgary, and Ottawa-Gatineau-ON). In smaller CMAs (e.g., Guelph, Abbotsford mission, Trois-Rivières, Barrie, Branford), the value of total sprawl varied between 4000 and 10000 MUPU. The results show that largest CMAs experienced a higher dispersion than the smaller CMAs.

To our knowledge, our study is the first to present *WUP* and *WSPC* values across Canada. Many of the large CMAs (Toronto, Montreal, Vancouver and Calgary) had relatively low *WSPC* values, because of their high densities. In contrast, smaller CMAs (Saint John, Thunder Bay, Greater Sudbury, and Peterborough) experienced comparably higher values of *WSPC* mostly due to their higher *LUP* values.

For some CMAs (e.g., Toronto, Montreal, and Vancouver), the CSDs with the highest densities were located in the downtown areas, and their lower *LUP* values resulted in lower values for *WUP*.

The sizes of CSDs in CMAs vary strongly. In some CMAs (e.g., Montreal and Vancouver), the highest *WSPC* values were observed in small CSDs with high values of *LUP* (such as Coquitlam 2 in Vancouver and L'Île-Dorval in Montreal). This can be explained by the very low numbers of inhabitant and jobs in these CSDs.

3.4.2. Historic development

For most of the CMAs, the sharpest increases in *WUP* were observed between 1991 and 2001, followed by a less pronounced increase between 2001 and 2011 (e.g., Abbotsford - Mission, Barrie, Brantford, Hamilton, Kitchener–Cambridge–Waterloo, Oshawa, St. Catharines–Niagara, St. John's, Vancouver, and Victoria).

In the 1991-2001 period, the Vancouver CMA experienced an increase in *WUP* by 3.04 UPU/m^2, with this trend slowing down between 2001 and 2011 (only +0.21 UPU/m^2). The observed reduction in the increase of *WUP* in Vancouver could potentially be explained by Vancouver's policy of encouraging high-density development, complete neighborhoods (i.e., with requisite community centers, schools, and parks), and protection of green space, which was codified in 1993's binding CityPlan (Fox, 2010).

According to Nazarnia et al. (2016), the degree of urban sprawl in Montreal increased by 5.8 UPU/m^2 (from 6.8 to 12.60 UPU/m^2) between 1996 and 2011. In contrast, in the current study, the degree of urban sprawl increased by 3.69 UPU/m^2 (from 14.55 to 18.24 UPU/m^2) between 1991 and 2011. The differences in the results are due to the different values of the components *PBA*, *DIS*, and *LUP*. According to Nazarnia et al. (2016), the values of *PBA* increased by 8.7 percentage points (from 17.8% to 26.5%), i.e., an increase by 49%, *DIS* increased by 1.50 UPU/m^2 (from 47.32 to 48.82 UPU/m^2), and *LUP* increased by 49.57 m^2/(inh. or job) (from 167.96 to 217.53 m^2/(inh. or job)) in the 1996-2011 period. In comparison, in the current study, the values of *PBA* increased by 6.27 percentage points (from 27.74% to 34.01%), i.e., by only 22.6%, *DIS* increased by 0.17 UPU/m^2 (from 48.07 to 48.24 UPU/m^2), and accordingly, *LUP* increased by only 10.49 (m^2/inh.or job) (from 261.77 to 272.26 m^2/(inh.or job)) between 1991 and 2011.

In this study, we observed a somewhat linear growth in *WUP* between 1991 and 2011. The increase in *WUP* was slightly slower (+1.79 UPU/m^2) in the second ten years (2001-2011) compared to the first ten years (1991-2001) (+1.90 UPU/m^2). Whereas, in Nazarnia et al. (2016) study, the trend in urban sprawl accelerated between 1986 and 2011.

In the Quebec CMA, the increase of *WUP* was slightly slower in the first decade (1991-2001) (+0.82 UPU/m^2) than the second decade (2001-2011) (by an increase of 1.03 UPU/m^2). However, according to Nazarnia et al. (2016) the degree of *WUP* increased by 2.60 UPU/m^2 between 1996 and 2011, which indicates a faster increase compared to the 1986-1996 decade (with an increase of 0.19 UPU/m^2).

According to Fox (2010), from 1968 to 1972, a strong regional government for Greater Vancouver was developed, titled the Livable Region Strategic Plan of 1972 (1972 LRSP). The 1972 LRSP had four main components, which lasted to guide the development of the 1999 Livable Region Strategic Plan (1999 LRSP). The first component involved a commitment to prioritizing mass transit over freeways. As a result, a dual-line light-rail system, called SkyTrain, was developed in 1985. In 2007, the SkyTrain averaged 220,000 riders per day, which reduced traffic congestion and fuel consumption. Translink, as a cooperation of the provincial government and the Greater Vancouver Regional District, was created in 1996 to organize regional transportation policy. Translink supplied extensive bus and ferry services which serviced Greater Vancouver.

The second component of the LRSP was that Greater Vancouver was to become a compact region. In 2000, 70% of development growth happened in the Growth Concentration Area, while most of the remaining 30% of growth occurred in selected town centers, which will eventually be connected to the core via transit.

The third policy direction of the 1972 LRSP was to promote complete communities, by distributing the network of downtowns across the region and giving the residents access to services and facilities within their town. These strategies helped reduce travel time and encourage the residents to improve their communities. The outcome was that 75% of all the houses under construction were multi-family developments by 2000. In 1991, that figure was only 25%.

The fourth policy direction of the 1972 LRSP was to protect the Green Zone. The Green Zone is defined as "the limit of urban expansion, and encourages a shared responsibility among the municipalities of the region to protect lands within it" (Fox, 2010, p. 53).
The Livable Region Strategic Plan explains why the increase of urban sprawl in Vancouver slowed down. Although these strategies were helpful to slow down the increase of urban sprawl, much stronger efforts are needed to discontinue sprawl growth pattern in Vancouver.

I had hypothesized that urban sprawl increased faster than the population and faster than the built-up areas in all parts of Canada between 1991 and 2011. However, in some CMAs, e.g., Toronto, Vancouver, Edmonton, and Calgary, urban sprawl increased more slowly than the population. The lower increase in Calgary can be explained by many policies that relate to transportation choices, transit use, quality of life, and the urban fabric in general. According to Land Use Planning & Policy of Calgary (2005), these policies were the following: "Calgary Plan (1998), the Calgary Transportation Plan (1995), and the Sustainable Suburbs Study (1995) contain important city-wide policy directions to encourage transit use, make optimal use of transit infrastructure, and improve the quality of the environment in communities" (Land Use Planning & Policy, 2005, p. 3). In the late 1990s, the policies in Calgary focused on the livability and sustainability of urban areas by promoting urban intensification and greater transit use (Taylor et al. 2014). According to Taylor et al. (2014), the density of Calgary's built-up areas has increased in the first decade of the 21st century. Moreover, by high-density suburban growth, less land was consumed compared with the previous decade. The development in Edmonton was slightly similar and the denser suburban growth promoted a somewhat more efficient consumption of rural land. The built-up area in Edmonton has also intensified to some degree, particularly in zones close to transit stations (Taylor et al. 2014). However, in Edmonton we observed a slower increase in population (38 %) than in Calgary (61%), but also a stronger increase in urban sprawl (22 % compared to 19%) between 1991 and 2011.

In the Toronto CMA, although the population has increased by 43% (1991-2011), urban sprawl has increased less fast by 25%. This can be explained by a "smart growth" paradigm that had appeared within the American planning profession in the 1990s (Hess & Sorensen 2015). This model had also become strongly adopted by Ontario's planning community, through the previous Progressive Conservative (PC) government's establishment of a Smart Growth Secretariat in 2001. In 2002, the province of Ontario introduced several policies with the aim of increasing densities including the creation of a new greenbelt (720,000 hectares) to protect lands especially in agricultural use where urbanization will not be permitted. The creation of Metrolinx as a new provincial agency for building and operating public transit in Toronto is another piece of anti-sprawl evidence for the political impact (Hess & Sorensen 2015).

Between all of the large CMAs in Canada, Montreal was the only CMA in which urban sprawl increased faster than the population between 1991 and 2011. According to Dupras et al. (2016), the policies applied by regional and provincial governments in Montreal to protect agricultural land have not been successful. Moreover since the 1990s, "urban pressure on agricultural land heightened, resulting in a new period of agricultural abandonment and speculation" (p. 62). This shows that there has been a lack of effective measures against urban sprawl in Montreal.

3.4.3. Strengths and weaknesses of the *WUP-WSPC* method

Weighted Urban Proliferation and Weighted Sprawl per Capita are useful in several ways:

- Their application in environmental monitoring, sustainability monitoring, landscape-quality monitoring, and biodiversity monitoring systems shows that it clearly contributes to the discussion of the issue of sprawl and its development.
- The *WUP* and *WSPC* metrics provide valuable assistance in addressing the need to limit and densify new and existing built-up areas. For instance, the density, location, and dispersion of new urban areas can be analyzed so as to control sprawl.
- The method meets all 13 suitability criteria for measuring urban sprawl, outlined by Jaeger et al. (2010a).
- These metrics have modest data requirements in order to analyze urban sprawl. The required data are solely the numbers of inhabitants and work places, together with the maps of built-up areas and reporting units.

- *WUP* and *WSPC* can be used at any scale and for a variety of reporting units (e.g., census metropolitan areas, census divisions, census subdivisions, census tracts, districts, municipalities).
- These metrics are particularly useful for a quantitative assessment of urban sprawl and for comparing potential future developments.

We used the number of full-time equivalents in our calculation of *LUP*, but these numbers may not always be available. Data about inhabitants and jobs may be more difficult to acquire for smaller reporting units. Nonetheless, even when the data for the number of jobs are unavailable, the *WUP* and *WSPC* metrics can still be used because the major contributions to sprawl come from residential areas, where there are barely any jobs. Alternatively, the total number of jobs could be used as a good proxy when FTEs are not available as cannot be calculated.

Reporting units' boundaries may change over time and this issue prevents a direct comparison of results from using different reporting units between different years. For example in this study, the boundaries of some reporting units were changed between 1991 and 2011, hence, we continued using the shapefiles of 2011 reporting units for 1991, 2001, and 2011 to compare the results and observe the changes in urban sprawl.

3.4.4. Limitations

The main limitation of the current study was posed by the changes in the boundaries of the census subdivisions over time. The layers of the CSDs for 2001 and 1991 were used to compare the changes of the boundaries between1991 and 2011 to address this issue, as mentioned above.

According to EEA and FOEN (2016), railways and roads outside of cities and towns are not included in the definition of built-up areas since they are not considered as a part of urban sprawl. Hence, to apply the *WUP* method, the railways and roads outside of cities should be excluded from the layers of built-up areas. However, the built-up area data that we used in this study include all the roads (inside and outside) of the cities. This choice was particularly made for reasons of feasibility of analysis. Because in the built-up area data layer, road information was recorded in a single field, it would have been challenging to identify, and tease apart, all the roads, in each of the CMAs and for each year. So all the roads remained as parts of the built-up area's shapefiles.

Measuring urban sprawl at different points in time is helpful to observe how urban sprawl occurred and accelerated in the past. The data for 1971 from Statistics Canada are available and can be used for a potential future study to measure urban sprawl and compare it with the results of this study.

3.5. Conclusion and Recommendations

In Canada, as in many other regions in North America, the built-up areas within CMAs are growing rapidly. Many of the CMAs in this country are affected by urban sprawl which generally leads to various impacts on the landscapes. This body of work contains a systematic analysis of the temporal dynamics of urban sprawl across all Canadian CMAs from 1991 to 2011, clearly identifying a steady increase in urban sprawl (*WUP*) within all CMAs, with *WSPC* increasing in more than half of the CMAs as well.

Providing extensive cross-regional comparisons, the results of this work are particularly relevant to (1) urban, regional, and land-use planning, and (2) the planning of various infrastructures like transportation. Additionally, our work can be leveraged to identify effective strategies for reducing urban sprawl, or to substantially reduce its adverse effects in Canada.

Particularly, establishing concrete quantitative targets, limits, and benchmarks would be an effective way to control urban sprawl (EEA & FOEN, 2016). For example, anti-sprawl policies can be applied to protect un-sprawled areas and sprawl-sensitive areas. Another solution would be limiting the extent of the built-up areas by using greenbelts (EEA & FOEN, 2016). High-quality densification of existing built-up areas should be practiced. The dispersion of built-up areas must be also controlled, and stronger protection of agricultural lands should be applied. It is also important to educate the public about the negative impacts of urban sprawl to first, encourage consumers to reduce land-up take per inhabitant, and second, help decrease the degree of urban sprawl by considering to increase the numbers of inhabitants and jobs in the built-up areas that already exist.

As sprawl is a major threat to sustainable land use in Canada, there is much need to identify effective solutions permitting the alleviation its negative impacts. Further research is needed to measure and analyze urban sprawl in recent times. Also, estimating the rates of change in the future by providing different scenarios of development and urban growth would be useful to control sprawl patterns. The work presented here contributes to this line of research by deepening the understanding of the temporal evolution of urban sprawl across all Canadian CMAs, and helps develop effective measures to reduce its adverse effects. Qualitative methods may extend the present quantitative work.

One example would be through an analysis of policies in one or more case study regions to understand which policies can be effective at reducing urban sprawl and which policies are not productive enough. The study of policies could also helpful to understand why some policies are effective and some of them are not, since these questions in particular can be difficult to answer adequately through a quantitative analysis.

COVID-19 is likely to change the morphology of many cities around the world (Acuto, 2020). The crisis in question underlines how urban planners and decision makers should manage urban life during a pandemic. Some surveys indicate that people prefer to live in the less dense areas due to social distancing. For example, a new poll by Léger (2020) conducted for realtor RE/MAX Québec illustrates that among 1400 Quebecers, 58% of respondents would contemplate to look for a larger property, and 55% for a larger home. Also, some 46% said they were considering the pros and cons of moving to the suburbs, and 21% were set on the country versus 28% who want to relocate in the city. This poll was provided in early March 2020, when lockdown measures were first put in place. Future research about the different impacts of COVID-19 on the cities and on urban sprawl in particular would be necessary to discover how sprawl in urban areas will look like in a post-coronavirus world.

4. Overall Conclusion

This study addressed the importance of monitoring and controlling urban sprawl over time. Discovering different drivers and consequences of urban sprawl in each region is also useful to find the most suitable solutions and to prevent a continuation of this pattern of growth.

Therefore, further research is needed to arrive at a better agreement on how to monitor and control urban sprawl and replace it by sustainable development, e.g., smart growth. It is noteworthy that the phenomenon of sprawl itself is distinct from its causes and consequences. Thus, measures of sprawl that only consider the effects of sprawl are not suitable for expressing the degree of urban sprawl.

In chapter 3 of this thesis, the method of Weighted Urban Proliferation (*WUP*) and Weighted Sprawl per Capita (*WSPC*) (Schwick et al. 2012 and Jaeger et al. 2010b) was used to measure the level of urban sprawl in all metropolitan areas of Canada. The vector data of the CMAs built-up areas converted to the raster data using Geographic Information System (15 m cells) for 3 points in time going back to 1991. The results of the quantification of urban sprawl were presented at two scales: census subdivisions and census metropolitan areas. This study, for the first time, presents a quantitative assessment of *WUP* and *WSPC* across all metropolitan areas of Canada and compares the results to distinguish which CMAs experienced the most and the least sprawl and rates of increase in sprawl.

It is important for the measurement of urban sprawl to be efficient and reliable. For example, the method of Weighted Urban Proliferation (Schwick et al. 2012) meets all of the fundamental suitability criteria for the measurement of urban sprawl. However, some other methods, e.g., entropy that many researchers have used over the past two decades, do not meet the fundamental suitability criteria for the measurement of urban sprawl (Nazarnia et al. 2019).

At the CMA level, Montreal exhibited the highest level of urban sprawl, followed by Vitoria and Kitchener–Cambridge–Waterloo in 2011. The largest metropolitan areas showed a higher level of percentage of built-up areas, with Montreal CMA and Toronto CMA ranking 1st and 2nd. The strikingly high value of sprawl in Montreal is mainly due to the high percentage of built-up areas and the high level of dispersion of built-up areas in this CMA. In Toronto, Vancouver, Edmonton, and Ottawa-Gatineau-ON, the highest increases in urban sprawl happened between 1991 and 2001. In contrast, in the Montreal CMA, the increase in urban sprawl did not decrease between 2001 and 2011 compared to 1991 and 2001. This continuous increase in urban sprawl in Montreal shows the lack of effective and sustainable planning in Montreal.

The different trends of increasing urban sprawl in the past among the CMAs are a result of the different planning strategies and policies that were applied in each region. By analyzing these differences and identifying the strategies that were effective, policymakers can learn some lessons to improve the pattern of development in all Canadian cities. Other factors that may also influence urban sprawl include differences in type and location of jobs, gasoline prices, incomes, and property prices. Moreover, the number of CSDs in a CMA might have some link to urban sprawl due to a less cooperative political system and centralization of power. The study by Klaus (2019) in Switzerland shows that the combinations of municipal autonomy and institutional fragmentation are associated with high values of urban sprawl, which can be explained by the competition between municipalities resulting in oversized designated zones.

Urban sprawl is happening in most Canadian cities especially in Toronto, Vancouver, Calgary, and Ottawa. However, Montreal experienced a very intense increase in urban sprawl over the past decade. The six largest metropolitan areas experienced lower values in *LUP* (higher density) than the other Canadian CMAs. According to Townsend et al. (2018), the six largest Canadian metropolitan regions did not exhibit a higher population density than 51 largest US metropolitan regions, although Canadian metropolitan regions are less automobile-oriented than the US metropolitan regions. The results of Townsend et al. (2018) are not directly comparable with this study due to the different methods that were used to measure utilization density.

Canada has witnessed a considerable amount of suburban-style growth in metropolitan areas owing to people relying more heavily on the automobile. This suburban growth has markedly changed urban spatial structure (Maoh et al. 2012). As Townsend et al. (2018) also point out, three of Canada's metropolitan regions (Calgary, Edmonton, and Vancouver) lack any freeway within their central cores. For example, Vancouver’s core is void of any pass-through freeways, with the nearest freeways still miles away. Townsend et al. (2018) call for greater nuance in extant generalizations dichotomizing Canadian and US metropolitan regions based on population density or transportation infrastructure.

More recently, the City of Montreal, under the new left-of-centre government of Mayor Valérie Plante (as of 2018), is adopting different policies to encourage people to move back into the city. However, there are a lot of challenges for the larger Montreal region in monitoring and controlling urban sprawl with the purpose of decreasing the negative consequences such as environmental impacts, loss of agricultural capacity, higher infrastructure costs, and the increase of car dependency.

The Communauté Métropolitaine de Montréal (CMM) was created by the Quebec government in 2000. After twelve years, the CMM – on behalf of 82 municipalities in the Greater Montreal region, started up the Metropolitan Land Use and Development Plan (PMAD) which focuses on Transit-Oriented Development (TOD) sectors to mitigate the effects of urban sprawl (PMAD, 2011). The PMAD's target is that by 2031, 40% of new housing is placed in 155 TOD cores. However, there were only 11 TOD pilot projects in 2018 (Marotte 2018).

TOD has become a more and more popular concept among urban planners, decision-makers, and politicians. This type of development is achieved by creating compact urban spaces. Such spaces help with the densification of housing and mixed-use communities centered around efficient and dependable public transit which is affordable. They also contribute positively to active transportation such as walking and cycling.

The progress towards controlling urban sprawl in the Montreal region does not seem strong enough. According to Beaudet (2017, cited in Marotte 2018), the most recent data from Statistics Canada (2016) show that urban sprawl continues in the Montreal CMA, that it is spreading out of the CMM territory and that it is also being fed by the oldest post-war suburbs, particularly Laval.

Policy makers and urban planners in Canada can also learn lessons from some European policies that were applied effectively in the European cities. For example, the Munich area has continued to develop in a remarkably dense and compact fashion compared to many other European cities. The main reason of this accomplishment might be the urban planners' decisions in the post-war years to restructure the historical center to be surrounded by a combined park and traffic ring. In the early 1960s, the traditional town planning in Munich was replaced with integrated urban development planning. Moreover, some responsibilities, e.g. economy, social matters, education, culture, and town planning were provided for all municipalities. In 1990s, the idea of keeping the Munich compact and green developed stricter plans based on a united urban development. The plans were established and included "the reuse of brownfield land, avoidance of expansion, mixed land use development integrating residential and commercial services, improvement of public transport as well as pedestrian and cycling facilities, and reinforcement of regional cooperation" (Ludlow, 2006, p. 45).

The Munich case study successfully implemented a compact city model in the planning of the city that has effectively contained urban sprawl. These lessons from Munich can also provide a good practice basis for all Canadian CMAs to control and limit urban sprawl with the aim of making urban development more sustainable.

For a long time, heated debates have been sparked about the impacts of urban sprawl among practitioners and scientists; however, sprawl has not yet been much of a concern for policy-makers and authorities in charge in Canada. I hope this study will contribute to raising awareness about urban sprawl and to addressing this critical issue for Canada's future.

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6. Appendices

6.1. Appendix 1: Manuscript for submission to the journal *Data in Brief*

Urban sprawl in Canada: Values in all 34 census metropolitan areas and corresponding 469 census subdivisions between 1991 and 2011

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Abstract

The dataset presented here provides the degree of urban sprawl across 34 Census Metropolitan Areas (CMAs) in Canada together with the 469 Census Subdivisions (CSDs) located within the boundaries of the CMAs, for the years 1991, 2001, and 2011. The dataset contains the values of weighted urban proliferation (*WUP*) and weighted sprawl per capita (*WSPC*) and their components. The landscape-oriented value of *WUP* indicates how strongly the landscape within the boundaries of a reporting unit is sprawled per square meter, while *WSPC* is inhabitant-oriented and reveals how much on average each inhabitant or workplace is contributing to urban sprawl in the reporting unit. The values of the components of the *WUP* and *WSPC* metrics are provided as well: percentage of built-up area (*PBA*), urban dispersion (*DIS*), land uptake per person (*LUP*), and urban permeation (*UP*). The values of full-time equivalents for the numbers of jobs, which were considered in the calculation of *LUP* values (pertaining to the number of inhabitants and jobs) are also included in order to facilitate future research.

Keywords

Built-up area, Dispersion, Land uptake, Suburbanization, Time series, Trends, Urban development, Urban growth, Urban permeation (*UP*), Urban sprawl, Weighted urban proliferation (*WUP*), Weighted sprawl per capita (*WSPC*)

Specifications Table

Subject	Geography, Environmental Sciences, Landscape Ecology, Sustainability, Urban Studies, Planning
Specific subject area	Urban Planning, Landscape Planning, Environmental Monitoring, Urban Sprawl, Urban Growth
Type of data	Tables, Excel files
How data were acquired	Instruments/Software: ArcGIS, Urban Sprawl Metrics toolset (USM toolset). Raw data were obtained from Statistics Canada [11, 12]. The analyzed data were calculated using ArcGIS version 10.3/10.7, USM toolset, and Excel.
Data format	Raw; Analyzed
Parameters for data collection	Data were collected for the years 1991, 2001, and 2011.
Description of data collection	A few corrections were applied to the raw data (e.g., by excluding waterbodies and parks from the layer of the built-up areas), using NAD_1983_Albers as a projected coordinate system. The modified data were entered into the USM toolset to calculate the *WUP* metric and its components. Numbers of full-time equivalents were derived from information about part-time and full-time employment provided by Statistics Canada [12]. The values of *WSPC* were calculated in Excel based on the components of *WUP*.
Data source location	Canada; all 34 Canadian Census Metropolitan Areas (CMAs) and the 469 Census Subdivisions (CSDs) within the boundaries of the CMAs.
Data accessibility	The data are available with this article.
Related research article	Pourali et al. [8] (in prep.)

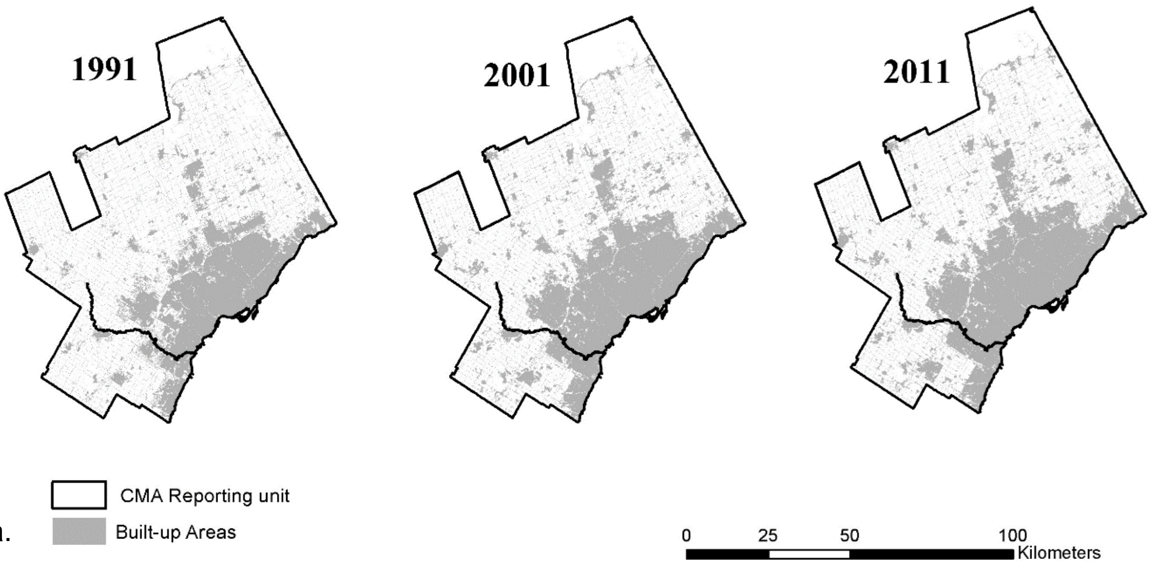
Value of the Data

- This research provides quantitative data about the levels and temporal changes in urban sprawl for a large country in North America to assess the sustainability of land-use trends and to assist in efforts to curtail urban sprawl.
- The data provided here are useful for environmental scientists, geographers, planners, and decision-makers and can be applied for environmental monitoring, sustainability monitoring, landscape quality monitoring, and biodiversity monitoring.
- The data can be used by researchers for statistical analysis to identify potential drivers and effects of urban sprawl and they can be used by urban planners and decision-makers to establish targets and limit to urban sprawl in Canada.
- Data collection can be continued in the future to reveal changes in trends, e.g., an acceleration or slowing down of the increase in urban sprawl as a consequence of the Covid-19 pandemic. They can be applied for performance evaluation of measures intended to limit urban sprawl.
- This dataset can be applied to identify effective strategies for reducing urban sprawl and to substantially reduce its adverse effects in Canada: The density, location, and contribution to dispersion resulting from alternative scenarios of newly proposed urban areas can be analyzed and compared so as to diminish sprawl.

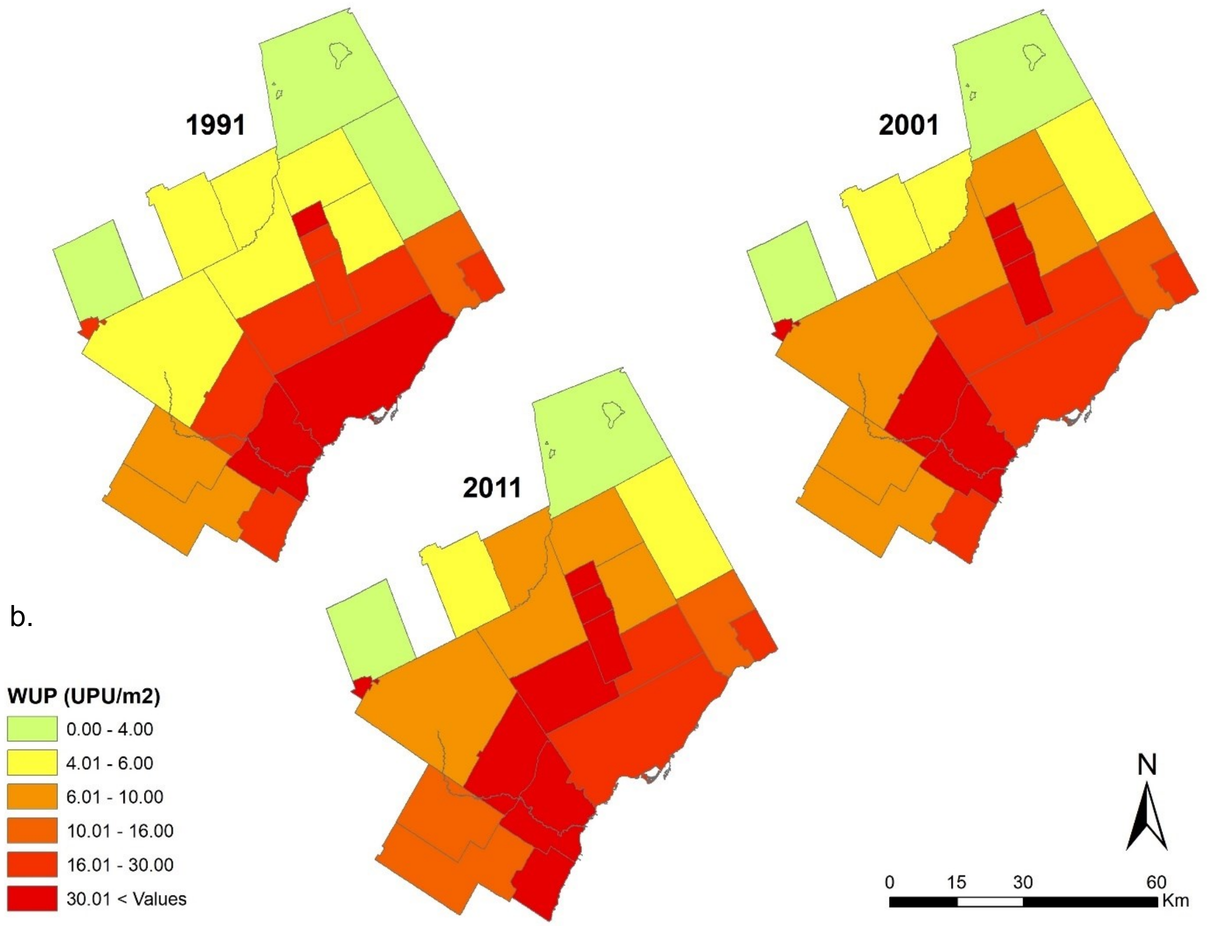
1. Data Description

We used the built-up area layers for Canada for the years 1991, 2001, and 2011 from the report titled "Human Activity and the Environment – The changing landscape of Canadian metropolitan areas" released by Statistics Canada in 2016 [11]. In this dataset, built-up area is considered as "land that is predominantly built-up or developed, including the vegetation associated with these land covers, such as gardens and parks. It is characterized by a high percentage of impervious surfaces including roadways, parking lots and roof tops. Low-density dwellings and small structures or buildings in rural areas outside core built-up areas may not be captured due to the resolution of the data and overlying tree canopy" ([11], p.331). To create these datasets, remote sensing imagery data were used from Agriculture and Agri-food Canada's Land Use for the years 1990, 2000 and 2010. These land use maps cover all of Canada south of 60°N at a spatial resolution of 30 m. The maps of the built-up areas were provided in a shapefile format. Figure A.1.a presents an example of the built-up areas and the corresponding reporting unit of the Toronto census metropolitan area (CMA) in 1991, 2001, and 2011. An increase of built-up areas is clearly noticeable in the Toronto CMA between 1991 and 2011. Figure

A1.b and Figure A.1.c present the changes of *WUP* and *WSPC* values at the level of CSDs in the Toronto CMA between 1991 and 2011.



a.


1991
2001
2011
b.
WUP (UPU/m2)
0.00 - 4.00
4.01 - 6.00
6.01 - 10.00
10.01 - 16.00
16.01 - 30.00
30.01 < Values
N
0 15 30 60
Km

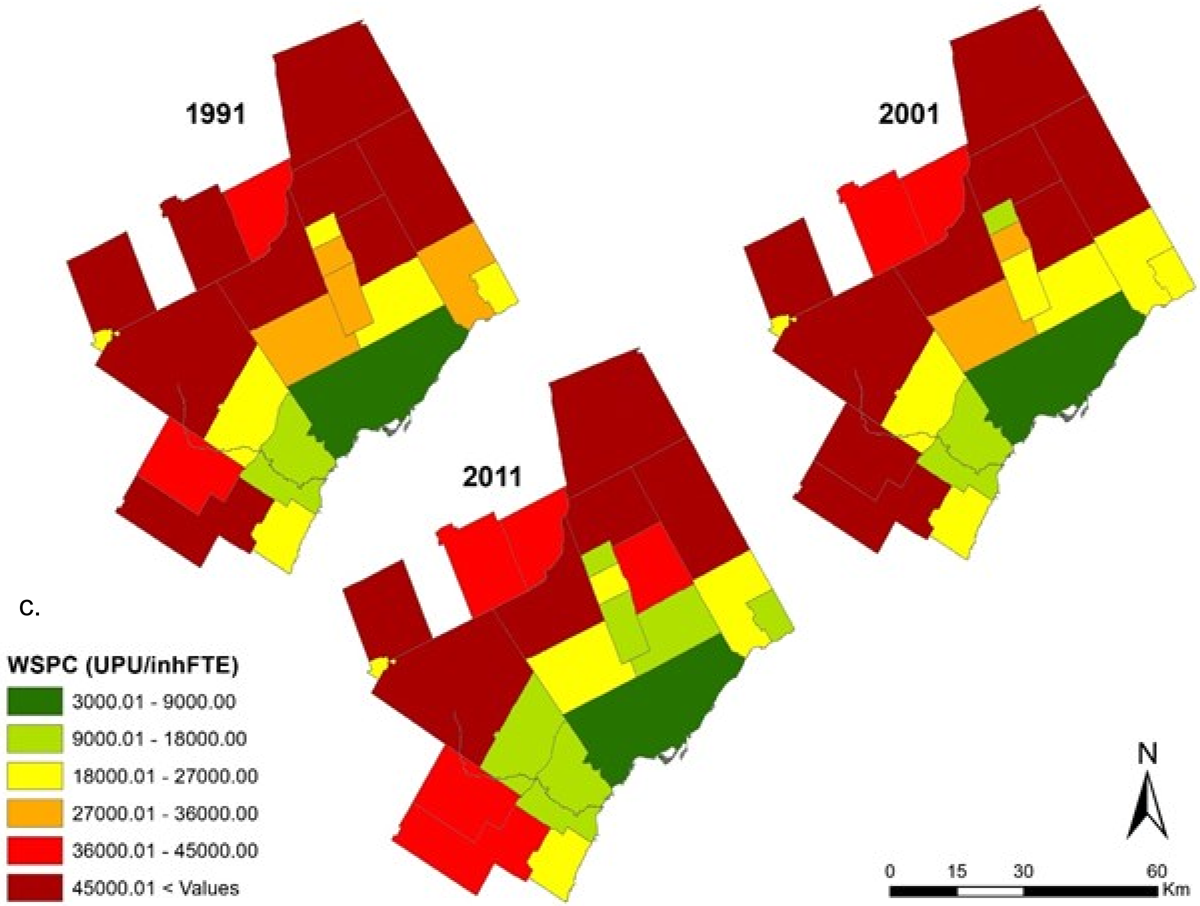


Fig. A.1. (a) The example of built-up areas in the Toronto CMA in 1991-2011. (b) Urban sprawl (*WUP*) at the level of census subdivisions in the Toronto CMA in 1991-2011. (c) *WSPC* at the level of census subdivisions in the Toronto CMA in 1991-2011 (Sources: a. [11]; b. and c. own calculations.)

Table A.1. The names of the 34 Census Metropolitan Areas (CMAs) in Canada, their sizes, number of inhabitants in 2011, and the number of CSDs located in each CMA (in alphabetical order). (Source: [11]

Name of CMA	Size of CMA (km^2)	Size of built-up area (km^2)	Number of inhabitants in 2011	Number of CSDs located in the CMA
Abbotsford - Mission	649.7589547	136.8855	170191	4
Barrie	967.4910868	144.72405	187013	3
Brantford	1086.242151	146.9475	135501	3
Calgary	5242.891799	631.723725	1214839	9
Edmonton	9853.51202	1051.0677	1159869	35

Greater-Sudbury	3853.459294	253.5165	160770	3
Guelph	604.0516143	97.295625	141097	3
Halifax	5963.033558	432.306225	390328	5
Hamilton	1404.627426	389.08395	721053	3
Kelowna	3144.898204	175.099725	179839	9
Kingston	2142.446055	195.6456	159561	4
Kitchener	840.4379039	256.901175	477160	5
London	2681.139785	393.38055	474786	8
Moncton	2471.089964	173.9403	138644	14
Montreal	4293.669384	1460.41515	3824221	91
Oshawa	907.8944319	219.0402	356177	3
Ottawa–Gatineau-On	3401.77751	582.2541	921823	3
Ottawa–Gatineau-Qc	3262.599557	278.1468	314501	12
Peterborough	1636.738651	153.270675	118975	7
Québec	3415.896212	447.1101	765706	28
Regina	3483.892007	211.7106	210556	17
Saguenay	2876.835491	178.88985	157790	8
Saint John	3645.756303	234.683325	127761	17
Saskatoon	5504.865258	310.844925	260600	24
Sherbrooke	1522.43474	187.6518	201890	11
St. Catharines	1425.291363	380.9502	392184	10
St. John's	850.3768227	172.244925	196966	13
ThunderBay	2617.838377	185.3127	121596	8
Toronto	6269.961443	1957.075425	5583064	24
Trois-Rivières	1053.496407	141.6168	151773	7
Vancouver	3041.420111	934.4448	2313328	39
Victoria	704.3698475	219.420675	344615	22
Windsor	1032.467334	240.863175	319246	5
Winnipeg	5409.257499	521.84565	730018	12

The data provided in the Excel file include the values of Weighted Urban Proliferation (*WUP*) (Fig A.1.b and c) and Weighted Sprawl per Capita (*WSPC*). The values of the three components used to calculate these two metrics are available as well, i.e., the information about the number of inhabitants, areas of the reporting units, and the full-time equivalents were included in this file. The meaning of the column headings is as follows:

- ‘Year’ refers to the year to which the data apply (1991, 2001, 2011).
- ‘CMA’ refers to the names of the Census Metropolitan Areas.

- The column ‘Area_Reporting unit_m^2’ provides the area of each reporting unit in square meters.
- The column ‘Urban_Area_m^2’ shows the areas of the built-up areas in each CMA in square meters.
- ‘*PBA*’ refers to the proportion of built-up areas (between 0 and 1).
- The column ‘*DIS* (UPU/m^2)’ provides the values of urban dispersion (in UPU per m^2).
- ‘w1DIS’ distinguishes the weighting function$_1$ of dispersion (values between 0.5 and 1.5).
- ‘*TS*’ refers to the total sprawl (in UPU).
- *‘UP’* is the value of urban permeation, expressed in urban permeation units per m^2 of land (UPU/m^2).
- ‘FTPT’ in several columns identifies the total number of jobs (Full-Time and Part-Time), i.e., without considering full-time equivalents. The ‘FTPT’ abbreviation after a component or metric indicates the values that were found by using the total number of full-time and part-time jobs (rather than full-time equivalents).
- The column ‘Sum_inhFTPT’ provides the sum of the number of inhabitants and the total number of jobs (full-time and part-time), i.e., without considering the full-time equivalents.
- ‘*UD*’ refers to the value of utilization density (sum of inhabitants and total number of jobs / area of the reporting unit).
- ‘w_2(*UD*)’ refers to the weighting function of utilization density (values between 0 and 1).
- The column ‘*LUP* (m2/inhFTPT)’ provides the values of land up take per person (m2/ the number of inhabitants and jobs (full-time + part-time).
- ‘*WUP*’ refers to the Weighted Urban Proliferation in urban permeation units per square meter of built-up area (UPU/m^2).
- ‘FTE’ in several columns refers to the number of full-time equivalents of jobs. The ‘FTE’ abbreviation after each component or metric indicates the values that were found by using the number of full-time equivalents (rather than the sum of full-time and part-time jobs).
- ‘*LUP* (m^2/inhFTE)’ corresponds to the values of land up take per person (m^2 / the number of inhabitants and full-time equivalents).
- ‘*w*2(*LUP*)’ refers to the weighting function of land up-take per inhabitant or job (between 0 and 1).
- ‘*WSPC*’ denotes Weighted Sprawl per Capita in urban permeation units per inhabitant or job (UPU / (inh. or job)).

- The heading 'CSD-codes' refers to the census subdivision (CSD) codes. This three-digit code is based on the Standard Geographical Classification (SGC). In order to uniquely identify each CSD in Canada, the two-digit province/territory (PR) code and the two-digit census division (CD) code must precede the CSD code.

The first sheet in the Excel file (CMAs1991_2011) includes all the above information at the CMA level. The second (CSD2011), third (CSD2001), and forth (CSD1991) sheets contain the same information at the CSDs level for the years 2011, 2001, and 1991 respectively. The fifth sheet (Job-Equivalence-Ratio) indicates the conversion factors for full-time equivalence and the relevant data that we used to calculate these factors, for each province, and for the years 1991, 2001, and 2011.

2. Experimental design, materials and methods

The method applied for measuring urban sprawl is based on the following definition: The degree of urban sprawl increases with (1) the size of the built-up areas in a given landscape (i.e., the percentage of built-up area), (2) the dispersion of the built-up area (spatial configuration), and (3) the uptake of built-up area per inhabitant or job [3, 1, 4]. The **Weighted Urban Proliferation** (*WUP*) method measures urban sprawl by integrating these three dimensions into a single metric [3, 2, 1] (Tab. 2; Fig. A.2):

$WUP = (PBA * DIS) * w_1(DIS) * w_2(LUP),$

where *PBA* = percentage of built-up areas, *DIS* = dispersion of built-up areas, *LUP* = land up take per person, $w_1(DIS)$ = weighting function$_1$ (Dispersion), and $w_2(LUP)$ = weighting function$_2$ (Land up take per inhabitant or job).

Since the land uptake per person and dispersion are weighted with the weighting functions $w_1(DIS)$ and $w_2(LUP)$, this metric of urban sprawl is referred to as Weighted Urban Proliferation (*WUP*).

We also provide the values of urban permeation and total sprawl:

Urban Permeation: Urban permeation (*UP*) is the product of *PBA* and *DIS* in each reporting unit: *UP* = (size of built-up area / size of reporting unit) * dispersion. Its value indicates the extent of permeation of urban areas into the landscape. It is an intensive metric and is expressed in urban permeation units per square meter of landscape (UPU/m^2) [5].

The value of Total Sprawl (*TS*) is the result of multiplication of *DIS* and the total amount of built-up areas (*TS* = *DIS* * Area of built-up area). It is an extensive metric.

Among these metrics, **Weighted Urban Proliferation *(WUP)*** is the main metric used to quantify urban sprawl.

Information about full-time and part-time jobs was combined by using full-time equivalents to better reflect the actual number of hours worked as these locations. The conversion factors for full-time equivalents were found by dividing the hours of part-time employment (all jobs, both sexes, and 15 years and over) by the hours of full-time employment (all jobs, both sexes, and 15 years and over). This resulted in conversion factors between 0.35 and 0.47. We obtained job data from the Statistics Canada, 2019 (Special tabulation, based on the 1971, 1991, 2001 censuses of population and the 2011 National Household Survey). The data provide information of the numbers of total type of work, the numbers of total employees who did not work during the reference week of the census and those who worked during the reference week separately, and finally the number of employees who worked full time and those who worked part time for all Census Subdivisions in Canada in 1991, 2001 and 2011. Reference week is defined as "the entire calendar week (from Sunday to Saturday) covered by the Labour Force Survey each month. It is usually the week containing the 15th day of the month. The interviews are conducted during the following week, called the Survey Week, and the labour force status determined is that of the reference week." ([12], p. 16).

However, the numbers of the part time and full-time employees, respectively, who did not work during the reference week was missing. To calculate the numbers of part-time employees who did not work during the reference week, we assumed that the proportion of part-time employees among the employees who did not work during the reference week was the same as for those who worked during the reference week. Based on this assumption, we applied the following equation:

(The number of employees who worked part time / (The numbers of employees who worked full time + The numbers of employees who worked part time)) * The numbers of total employees who did not work during the reference week= numbers of part-time employees who did not work during the reference week.

Accordingly, we estimated the numbers of full-time employees who did not work during the reference week by calculating the difference of the numbers of total employees who did not work during the reference week and the numbers of part time employees who did not work during the reference week. Finally, we summed the numbers of part time employees who did not work during the reference week to the number of employees who worked part time to find the best possible estimate for part time jobs. To discover the best estimate for full time jobs, we summed the numbers of full-time employees who did not work during the reference week to the numbers of employees who worked full time.

One of the main advantages of the *WUP* method is that it meets all 13 suitability criteria for measuring urban sprawl, outlined by [4]. Some of the criteria are necessary conditions while others represent desirable additional criteria. The ideal metric would meet all 13 criteria. The criteria are: (1) intuitive interpretation, (2) mathematical simplicity, (3) modest data requirements, (4) low sensitivity to very small patches of urban area, (5) monotonous response to increases in urban area, (6) monotonous response to increasing distance between two urban patches when within the scale of analysis, (7) monotonous response to increased spreading of three urban patches, (8) same direction of the metric's responses to the processes in criteria 5, 6 and 7, (9) continuous response to the merging of two urban patches, (10) independence of the metric from the location of the pattern of urban patches within the reporting unit, (11) continuous response to increasing distance between two urban patches when they move beyond the scale of analysis, (12) mathematical homogeneity, and (13) additivity [4]

Table A.2. Overview of the metrics and their units.

Name of the variable	**Name of the metric**	**Unit**	**Mathematical homogeneity**	**Name of the column heading in the Excel table**
WUP	Weighted Urban Proliferation	UPU per m^2 of landscape	Intensive	*WUP*
PBA	Percentage of Built-up Area	–	Intensive	*PBA*

DIS	Dispersion	UPU per m^2 of built-up area	Intensive	*DIS* (UPU/m^2)
LUP	Land Uptake per Person (per inhabitant or job)	m^2 per inhabitant or job	Intensive	*LUP* (m^2/inhFTE)
UD	Utilization Density	Inhabitants and jobs per km^2 of built-up area	Intensive	*UD*
UP	Urban Permeation	UPU per m^2 of landscape	Intensive	*UP*
TS	Total Sprawl	UPU	Extensive	*TS*
WSPC	Weighted Sprawl per Capita	UPU per inhabitant or job	Intensive	*WSPC*

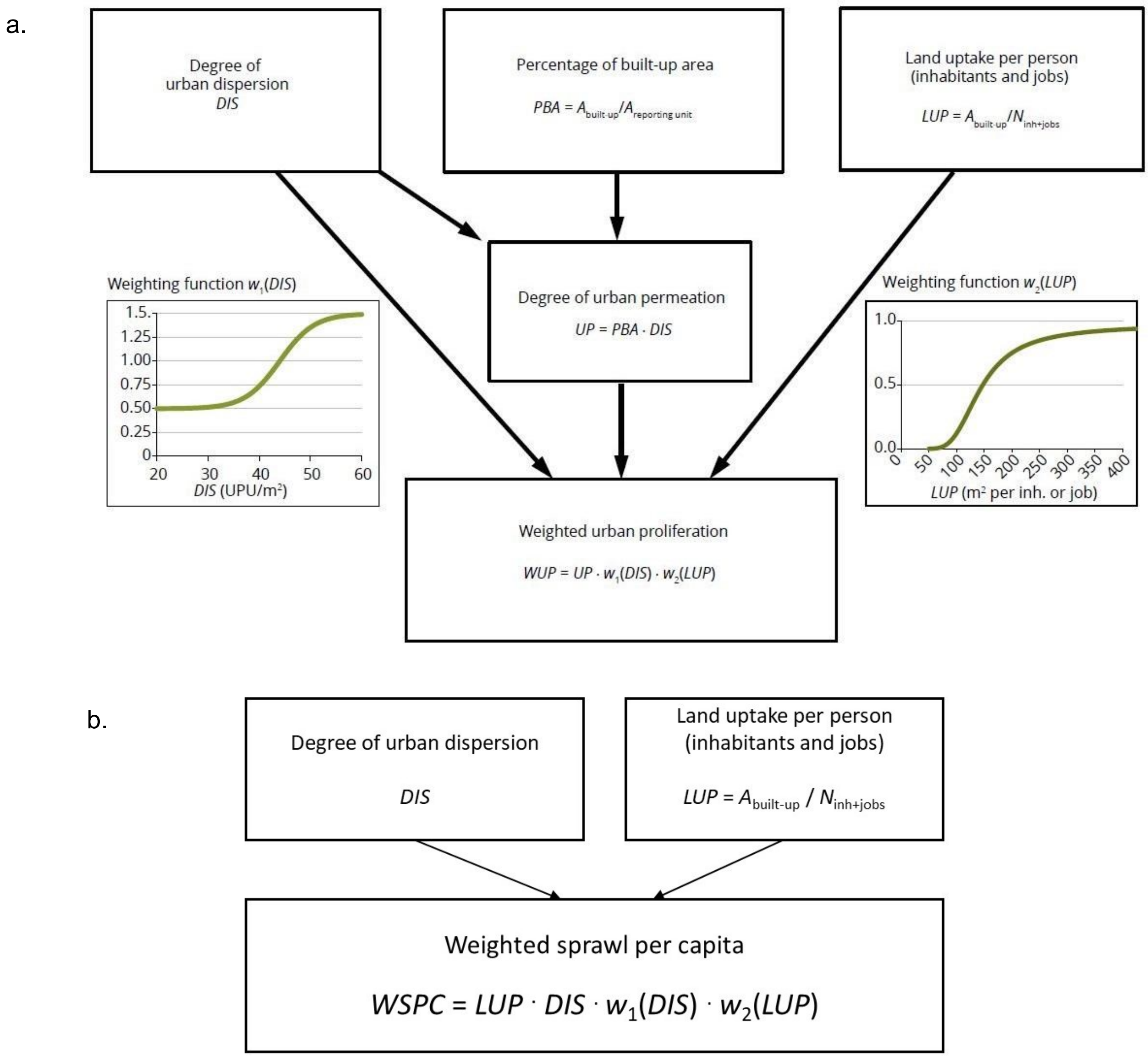


Figure. A.2. (a) The relationships between the *WUP* metric and its components *DIS*, *PBA*, and *LUP*. Adapted from [2]. (b) The relationships between the *WSPC* metric and its components *DIS* and *LUP*.

In the built-up area shapefiles, most of the parks and green spaces were identified as built-up areas, such as Park du Mont-Royal, Park La Fontaine, and Jean Drapeau in the Montreal CMA. Some small water bodies were also included in the built-up area shapefiles. To increase the accuracy of the built-up area shapefiles and exclude the green spaces, parks and water bodies from them, we applied some corrections (Tables A.3 and A.4).

Table A.3. Information of data, sources, and the corrections that were applied when calculating urban sprawl.

Data	**Source**	**Corrections**
Built-up areas 1991, 2001, 2011 and **Reporting units 2011:** Census metropolitan areas and census subdivisions in Canada 2011 Census Metropolitan Area (CMA) boundaries shapefiles were used for the years 1991, 2001, and 2011.	"Human Activity and the Environment - The changing landscape of Canadian metropolitan areas", released by Statistics Canada) [11].	1. We excluded waterbodies from being counted as built-up areas (River shapefiles from Statistics Canada 2019). 2. The Canadian park layer was used (Concordia Library, CanMAp 2018) to remove all parks from built-up area layers (Tab. 4). 3. The projected coordinate system was changed to: NAD_1983_Albers.
Population data	"Human Activity and the Environment - The changing landscape of Canadian metropolitan areas", released by Statistics Canada [11].	No corrections
Job Data The number of full-time and part-time jobs	Statistics Canada. 2019. Special tabulation, based on the 1971, 1991, 2001 censuses of population and the 2011 National Household Survey [12].	To calculate full-time equivalents, conversion factors were found by dividing the hours of part-time employment by the hours of full-time employment [2]. We applied the same steps separately for the years 2011, 2001, 1991 for Canada, and also separately for the provinces.

Table A.4. Types of parks that were excluded or not excluded, respectively, from the layer of built-up areas.

Types of parks	**Excluded**	**Not excluded**
AMUSEMENT PARK		✓
BOTANICAL GARDEN	✓	
CAMPGROUND	✓	
CEMETERY		✓
DRIVE-IN THEATRE		✓
ECOLOGICAL RESERVE	✓	
EXHIBITION GROUND		✓
GOLF	✓	

HISTORIC SITE		✓
LOOKOUT		✓
NATIONAL PARK	✓	
NATIONAL WILDLIFE AREA	✓	
NATURAL AREA	✓	
PARK RESERVE	✓	
PARK/SPORTS FIELD	✓	
PROTECTED AREA	✓	
PROVINCIAL PARK	✓	
RECREATION AREA	✓	
SANCTUARY	✓	
SPORTS/RACE TRACK		✓
SWIMMING POOL		✓
TERRITORIAL PARK	✓	
WILDERNESS AREA	✓	
WILDERNESS PARK	✓	
WILDLAND PARK	✓	
ZOO		✓

To apply the *WUP* method, the railways and roads outside of cities should be excluded since they are not included in the definition of built-up areas and are not considered as a part of urban sprawl [1]. Nevertheless, the built-up area data that have been used in this work include all the roads of the CMAs (inside and outside of cities). This choice was particularly made because in the built-up area shapefiles, roads were recorded in a single field, it would have been challenging to identify, and separate, all the roads, in each of the CMAs for each year. Therefore, the roads remained part of the built-up area shapefiles.

We used the USM toolset, which was developed for the calculation of Weighted Urban Proliferation (*WUP*) by Miroslav Kopecky, Erika Orlitova, and Tomas Soukup at GISAT in Prague, Czech Republic [7, 10]. This geographic information system (GIS) toolset is freely available on the website of the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) (https://www.wsl.ch/de/services-und-produkte/software-websites-und-apps/urban-sprawl-metrics-tool-usm.html). Before using this toolset, the polygon layers of built-up areas were converted to 15 m raster cells in accordance with [6].

The value of *WUP* indicates how strongly the landscape within the boundaries of a reporting unit is sprawled. This research also presents **Weighted Sprawl per Capita (*WSPC*)**, which quantifies how much on average each inhabitant or workplace contributes to urban sprawl in a reporting unit, i.e,. this metric refers to the number of inhabitants and jobs in the reporting unit instead of the area of the reporting unit: $WSPC = WUP_{\mathrm{p}} \times A_{\mathrm{reporting\ unit}} / N_{\mathrm{inhabitants+jobs}}$.

Accordingly, $WSPC = w_1(DIS) \times w_2(LUP_{\mathrm{p}}) \times DIS \times A_{\mathrm{built\text{-}up}} / N_{\mathrm{inhabitants+jobs}}$

$= w_1(DIS) \times w_2(LUP_{\mathrm{p}}) \times DIS \times LUP_{\mathrm{p}}$.

Therefore, *WSPC* is the combination of *LUP*, *DIS*, the weighting of *LUP* (in $w_2(LUP)$), and the weighting of *DIS* ($w_1(DIS)$).

While the value of WUP_{p} answers the question of how much urban sprawl there is in a reporting unit per square kilometre, i.e., it is landscape-oriented, the value of *WSPC* answers the question of how much on average each inhabitant or workplace contributes to urban sprawl in the reporting unit in which the person is living, i.e., it is an inhabitant-oriented measure of urban sprawl.

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6.2 Appendix B

Distribution of census subdivision types by province and territory, 2011

Standard Geographical Classification (SGC) 2011

Table. B.1. The number of census subdivision types in each province and Canada

(Statistics Canada, 2011) https://www.statcan.gc.ca/eng/subjects/standard/sgc/2011/sgc-tab-b

Census subdivision type	Canada	N.L.	P.E.I.	N.S.	N.B.	Que.	Ont.	Man.	Sask.	Alta.	B.C.	Y.T.	N.W.T.	Nvt.
City / Cité (C)	6	...	...	...	4	...	2	...	...	...	...	...	...	...
Chartered community (CC)	3	...	...	...	...	...	...	...	...	...	...	...	3	...
Community government (CG)	4	...	...	...	...	...	...	...	...	...	...	...	4	...
Crown colony / Colonie de la couronne (CN)	1	...	...	...	...	...	...	...	1	...	...	...	...	...
Community (COM)	33	...	33	...	...	...	...	...	...	...	...	...	...	...
Canton (municipalité de) (CT)	45	...	...	...	...	45	...	...	...	...	...	...	...	...
Cantons unis (municipalité de) (CU)	2	...	...	...	...	2	...	...	...	...	...	...	...	...
City / Ville (CV)	2	...	...	...	...	...	2	...	...	...	...	...	...	...
City (CY)	149	3	2	...	4	...	46	9	16	17	49	1	1	1
District municipality (DM)	52	...	...	...	...	...	...	...	...	...	52	...	...	...
Hamlet (HAM)	36	...	...	...	...	...	...	...	...	...	...	2	10	24

Census subdivision type	Canada	N.L.	P.E.I.	N.S.	N.B.	Que.	Ont.	Man.	Sask.	Alta.	B.C.	Y.T.	N.W.T.	Nvt.
Improvement district (ID)	7	...	...	...	...	...	...	...	...	7	...	...	...	...
Indian government district (IGD)	2	...	...	...	...	...	...	...	...	...	2	...	...	...
Island municipality (IM)	1	...	...	...	...	...	...	...	...	...	1	...	...	...
Indian reserve / Réserve indienne (IRI)	961	3	4	25	18	27	139	75	168	81	419	...	2	...
Local government district (LGD)	2	...	...	...	...	...	...	2	...	...	...	...	...	...
Township and royalty (LOT)	67	...	67	...	...	...	...	...	...	...	...	...	...	...
Municipality / Municipalité (M)	3	...	...	...	...	...	3	...	...	...	...	...	...	...
Municipal district (MD)	76	...	...	12	...	...	...	...	...	64	...	...	...	...
Municipalité (MÉ)	619	...	...	...	...	619	...	...	...	...	...	...	...	...
Municipality (MU)	54	...	...	...	...	...	54	...	...	...	...	...	...	...
Northern hamlet (NH)	11	...	...	...	...	...	...	...	11	...	...	...	...	...
Nisga'a land (NL)	1	...	...	...	...	...	...	...	...	...	1	...	...	...
Unorganized / Non organisé (NO)	137	...	...	...	...	96	16	10	2	...	...	4	6	3
Northern village (NV)	11	...	...	...	...	...	...	...	11	...	...	...	...	...
Parish / Paroisse (municipalité de) (P)	150	...	...	...	150	...	...	...	...	...	...	...	...	...

Census subdivision type	Canada	N.L.	P.E.I.	N.S.	N.B.	Que.	Ont.	Man.	Sask.	Alta.	B.C.	Y.T.	N.W.T.	Nvt.
Paroisse (municipalité de) (PE)	179	...	...	...	...	179	...	...	...	...	...	...	...	...
Rural community / Communauté rurale (RCR)	4	...	...	...	4	...	...	...	...	...	...	...	...	...
Regional district electoral area (RDA)	158	...	...	...	...	...	...	...	...	...	158	...	...	...
Region (RG)	1	1	...	...	...	...	...	...	...	...	...	...	...	...
Regional municipality (RGM)	4	...	...	3	...	...	...	...	...	...	1	...	...	...
Rural municipality (RM)	413	...	...	...	...	...	...	117	296	...	...	...	...	...
Resort village (RV)	40	...	...	...	...	...	...	...	40	...	...	...	...	...
Indian settlement / Établissement indien (S-É)	28	...	...	...	...	6	5	4	1	4	3	5	...	...
Special area (SA)	3	...	...	...	...	...	...	...	...	3	...	...	...	...
Subdivision of county municipality / Subdivision municipalité de comté (SC)	28	...	...	28	...	...	...	...	...	...	...	...	...	...
Settlement / Établissement (SÉ)	13	...	...	...	...	...	...	...	...	...	...	13	...	...
Settlement (SET)	13	...	...	...	...	...	...	...	...	...	...	...	10	3
Self-government / Autonomie gouvernementale (SG)	4	...	...	...	...	...	...	...	...	...	...	4	...	...

Census subdivision type	Canada	N.L.	P.E.I.	N.S.	N.B.	Que.	Ont.	Man.	Sask.	Alta.	B.C.	Y.T.	N.W.T.	Nvt.
Specialized municipality (SM)	5	...	...	...	...	...	...	...	...	5	...	...	...	...
Subdivision of unorganized / Subdivision non organisée (SNO)	92	92	...	...	...	...	...	...	...	...	...	...	...	...
Summer village (SV)	51	...	...	...	...	...	...	...	...	51	...	...	...	...
Town (T)	743	277	7	31	13	...	88	51	147	108	14	3	4	...
Terres réservées aux Cris (TC)	8	...	...	...	...	8	...	...	...	...	...	...	...	...
Terre inuite (TI)	12	...	...	...	...	12	...	...	...	...	...	...	...	...
Terres réservées aux Naskapis (TK)	1	...	...	...	...	1	...	...	...	...	...	...	...	...
Teslin land (TL)	1	...	...	...	...	...	...	...	...	...	...	1	...	...
Township (TP)	207	...	...	...	...	...	207	...	...	...	...	...	...	...
Town / Ville (TV)	15	...	...	...	14	...	1	...	...	...	...	...	...	...
Ville (V)	222	...	...	...	...	222	...	...	...	...	...	...	...	...
Village cri (VC)	8	...	...	...	...	8	...	...	...	...	...	...	...	...
Village naskapi (VK)	1	...	...	...	...	1	...	...	...	...	...	...	...	...
Village (VL)	550	...	...	...	66	45	11	19	266	95	43	4	1	...
Village nordique (VN)	14	...	...	...	...	14	...	...	...	...	...	...	...	...

Census subdivision type	Canada	N.L.	P.E.I.	N.S.	N.B.	Que.	Ont.	Man.	Sask.	Alta.	B.C.	Y.T.	N.W.T.	Nvt.
Total	**5,253**	**376**	**113**	**99**	**273**	**1,285**	**574**	**287**	**959**	**435**	**743**	**37**	**41**	**31**

6.3 Appendix C

Comparing the values of *WUP* between Victoria with Kelowna

Within BC, the *WUP* value for Victoria is high (17.93 UPU/m^2), while the *WUP* value for Kelowna is very low (3.01 UPU/m^2). Although the Kelowna CMA represents a bigger area (with a much lower population) compared to the Victoria CMA (which has a bigger population but a smaller CMA area), the lower *WUP* for Kelowna can be explained by the lower values in *PBA* (5.6 %) and *DIS* (46.80 UPU/m^2) compared to the Victoria CMA with the higher values in *PBA* (31.2 %) and *DIS* (48.06 UPU/m^2) (Figure C.1, Table C.1).

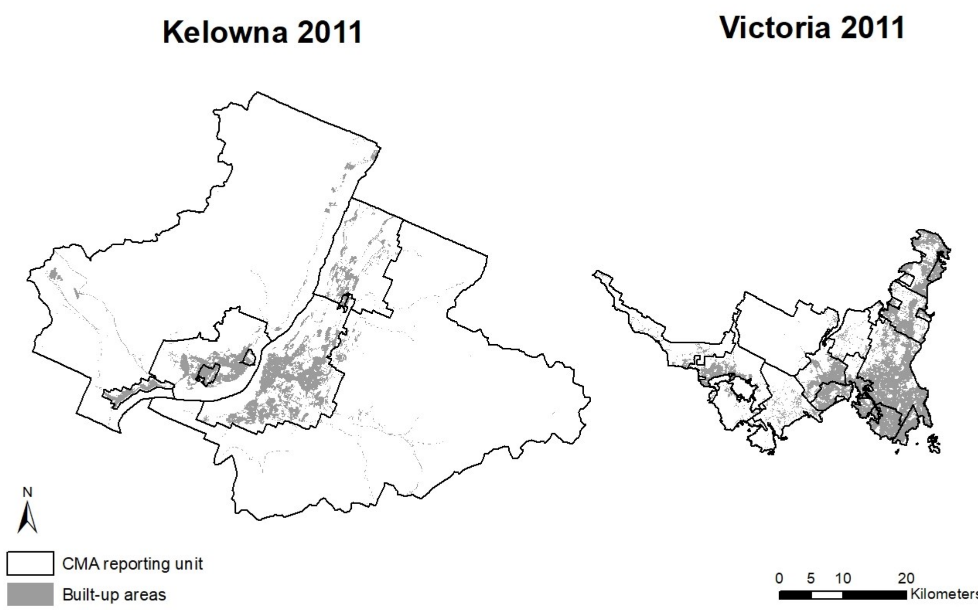

Figure C.1. The Kelowna and Victoria CMAs (2011)

Table C.1. The Values of *WUP* and *WSPC* and their components for the Kelowna and Victoria CMAs (2011)

Values	Kelowna 2011	Victoria 2011
WUP **(UPU/m^2)**	3.01	17.93
WSPC **(m^2/(inh. or job))**	39774.53	26681.08
LUP **(m^2/(inh. or job))**	737	464
PBA **(%)**	5.57	31.15
DIS **(UPU/m^2)**	46.80	48.06
Area_Reporting unit (km^2)	3144.90	704.37
Urban_Area (km^2)	175.10	219.42

6.4 Appendix D

The values of *WUP*, *WSPC*, and their components in all CMAs in 1991, 2001, and 2011

Table D.1. The values of *WUP* and *WSPC* and their components for the CMAs in 1991, 2001, and 2011.

Year	CMA	*PBA* %	*DIS* (UPU/m2)	*LUP* (m2/inhFTE)	*WUP*_FTE (UPU/m2)	*WSPC* (UPU/inhFTE)
1991	Abbotsford - Mission	15.36	48.19	697.37	9.10	41287.51
2001	Abbotsford - Mission	19.76	48.30	872.35	11.84	41247.16
2011	Abbotsford - Mission	21.07	48.22	628.17	12.45	37117.66
1991	Barrie	10.44	47.31	762.57	5.85	42729.21
2001	Barrie	14.03	47.04	707.68	7.70	38847.33
2011	Barrie	14.96	47.09	599.66	8.19	32822.59
1991	Brantford	9.53	47.86	700.79	5.53	40632.29
2001	Brantford	13.11	47.52	896.23	7.48	51148.81
2011	Brantford	13.53	47.51	827.67	7.70	47124.99
1991	Calgary	9.88	48.36	472.23	5.80	27723.05
2001	Calgary	10.86	48.39	418.61	6.33	24379.99
2011	Calgary	12.05	48.36	365.09	6.90	20906.20
1991	Edmonton	8.71	48.33	714.51	5.21	42684.75
2001	Edmonton	10.11	48.41	758.32	6.08	45587.97
2011	Edmonton	10.67	48.37	628.89	6.36	37488.64
1991	Greater-Sudbury	5.02	46.54	848.85	2.67	45103.23
2001	Greater-Sudbury	6.08	46.58	1107.65	3.26	59326.37
2011	Greater-Sudbury	6.58	46.57	1147.70	3.52	61455.49
1991	Guelph	12.40	48.05	504.40	7.17	29166.10
2001	Guelph	16.11	47.89	536.88	9.25	30843.72
2011	Guelph	16.11	47.89	471.59	9.18	26877.76
1991	Halifax	4.81	46.35	607.49	2.49	31492.75
2001	Halifax	6.63	46.84	794.85	3.60	43131.66
2011	Halifax	7.25	46.82	778.07	3.93	42124.82
1991	Hamilton	20.90	48.29	357.83	11.88	20344.07
2001	Hamilton	26.10	48.28	417.20	15.09	24118.66
2011	Hamilton	27.70	48.30	408.44	16.00	23599.44
1991	Kelowna	4.22	46.62	899.64	2.26	48153.49
2001	Kelowna	4.97	46.74	805.62	2.68	43406.36

2011	Kelowna	5.57	46.80	736.55	3.01	39774.53
1991	Kingston	7.70	47.04	851.86	4.25	46970.40
2001	Kingston	8.52	47.10	911.82	4.72	50584.93
2011	Kingston	9.13	46.92	874.27	5.00	47822.22
1991	Kitchener	23.49	48.45	386.23	13.62	22384.03
2001	Kitchener	28.76	48.42	410.41	16.74	23888.86
2011	Kitchener	30.57	48.46	380.67	17.70	22043.60
1991	London	11.60	48.20	543.37	6.80	31855.75
2001	London	14.01	48.07	620.91	8.20	36339.90
2011	London	14.67	48.14	602.54	8.61	35363.86
1991	Moncton	4.99	46.79	802.56	2.70	43407.25
2001	Moncton	6.48	47.14	930.07	3.61	51731.48
2011	Moncton	7.04	47.25	860.03	3.94	48148.15
1991	Montreal	27.74	48.07	261.77	14.55	13728.98
2001	Montreal	30.30	48.20	287.41	16.45	15606.28
2011	Montreal	34.01	48.24	272.26	18.24	14602.90
1991	Oshawa	17.41	48.44	486.29	10.29	28737.98
2001	Oshawa	22.44	48.31	535.76	13.24	31603.43
2011	Oshawa	24.13	48.36	490.22	14.19	28839.82
1991	Ottawa–Gatineau-On	15.30	47.57	486.56	8.56	27224.22
2001	Ottawa–Gatineau-On	17.12	47.62	484.74	9.61	27211.31
2011	Ottawa–Gatineau-On	17.12	47.62	427.16	9.52	23747.59
1991	Ottawa–Gatineau-Qc	6.32	46.83	672.17	3.41	36274.44
2001	Ottawa–Gatineau-Qc	6.80	46.97	775.45	3.72	42442.32
2011	Ottawa–Gatineau-Qc	8.53	46.68	671.22	4.55	35821.73
1991	Peterborough	7.02	47.66	798.27	4.03	45869.86
2001	Peterborough	8.87	47.48	988.39	5.06	56345.15
2011	Peterborough	9.36	47.35	951.61	5.29	53738.01
1991	Québec	9.90	47.35	364.35	5.31	19554.52
2001	Québec	11.18	47.54	398.70	6.14	21890.93
2011	Québec	13.09	47.47	404.77	7.17	22167.93
1991	Regina	5.55	47.77	709.59	3.20	40914.26
2001	Regina	5.77	47.78	733.66	3.33	42383.64
2011	Regina	6.08	47.78	688.95	3.50	39721.83
1991	Saguenay	5.04	46.51	652.17	2.65	34333.64
2001	Saguenay	5.53	46.70	746.39	2.97	40021.30
2011	Saguenay	6.22	46.59	819.57	3.31	43683.91
1991	Saint John	4.51	46.20	943.54	2.34	48966.55
2001	Saint John	6.13	46.70	1345.00	3.32	72880.22
2011	Saint John	6.44	46.72	1334.38	3.49	72391.79

1991	Saskatoon	5.13	47.59	964.66	2.95	55406.64
2001	Saskatoon	5.37	47.62	944.92	3.09	54351.57
2011	Saskatoon	5.65	47.64	843.41	3.24	48450.96
1991	Sherbrooke	9.28	47.39	623.39	5.19	34900.81
2001	Sherbrooke	10.23	47.47	628.73	5.76	35410.40
2011	Sherbrooke	12.33	47.46	673.37	6.95	37974.32
1991	St. Catharines	19.95	48.23	580.39	11.75	34193.13
2001	St. Catharines	25.55	48.32	722.76	15.26	43174.65
2011	St. Catharines	26.73	48.33	734.41	15.98	43908.73
1991	St. John's	13.39	47.24	482.23	7.32	26368.42
2001	St. John's	18.90	47.57	672.31	10.74	38193.91
2011	St. John's	20.26	47.64	616.73	11.53	35093.50
1991	ThunderBay	5.22	47.28	779.26	2.92	43609.37
2001	ThunderBay	6.84	47.44	1084.26	3.89	61741.04
2011	ThunderBay	7.08	47.39	1121.37	4.02	63664.61
1991	Toronto	24.27	48.74	272.58	13.41	15062.93
2001	Toronto	28.90	48.67	270.23	15.87	14833.98
2011	Toronto	31.21	48.72	250.34	16.75	13435.01
1991	Trois-Rivières	10.70	46.87	597.56	5.77	32185.28
2001	Trois-Rivières	11.89	46.96	671.97	6.47	36589.63
2011	Trois-Rivières	13.44	46.95	680.09	7.32	37022.31
1991	Vancouver	24.49	48.54	333.31	13.99	19035.55
2001	Vancouver	29.62	48.68	331.04	17.03	19034.64
2011	Vancouver	30.72	48.64	295.51	17.24	16578.32
1991	Victoria	24.28	47.93	438.20	13.80	24911.33
2001	Victoria	28.94	48.10	493.92	16.76	28613.42
2011	Victoria	31.15	48.06	463.58	17.93	26681.08
1991	Windsor	19.32	48.02	540.74	11.20	31341.91
2001	Windsor	22.54	48.02	544.75	13.07	31584.67
2011	Windsor	23.33	48.06	567.83	13.59	33083.05
1991	Winnipeg	8.92	48.33	512.30	5.25	30162.90
2001	Winnipeg	9.23	48.26	521.41	5.42	30612.61
2011	Winnipeg	9.65	48.24	505.57	5.65	29593.25