Measurement of urban sprawl in the metropolitan areas of Montreal and Quebec over 60 years

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ABSTRACT

Measurement of urban sprawl in the metropolitan areas of Montreal and Quebec over 60 years

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Increasing awareness of the negative effects of urban sprawl has made this phenomenon a topic of great debate. However, there still are no agreed methods for measuring this phenomenon. This thesis uses the current and historical data and applies the newly developed metrics of urban permeation and weighted urban proliferation to measure the level of urban sprawl in the Montreal and Quebec census metropolitan areas over the past sixty years. This study also compares the two study areas with Zurich metropolitan area with regard to urban sprawl and its change over time.

The results indicate that since 1951, and more significantly during the past 25 years, urban sprawl has been rapidly increasing in the Montreal and Quebec census metropolitan areas. In Zurich, the sharpest increases of urban sprawl occurred during the period 1960 to 1980. Three major reasons for this striking difference in sprawl dynamics are the planning laws legislation since 1979 in Switzerland, the much lower level of public transportation availability in Montreal and Quebec and the polycentric settlement structure in Zurich.

The comparative assessment of urban sprawl presented in this study can be used for scenario analysis and decision-making. Its results provide a basis for monitoring and controlling urban sprawl and its negative consequences and thus, would greatly help land-use planners critically assess projected plans.

The thesis also provides an assessment of Entropy, which is among the mostly used methods for measurement of urban sprawl. The results showed that Entropy is not a

reliable method since it does not meet fundamental criteria for the measurement of urban sprawl.

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The work that I accomplished during my master's program, gave me a good insight on the issue of urban sprawl, methods for quantifying the degree of this phenomenon and more specifically the situation of urban sprawl in Montreal and Quebec. I would like to take this opportunity to thank those who have helped me during this journey.

To begin with, I would like to express my deepest appreciation to my supervisor, Dr. Jochen Jaeger, for giving me the opportunity to join his group and begin this research project. A special gratitude I give to him regarding all his patience, enthusiasm, engagements, and finally his immense knowledge. His guidance helped me from the beginning of this project to the very end; I could not imagine having a better supervisor for my master's study.

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Contributions of Authors

The first paper of this research work, titled “Historical analysis of urban sprawl in Montreal and Quebec and a comparison with the results from Zurich” is presented in chapter 5. The paper presents quantitative measurements of urban sprawl in the metropolitan areas of Montreal, Quebec and Zurich at different scales from metropolitan area to municipality and census tract levels. It looks at similarities and differences between the three study areas regarding urban sprawl and its change over time and discusses the potential reasons for these differences.

This paper was presented in an earlier version at the 25th International Conference of European Network for Housing Research (ENHR), held in Tarragona, Spain on June 22, 2013.

- Nazarnia, N.[a], Schwick, C.[b], Jaeger, J.A.G.[c] (to be submitted).

a: first author: responsible for the conception of the paper, acquisition of data, data collection for inhabitants and jobs and historic topographic maps, digitization of topographic maps using GIS for the years 1951,1971 and 1986, data analysis and quantitative calculations for Montreal and Quebec, interpretation of data and results and writing up the paper.

b: second author: contributed to conception and design, data analysis and quantitative calculations for Zurich.

c: third author as well as corresponding author: contributed on conception and design, critical revision of the content of the paper.

The second paper of this research work entitled “How reliable is the Entropy method as a measure of urban sprawl?” is presented in Appendix 1.The paper presents a critical assessment of a commonly used method for the measurement of urban sprawl, called Shannon's Entropy. The paper provides four different procedures to assess the reliability of Entropy as a measure of sprawl.

- Jaeger, J.A.G.[a], Nazarnia, N.[b], Harding, C[c]., (to be submitted).

a: first author: shared the idea, contributed to the design of the study and methods for performing the study and critical revision of the content.

b: second author: contributed to conception and design, writing and drafting the paper, quantitative analysis for measurement of Entropy and interpretation of the results.

c: third author: contributed to conception and design, quantitative analysis for measurement of Entropy in real case studies.

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1. Introduction

It has been predicted that by 2050, 70% of the world's human population will be living in urban areas (Population Reference Bureau, 2007). This is mostly due to fast population growth, as well as growth in urban areas. Basically, there are two main types of growth: First, traditional neighbourhoods, which are the basic form of development in European regions represented by mixed use pedestrian communities, and second, suburban sprawl, which is a post-war invention of planners and is now the standard pattern of urban development in North America (Duany et al. 2001). In his book, 'Suburbia', Thorns (1972) expressed that in the U.S., the first group of people who moved to the suburbs were wealthier people, but this movement has continued and in 1972 (when the book was published) fifty percent of people in the U.S. lived in suburbs (Thorns 1972). This amount has even increased since 1970. Putnam (2000), in his book 'Bowling Alone', also declared that in 1950, only half of Americans lived in cities; however, in the year 2000, four in five Americans lived in metropolitan areas (Putnam 2000).

Despite many negative effects of sprawl, people keep moving from city centers to surrounding suburbs which may have economic reasons. Monthly housing mortgages on homes in the suburbs may be cheaper than rents of a similar home in the city (Wright and Boorse, 2013). Therefore, more and more people have been interested in buying a house in low density suburbs. Also, "people perceive that it is better to live in such areas so they move there" (Wright and Boorse, 2013, p. 581). But it is important to know that "People tend to make choices based on personal good rather than common good" (Wright and Boorse, 2013, p. 581).

In general, cities are full of positive and negative elements that have different strengths (Anas et al. 1998). In today's life, some people tend to interact face to face, but others prefer to use telecommunications and interact remotely, these interactions along with history and a "good deal of chance" are elements of the spatial structure of cities (Anas et al. 1998).

The perceived benefits of sprawl are low density residential neighborhoods, large single family houses with large size lots, higher quality public schools, higher level of social services and more homogeneous neighborhoods (Wright and Boorse, 2013). However, when comparing these perceived benefits to the costs of sprawl, most researchers and scholars believe that the negative costs of sprawl by far outweigh its benefits and that urban sprawl is not an acceptable form of development.

Urban sprawl has harmful effects on various environmental, economical and social aspects, including loss of open space, soil sealing, increase in traffic, decrease in neighbourhood aesthetics, different kinds of pollution, decrease in social capital, and many other negative impacts (Haber 2007, EEA 2006, Putnam 2000). Therefore, urban sprawl is an important local, regional and national issue.

The loss of agricultural lands due to urbanization has put international and local bodies under pressure. The negative consequences of sprawl, such as concerns for adequate land resources for energy and food production, recognizing rural lands as recreational areas, and the desire to preserve culturally-valued landscapes, make studying urban sprawl important.

Measuring urban sprawl would greatly help to describe how urban development spreads. First, we need to better understand the rate and degree of landscape change and its trends over time. Second, once we know the degree at which sprawl occurs, we can identify potential correlations between sprawl and different indicators such as car dependency. Third, the output of the study of sprawl could be utilized in environmental monitoring systems to introduce quantitative environmental quality standards.

Most of the methods that researchers have applied in real-world case studies to measure the level of urban sprawl, lack suitability and reliability due to various problems (the literature review presents a more detailed discussion, chapter 2). So far, only few convincing and reliable metrics have been developed for measuring urban sprawl (Jaeger et al. 2010b).

In Canada, there are only few studies conducted for the quantitative measurement of urban sprawl. The focus of most of them is on the consequences and associated relevant topics of sprawl rather than the sprawl itself. A study on the differences between urban densities in major metropolitan areas of Canada (Filion et al. 2010), and a study on the direct and indirect impacts of urban development on agricultural lands in two county of Oxford and La prairie (Pond and Yeates 1993), are among them.

In Canada, as in many other regions in North America, cities are growing dramatically. Many cities of this country suffer from urban sprawl including the two important metropolitan areas of the Quebec province, Montreal and Quebec. While the preservation of agricultural land that is the most important source of energy and food (Haber 2007) plays a vital role in these areas, many fertile agricultural lands in Montreal and Quebec have been converted to urban areas in the past few decades. This is particularly problematic in Quebec because the proportion of Quebec’s land area that is suitable for agriculture is very small (less than 2%). In 2006, the Census of Agriculture reported a 4.6% decline in the number of agricultural farms in Quebec within a period of 5 years from 2001 to 2006 (Statscan 2006a).

This thesis will first provide the reader with an overview of the most important literature related to urban sprawl, focusing on the methods for the measurement of this phenomenon. In the third chapter, the methods that were used for conducting the present study are introduced. Chapters 5 presents the manuscript for peer-reviewed journal as the output of this research project. This manuscript does not explain the complex causes and consequences of sprawl in detail, but rather compares the degree of urban sprawl and its change over the past sixty years in the two major metropolitan areas of Montreal and Quebec. Chapter four also provides a comparison between these two study areas with a European example (Zurich metropolitan area in Switzerland) regarding sprawl and its changes over time. Finally, chapter 6 presents the overall discussion and conclusion of the whole thesis. The overall research question of the thesis is:

"What is the current degree of urban sprawl in the Montreal and Quebec census metropolitan areas and what are the trends of sprawl over time?"

And the sub-questions are:

1. What are the similarities and differences between MCMA and QCMA and how do they compare with the Zurich metropolitan area (ZMA) regarding their current degree of urban sprawl and its change over time?
2. How quickly has the degree of urban sprawl increased since 1950 to the current time in the selected case studies? What were the trends of sprawl during the past 60 years? What are the current trends?

3. Where are the highest levels of sprawl, and when did the strongest increases of sprawl occur in the selected study areas?

I also attempt to answer several additional questions in the discussion of my results such as:

1. What are the potential reasons for the strong increases or decreases of sprawl at a specific space and time based on the trend of urban sprawl during the past 60 years?
2. What are the limitations and potential thresholds of urban sprawl in some specific regions, based on planning regulations?
3. What challenges will the future bring, and which particular issues need immediate action, and how effective are existing mechanisms in protecting landscapes against sprawl?

2. Literature Review

2.1. Introduction

In order to achieve the goals discussed in chapter one, it is useful to understand the importance of urban sprawl, its causes and consequences, and also the different methods that have been applied to measure this phenomenon.

The review of the literature firstly goes over different definitions that exist for urban sprawl. Afterwards the discussion of causes and the consequences of urban sprawl is presented. Also, different approaches that have been used to measure the degree of urban sprawl and important criteria for measurement of urban sprawl are reviewed. This section also tries to investigate the similarities and differences of the most common methods, and of their potential problems by evaluating the reviewed methods with regard to criteria for measurement of urban sprawl. Finally, the studies that aimed to quantify the degree of urban sprawl in Canada are reviewed.

2.2. Definitions of urban sprawl

The word sprawl itself means that the boundaries of the city extend out into the countryside, without having plans as to where this expansion is going and where it will stop (Wright and Boorse 2013).

The term “urban sprawl” was first used by William Whyte in Fortune magazine in 1958 (Whyte 1958). In German literature the term ‘‘Zersiedelung’’ (meaning sprawl) was even used earlier in the 1920s, but was mostly used in the German-speaking countries after the second world war (Akademie für Raumforschungund Landesplanung 1970).

Since that time, many researchers defined “urban sprawl” in different ways (the most common definitions in the literature are collected in table 2-1).

Unclear definitions and various characterizations of urban sprawl in the literature have made it very difficult to compare the results from different studies. Many researchers use causes and consequences of urban sprawl in their definition, and most of the time, urban sprawl is defined qualitatively rather than quantitatively (Jaeger et al. 2010a, Daniels 1998). Theobald (2001) also pointed to the relationship between the definition of urban sprawl and its indicators: Most definitions of urban sprawl emerge from indicators of sprawl; for example, increased traffic, development of auto dependency, low-density housing, and scattered development (Theobald 2001). In other words, most of the definitions of sprawl seek to describe urban sprawl rather than define this phenomenon (Wilson et al. 2003).

Generally, there are three main reasons for the variety of definitions in the literature. Firstly, since urban sprawl is studied in different fields and disciplines, how sprawl is defined depends on the perspective of the person who presents the definition (Barnes et al. 2001); secondly, it is hard for researchers to distinguish sprawl from related terms, such as “suburbanization” or “suburban development” (Franz et al. 2006); and finally, some variation in the definition of urban sprawl is due to the fact that in many studies, causes and consequences of sprawl are confused with its definition (Jaeger et al. 2010a). For a better understanding of the nature of urban sprawl, it is necessary to have a satisfactory definition for this phenomenon. In particular, when it comes to measuring the degree of urban sprawl, a lack of a consistent definition disables the development of reliable methods for measuring urban sprawl. Therefore, until now, there is no agreed way of measuring urban sprawl, as there is no generally accepted definition for this phenomenon (Bhatta et al. 2010, Jaeger et al. 2010a). One of the best definitions in the literature which distinguishes causes and consequences of urban sprawl from the phenomenon itself, is the definition by Jaeger et al. (2010a), which is presented below:

"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, p.400).

This definition was further developed by Schwick et al. (2012) by including population density as an important dimension of urban sprawl (Figure 2-1).

"Urban sprawl therefore denotes the extent of the area that is built-up and its dispersion in the landscape in relation to the utilization of built-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" (Schwick et al. 2012, p.13).

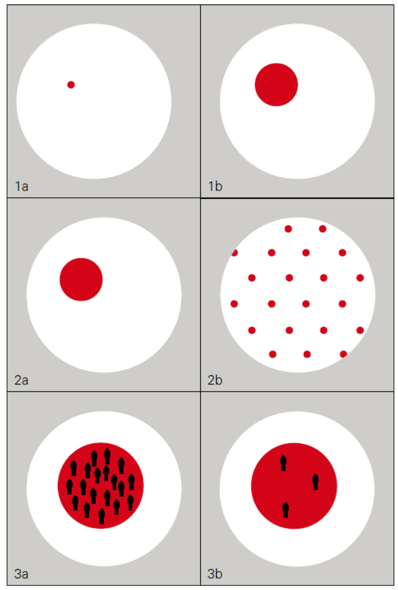


Figure 2-1: Three dimensions of sprawl. Urban sprawl is higher when 1) the settlement area increases (1a to 1b), the settlement area is more dispersed (2a to 2b), or the utilization density is lower (3a to 3b), (Schwick et al. 2012).

Many proposed definitions for urban sprawl in the literature use car dependency to describe it, mostly because a positive feedback loop exists between sprawl and car dependency and one directly impacts the other. However, since my research measures sprawl as a land-use pattern, car dependency is not used as a part of the definition for urban sprawl.

Table 2-1: An overview of the existing definitions of urban sprawl in the literature.

Definition	Source
"Sprawl is not suburbanization generally, but rather forms of suburban development that lack accessibility and open space, sprawl is not a natural response to market forces, but a product of subsides and other market imperfections".	Ewing (1994)
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".	Ewing (1997)
Sprawl is ''low-density development beyond the edge of service and employment, which separates where people live from where they shop, work, recreate and educate—thus requiring cars to move between	Sierra Club (1998)

Definition	Source
zones’’.	
“The metropolitan area can be characterized as sprawling when land is being consumed at a faster rate than population growth”.	Fulton et al. (2001)
Sprawl is “the process in which the spread of development across the landscape far outpaces population growth. The landscape sprawl creates 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 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. (2003)
Sprawl occurs “When the rate of development of land outstrips the rate of population growth”.	(Sudhira 2004)
“Sprawl is low-density, leapfrog development characterized by unlimited outward extension. In other words, sprawl is significant residential or nonresidential development in a relatively pristine setting. In nearly every instance, this development is low density, it has leaped over other development to become established in an outlying area, and its very location indicates that it is unbounded”.	Burchell and Galley (2003)
“Sprawl is usually characterized by auto-center, low density communities that consume large amount of space per capita”.	Davis and Schaub (2005)
Sprawl is “physical pattern of low density expansion of large areas under market conditions mainly into the surrounding agricultural areas”.	EEA (2006)
“Sprawl is characterized by unplanned and uneven pattern of growth driven by a multitude of processes and leading to inefficient resource utilization”.	Bhatta (2010)
“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)

Definition	Source
"Urban 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 built-up and its dispersion in the landscape in relation to the utilization of built-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".	Schwick et al. (2012)

2.3. Causes of urban sprawl

According to the literature, urban sprawl is caused by large and limitless extensions of urban areas, decline in urban densities, and the increasing consumption of land resources by urban dwellers (Angel et al. 2007). The increase of distances between the built-up areas to each other along with unorganized growth, which is the result of lack of sustainable planning for landscape development, desire to live in a green and open neighbourhood, the building of second homes, and the wish for low-priced lots, are further causes of urban sprawl (Jaeger et al. 2010a).

In 1958, Whyte stated that when high population density and wealth come together, the extent of sprawl becomes higher and higher, and, therefore, open space becomes a scarce resource (Mann 2009). Solid consumer preference for single-family detached housing, which is stronger in suburbs, telecommunication innovations, which have allowed many activities to disperse, as well as low gasoline prices and independency of distance between home and central facilities, are key drivers of urban sprawl (Ewing 1997).

All landscape patterns, including urban sprawl, should be judged by their effects (Ewing et al. 2003). Negative outcomes of urban sprawl, such as high vehicle miles traveled, make this phenomenon an important regional and national issue (Ewing et al. 2003).

In fact, the relationship between transportation and sprawl is so close that which one is the cause/effect of the other cannot be distinguished. Telecommunication innovation and new highway construction are key drivers of sprawl. “Sprawl is created by transportation decisions that use urban highways and six-lane arterials rather than modest roads” (Marshall, p. 47).

According to several studies, the origin of the growth in cities and suburbs is not clear, and it seems that it is difficult to determine the exact time in which suburbs have started to develop around the cities in North America. However, there are several important dates at which the rate of suburbanization sharply increased. One of the most important dates is at the end of the Second World War when massive middle-class suburbanization took place in the United State (Angel et al. 2010). In the North American cities, suburban sprawl is the result of a number of policies that caused urban dispersion (Duany et al. 2001). The most significant of these were the federal housing administration and Veterans administration loan programs after the Second World War and, consequently, the creation of eleven million houses within the new economic framework in the US (Duany et al. 2001).

With the invention of the automobile, the cities of Montreal and Quebec similar to many other North American cities has started to sprawl, particularly since 1950 (Gauthier et al. 2009). City growth has been always affected by the history of transportation (Gauthier et al. 2009). From the beginning of the formation of the cities to 1870, the cities were built for walking and horse riding. But, from roughly 1870 with the invention of the tramway and trains cities started to stretch out especially close to the new metro stations (Gauthier et al. 2009).

2.4. Consequences of urban sprawl

Arguments opposing urban sprawl cover a wide spectrum, from health and environmental issues to social and economic concerns. In this section, negative impacts of urban sprawl are divided into five groups: environmental issues, impacts on biodiversity, economic issues, impacts on public health, and communities.

2.4.1 Environmental issues

There are many environmental issues that urban sprawl brings to modern societies. Soil sealing, land consumption and landscape fragmentation, loss of agricultural lands due to conversion into built-up areas and, therefore, increasing scarcity of land for food production, and renewable energy supplies, are major issues caused by urban sprawl (Siedentop and Fina 2010, Yeh and Li 2001, Muller et al. 2010, Jaeger et al. 2010a). Reductions of the capacity of the soil to act as a carbon sink (EEA 2006), pollution by oil, fuel and other pollutants are additional negative effects that urban sprawl has on land and soil. Further impacts include the increase of urban greenhouse gas emissions (Frumkin 2002), higher noise levels produced by vehicles and the rapid growth in transport volumes and urban air pollution through higher dependence on cars (Siedentop and Fina, 2010).

Urban sprawl also has negative effects on hydrological systems. Sprawling areas that were previously covered by forests, or used for agricultural purposes, are now covered with impassable surfaces, such as concrete and asphalt, prompting rainfall to be less effectively absorbed into the groundwater aquifers (Frumkin 2002, EEA 2006). Loss of permeability of soil for water and increased water pollution that usually occurs when rain water picks up gasoline, oil, and other pollutants while running off from parking lots and roads, are additional negative consequences of urban sprawl (Frumkin 2002).

2.4.2 Impacts on flora and fauna (biodiversity)

The loss of valuable ecosystems due to the conversion of forests and open spaces into built-up areas has negative impacts on biodiversity. For example, negative impacts on abundance, species richness and evenness of forest breeding birds were reported by Gagne and Fahrig (2010). They showed that in compact housing developments where more open space was left, the impact of the human population on forest breeding birds is minimized compared to other types of development (Figure 2-2) (Gagne and Fahrig 2010).

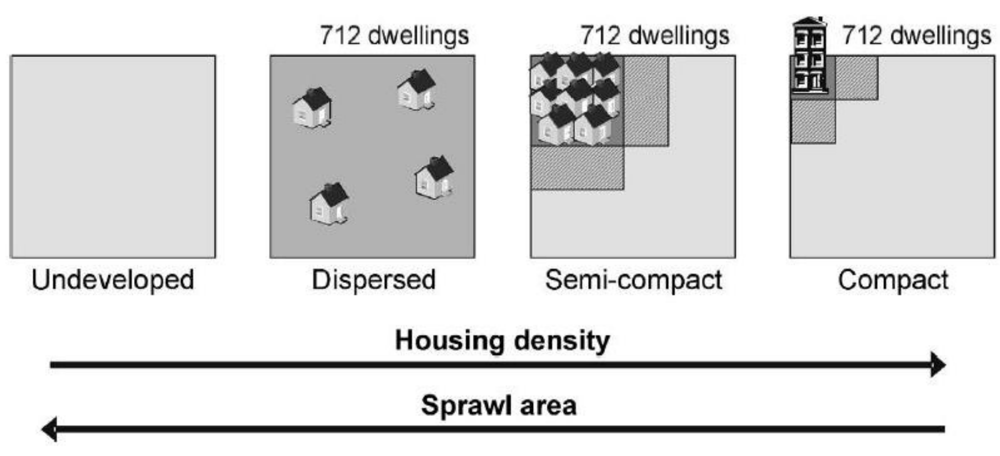


Figure 2-2: Hypothetical scenarios of the increase of housing density and decrease of sprawl for a specific forested area. As the developed areas become more compact in the landscape, more open space is left for forest breeding birds, and the impact of the human population on forest breeding birds decreases (source: Gagne and Fahrig 2010).

Urban sprawl has caused the evanescence of many kinds of birds and an increase in feral birds (Sushinsky et al. 2013). In this study the authors developed two different scenarios of compact urban development and sprawled development and concluded that in sprawled scenario many urban-sensitive birds will disappear whereas a compact scenario makes city more biodiverse (Sushinsky et al. 2013).

Landscape fragmentation as well as conversion of habitats to urban areas are the negative impacts of urban sprawl on biodiversity. Animal activities can change along with the change in land use (McClennen et al. 2001). In sprawled areas, conversion of habitat to roads and built-up areas is not the only threat for biodiversity; in fact, in sprawled regions, the effects of human disturbance which are distributed over larger areas are the main threats for biodiversity (Forys and Allen 2005).

Also, construction of numerous roads close to habitats has an effect on animal populations. As an example, the study on the effect of roads on amphibian populations in Djursland in northern Denmark showed that each year, 10% of *fuscus* frogs and Brown frog's population are killed on the roads (Hels and Buchwald 2001).

2.4.3 Economic issues

Although some economists found urban sprawl and suburbanization to be helpful phenomena for the economy (e.g. Gorden and Richardson 1997), there are serious negative impacts that urban sprawl imposes on the economy. These include higher infrastructure expenditure for construction and maintenance and higher public service costs, such as public transportation costs (Siedentop and Fina 2010, Ewing 1997). In dispersed cities, designers and city planners are forced to build a larger number of highways and parking infrastructures to link the working places to living areas, which requires larger amounts of money. Providing services, such as water, sewers, and electricity is also more expensive in less dense areas.

2.4.4 Impacts on social issues

Many researchers found that sprawl and suburbanization cause a lack of sense of community and safety among people (Duany et al. 2001). They believe that the lack of civic engagement and other aspects of social capital are even higher in suburbs and dispersed areas than in inner city areas. According to the responses to various questions about social trust among citizens of the United States, most studies suggested that social trust in the United States has declined for more than a quarter century (Putnam 1993). In other words, "strong communities of place where neighbours interact, have a sense of belonging, and have a feeling of responsibility for one another are harder to find" (Ewing 1997, p.117), specifically in suburbs with a dispersed character rather than in small traditional neighbourhoods.

Unlike traditional neighbourhoods, suburbs are considered unhealthy forms of development (Duany et al. 2001), mainly because in suburbs, human experiences and social communications are ignored.

Long car driving and long commutes in dispersed areas have negative effects on community life. Every extra ten minutes in daily commuting time cuts the involvement in community interactions by 10 percent fewer public meeting attendance and other different social involvements (Putnam 2000). Putnam argues that sprawl is associated with increasing social divisions based on the similarities of a group of people living together (Putnam 2000). These social similarities reduce the motivation to civic involvements in the society, and a reduction of opportunities for social networks that are based on class and race of people is the consequence of sprawl, so much that "sprawl is toxic for bridging social capital" (Putnam 2000).

The study on the relationships between social capital and built environment indicated that "persons living in walkable, mixed-use neighborhoods have higher levels of social capital compared with those living in car-oriented suburbs" (Leyden 2003, p 1546).

2.4.5 Impacts on public health

There is a relationship between urban sprawl and public health. Social capital, which is associated with a lower level of violence and crime, less frequent drinking, more leisure time, more physical activities, and fewer health issues, is in serious danger in dispersed and fast growing cities (Frumkin et al. 2004). Urban form is significantly associated with some health outcomes (Ewing et al. 2003). Higher levels of disturbance and stress, increases in traffic and traffic-related fatalities, and delays in emergency services due to high traffic volumes and long distances are other public issues that sprawl brings to societies (Lambert and Meyer 2008).

Many negative issues are caused by urban sprawl and city growth (Table 2-2). Understanding the consequences of urban sprawl helps urban planners and city governors learn that it is essential to stop urban sprawl or at least lower and control the rate of its increase in cities.

Table 2-2: Consequences of urban sprawl

Theme	Consequences of urban sprawl	References
Energy	• Less land available for renewable energy supplies and industrial purposes • Higher energy consumption (e.g. due to dispersed character of sprawled areas)	• Haber (2007) • Ewing (1997)

Food	• Less land available for food production • Reduced quality of agricultural products (e.g. due to soil contamination or over fertilization	• Haber (2007) • EEA (2011)*
Land	• Land consumption and soil sealing • Landscape fragmentation • Loss of agricultural lands due to conversion into higher built-up areas	• Siedentop and Fina (2010)* • Siedentop and Fina (2010)* • Yeh and Li (2001)
Climate	• Modification of temperature conditions (e.g. heat island effect, heating up of roads) • Modification of wind conditions (e.g. due to aisles in forests in fragmented areas)	• Frumkin (2002) • EEA (2011)*
Economic	• Higher infrastructure expenditure for construction and maintenance •Higher public service costs (e.g. higher public transport costs) • Increase in personal transportation costs due to long commutes	• Siedentop and Fina (2010) • Ewing (1997) • TCRP (2000)
Human being	• Negative health effects, such as obesity • Increase in traffic and traffic-related fatalities • Lack of physical activity (e.g. due to higher automobile dependency) • Higher mental health problems (e.g. higher level of stress due to long time automobile commuting, which may lead to road rage)	• Ewing et al. (2003) • Frumkin (2002) • Frumkin (2002) • Frumkin (2002)
Landscape scenery	• Change in look of landscape (e.g. penetration of the landscape by posts and wires) • Change of landscape character due to its less recreational character in sprawled areas.	• Muller et al. (2010) • Muller et al. (2010)
Flora and fauna	• Loss of valuable ecosystems for different kinds of animals • Impacts on forest-breeding birds (e.g. birds abundance, species richness and eveness) • Death of animals caused by road mortality • Change in animal movement behavior due to changes in the land use (e.g. change of coyote movement pattern in suburban areas)	• Forys and Allen (2005) • Gagne and Fahrig (2010) • EEA (2011)* • Forys and Allen (2005)
Water	• Negative impact on hydrological systems (for example, accelerated drainage of water through road drains and city sewer systems, which alters the rates of infiltration, evaporation, and transpiration) • Loss of permeability of soil for water. • Increased water pollution (e.g pollution by oil and fuel)	• Muller et al. (2010) • Frumkin (2002) • EEA (2011)*

Pollution	• Higher noise pollution (e.g. the noise produced by vehicles and rapid growth in transport volumes) • Urban air pollution (e.g. air pollution due to higher dependency on cars and higher use of fuel and oil)	• EEA report (2006) • Siedentop and Fina (2010)* • Frumkin (2002)
Social behavior	• Higher racial and social segregation based on race and class in suburbs, which leads to less social interactions • Reductions in social interactions due to long time car driving and having less time for social involvements.	• Putnam (2002) • Putnam (2002)

Note: * indicates that the statement is taken from an indirect (second) source.

2.5. Measurement of urban sprawl

There has been a lack of agreement on defining urban sprawl which complicates the measurement of this phenomenon (Wilson et al. 2003, Jaeger et al. 2010). Therefore, finding a suitable method for measuring urban sprawl is still an important issue.

2.5.1 Methods for measurement of urban sprawl

In most of the methods in the literature, causes or consequences of urban sprawl are used as indicators for the measurement of urban sprawl. In this part, a short review of the most common methods is presented.

1) Angel et al. (2007) used five metrics for characterizing sprawl, and five metrics for defining “key manifestations” of sprawl (metrics of main urban core, secondary urban core, urban fringe, ribbon development and scatter development). They applied these metrics to two case studies: Bangkok and Minneapolis. The authors defined and measured sprawl both as a pattern, and as a process. They considered sprawl as a geographic pattern and measured its change over time. This method is suitable for comparing either the sprawl in two different cities or in two different time steps in one city (Angel et al. 2007, Bhatta et al. 2010). However, it lacks an independent metric or

overall indicator to show the level of sprawl as a matter of degree. In this study, the authors used five attributes to characterize sprawl, developing several metrics for each attribute to measure it. However, they did not recommend any standard threshold that can be used to distinguish a sprawling city from a non-sprawling one. In addition, since they used so many metrics, interpreting their results is complicated and they suggest no single metric as representing the level of sprawl.

2) Jiang et al. (2007) used 13 geospatial indices in three groups (urban growth efficiency, spatial configuration and external impacts). Various types of datasets, including former land use maps, land use maps, land prices maps, floor area maps, land use planning maps and population datasets were used for calculating these 13 indices. In this method, an integrated urban sprawl index (*USI*) was calculated by summing the value of weighted indices after the four steps of data preparation, integrating all indices into the same platform, a standardization process of the indices with different dimensions, and weighting all of the indices by a paired comparison method (Jiang et al. 2007).

By using the *USI*, the authors were able to create a map, which consists of four different types of sprawl patterns in the city (including areas with rational growth, areas with low sprawling pattern, areas with moderate sprawling patterns, and high sprawling areas). The major disadvantage of the *USI* metric is that numerous datasets are needed for the calculation of the 13 geospatial indices.

3) Mann (2009) used two different measurements of rural and urban sprawl in Gempenach, Tartegnin, Concise and Bure, municipalities of Switzerland. First, a static analysis, indicated why some municipalities use more settlement area per person than other municipalities, and second, a dynamic analysis indicated why some municipalities

managed to reduce the amount of built-up areas per person, while others expanding this amount (Mann 2009). Four response variables of residential building area per person, building area per person (all the buildings areas other than residential buildings area per person), traffic area per person, and a sum variable, which is the sum of traffic and building area per person, were used in the static analysis. Also, three response variables of building area per person, traffic area per person, as well as a settlement variable, which describes the whole settlement area, was used in the dynamic analysis. For the static analysis, the author used 17 independent variables, and for the dynamic analysis, the author used four other independent variables. This method is useful for better understanding the effects of different variables on urban or rural sprawl and their role in increasing or decreasing future developments.

4) Siedentop and Fina (2010) introduced a new measurement of urban sprawl through an indicator-based framework. Urban sprawl is seen as a multi-dimensional phenomenon, which can be measured only through a multiple-indicator approach. Therefore, they used three metrics of density, pattern, and surface, and measured these metrics by calculating multiple indicators for each of them. First, they developed methods to calculate indicator values using a number of mathematical formulas. Next, using GIS transformation routines, all outputs of the calculations were scaled to a grid of 10×10 km cells. Afterwards, they analyzed the results statistically to find the areas with high values of sprawl. The objective of the statistical analyses was to generate a classification for urban sprawl. Siedentop and Fina (2010) conceptualized five clusters of sprawl in semantic terms. The five clusters were non-sprawl areas, suburban areas, exurban areas, shrinkage areas, and metropolitan areas.

5) Galster et al. (2001) used eight different metrics of land use patterns (density, continuity, concentration, clustering, centrality, nuclearity, mixed uses, and proximity) to measure sprawl in 13 American cities. Similar to many other studies, in this study there is no proposed metric to measure level of urban sprawl independently.

6) Ewing et al. (2002) developed four factor sprawl index of (1) Residential density; 2) neighborhood mix of homes, jobs, and services; 3) strength of activity centers and downtowns and 4) accessibility of the street network for measurement of sprawl in 83 metropolitan regions in the U.S. Authors developed 22 indicators to measure these four factor index. Overall Four Factor Sprawl Index which is obtained by the combination of scores for four mentioned sprawl index indicates the level of sprawl in each metropolitan region.

This method evaluates the main indicators of sprawl such as density, mix of land uses, strength of activity centers, and connectedness of the street network and also looks at the relationship between sprawl and its impacts. However large number of indicators used to calculate the defined four factor sprawl index is the main limitation with this method.

There are many other methods in the literature, in which different indicators are compared or summed up to determine the level of sprawl. (e.g., Tsai (2005) used density, diversity and spatial structure patterns to measure sprawl and the Sierra Club (1998) used four different attributes including population that moved from the inner city into suburban areas, proportion of land use and population growth, the time spent on traffic, and the amount of decrease in open space to rank capital cities of the United States regarding sprawl). However, many of these methods use large number of dataset and compare different sprawl indicators to determine the extent of sprawl. There are only few methods in which reasonable amount of data is used to measure the degree of sprawl (e.g., Entropy and weighted urban proliferation methods).

7) Yeh and Li (2001) used Shannon's Entropy as a new method for the measurement of urban sprawl. Shannon's Entropy can be used to measure the degree of dispersion or concentration of built-up areas among *n* zones and is calculated as:

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

where P_i is the proportion of built-up areas in the *i*th zone.

Using remote sensing data and GIS, authors created zones around city centers, and also a number of zones along roads to calculate the dispersion or concentration of the built-up areas in each specific zone.

Entropy is sensitive to the variations in form and size of the regions (Yeh and Li 2001). For example, if larger regions or zones are divided into smaller zones, the Entropy would increase according to:

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

The authors declared that this method can be useful for planners and city governors to monitor urban sprawl and land use pattern changes.

8) Jaeger et al. (2010b) introduced four metrics with geometric character for measuring urban sprawl: urban permeation (*UP*), urban dispersion (*DIS*), total sprawl (*TS*) and sprawl per capita (*SPC*). Following this study, Schwick et al. (2012) proposed the weighted urban proliferation (*WUP*) metric to serve as the level of urban sprawl

indicator. *WUP* combines *UP*, weighted *DIS* (w_1 (DIS)), and the new metric weighted utilization density *(w_2 (UD))*.

Urban permeation measures the total sprawl divided by the total size of the reporting unit. *UP* describes the degree to which the landscape is permeated by settlement areas and buildings (Jaeger et al. 2010b). Dispersion measures the average weighted distance between any two points chosen within a distance less than the scale of analysis (Jaeger et al. 2010b). Total sprawl is the combination of dispersion and total amount of urban areas (Jaeger et al. 2010b). Sprawl per capita is equal to total sprawl divided by the number of inhabitants and number of jobs in the reporting unit (Jaeger et al. 2010b). *SPC* relates sprawl to the number of inhabitants and jobs; thus, it is a useful metric in the studies in which sprawl is considered in relation to human population density (Jaeger et al. 2010b). *UD* measures the density of inhabitants and jobs in the settlement areas (built-up areas) (Schwick et al. 2012). And finally *WUP* which is the indicator of sprawl is the combination of *UP, DIS* and *UD* $\left(WUP = UP \cdot w_1\,(DIS) \cdot w_2(UD)\right)$.

In this study, a very important concept, named "horizon of perception" (*HP*), is introduced. *HP* defines the scale of analysis as a maximum distance between two independent points of built-up areas considered in the calculation of the metrics (Jaeger et al. 2010b).

2.5.2 Criteria for measures of urban sprawl

Any landscape metric must meet several specific requirements depending on its purpose. Jaeger et al. (2010a) introduced 13 suitability criteria which contain all the requirements that a specific method for measuring urban sprawl should meet. The 13 suitability criteria help better understand the behavior of metrics and their reliability.

These 13 important 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 (Jaeger et al. 2010a).

Bhatta et al. (2010) also mentioned number of criteria for assessing sprawl metrics, including a reasonable number of indices and datasets as well as the existence of a specified threshold, to distinguish sprawl from non-sprawl condition (Bhatta et al. 2010).

2.5.3 Assessing the metrics for urban sprawl measurement

I assesses the methods described in the previous section according to six different criteria driven by those introduced by Jaeger et al. (2010a), Bhatta et al. (2010) and two additional criteria: 1) the possibility of applying the method at any scale and for different reporting units and 2) the existence of an independent metric for quantifying the degree of sprawl. The complete list of selected criteria is as follows: 1) intuitive interpretation of the method, 2) mathematical simplicity, 3) modest data requirements (reasonable number of indices), 4) existence of a specific threshold to distinguish sprawl from a non-sprawl areas, 5) possibility of applying the method at any scale and for different reporting units (e.g., census tracts, districts, municipalities, *etc*.), and 6) an independent metric indicating quantitative degree of sprawl. Table 2-3 presents the assessment of methods with regard to these six criteria.

Table 2-3: Assessment of the reviewed methods regarding six different criteria for the quantitative measurement of urban sprawl.

Criterion	Angel et al. (2007)	Jiang et al. (2007)	Mann (2009)	Sidentop and Fina (2010)	Galster et al. (2001)	Ewing et al. (2002)	Yeh and Li (2001)	Schwick et al. 2012
1) Intuitive interpretation	+	-	+	-	+	+	+	+
2) Mathematical simplicity	+	+	+	-	-	+	+	+
3) Modest data requirements	-	-	-	-	-	-	+	+
4) Threshold for sprawl	-	+	-	+	-	-	-	+
5) Possibility of using different reporting units	+	+	+	+	+	+	+	+
6) Independent metric for quantification of degree of sprawl	-	+	-	+	+	+	+	+

One major problem with most of the metrics is the high number of indices required for sprawl analysis (e.g., Angel et al. 2007, Jiang et al. 2007, Sidentop and Fina 2010 and etc.). Dataset availability is an important issue, specifically in developing countries (Bhatta et al. 2010). It is difficult for urban planners or city governors to use a large number of metrics to describe the development situation in a rapidly growing region, because interpreting results from multiple indices is complicated and confusing. Another common problem is that, in most of these metrics, no threshold is specified to distinguish a sprawl from non-sprawl region. Additionally, many of the proposed metrics do not offer an independent metric that indicates the value of sprawl as a matter of degree (e.g., value of sprawl = 2 (appropriate unit of sprawl)). My evaluation of the studied methods indicates that Entropy and weighted urban proliferation are among the most suitable sprawl measurement methods. Therefore, I investigated the behaviour of these two methods further with regard to 13 suitability criteria (Table 2-4).

My results revealed that Entropy does not meet 7 out of 13 suitability criteria. For example, it does not meet mandatory criterion number 6 meaning that it is not sensitive to the compactness and dispersion of urban patches (a comprehensive investigation on the behaviour of Entropy as a measure of sprawl is presented in Appendix 1).

Contrary to the Entropy method, the urban permeation and weighted urban proliferation method fulfill all suitability criteria (see Jaeger et al. 2010b).

The metrics of *UP* and *WUP* have been used in a study of monitoring urban sprawl in Switzerland, this study demonstrated that the metrics have three important advantages: (1) the metrics are useful to measure the speed of urban development, (2) the metrics are intensive therefore they are suitable for comparing regions of different sizes, and (3) the metrics can be used to suggest limits to urban sprawl (Jaeger et al. 2010b).

Table 2-4: Investigation of the metrics of Entropy, urban permeation (*UP*) and weighted urban proliferation (*WUP*) with regard to 13 suitability criteria for measurement of urban. Assessments of *UP* and *WUP* metrics is driven from the conducted study by Jaeger et al. (2010b).

Suitability criteria	Mandatory (M)/ Highly desirable (HD)/ Desirable (D)	Assessment of the Entropy method	Suitability of Entropy	Assessment of the *UP* and *WUP* metrics	Suitability of *UP* and *WUP*
Intuitive interpretation	HD	Entropy is easy to understand.	+	*UP* and *WUP* are both calculated according to the definition used to define urban sprawl and the interpretation of them is easy.	+

Suitability criteria	Mandatory (M)/ Highly desirable (HD)/ Desirable (D)	Assessment of the Entropy method	Suitability of Entropy	Assessment of the *UP* and *WUP* metrics	Suitability of *UP* and *WUP*
Mathematical simplicity	HD	Calculation of Entropy is easy.	+	The formulas used to calculate *UP* and *WUP* are conceptually straightforward and can be calculated numerically for any landscape.	+
Modest data requirements	HD	Entropy has low data needs (map of built-up areas).	+	Both *UP* and *WUP* have low data needs (map of built-up areas for calculation of *UP*) and map of built-up area as well as information on population and jobs for calculation of *WUP*.	+
Low sensitivity to very small patches of urban area	M	The contribution of each patch of built-up area is proportional to its contribution to the total size of urban patches in a region, so smaller patches have less influence on the value of the metric.	+	The contribution of each patch of built-up area to *UP* and *WUP* is proportional to its size. Therefore, smaller patches of built-up area have less influence on the metrics values.	+
Monotonous reaction to increases in urban areas: a) while the dispersion of built-up areas stays constant, b) while their dispersion changes	a) M, b) D	Entropy is in many cases not sensitive to this criterion, e.g. when the urban areas in all zones increase by the same percentage (e.g. by 10%) all p_i will be the same.	-	When new urban areas are added to a landscape, the value of *UP* and *WUP* always increases, (with the exception of exceptional cases of high dispersion where *UP* and *WUP* can be slightly reduced by building densely).	+

Suitability criteria	Mandatory (M)/ Highly desirable (HD)/ Desirable (D)	Assessment of the Entropy method	Suitability of Entropy	Assessment of the *UP* and *WUP* metrics	Suitability of *UP* and *WUP*
Monotonous reaction to increasing distance between two urban patches when within the scale of analysis	M	Entropy is in many cases not sensitive to the change of distance between two urban patches, e.g. when the built-up areas are located and stayed in one single zone or when they are distributed in two different zones and stayed in these zones.	-	When the distance between two urban patches increases (within the scale of analysis (HP)), the value of *UP* and *WUP* always increases.	+
Monotonous reaction to increased spreading of three urban patches	M	Entropy is in many cases not sensitive to this change, e.g. when all the built-up areas are distributed in one single zone or when they are distributed in number of zones.	-	The value of *UP* and *WUP* increases faster at shorter distances, i.e., increase in value of *UP* and *WUP* due to increase in the distance to close urban patches is larger than the loss in value of *UP* and *WUP* due to decreases in the distance to distant urban patches	+
Same direction of the metric's responses to the processes in criteria 5, 6 and 7	M	Entropy does not meet this criterion, since it does not meet criteria 5 to7.	-	The response of *UP* and *WUP* to the three processes (criteria 5, 6 and 7) are all in the same direction (i.e., increasing)	+
Continuous reaction to the merging of two urban patches	M	Entropy is in many cases not sensitive to this change e.g. when the two urban patches are located with a single zone.	-	When two urban patches merge, the contribution of the inter-patch distances to *UP* and *WUP* decrease continuously, since the weighting function is a continuous function.	+

Suitability criteria	Mandatory (M)/ Highly desirable (HD)/ Desirable (D)	Assessment of the Entropy method	Suitability of Entropy	Assessment of the *UP* and *WUP* metrics	Suitability of *UP* and *WUP*
Independence of the metric from the location of the pattern of urban patches within the reporting unit	M	The value of Entropy in many cases depends on the location of the zones e.g. when they are created around the city center for the analysis and the city center may be chosen at different locations.	-	The values of *UP* and *WUP* only depend on the spatial pattern of the urban area within the investigated landscape. Values will not change if the location or position of the landscape changes.	+
Continuous reaction to increasing distance between two urban patches when they move beyond the scale of analysis	HD	Entropy is not sensitive to this change in the landscape and does not have any parameter to represent the scale of analysis. Even if we interpret that zones are representing the scale of analysis, Entropy does not meet this criteria.	-	When the distance between two urban patches increases beyond the scale of analysis (HP) the value of *UP* and *WUP* will change continuously because the decrease in the value of UP is proportional to the amount of built-up areas and the movement across the HP distance is continuous.	+
Mathematical homogeneity (i.e., intensive or extensive measures)	D	Entropy is not an extensive metric, since it is not additive for non interacting landscapes.	-	*UP* is an intensive measure in relation to the size of the reporting unit and therefore its value can be compared among reporting units with different sizes. However, *WUP* is neither intensive nor extensive, because of the weighting factors for *DIS* and *UD*.	+

Suitability criteria	Mandatory (M)/ Highly desirable (HD)/ Desirable (D)	Assessment of the Entropy method	Suitability of Entropy	Assessment of the *UP* and *WUP* metrics	Suitability of *UP* and *WUP*
Additivity (i.e., additive or area-proportionately additive measure)	D	Entropy is not an additive or area proportionately additive measure. Simple theoretic examples showed that when a landscapes (landscape 1) with n (e.g. n = 4) number of zones and evenly distributed built-up areas is added to a similar landscape (e.g. landscape 2) with m (e.g. m = 4) number of zones, the value of the Entropy in the new landscape with n+m = 8 zones is not the sum of the two values of Entropy for landscape 1 and landscape 2.	-	*UP* is an area-proportionately additive metric, (e.g., the value of *UP* for the combination of two reporting units is the area-proportionate average of the values of *UP* for the reporting units).	+

2.6. Measurement of urban sprawl in Canada

It seems that most of the studies done in Canada focus on the consequences and certain other relevant aspects of sprawl (e.g., relationship between sprawl and travel behaviour or sprawl and municipal fragmentation), rather than measuring the degree of sprawl. In this section it is tried to review only those studies that aimed to measure sprawl quantitatively.

A study by Filion et al. (2010) examined the similarities and differences in urban density between four metropolitan areas of Vancouver, Toronto, Ottawa and Montreal to describe intensification and sprawl in these metropolitan areas (Filion et al. 2010). However, it should be considered that although urban density is an important dimension of sprawl, using urban density is not sufficient for determining the degree of urban sprawl. In this study it is suggested that topography, economy, demographic performance and land use are the most important factors for the distinction of urban density patterns in the four metropolitan areas of Vancouver, Toronto, Ottawa and Montreal.

Authors pointed to the adaption of urban form to modernism, car demand and the desire to live in large houses as the main reasons for the decrease in urban densities in North American cities (Filion et al. 2010). Their measurement of residential density was based on gross census tracts (the population of census tracts divided by the area of census tracts). Over 1971-2006 inner city densities in all metropolitan areas have declined sharply (with the exception of Vancouver). For example, in Montreal, from 1971 to 2006, population density per square kilometer declined from 4994 residents/km^2 to 3356 residents/km^2 (Filion et al. 2010). However, in contrast to the decentralization in the United States which is the result of a reduction in the number of inner city housing units, the decline in density in Montreal was mostly caused by the increase in residential spaces used per person (Filion et al. 2010). Montreal has several islands in the St. Lawrence River, but the access to these islands is very easy due to the bridges that were constructed during the past years. Filion et al. (2010) recognized these bridges as one of the factors which have lead to the growth of suburbs beyond waterways (Filion et al. 2010). In comparison to the other three metropolitan areas in this study, Montreal was identified as a highly administrative fragmented city. Filion et al. (2010) suggested that this administrative fragmentation is mainly due to the absence of planning agencies during the past decades.

Pond and Yeates (1993) investigated the direct and indirect impacts of urban development on agricultural lands in two central counties of Oxford and La Prairie. They believe that none of the previous studies on the conversion of agricultural land into urban development provided a reliable method for planners to estimate the amount of land that is transferred from agricultural lands into urban areas, mainly because they did not include indirect impacts of the conversion of lands in their analysis (Pond and Yeates 1993). Most of the previous studies on land conversion in Canada were done in southwestern Ontario and in the lower Fraser valley in British Columbia (Pond and Yeates 1993). However, the authors argue that rural and urban land conversion are also important in the rapidly urbanizing areas between Windsor and Quebec City, areas which contain more than one-half of the highest quality agricultural land in the country (Pond and Yeates 1993).

Pond and Yeats (1993) used $LC_t = DL_t + IVL_t + ILVL_t$ to measure the direct and indirect impact of urban development on rural land, where LC_t is the amount of land influenced directly or indirectly by urban development at time t, DL_t is the amount of land in direct urban use at time t, IVL_t is the amount of land in indirect visible use at time t and $ILVL_t$ is the amount of land in indirect less visible land use at time t (Pond and Yeates 1993). Their result provides an estimate of the ratio of the direct and indirect impacts of urban development on the rural area’s land conversion. For example, in La Prairie County, this ratio was 1:1.4, and for Oxford County, it was 1:2.23. The lower ratio of La Prairie County shows the greater level of urban development in this area (Pond and Yeates 1993).

There is another study that presented a quantitative measurement of urban sprawl for the city of Calgary (Sun et al. 2007). In this study eCognition software was used to classify Landsat images in six points in time from 1985 to 2001. The Shannon's Entropy was used to measure the level of urban sprawl quantitatively in each time step. The results demonstrated that Shannon's Entropy with the value of 0.850 in 1985 increased to 0.905 in 2001 indicating that urban sprawl had continuously increased during the period of study (Sun et al. 2007).

A study that examined the relation between municipal fragmentation and sprawl in more than 100 North American cities identified Montreal and Quebec as the most municipal fragmented metropolitan areas in Canada (Razin and Rosentraub 2000). In this study sprawl was quantified by measures of density: (1) the percentage of dwellings in single-unit detached houses, (2) population per square kilometer, and (3) housing units per square kilometer (Razin and Rosentraub, 2000). And municipal fragmentation was measured based on (1) number of local governments in relation with number of residents, (2) existence of multipurpose metropolitan government and (3) proportion of population in the largest cities and cities of more than 100,000 residences in the metropolitan area (Razin and Rosentraub, 2000). Authors concluded that low level of municipal fragmentation does not directly correlate with compact urban development. However, a low level of municipal fragmentation could be a precondition for less dispersed urban development (Razin and Rosentraub, 2000).

The study of urban growth in Winnipeg is another quantitative study conducted in Canada by Hathout (2002). In this study aerial photographs of the years 1960 and 1989 and Geographic Information System and Markov probability chain analysis were used to predict the amount of urban growth in the two municipalities of East St Paul and West St Paul (Hathout 2002).

In this study three classes of ‘urban’, ‘agricultural’ and ‘other’ were developed by classification of aerial photographs of the years 1960 and 1989. Then each classified map was digitized and converted from vector to raster for the measurement of urban growth. Having the raster file of land use layer, Markov probability chain analysis was used for prediction of the changes in the land use. This method investigates the transitional probability of changes within and between classes and calculates the frequency of a predicted class (e.g., urban) from a chain of time factor analyzed for the two time steps (Hathout 2002). Results of this study indicated that East St Paul had a higher rate of urbanization (10.14% to 43.75%) than West St Paul (7.36% to 23.57%) between the years 1960 and 1989 (Hathout 2002).

The study by Behan et al. (2008) on the benefits of smart growth policies from transportation aspects pointed to some negative attributes of sprawl in the city of Hamilton, including decentralization of the urban areas, increases in automobile dependency and in commuting distances (Behan et al. 2008). Although this study has not developed a metric for measurement of sprawl it is interesting since it has estimated the benefits of smart growth strategies quantitatively. In this study the effect of urban residential intensification (URI) on changes in vehicle emissions and traffic congestion are examined.

The authors considered anticipated household growth in the city of Hamilton (80000 more households by 2031) and used integrated urban transportation and land-use model (IMULATE) to model variety of development scenarios (e.g., increases in automobile dependency and commuting distances). The results of this study showed that smart growth policies such as urban residential intensification (URI), which aim to increase population densities in the inner city areas, provide planners with the best solutions to stop urban sprawl and its negative impacts (Behan et al. 2008).

2.7. Conclusion

With the increasing acceptance of sustainable development as the best concept for future developments, researchers have more focused on finding a sustainable urban form to improve economic and social fairness and reduce the negative effects on the environment (Huang et al. 2007). In spite of these efforts and debates on urban studies, and more specifically urban sprawl, there is still no agreement on how to measure and control urban sprawl in order to avoid the negative aspects it brings to our planet. Therefore, more focus on this issue is needed.

An ideal study of urban sprawl would use one measure to quantify the degree of urban sprawl, and a set of indicators to measure causes, consequences, and other relevant attributes of urban sprawl (Jaeger et al. 2010b). However, metrics for the measurement of urban sprawl should meet fundamental criteria to be reliable.

The newly developed metrics of urban permeation and weighted urban proliferation for measuring the level of urban sprawl (Jaeger et al. 2010b, Schwick et al. 2012) meet all the 13 suitability criteria mentioned in the section 2.7.4. This particular feature distincts these metrics from most other available methods in the literature. Therefore, in this study we used this method for the measurement of urban sprawl.

3. Study areas

The two main regions of focus are the Quebec and Montreal Census Metropolitan Areas. The MCMA (Figure 3.1) is located in the southwest of the Canadian province of Quebec, where the St. Lawrence and Ottawa Rivers meet. The MCMA, with an area of 4,260 km^2, and with a population of approximately 3,824,200 people, is Canada's second most densely populated urban area (Statscan 2012a). Four of the 25 fastest growing municipalities in Canada are located in the MCMA, which are Notre-Dame-de-l'Île-Perrot, Blainville, Mirabel and Saint-Colomban (Statscan 2003). The QCMA with an area of 3,350 and a population of 765,700 (Statscan 2012b) is the second largest metropolitan area of the Quebec province. It contains Quebec City as the political capital of the province (Figure 3-1).

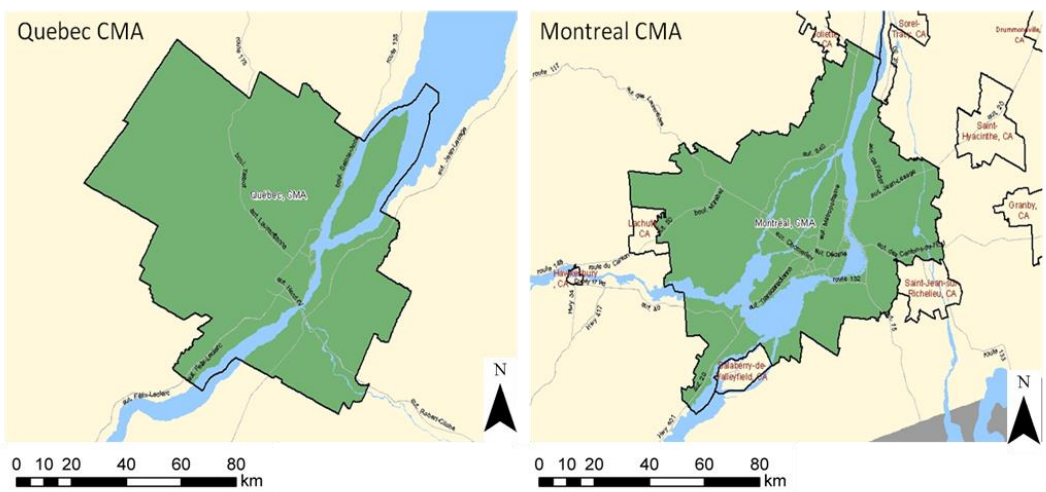


Figure 3-1: The Quebec and Montreal Census Metropolitan Areas (delineation of 2011). Source: Statistics Canada.

4. Methods

4.1. Introduction

This chapter includes a description of the methods and data sources that were used to calculate the degree of urban sprawl (first paper) and the methods and data sources that were used to examine the reliability of the Entropy method as a measure of urban sprawl (second paper).

4.2. Methods used for the measurement of urban sprawl in Montreal and Quebec

This section represents the methods used in the first paper as well as some additional information about the data sources and reporting units.

4.2.1. Combination of urban area, dispersion and utilization density for the measurement of urban sprawl

The newly developed metrics of urban permeation (*UP*) and weighted urban proliferation (*WUP*) (Jaeger et al. 2010b, Schwick et al. 2012) were used for the measurement of urban sprawl in the Montreal and Quebec CMAs over the past 60 years for five different points in time. Besides *UP*, Jaeger et al. (2010b) introduced sprawl per capita (*SPC*) and total sprawl (*TS*) (presented in literature review). However, I use *WUP* to report the degree of sprawl in different reporting units, since it is the most appropriate metric for measuring urban sprawl.

The metrics of *UP* and *WUP* have been previously used for the measurement of urban sprawl in Switzerland by Schwick et al. (2012). Following is the description of all the metrics that have been used in this study.

4.2.1.1. Dispersion (*DIS*)

This metric is expressed in urban permeation units per square meter of urban area (UPU/m^2). This intensive metric characterizes the pattern of built-up areas from a geometric point of view to calculate one of the most common properties of sprawl, which is the dispersion of built-up areas. This metric is based on the distances between any two points within the urban areas (Schwick et al. 2012, Jaeger et al. 2010b). Indeed, *DIS* describes the average effort of delivering some service from all urban points (e.g., every building) to randomly chosen delivery points within a specified scale of analysis that we call horizon of perception (HP) (Jaeger et al. 2010b). HP is the maximum distance between two points (the following section describes HP more in detail). The farther away the two points within the horizon of perception the greater the value of dispersion. In this study for the calculation of *DIS* in Montreal and Quebec horizon of perception of 2 km was selected.

In the calculation of urban sprawl (using *WUP*, see below), a function of weighting was used for *DIS*. Weighted *DIS* has values between 0.5 and 1.5, allowing those built-up areas that are more compact to be multiplied by a lower weighting value. With the use of this function, different values are given to the built-up areas to make the more dispersed parts of the landscape more clearly perceived (Schwick et al. 2012).

4.2.1.2. Urban permeation (*UP*)

Urban permeation is expressed in urban permeation units per square meter land (UPU/m^2). *UP* is an intensive and additive landscape metric. It can measure the degree of permeation in different types of landscapes of various sizes (Schwick et al. 2012, Jaeger et al. 2010b). Urban permeation is the product of degree of dispersion (*DIS*) and the amount of built-up areas per unit area of landscape (area of reporting unit).

$$UP = \frac{\text{Settlement area} \cdot DIS}{\text{Area of the reporting unit}},$$

where settlement area is the area of built-up areas and area of reporting is the area of landscape in which the analysis is done and for which the result is reported for (e.g., census metropolitan area census sub division, census tract etc.)

4.2.1.3. Utilization density (*UD*)

Utilization density measures the density of inhabitants and jobs in the settlement areas (built-up areas) (Schwick et al. 2012).

$$UD = \frac{\text{Number of inhabitants and jobs}}{\text{Settelement area}}$$

Areas with a higher level of utilization density are considered less sprawled than other parts of the landscape, since we consider the lands with a higher population and job density more efficient in terms of sustainability. Accordingly, in the calculation of urban sprawl *UD* is weighted with a weighting function. The value of weighted *UD* is always between 0 and 1. The higher the utilization density, the lower the factor. When there are less than 40 inhabitants and jobs per hectare of built-up area the value of *UD* is close to 1. Value of weighted *UD* is close to 0 when there are more than 100 inhabitants and jobs per hectare of built-up area, meaning that these areas are not considered as sprawled areas (Jaeger and Schwick subm.) In areas that there are 45 to 90 inhabitants and jobs per hectare, the weighting factor reduces proportionately from 80% to 20%, and in areas with 68 inhabitants and jobs per hectare, the factor is 50% (Jaeger and Schwick subm.).

"The value of 45 inhabitants and jobs per hectare corresponds to a land requirement of 400 m^2 of urban area per inhabitant suggested by the Swiss Federal Council in 2002 as a maximum value" (Jaeger and Schwick subm., p 26). This means that when the weighted *UD* is close to 1, inhabitants (or jobs) occupy more area, but weighted *UD* is less than 80% when inhabitants (or jobs) occupy less than 400 m^2 per head (Jaeger and Schwick subm.).

4.2.1.4. Weighted Urban Proliferation (*WUP*)

WUP is the result of the combination of all three dimensions of sprawl (UP, DIS and UD) and is the most appropriate metric for determining the degree of urban sprawl. The following equation presents the calculation of WUP:

$$WUP = UP \cdot w_1\,(DIS) \cdot w_2(UD)$$

4.2.2. Choice of the horizon of perception (Cut-off radius)

The horizon of perception defines the scale of the analysis. Urban areas that are further away from each other than *HP* chosen for the analysis are not considered in the measurement (Jaeger et al. 2010b). A person with an eye height of 180 cm can see the surrounding area within a radius of 4.9 km due to the curvature of the Earth (assumed there are no obstacles obstructing the view); therefore, a distance between 1km and 10 km is suitable for *HP* in most cases (Jaeger et al. 2010b).

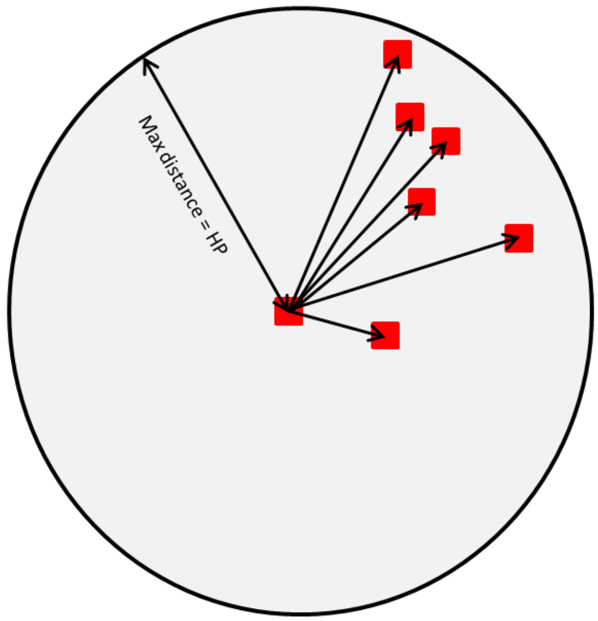


Figure 4-1: Illustration of the horizon of perception (*HP*). All urban cells within the circle that are located around the cell in the center are taken into account in the calculation.

4.2.3. Mathematical calculation of the metrics

The mathematical formulas to calculate the urban sprawl metrics introduced by Schwick et al. (2012) are:

$$(1)\quad DIS = \frac{1}{A_{\text{built-up}}} \cdot \int_{\vec{x} \in \text{built-up areas}} \frac{1}{\int_{\substack{\vec{y} \in \text{built-up areas} \\ \text{and } |\vec{x}-\vec{y}| < HP}} d\vec{y}} \int_{\substack{\vec{y} \in \text{built-up areas} \\ \text{and } |\vec{x}-\vec{y}| < HP}} \sqrt{\frac{2 \cdot |\vec{x}-\vec{y}|}{1\,\text{m}} + 1} - 1 \, d\vec{y} \, d\vec{x} \; \frac{\text{UPU}}{\text{m}^2},$$

$$(2)\quad TS = \int_{\vec{x} \in \text{built-up areas}} \frac{1}{\int_{\substack{\vec{y} \in \text{built-up areas} \\ \text{and } |\vec{x}-\vec{y}| < HP}} d\vec{y}} \int_{\substack{\vec{y} \in \text{built-up areas} \\ \text{and } |\vec{x}-\vec{y}| < HP}} \sqrt{\frac{2 \cdot |\vec{x}-\vec{y}|}{1\,\text{m}} + 1} - 1 \, d\vec{y} \, d\vec{x} \; \frac{\text{UPU}}{\text{m}^2},$$

$$(3)\quad UP = \frac{1}{A_{\text{reporting unit}}} \cdot \int_{\vec{x} \in \text{built-up areas}} \frac{1}{\int_{\substack{\vec{y} \in \text{built-up areas} \\ \text{and } |\vec{x}-\vec{y}| < HP}} d\vec{y}} \int_{\substack{\vec{y} \in \text{built-up areas} \\ \text{and } |\vec{x}-\vec{y}| < HP}} \sqrt{\frac{2 \cdot |\vec{x}-\vec{y}|}{1\,\text{m}} + 1} - 1 \, d\vec{y} \, d\vec{x} \; \frac{\text{UPU}}{\text{m}^2}.$$

where $A_{\text{built-up}}$ is the total size of settlement area within the investigated reporting unit (area of study), $A_{\text{reporting unit}}$ is the size of the area of the reporting unit, and *HP* is the horizon of perception.

According to Schwick et al. (2012), the weighting function for the distance between point $\vec{x}$ and point $\vec{y}$ within the settlement area is:

$$f(|\vec{x}-\vec{y}|) = \left(\sqrt{\frac{2.\,|\vec{x}-\vec{y}|}{1\text{m}}} + 1 - 1\right)\frac{\text{UPU}}{\text{m}^2}$$

The above formulas can be simplified to:

$$DIS(b) = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{n_i}\left(\sum_{j=1}^{n_i}\left(\sqrt{\frac{2\cdot d_{ij}}{1\text{m}}} + 1 - 1\right)\frac{\text{UPU}}{\text{m}^2} + WCC(b)\right)$$

$$TS(b) = b^2\sum_{i=1}^{n}\frac{1}{n_i}\left(\sum_{j=1}^{n_i}\left(\sqrt{\frac{2\cdot d_{ij}}{1\text{m}}} + 1 - 1\right)\frac{\text{UPU}}{\text{m}^2} + WCC(b)\right)$$

$$UP(b) = \frac{b^2}{\text{A}_{\text{reporting unit}}}\sum_{i=1}^{n}\frac{1}{n_i}\left(\sum_{j=1}^{n_i}\left(\sqrt{\frac{2\cdot d_{ij}}{1\text{m}}} + 1 - 1\right)\frac{\text{UPU}}{\text{m}^2} + WCC(b)\right),$$

where *WCC*(*b*) denotes the within-cell contribution of a cell with the size of *b*. *n* stands for the total number of settlement cells size of *b*, n_i denotes the number of settlement cells within the horizon of perception around the settlement cell *i*, and d_{ij} symbolizes the distance between settlement cell *i* and settlement cell *j* (Schwick et al. 2012).

The value of the within-cell contribution for the cells with the sizes of *b=0* to *b=1000* m can be approximated by following equation (Schwick et al. 2012):

$$WCC\ (b) = \sqrt{(0.97428 \cdot b/1\text{m}) + 1.046} - 0.996249)\ \frac{\text{UPU}}{\text{m}^2}$$

Values of the within-cell contribution for different sizes are given in table 4-1:

Table 4-1: Values of the within-cell contribution for different cell sizes (Jaeger et al. 2010b, p: 431).

Cell size (in m)	Within cell contribution (in UPU/m2)
0	0
1	0.41853
2	0.73279
5	1.43842
10	2.29088
15	2.96326
20	3.53682
30	4.50733
45	5.70447
50	6.05853
60	6.71803
75	7.61312
90	8.42355
100	8.92714
150	11.13557
200	12.99981
300	16.13012
400	18.77086
500	21.09824
600	23.20286
700	25.13853
800	26.94043
900	28.63298
1000	30.2339

The weighting functions for utilization density and dispersion (Schwick et al. 2012) are:

$$w_1(DIS) = 0.5 + \frac{e^{0.294432\mathrm{m}^2/\mathrm{UPU}.DIS-12.955}}{1+e^{0.294432\mathrm{m}^2/\mathrm{UPU}.DIS-12.955}}, \text{ and}$$

$$w_2(UD) = \frac{e^{4.159-0.000613125\mathrm{km}^2/(\mathrm{INH+J}).UD}}{1+e^{4.159-0.000613125\mathrm{km}^2/(\mathrm{INH+J}).UD}}$$

4.2.4. The urban sprawl metrics calculation tool (URSMEC)

For the calculation of the urban sprawl metrics, the tool URSMEC programmed by Michael Wenzlaff, is used. The calculation is based on all the distances between any two points which are located within the built-up areas (Jaeger et al. 2008).The input for the tool is a Boolean map of built-up areas, and the output of the tool consists of a file which contains the S_i values that are assigned to all cells in the built-up areas (Jaeger et al. 2008).

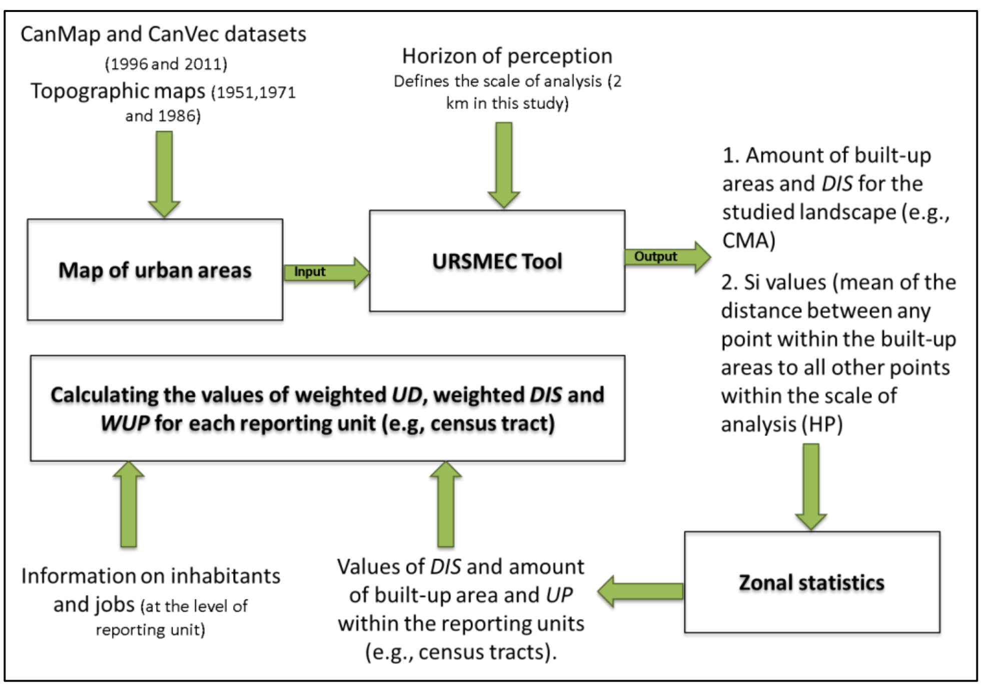


Figure 4-2: Overview of the process of calculation of sprawl metrics.

In order to calculate the metrics within the selected reporting units, the result file, which contains the S_i values, will be opened in ArcGIS. Then, the calculation will be done by using the following formulas (Jaeger et al. 2008):

$$DIS(b) = \frac{1}{Gsum} \sum_{i=1}^{n} S_i \; \frac{\text{Sprawl units}}{\text{m}^2}, (\text{where } Gsum = \sum_{i=1}^{n} G_i)$$

$$TS(b) = b^2 \cdot \sum_{i=1}^{n} S_i \; \frac{\text{Sprawl units}}{\text{m}^2}, (\text{where } b = \text{edge of urban cells in meter})$$

$$UP(b) = \frac{b^2}{A_{\text{reporting unit}}} \sum_{i=1}^{n} S_i \; \frac{\text{Sprawl units}}{\text{m}^2} = \frac{1}{A_{\text{reporting unit}}} \, TS(b)$$

The value of *DIS* (*b*) is the degree of dispersion for a single cell within the horizon of perception. In the calculation, all the other urban cells that are close to that specific cell are taken into account. Dispersion is calculated based on the distance of one cell to the other cells. The amount of *DIS* is higher when the urban areas are more dispersed over the landscape, and it is lower when the buildings are clumped together in a more compact form.

4.2.5. Reporting units and their boundaries

To calculate the metrics of sprawl, it is necessary to select reporting units. This study measured urban sprawl for three types of reporting units: Census metropolitan areas, census tracts, and districts. In addition, Montreal Island, Quebec City and the Inner Zurich metropolitan area were used as the constant reporting units for a comparison of urban sprawl in different time steps.

Census tracts are one of the smallest territorial units in urban studies. The existence of a wide range of census data at the scale of census tracts has made them one of the most important reporting units in urban studies. Therefore, calculating the level of urban sprawl at the level of census tracts or districts will allow municipalities to understand and control urban sprawl in their region in more detail and to compare different parts of the landscape regarding urban sprawl.

In this study the districts of Quebec contain 6 boroughs of Quebec as well as the South Shore and the region of L'Ancienne Lorette, and the districts of Montreal are the combination of 19 boroughs, 15 municipalities, and 13 regional county municipalities (RCMs) of Montreal.

4.2.6. Data sources

The base data was the CanVec dataset (updated version of 2011), which is provided in vector format by Natural Resource Canada. CanVec is produced from the national topographic database (NTDB), landsat 7 imagery coverage, and Geobase data. This data contains 11 different themes, one of which is a layer of the buildings and the structures in the landscape. This is the main layer that was used in the analysis of urban sprawl for both study areas. However, as the real date of entities corresponding to built-up areas goes back to 1996, this data is used for the calculation of urban sprawl in 1996.

The CanVec dataset is also used for the creation of built-up areas for the previous time steps for which there are no digitized data available. Therefore, national topographic maps of the years 1951, 1971 and 1986 at the scale of 1/50000 were consistently digitized based on the CanVec dataset using a geographic information system (GIS).

For the calculation of urban sprawl in 2011, the CanMap Route Logistics version 2011.3, (a product of DMTI spatial) was used. Being consistent with the CanVec dataset, those features of CanMap that present urban areas, was used for calculation of urban sprawl (Appendix 2 presents the detailed information).

Information about inhabitants was taken from the Statistics Canada census of population which is conducted every five years. Accordingly, census data of the years 1951, 1971, 1986, 1996 and 2011 were used (Statscan 1951, Statscan 1971, Statscan 1986, Statscan 1996a, Statscan 2011c). Job information for the calculation of urban sprawl in Montreal and Quebec for the years 1996 and 2011 were taken from Statistics Canada census of workplace of the years 1996 and 2006 respectively (job information at census tract level for the year 2011 was not available by the time of this project) (Statscan 1996b, Statscan 2006b). Canadian censuses have been conducted every five years by Statistics Canada. However, since the information on jobs was not available for the years 1951 to 1986 in Montreal and Quebec, a correction factor was used for the calculation of utilization density for these years (a more detailed information is presented in Appendix 3).

4.2.7. Delineation of built-up areas

As Jaeger et al. (2010b) argue, the value of the metrics of urban sprawl will depend on how built-up areas are defined (e.g., whether or not transportation infrastructures are included in the built-up areas). Therefore, an essential step before quantifying urban sprawl metrics is to establish a meaningful and consistent definition and delineation for built-up areas.

Built-up area has a place-based characteristic that incorporates elements of the built environment. Therefore, all the manmade buildings and structures as well as small roads and alleys that are located between settlement areas constitute built-up areas. However, highways and infrastructure that connect urban patches within the landscape are not considered as a part of built-up areas. Moreover, areas such as airports and runways, domestic and industrial wastes as well as cemeteries that are smaller than 4 hectares are considered a part of urban areas. Appendix 2 presents all the entities of built-up areas that were taken from the CanMap and CanVec datasets.

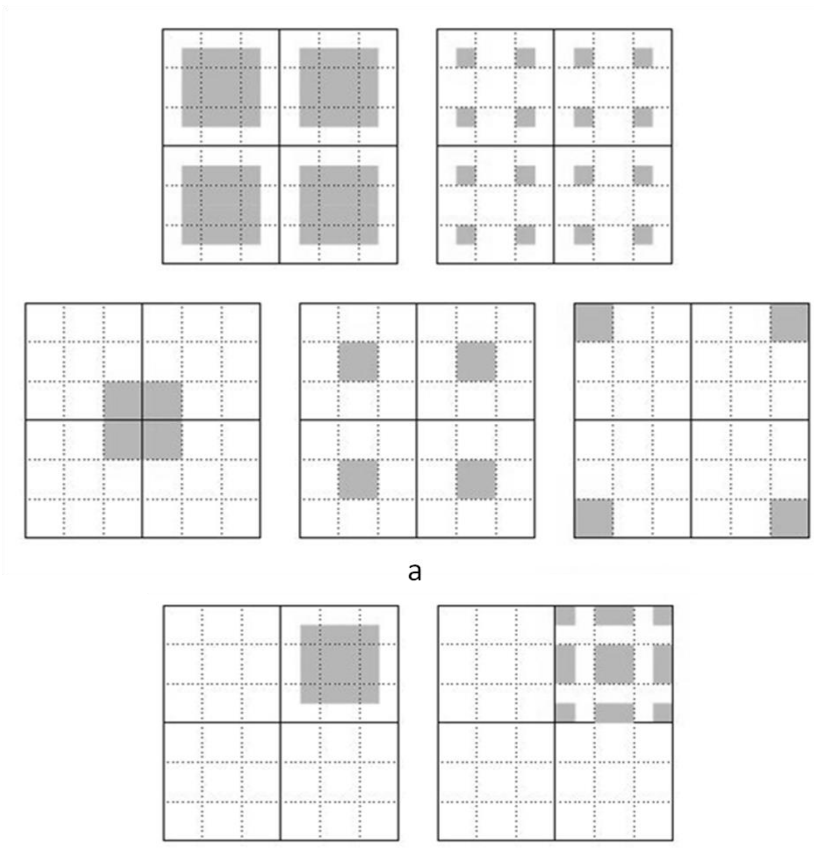
4.3. Methods used for the investigation of the reliability of Entropy method as a measure of sprawl

The behaviour of the Entropy method (as explained in the second chapter) as an approach for the measurement of urban sprawl is studied more in detail and is presented as a separate manuscript in Appendix 1. The results of this study demonstrated that Entropy is not a reliable method for the measurement of urban sprawl since it does not meet fundamental criteria for measurement of urban sprawl. Four different procedures which were used for this investigation are as follow:

4.3.1 First procedure

First, Entropy was measured for five different landscapes with similar configurations (same size and same number of zones) and similar amount of built-up areas, but within different distribution patterns (Figure 4-3a). We also calculated Entropy for two same-sized landscapes in which all their built-up areas were located in a single zone but in two different ways (Figure 4-3b).

With these simple examples we were able to check the sensitivity of entropy method to the distribution of built-up areas within the landscape. Either they were all located in a single zone or they were dispersed in different zones of a landscape.



a

b

Figure 4-3: a) Illustration of the distribution of built-up areas in five different configurations. Each configuration consists of four zones of the same size (delineated by solid lines). b) Illustration of the distribution of built-up areas in one single zone of similar landscapes in two different forms.

4.3.2 Second procedure

Second, Entropy was tested in six real-world case studies to check the behaviour of this method when of the size and number of zones are varied. These case studies include: Drummondville, Trois Rivières, Toronto, Sherbrooke, Montreal and Quebec. In each case study, four sets of buffers of the same size were created around the city center of each study area. This procedure was done following the study of Yeh and Li (2001) in which the Entropy method was introduced as a measure of urban sprawl. With this approach, we were able to check the behaviour of the Entropy method regarding the increase in its value versus the number of zones.

4.3.3 Third procedure

In the third step, the behaviour of Entropy was tested with regard to the choice of the location of city center in one of case studies (Quebec City). In this method, two different points within a distance of 3 kilometers were selected as the two city centers. Then Entropy was calculated twice: for a landscape with the size of 14 km by 14 km using the first selected city center and for the same landscape but with the second selected city center.

4.3.4 Fourth procedure

In the fourth step, we examined the reliability of the Entropy method with regard to 13 suitability criteria for the measurement of urban sprawl which were introduced by Jaeger et al. (2010a). These 13 suitability criteria contain every single criterion that each metric for a measure of urban sprawl should meet. Some of these criteria are fundamental and any method for measurement of sprawl must meet them and some of them are additional characteristics that an ideal metric of urban sprawl should meet them. This approach enabled us to better understand the behaviour of Entropy method while thinking about each criterion and the behaviour of Entropy regarding that criterion.

5. Historical analysis of urban sprawl in Montreal and Quebec and a comparison with the results from Zurich

5.1. Introduction

It is predicted that by 2008, more than half of the world's human population has been living in urban areas as a consequence of a steady movement of people from rural lands to urban areas (EEA 2006). For example, in 1950, only 50% of Americans lived in cities, but by the year 2000, four in five Americans lived in metropolitan areas (Putnam 2000). More recently, a second wave of migration has taken place from inner cities to the suburbs in most North American cities. As a consequence, the population living in the suburbs of U.S doubled between 1900 and 1950, and doubled again between 1950 and 2000 (Caplow et al. 2001). This massive growth in urban areas has resulted in urban sprawl in North America, and also in many other places all over the world for similar reasons.

5.1.1 Causes and consequences of urban sprawl

Many factors contribute to urban sprawl, e.g., consumer preference for single-family detached housing and a desire to find low priced lots and to live in a green neighbourhood make suburbs attractive; telecommunication innovations have allowed many activities to disperse, while low gasoline prices have made human choice of dwelling locations more independent of their distances from central facilities (Ewing 1997). Unorganized patterns of growth that are the result of planning without a clear vision for the future landscape development, the wish for second homes and people's belief that it's better to live in low-density neighborhoods are all causes of urban sprawl (Jaeger et al. 2010, Wright and Boorse, 2013).

The ongoing interactions in the cities along with history and "good deal of chance" are the elements of spatial structure of cities (Anas et al. 1998). Among the different interactions there are different rising forces in the world that causes decentralization and dispersion of cities, for example, automobile- age development caused the creation of great suburbs far away from city centers (Anas et al. 1998).

Sprawl is an unsustainable form of development due to its harmful effects on various environmental, economic and social aspects. Soil sealing and therefore scarcity of land for energy and food production, increase of urban greenhouse gas emissions and hydrological pollutions, loss of valuable ecosystems, higher infrastructure and higher public transportation costs, Long commuting time and its negative effect on civic involvements in the society are all consequences of urban sprawl (Haber 2007, Frumkin 2002, Forys and Allen 2005, Sidentop and Fina 2010, Ewing 1997, Putnam 2000).

In Canada, urbanization has been identified as the second most common human activity causing habitat loss, which in turn is the most prevalent threat to endangered species in Canada (Venter et al. 2006). The effects of urban sprawl are cumulative, i.e., they result from development projects in combination with all other projects or activities that have been or likely will be carried out in its vicinity, and they are irreversible in human time spans. Therefore, more effective efforts are needed to apprehend, measure, and control this phenomenon.

5.1.2 Definitions of urban sprawl

The wide variety of definitions and characterizations of urban sprawl have rendered this phenomenon unclear and laborious to study since "the term is so abused that it lacks a precise meaning and defining sprawl has become a methodological quagmire" (Audirac et al. 1990 p 475 cite Harvey and Clark 1965). The main three reasons for this confusing multitude of definitions of sprawl are (1) that sprawl has been defined under various perspectives since it has been studied in different disciplines (Barnes et al. 2001); (2) difficulties in distinguishing sprawl from similar terms such as "suburbanization" or "suburban development" (Franz et al. 2006); and (3) that causes and consequences of sprawl are often confused with the phenomenon of sprawl itself (Jaeger et al. 2010a). Most of the descriptions of sprawl are qualitative rather than quantitative (Jaeger et al. 2010a), and many researchers used indicators to describe various aspects of sprawl rather than defining this phenomenon (Daniels 1998).

Regardless of these problems, a reliable definition of urban sprawl is needed. This study used the following definition according to which sprawl is visually recognizable and has three dimensions: the amount of built-up areas, their dispersion in the landscape, and the density of inhabitants and jobs in the built-up areas: "Urban sprawl denotes the extent of the area that is built-up and its dispersion in the landscape in relation to the utilization of built-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" (Schwick et al. 2012 p.115). This definition is based on a comparison of existing definitions in the literature (Jaeger et al. 2010a) and served to develop a new metric of sprawl according to 13 suitability criteria (Jaeger et al. 2010b; see section 2.2).

5.1.3 Comparing urban sprawl in Canada and Switzerland

There is an increasing consensus among scholars, decision makers, and the general public that most Canadian cities severely suffer from urban sprawl. However, most studies in Canada focus on the consequences and other relevant aspects of sprawl rather than quantifying the degree of sprawl. For example, a comparison of the similarities and differences in urban density between four major metropolitan areas of Canada by Filion et al. (2010), or an investigation of the impacts of urban development on agricultural lands and providing an estimate of the ratio of direct and indirect impacts of urban development on the land conversion by Pond and Yeates (1993). The first study indentifies Montreal as the most administratively fragmented metropolitan area compare to three major metropolitan areas of Toronto, Vancouver and Ottawa meaning that Montreal is the most decentralizing metropolitan area (Filion et al. 2010). The second study showed that the direct:indirect ratio for two county of Laprairie and Oxford was 1:1.4 and 1:2.23 respectively (the lower ratio for Laprairie County indicates the greater level of urban development in this county) (Pond and Yeates, 1993).

Another study which examines the relation between municipal fragmentation and suburban sprawl in more than 100 North American cities, identified Montreal and Quebec as the most municipal fragmented metropolitan areas in Canada (Razin and Rosentraub 2000). Municipal fragmentation was measured based on different factors that basically include number of local governments in relation with number of residents, and existence of multipurpose metropolitan government as well as proportion of population in the largest cities and cities of more than 100,000 residences in the metropolitan area. This study showed that a low level of municipal fragmentation does not directly correlate with compact urban development. However, a low level of municipal fragmentation could be a precondition for less dispersed urban development (Razin and Rosentraub, 2000). "There seems to be acceptance of the idea that the existence of numerous local governments encourages sprawl by discouraging uncoordinated planning" (Razin and Rosentraub, 2000, p.822).

Few studies performed a measurement of urban sprawl in Canada. For example, Sun et al. (2007) used eCognition software and classified Landsat images in six points in time from 1985 to 2001 and then used Shannon's Entropy to measure the level of urban sprawl in Calgary. The main result demonstrated that Shannon's Entropy with the value of 0.850 in 1985 increased to 0.905 in 2001 indicating that urban sprawl had continuously increased during the period of study (Sun et al. 2007).

The Montreal and Quebec census metropolitan areas (CMAs) are two major Canadian metropolitan areas that lack a quantitative assessment of urban sprawl. In 2011, the Communauté Metropolitaine de Montreal council (CMM) published a metropolitan land use and development plan titled "Plan Metropolitan d'Amenagement et de Developpement" (PMAD). The PMAD is based on various analyses of the CMM conducted between 2002 and 2010. One important subject of the PMAD is the projected urban development and the associated land-use challenges in greater Montreal. The CMM estimated that the population of greater Montreal will increase by 530,000 additional people (or 320,000 households) by 2031. It also predicted that 150,000 new jobs will be created by 2031 (PMAD 2011). The PMAD suggested that transit-oriented development (TOD) neighbourhoods should be the main focus for future urban development to increase mass-transit use and reduce the proportion of private transport. It also suggested that the densification of the urban areas between the vacant lands outside of the TOD zones should be considered in projected developments (PMAD 2011).

In Montreal, population growth in combination with reduced population densities in the central zones of the city can partly explain the current level of urban sprawl. Although between 1976 and 1994, the rate of population growth in Montreal had slowed down, the population spread across different parts of the metropolitan area resulting in a high increase of urban sprawl (Linteau 2013). In the sixties, the population spread towards the Eastern and the Western parts of the Montreal Island and to Laval Island to the north of Montreal Island. However, since 1996, immigration to suburbs located around the Montreal Island at farther distances has also risen strongly (Linteau 2013).

The Montreal and Quebec CMAs comprise lands that are among the most fertile in Canada. During the past decades, many fertile agricultural lands of Montreal and Quebec have been converted to urban areas. Soil sealing is an important negative consequence of urban sprawl diminishing fertile arable lands and greatly affecting biodiversity. Soil sealing also increases the probability of water scarcity and contributes to global climate change. Therefore, finding solutions to limit urban sprawl or at least to slow down its rapid rate of increase is essential. As a first step, a comprehensive study on urban sprawl is needed.

Montreal has a central position in the system of cities of the St-Lawrence valley. About half of the population of Quebec lives in the Montreal CMA, and one-tenth of Quebec's population lives in the Quebec CMA. Quebec City, located north of the Saint Lawrence river where it cross the St. Charles river is a city with different types of neighborhoods and a long history (Quebec City is among the oldest settlements in North

America). Quebec City is the political capital of the Quebec province and has a different socio-economic structure compared to Montreal.

We wanted to compare these two regions with a contrasting region that (1) has a significantly higher modal share for public transport, that (2) has a longer history of development that already exhibited a significant level of sprawl in the early sixties, and (3) has a stronger regional planning legislation than Canada, while (4) it also is from the Western culture and has a comparable lifestyle. Therefore, we decided to select a region from Europe.

We chose the Zurich metropolitan area (MA) for this comparison. Reasons were the availability of high-quality data from a study of urban sprawl in Switzerland since 1935 (Jaeger and Schwick, subm.) and the similar size of the Zurich MA to Montreal and Quebec. In addition, Zurich contrasts with the selected Canadian case studies in some interesting aspects, for example, in its historic development. The foundation of Montreal and Quebec foundations as cities goes back the 17th century (Montreal in 1642 and Quebec in 1608), whereas early settlements in Zurich have been found about from 6000 years ago and the city has been settled since 2000 years ago. Zurich also has a more rigorous regional planning legislation than Montreal and Quebec. The Zurich MA is distributed among 26 cantons, and as a consequence, settlement structure is polycentric in Zurich, while it is mono-centric in Montreal and Quebec. Zurich has much higher availability of public transportation than Montreal and Quebec: Modal share of public transport in Zurich is 63%, whereas it is only 21.7% in Montreal and a bare 9.8% in Quebec City (Quebec Public Transit Policy 2006 records 2001 census). However these values improved during the 5 year period and according to 2006 census, modal share in Montreal is 34.7% and in Quebec is 13.3%.

In Switzerland, Federal President of the Swiss Confederation Leuthard and Federal Chancellor Casanova recently concluded that “urban sprawl and the destruction of arable land are unsolved problems of regional planning” (Leuthard and Casanova 2010). The Federal Statute on Regional Planning of 1979 already included the responsibility to avoid sprawl by ensuring that land is used economically and that the extension of settlements must be limited (Loi fédérale sur l’aménagement du territoire 1979). This Statute strengthened the role of the designated building zones and clearly reduced the number of new buildings constructed outside of the building zones. However, the built-up areas and the building zones in Switzerland have grown apace since (Office fédéral de la statistique 2012) because the municipalities can designate new building zones almost entirely autonomously. Thus, the Federal Statute has not prevented the extension of built-up areas. It is primarily for this reason that the Swiss parliament proposed a revision of the Federal Statute in 2013. The revision states (1) that the designation of new building zones must be limited to the anticipated need based on predicted population growth in the next 15 years, and (2) the introduction of levies to compensate for the increase of property values following the designation of new building zones (The Federal Assembly – the Swiss Parliament 2012). The Swiss voters accepted this proposal in March 2013 with a majority of 62.9%.

5.1.4 Research questions

This study addresses two research questions:

1) What is the current degree of sprawl in the Montreal and Quebec CMAs, what is their spatial pattern of sprawl, and how quickly has the level of sprawl increased since the 1950s?

2) What are the similarities and differences between Montreal and Quebec (representing Canada) and Zurich (representing Switzerland) in terms of their current degree of sprawl and its change over time?

We also speculate about potential reasons for the differences. We compare these three regions as examples illustrating the more general question of how large the differences are between monocentric North-American and polycentric European metropolitan areas of similar size and lifestyle. Throughout this paper, we use the terms built-up area, settlement area, and urban area synonymously.

5.2. Methods

5.2.1 Study areas

The three regions studied are the Montreal and Quebec Census Metropolitan Areas (CMAs) in Canada and the Zurich metropolitan area (MA) in Switzerland. Nested in them are the three inner areas: the Island of Montreal, the City of Quebec, and the Inner Zurich MA (Figure 5-1a).

The Montreal CMA is located in the southwest of the province of Quebec, where the St-Lawrence and Ottawa Rivers meet. Montreal CMA with the land area of 4,260 km^2 and a population of approximately 3,824,200 inhabitants, is the Canada‘s second most densely populated urban area (Statscan 2012a). The Island of Montreal has a population of 1,886,500 people and a land area of 500 km^2 (Statscan 2012c).

The Quebec CMA is the second most populous area in the province of Quebec. It has a land area of 3,350 km^2 and a population of 765,700 inhabitants (Statscan 2012b). Quebec City with the land area of 454 km^2 and population of 516,620 inhabitants is the capital of the Quebec province (Statscan 2012d). In our definition of Quebec City, we included the south shore as a part of the City, even though the south shore is not officially a part of Quebec City (including the south shore, the land area of Quebec City is 554 km^2 and the population is 612,092 inhabitants).

The Zurich MA has a population of 1,660,000 (Federal Office 2000) and 1,820,000 in 2010 (BFS 2010) and a land area of 2131 km^2. It is located in the north of Switzerland (Figure 5-1b). Inner Zurich MA has a population of 929,000 inhabitants in 2010 and a land area of 514 km^2. It is the largest continuously urbanized area of Switzerland.

The extent of the CMAs of Montreal and Quebec changed between 1951 and 2011; as a consequence, the information about inhabitants and jobs was not available for the whole extent of the 2011 CMAs for earlier points in time. Therefore, for some areas estimated values of inhabitants and jobs were used for the calculation of urban sprawl in 1951, 1971, 1986 and 1996. Description of the calculation of estimated values are presented in Appendix 3.

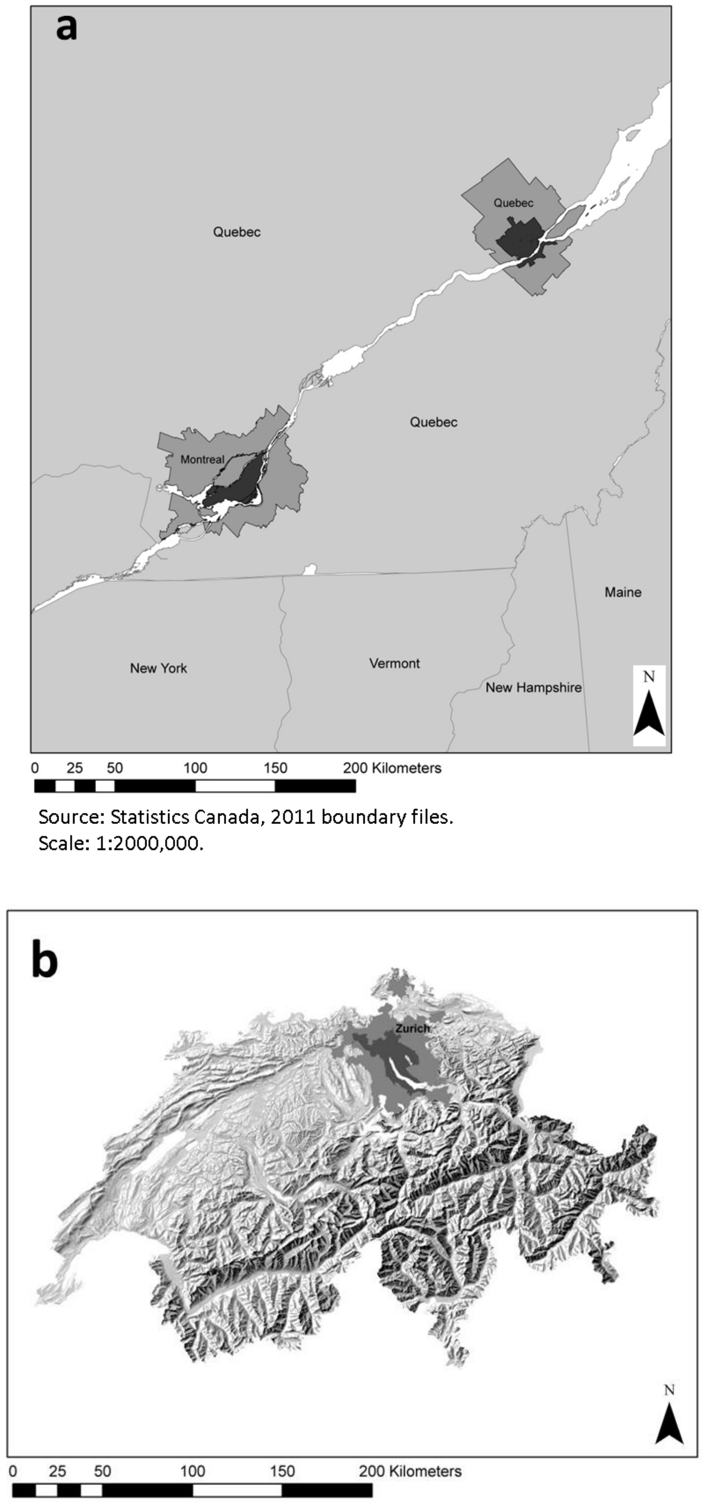


Figure 5-1: Study areas. a) The Montreal and Quebec CMAs (medium grey, delineation of 2011). The inner areas (Montreal Island and Quebec City) are shown in dark. b) The Zurich MA (medium grey) and the Inner Zurich MA (dark area).

5.2.2 Metrics of urban sprawl

For the measurement of urban sprawl, we used the metric of weighted urban proliferation (*WUP*), which denotes the level of sprawl as a matter of degree (Jaeger et al. 2010, Jaeger and Schwick subm.). *WUP* is a combination of urban permeation (*UP*), urban dispersion (*DIS*), and utilization density (*UD*) (Figure 5-2).

DIS measures the dispersion of the built-up areas based on the distances between any two points within the built-up areas. It is expressed in urban permeation units per square meter of built-up area (Jaeger et al. 2010b). This metric is an intensive metric, i.e., its value remains invariant when the study area is enlarged with a constant spatial pattern. In the calculation of *WUP*, dispersion is weighted with the w_1 (*DIS*) function, which assumes values between 0.5 and 1.5 to give higher weights to the more dispersed parts of the built-up areas.

UP measures the extent of the urban area and its level of dispersion (*UP* = built-up area * *DIS*). *UP* is an area-proportionately intensive metric (Jaeger et al. 2010b) and is expressed in urban permeation units per square meter of land (UPU/m^2).

UD measures the density of inhabitants and jobs in the built-up areas (number of inhabitants and jobs/ built-up area). In the calculation of *WUP*, *UD* is weighted with the w_2 (*UD*) function, which assumes values between 0 and 1. w_2 (*UD*) gives a lower weight to more densely utilized areas, i.e., those parts of the urban area that have more inhabitants and jobs have lower values of w_2(*UD*). The value of w_2 (*UD*) is close to 1 when there are less than 40, and close to 0 where there are more than 100 inhabitants and jobs per hectare of built-up area (Jaeger and Schwick subm.).

WUP is the result of the combination of all the dimensions of sprawl (*UP*, *w_1 (DIS) and w_2 (UD)*) and is the most appropriate metric of sprawl. Calculation of *WUP* requires the specification of the scale of analysis, which is denoted by the horizon of perception (*HP*). A person with an eye height of 180 cm can see the surrounding area within a radius of 4.9 km due to the curvature of the Earth (assuming there are no obstacles obstructing the view); therefore, distances between 1 km and 5 km are suitable for the choice of *HP* (Jaeger et al. 2010b). This study uses an *HP* of 2 km. Accordingly, the maximum used distance between two points was 2 km.

The URSMEC tool was used for the calculation of the dispersion metric (Jaeger et al. 2008). The input for the tool was a binary map of built-up areas (1 for urban area, 0 for other areas). The output of the tool was a map of so-called S_i values that are assigned to each cell and are the mean of the weighted distances between any pixels of urban area and all other urban pixels within the horizon of perception.

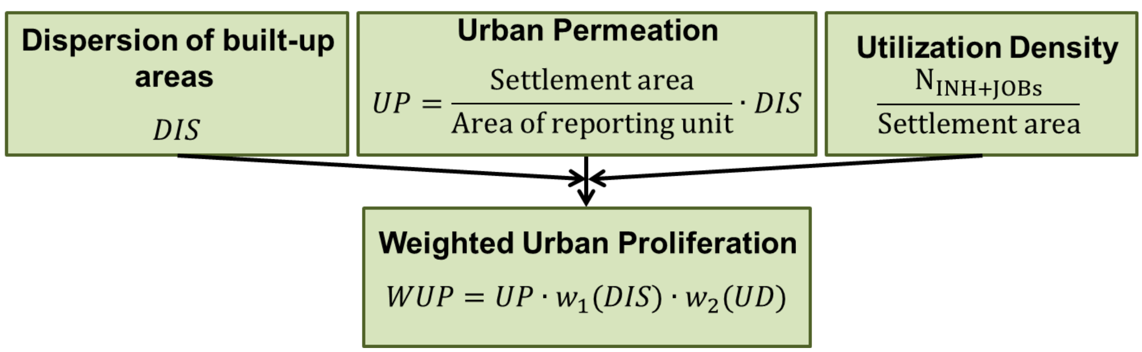


Figure 5-2: Relationships between the metrics of urban sprawl. *WUP* = weighted urban proliferation, *DIS* = dispersion of built-up areas, *UP* = urban permeation, *UD* = utilization density, w_1 and w_2 = weighting functions for *DIS* and *UD* (Jaeger and Schwick subm.).

5.2.3 Data sources

Contrary to many other methods which require a large amount of data to measure urban sprawl, this study needed only two datasets: a map of built-up areas and the information about inhabitants and jobs.

The base data used for Montreal and Quebec was the CanVec dataset, which was provided in vector format in 2007 by Natural Resource Canada and updated in 2011. CanVec was produced from three main sources: the national topographic database (NTDB), landsat 7 imagery coverage, and Geobase data. CanVec contains 11 different themes, one of which is the layer of buildings and urban structures. This layer includes all types of buildings and urban structures defined as "permanent walled and roofed constructions". The layer of buildings and structures consists of 41 types of buildings which are available in the form of areas or points. Some other features such as airports, domestic and industrial waste, and gas and oil facilities are not included in this layer, but were added to the analysis because these areas are also considered as urban areas. Table A2-1 in Appendix 2 presents a complete list of all features considered as urban areas as well as their definitions and generic codes.

Although the latest update of the CanVec dataset was in 2011, the most recent date of update for the buildings and urban structures was as far back as 1996 in the Montreal CMA, and even earlier in some parts of the Quebec CMA. Therefore, the CanVec layers were used as the base layer for the analysis of urban sprawl in 1996 and were modified for the earlier time steps according to historic topographic maps. The CanMap Route Logistics (version 2011.3, a product of DMTI spatial) was used for the calculation of urban sprawl in 2011. Being consistent with the CanVec dataset, those features of CanMap that present urban areas were used for calculation of urban sprawl. A list of these features is presented in Table A2-2 of Appendix 2.

After gathering all entities from CanVec and CanMap datasets that make up built-up areas, several limitations were identified in these layers. Therefore, some modifications were applied. The main modification was the manual delineation of the settlement areas based on the solitary buildings that were available in point format in CanVec dataset. According to our definition of urban areas, small vacant lands located between solitary buildings are part of the urban area. Therefore, these small open pieces of land were included in the category of urban areas. Wherever four or more buildings were close to each other at a distance of less than 100 meters, a new settlement area was delineated (examples in Figure 5-3a). There was one exception to this rule: When four or more buildings were located in a row, the buildings were kept in their original pattern. In order to make the comparison between Canadian case studies and Zurich MA feasible, in this study, the same method that was used to calculate the area of single buildings in the study of urban sprawl in Switzerland by Schwick et al. (2012) was used. Therefore, around all the single points that represent solitary buildings, buffers with the radius of 15 meters was created (in GIS), meaning that the assumed area of each solitary building was 706.5 m^2 ($\pi r^2 = 706.5$ m^2 when $r = 15$ m).

The other modification was related to urban footprints. The CanVec and CanMap datasets represent some urban features in the form of building footprints, whereas they present other industrial areas and residential areas in the form of settlement areas that include alleys and small vacant lands between the buildings. The use of the building footprints alone would not allow for a comparison of the results with the study from

Switzerland. Therefore, we delineated urban areas around the building footprints in a way that small alleys and vacant lands between the buildings were included in the settlement areas (Figure 5-3b). This procedure is similar to the approach used in the study of urban sprawl in Siwtzerland (Schwick et al. 2012, Jaeger and Schwick subm.).

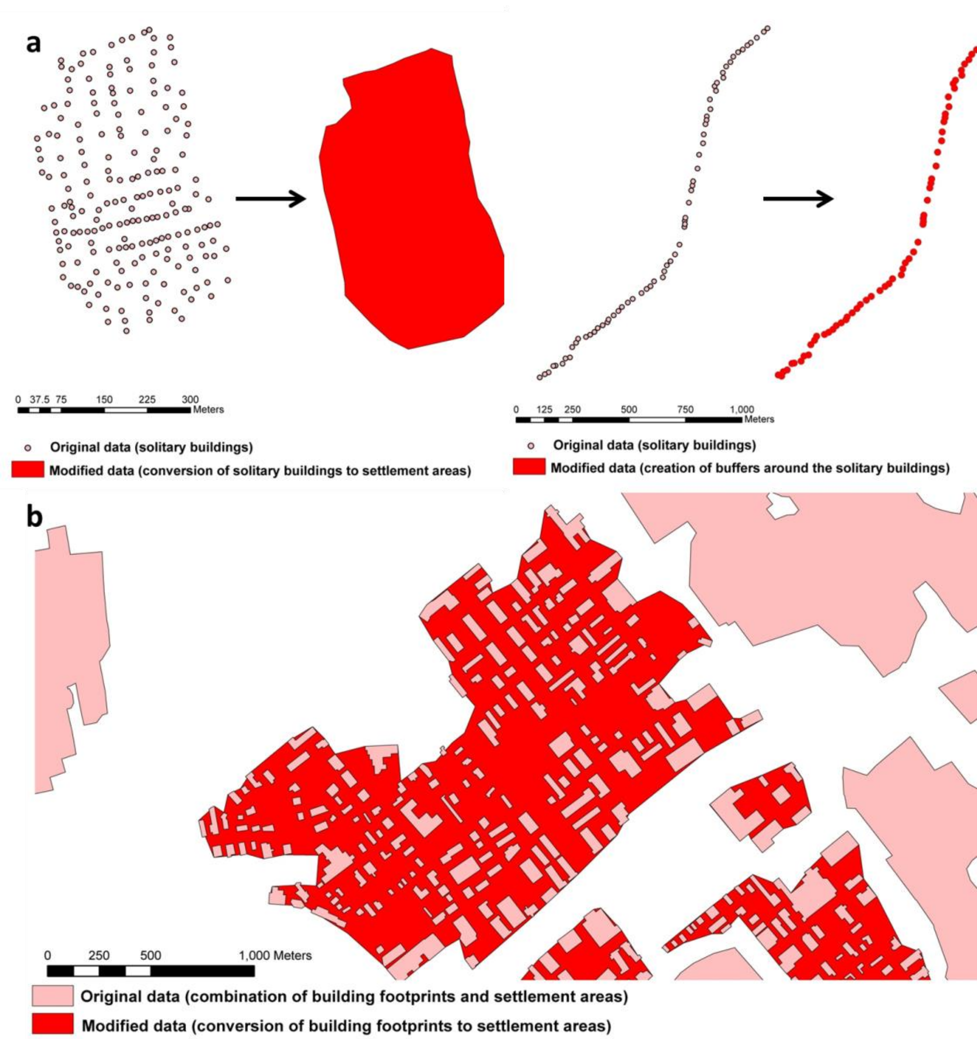
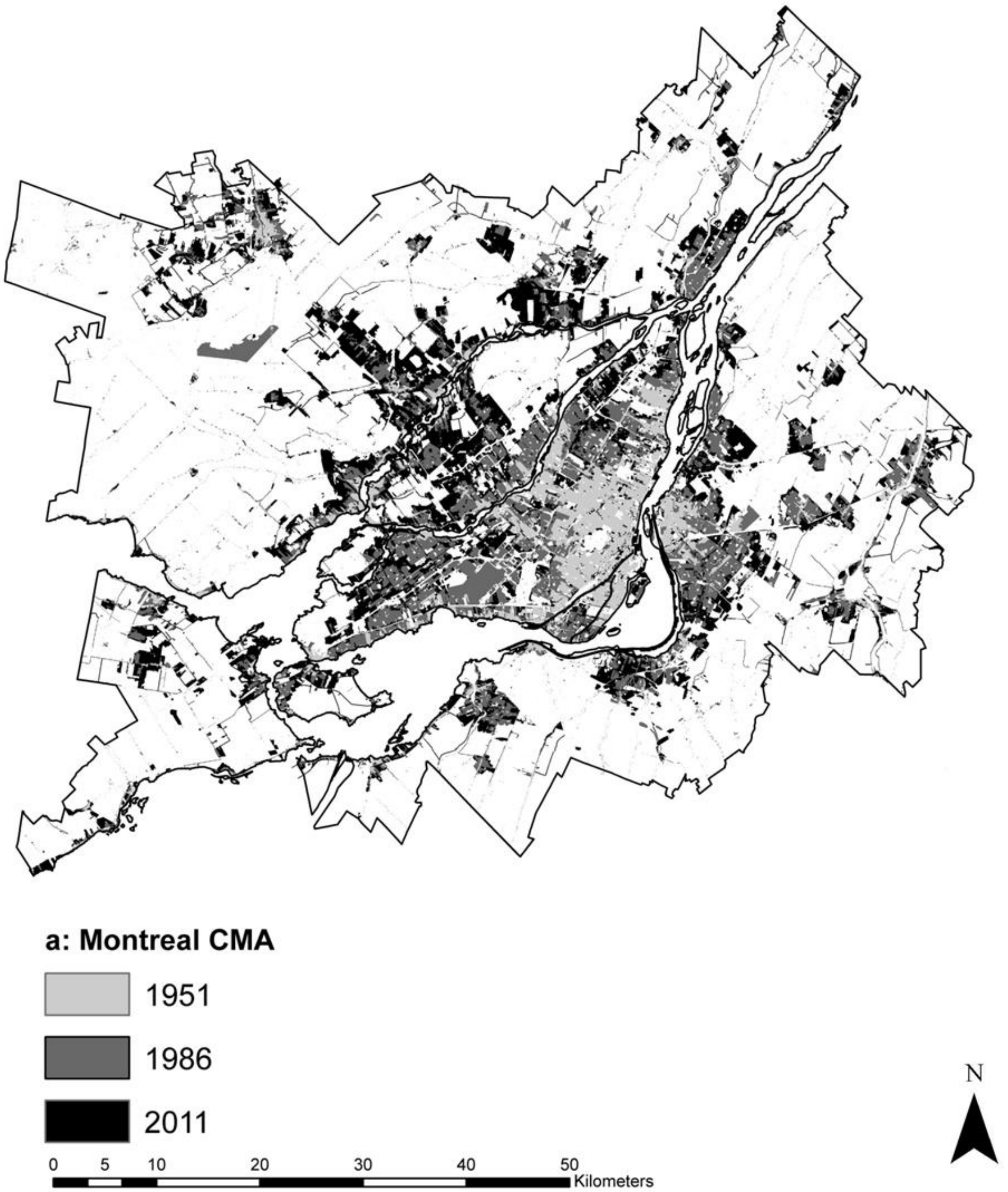
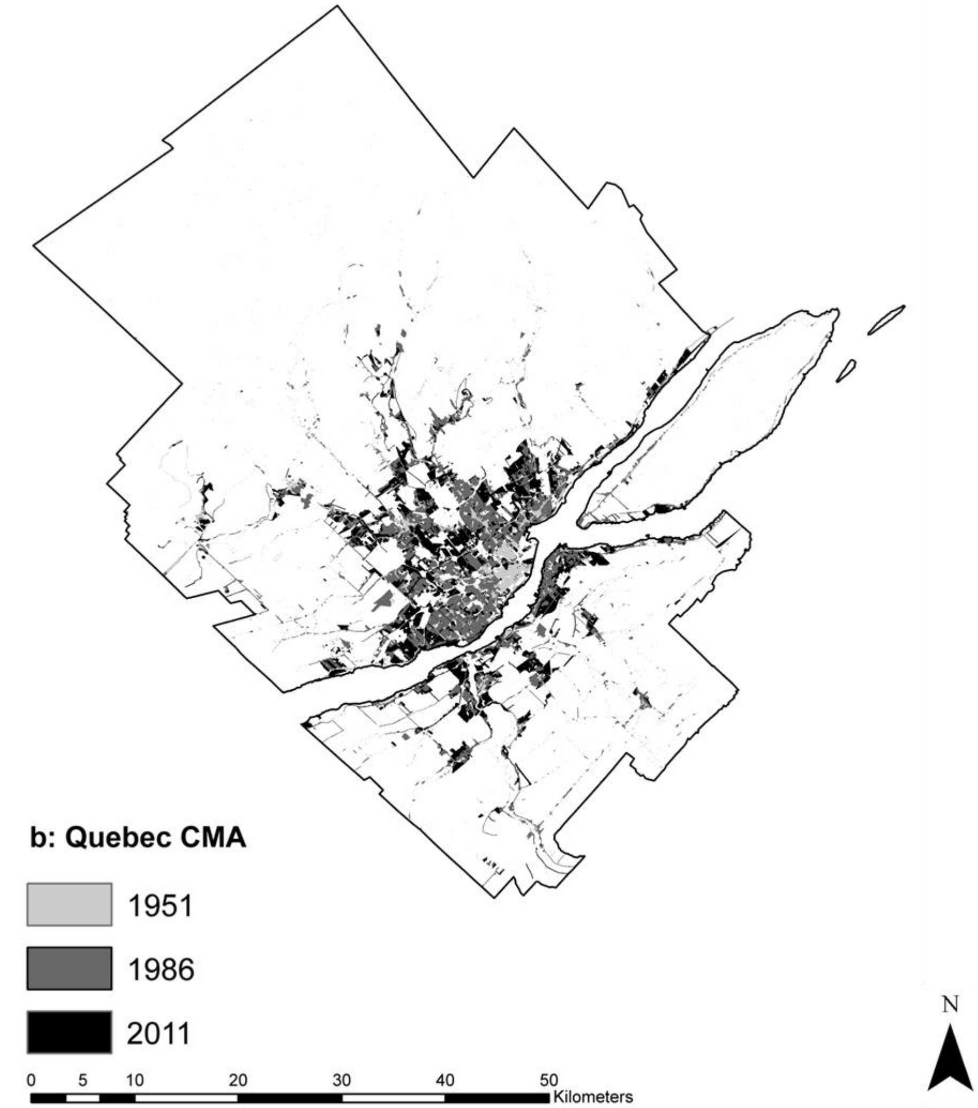


Figure 5-3: a) Delineation of built-up areas based on solitary buildings: delineation of settlement areas around building footprints located at distances less than 100 meters from one another (left); solitary buildings located in a row were kept in their original pattern and a buffer with the radius of 15 meters was created around them for the calculation of the amount of built-up areas (right). b) Delineation of built-up areas was done by converting building footprints to settlement areas. Vacant areas between building footprints are part of urban areas. Therefore, they should be considered in the measurement of urban sprawl.

For the earlier years (1951, 1971 and 1986), historic datasets were not available in digital format. Therefore, national topographic maps of Montreal and Quebec at the scale of 1:50000 were geo-referenced and digitized backwards in time, starting from the base layer that represents urban areas in 1996. We created vector data using ArcGIS 10.1 (ESRI 2011). Figure 5-4 presents the built-up areas at three points in time.



Source: built-up areas in 2011: CanVec (2011) and CanMap (2010) vector datasets, built-up areas in 1986 and 1951: national topographic maps at the scale of: 1:50,000 product of National Resource Canada.



Source: built-up areas in 2011: CanVec (2011) and CanMap (2010) vector datasets, built-up areas in 1986 and 1951: national topographic maps at the scale of: 1:50,000 product of National Resource Canada.

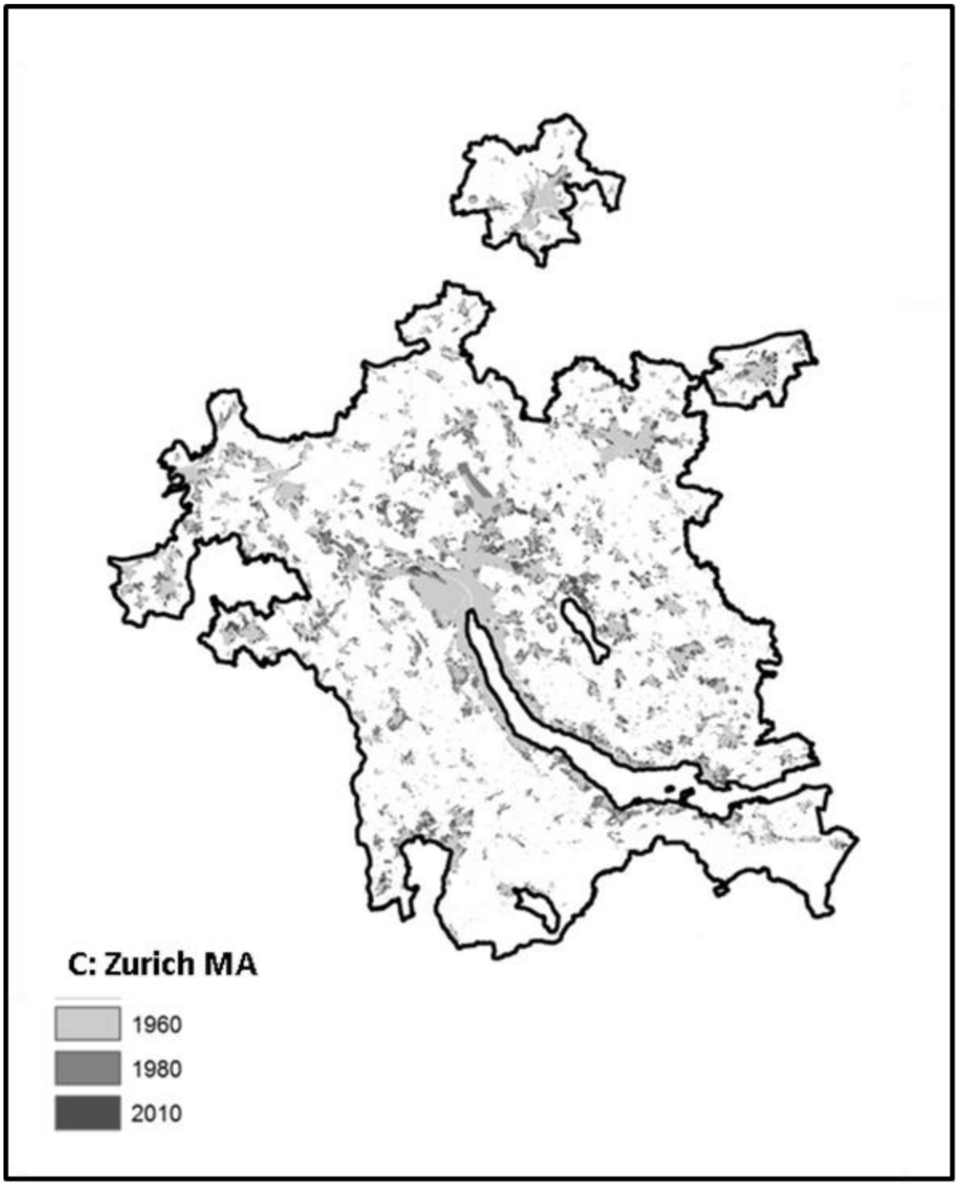


Figure 5-4: Built-up areas in the study areas in three points in time: a) Built-up areas of the Montreal CMA in the years 1951, 1986 and 2011, b) Built-up areas of the Quebec CMA in the years 1951, 1986 and 2011, c) Built-up areas of the Zurich MA in the years 1960, 1980 and 2010**.**

A lack of homogeneous data has always been one of the main challenges for studies that aim to analyze urban growth over time. Although the source data used in the creation of the CanVec and CanMap datasets are very similar, there are some minor differences. For example, solitary buildings in the CanVec dataset are presented in the form of points; however, these buildings are presented in the form of building footprints in the CanMap dataset. To reduce potential errors resulting from such differences, data of 1996 was used together with 2011 data to produce built-up areas in 2011. Meaning that all the features that create 1996 built-up areas are a part of 2011 data and those newly developed built-up areas that were created between the years 1996 and 2011 were included in the analysis using CanMap 2011 data.

The lack of homogeneous data for the years 2011 and 1996 is a limitation of this study, resulting in a neglect of those built-up areas that have been removed between 1996 and 2011. In addition, using a constant average area (of 706.5 m^2) for solitary buildings and potential digitization errors of topographic maps may have led to errors up to 10% in the final results.

The information about inhabitants in Montreal and Quebec was taken from the Canadian census for the years 1951, 1971, 1986, 1996 and 2011 (Statscan 1951, Statscan 1971, Statscan 1986, Statscan 1996a, Statscan 2011c). Job information for the calculation of urban sprawl in Montreal and Quebec for the years 1996 and 2011 were taken from Statistics Canada census of workplace of the years 1996 and 2006 respectively (job information at census tract level for the year 2011 was not available by the time of this project) (Statscan 1996b, Statscan 2006b). Canadian censuses have been conducted every five years by Statistics Canada and are the main source of detailed socio-economic and demographic information. However, information on jobs was not available for the years 1951 to 1986 in Montreal and Quebec. Therefore a correction factor was used for the calculation of utilization density for these years (a more detailed information is presented in Appendix 3).

The base data used in the Zurich MA for 2010 were provided by Swisstopo's digital topographic landscape model TLM VECTOR25 at a scale of 1:25,000. The TLM includes the layer of settlement areas, which were manually captured along their borders. Larger open spaces within settlements were not recorded as urban areas, but were excluded (if they covered 2 to 4 hectares or more). However, this data acquisition method is a little imprecise. In widely scattered settlements it is especially difficult to draw a clear distinction between closed urban areas and single buildings outside them. Despite this methodical drawback, the TLM data set is still the best available for delimiting settlements in Switzerland. Data for the settlement area of the year 2002 were obtained by using the digital landscape model VECTOR25 (the predecessor of the TLM). On the basis of this data set, settlement areas of older periods were digitized using a geographic information system. For 1960, 1980 and 1990, the 1:100,000 maps were used. Urban areas were then delimited using the same criteria as TLM and VECTOR25. Single buildings outside the closed urban areas were also manually digitized using the 1:100’000 maps for all time steps. Using existing data (VECTOR25, the National Register of Buildings and Dwellings), these individual buildings were assigned spaces.

Data about inhabitants and jobs in Zurich were drawn from two sources: Population data are from the censuses of 2010, 2000, 1990, 1980 and 1960. Data about jobs for the two newest periods (2010 and 2002) were drawn from the federal business census of 2001 and 2008. For time periods longer ago, commuter statistics from the censuses were used.

5.2.4 Reporting units

We used three sets of reporting units: (1) the entire metropolitan areas and their inner areas (Montreal Island, Quebec City, and Inner Zurich MA), (2) municipalities (in Zurich) and districts (in Montreal and Quebec), and (3) census tracts.

A census metropolitan area defines an area that consists of one or more neighboring municipalities located around a core that at least have a total population of 100,000 people (Statscan 2011a). A disadvantage of using CMAs as reporting units is that their extension has changed significantly between 1951, when the term "census metropolitan area" was used for the first time, and 2011. As a consequence, the suitability of CMAs as reporting unit to assess urban sprawl over time is limited. Therefore, to better be able to directly compare these three regions, we removed the effect of the larger reporting units on the value of *WUP* by focusing on the central, most densely populated zones of similar size: Montreal Island size of 500 km^2, Quebec City size of 554 km^2, and Inner Zurich MA size of 514 km^2.

Census tracts are one of the smaller territorial units used by urban planners (e.g., the Montreal CMA of 2011 consists of 921census tracts). The characteristics of census tracts and the existence of a wide range of census data at the census tract level has made census tracts one of the most important reporting units in urban studies. In Canada, census tracts have a population between 2,500 and 8,000 people (Statscan 2011a). One potential (but usually negligible) limitation of census tracts in studies using time series is the change of census tract delineations over time. However, in most cases, these changes consist in the split of census tracts into two or more new census tracts (Statscan 2011b), and they are usually done in a way that allows users to reaggregate the new census tracts to the original census tract for historical comparison. Neighborhood growth, community reformation, and municipal integration are some of the reasons for the changes in census tract boundaries (Statscan 2011b).

Presenting the degree of urban sprawl at the level of districts and municipalities provides a aggregated picture of similarities and differences across study areas. Districts are a combination of boroughs and municipalities and we delineated them based on census tract boundaries of 2011 (and kept them constant for all points it time). Therefore, by aggregating the population and job information of a group of census tracts, we were able to calculate population and job information at the district level. The six districts of Quebec are a combination of six boroughs of Quebec as well as the South Shore and the L'Ancienne Lorette region. The current Montreal CMA contains 46 districts, which are a combination of 19 boroughs, 15 municipalities, and 13 regional county municipalities (RCMs).

The Zurich MA was defined by the Swiss Federal Statistical Office (FSO) based on the results of the census of the year 2000. Any municipality is part of the metropolitan area if: it is part of the central city (e.g., the town of Zurich), or if the urban areas have grown to form a continuous built-up area, or at least 1/12 of the population of a given municipality is working in the core city (Zurich), or if it is part of an agglomeration that itself is part of the metropolitan area of Zurich. These are the agglomerations of Winterthur, Baden/Brugg, Zug, Schaffhausen, Rapperswil-Jona/Rüti, Wetzikon/Pfäffikon, Lachen, Frauenfeld, Lenzburg, Wohlen AG, and the city of Einsiedeln (Schuler et al. 2005). Zurich MA therefore consists of 226 municipalities from seven cantons.

The inner ZMA is not officially defined. We chose its delineation based on the objective that its size should be similar to the sizes of Montreal Island and Quebec City (about 500 km^2). Therefore, only the criteria 1 and 2 of the official FSO definition were used. Inner Zurich MA consists of 51 municipalities from three cantons of Zurich, Argau and Schwyz.

All these reporting units follow the official definitions that have been used by the administrative institutions and therefore are relevant for their planning and policy making, while they allow for temporal comparisons. The only exception is that our definition of Quebec City included the south shore, even though the south shore is not officially a part of Quebec City.

5.3. Results

5.3.1 Current level of urban sprawl

The current *WUP* value (2011) in the Montreal CMA is 12.09 UPU/m^2. It is less than half of this value in the Quebec CMA with 4.91 UPU/m^2, and between these two in the Zurich MA with 7.46 UPU/m^2 (Table 5-1). That the highest value is observed in Montreal is mainly due to the fact that Montreal has by far the largest built-up area (1137 km^2) and the highest *DIS* (47.8 UPU/m^2). The Zurich MA, exhibiting the second highest *WUP*, has a built-up area of 466 km^2 and a *DIS* of 46.4 UPU/m^2, clearly lower than in the Montreal CMA. The built-up area in Quebec CMA amounts to 328 km^2, with a somewhat higher *DIS* (46.9 UPU/m^2) than in the Zurich MA.

Table 5-1: Values of the urban sprawl metrics in the Inner Zurich MA, Zurich MA, Montreal Island, Montreal CMA, Quebec City, and Quebec CMA. The boundaries of these areas were constant over time: Inner Zurich MA, Zurich MA, Montreal Island, and Quebec City, whereas the boundaries of the Montreal and Quebec CMAs were extended over time (as shown in Figure 5-8). Utilization density = *UD*, urban dispersion = *DIS*, urban permeation = *UP*, weighted urban proliferation = *WUP*.

Montreal Island					
Year	**1951**	**1971**	**1986**	**1996**	**2011**
Area of reporting unit (km^2)	500	500	500	500	500
Built-up area (km^2)	114.2	220.4	247.5	281.8	342
Inhabitants + Jobs	-	-	-	2794310	3017420
***UD* ((inhb+jobs/km^2))**	17959.002	13931.380	10821.505	9915.441	8823.304
Inhabitants	1308989	1959145	1709465	1783315	1882440
***UD'* (inh/km^2)**	11461.35	8890.939	6906.232	6327.986	5504.484
***DIS* (UPU/m^2)**	47.21	48.276	48.485	48.658	48.91
***UP* (UPU/m^2)**	10.7837	21.2754	24.0028	27.425	33.4531
***WUP* (UPU/m^2)**	0.0139	0.3357	2.4003	4.5486	9.7486
WUP' (UPU/m^2)	0.7072	5.8625	14.8902	20.2608	30.0720
Montreal Census Metropolitan Area					
Year	**1951**	**1971**	**1986**	**1996**	**2011**
Area of reporting unit (km^2)	568.18	2694.68	3546.91	4071.96	4291.69
Built-up area (km^2)	130.47	416	551.77	763.7	1137.08
Inhabitants + Jobs	-	-	-	4787902	5567421
***UD* ((inhb+jobs/km^2))**	15394.771	9470.721	7620.570	6269.349	4896.244
Inhabitants	1395436	2737250	2921352	3326452	3824221
***UD'* (inh/km^2)**	10695.7	6579.896	5294.482	4355.705	3363.194
***DIS* (UPU/m^2)**	47.189	47.077	47.08	47.321	47.821
***UP* (UPU/m^2)**	10.8356	7.2677	7.3239	8.8751	12.6702
***WUP* (UPU/m^2)**	0.0669	1.4220	3.3244	6.2940	12.0966
WUP' (UPU/m^2)	1.0997	4.6792	6.3359	8.8819	14.1607
Quebec City					
Year	**1951**	**1971**	**1986**	**1996**	**2011**
Area of reporting unit (km^2)	-	554.29	554.29	554.29	554.29
Built-up area (km^2)	-	79.2146	123.122	132.584	219.825
Inhabitants + Jobs	-	-	-	817070	913626
***UD* ((inhb+jobs/km^2))**	-	8713.832	6142.620	6162.659	4156.151
Inhabitants	-	464594	509036	549944	606108
***UD'* (inh/km^2)**	-	5865.005	4134.403	4147.891	2757.230
***DIS* (UPU/m^2)**	-	46.3979	47.1639	47.4276	48.2156
***UP* (UPU/m^2)**	-	6.6308	10.4763	11.3445	19.1218
***WUP* (UPU/m^2)**	-	1.818	7.613	8.308	20.334

WUP' (UPU/m²)		4.941	10.654	11.668	22.490
Quebec Census Metropolitan Area					
Year	1951	1971	1986	1996	2011
Area of reporting unit (km^2)	386.66	944.04	3211.79	3211.79	3343.56
Built-up area (km^2)	18.36	87.23	176.47	191.08	327.91
Inhabitants + Jobs	-	-	-	972604	1125143
***UD* ((inhb+jobs/km^2))**	20888.557	7974.179	4948.654	5090.036	3431.297
Inhabitants	264924	480500	603267	671889	761818
***UD'* (inh/km^2)**	14430.12	5508.679	3418.602	3516.271	2323.282
***DIS* (UPU/m^2)**	43.689	45.99	45.684	45.962	46.94
***UP* (UPU/m^2)**	2.0744	4.2493	2.51	2.7344	4.6034
***WUP* (UPU/m^2)**	0.0004	1.5785	2.1249	2.3031	4.9126
WUP' (UPU/m^2)	0.0185	3.3303	2.4975	2.7479	5.2039
Inner Zurich Metropolitan Area					
Year	1960	1980	1990	2002	2010
Area of reporting unit (km^2)	514.2	514.2	514.2	514.2	514.2
Built-up area (km^2)	122.3	169.4	176.3	188.5	198.658
Inhabitants + Jobs	1,060,962	1,232,296	1,323,668	1,384,210	1,485,220
***UD* ((inhb+jobs/km^2))**	8675.1	7274.5	7508	7343.3	7476.3
***DIS* (UPU/m^2)**	46.563	47.166	47.188	47.3	47.39
***UP* (UPU/m^2)**	11.0747	15.5379	16.1766	17.338	18.3089
***WUP* (UPU/m^2)**	3.1195	8.0443	7.7001	8.8152	8.9083
Zurich Metropolitan Area					
Year	1960	1980	1990	2002	2010
Area of reporting unit (km^2)	2131	2131	2131	2131	2131
Built-up area (km^2)	272.1	376.7	400.7	428.8	465.5
Inhabitants + jobs	1,718,770	2,141,256	2,373,531	2,526,852	2,758,880
***UD* ((inhb+jobs/km^2))**	6316.7	5684.2	5923.5	5892.8	5926.7
***DIS* (UPU/m^2)**	45.42	46.079	46.121	46.259	46.417
***UP* (UPU/m^2)**	5.7986	8.1459	8.6713	9.3074	10.1402
***WUP* (UPU/m^2)**	3.6513	6.1968	6.2764	6.838	7.4605

Even though Zurich MA has a much higher utilization density (5927 inh. and jobs per km^2) than the Quebec CMA (3431 inhabitants and jobs per km^2), and the settlement area in Quebec CMA is 70% of Zurich's, the value of *WUP* in Quebec CMA is much lower than in the Zurich MA. The main reason is that the Quebec CMA is much larger

(3344 km^2) than the Zurich MA (2131 km^2), i.e., by 57% larger. (Recall that *WUP* includes the factor 1/(area of reporting unit) in its formula; figure 4.2).

The areas in the Montreal CMA exhibiting the highest levels of sprawl are located in the west of the main Island, Laval Island, Longueuil and its surroundings, and along the shoreline at the north of Laval. Highly sprawled areas in the Quebec CMA include Sillery, Sainte-Foy, Loretteville, Ancient Lorette, Vanier, and Charles Bourg. In the Zurich MA, areas of highest sprawl are Kilcherg, Rüschlikon and Erlenbach.

The lowest levels of sprawl in the Montreal CMA were observed in the downtown area with high *UD* value and in the regions that are located outskirt of the CMA such as Mirable and Rouville which have lower amount of built-up areas compared to suburbs that are located more closely to the city center. Similarly the lowest values of *WUP* in the Quebec CMA were observed in downtown area and areas with large open lands that are located very far from the city centers and at outskirt of boundary of CMA.

The results of *WUP* for the three inner study areas are directly comparable. The *WUP* value on the Montreal Island in 2011 was 9.74 UPU/m^2, whereas it was significantly higher in Quebec City with 20.3 UPU/m^2, and much lower in the Inner Zurich MA with 8.9 UPU/m^2. The strikingly high value in Quebec City is mostly caused by the low utilization density of only 4156 inhabitants and jobs per km^2, whereas both Quebec's built-up area and *DIS* are high, considering the rather low total number of inhabitants and jobs (about 913,000). In contrast, both Montreal Island and the Inner Zurich MA have a significantly higher utilization density of 8823 inhabitants and jobs per km^2 and 7476 inhabitants and jobs per km^2, respectively. As a consequence, the large built-up areas on the Montreal Island of 342 km^2 are in many parts not viewed as sprawled, which resulted in a lower value of *WUP*. The *WUP* value in the Inner Zurich MA is lower than in Quebec City because utilization density is higher and because the Inner Zurich MA has 199 km^2 of built-up area with about 1,485,000 inhabitants and jobs, whereas Quebec City has a larger built-up area of 220 km^2, but only 913,000 inhabitants and jobs.

The *UD* values on the Montreal Island and in the Inner Zurich MA are close to each other. Even though *UD* is higher in Montreal, *WUP* is lower in Zurich because *UP* is much lower in Zurich (18.3 UPU/m^2) than in Montreal (33.45 UPU/m^2) due to a lower amount of urban area (199 km^2) than in Montreal (342 km^2). The value of *UP* in Quebec City (19.1 UPU/m^2) is close to the value for the Inner Zurich MA.

Urban sprawl in the Inner Zurich MA is slightly higher than in the Zurich MA (8.90 UPU/m^2 vs. 7.46 UPU/m^2). However, there is a much larger difference between the values of *WUP* in Quebec City (20.33 UPU/m^2) and Quebec CMA (4.91 UPU/m^2).

The relationships between the values of *WUP* and the metrics of *DIS*, *UD*, the number of inhabitants and jobs, and the amount of built-up areas provide additional insight about how the sprawl patterns differ (Figure 5-5). The amount of built-up areas in the Montreal CMA is more than 3 times higher than on the Montreal Island. Similarly, the amount of built-up areas in the Zurich MA is more than twice as large than in the Inner Zurich MA. In contrast, the amount of built-up areas in the Quebec CMA is just slightly larger than in Quebec City, i.e., 67% of the built-up areas of the Quebec CMA are located in Quebec City. Similarly, the number of inhabitants and jobs in the Montreal CMA is about as twice as this amount on the Montreal Island, and the number of inhabitants and jobs in the Zurich MA is 46% higher than in the Inner Zurich MA.

However, the number of inhabitants and jobs in QCMA is only slightly higher than in Quebec City (by factor of 1.2). Moreover, urban dispersion in each CMA/MA was lower than in its respective inner areas. However, the biggest difference in the value of *DIS* was observed between Quebec City (48.21 UPU/m^2) and the Quebec CMA (46.94 UPU/m^2). Utilization density at the city level was always higher than at the metropolitan scale in Montreal and Zurich. However, *UD* in Quebec City (4156 inhabitants and jobs. per km^2) was only 17% higher than in the Quebec CMA (3431 inhabitants and jobs. per km^2).

As a result, the high value of *WUP* in Quebec City can be explained by the large difference in dispersion between Quebec City and the Quebec CMA, along with the small differences in *UD* and built-up areas compared to the other two cities and their metropolitan areas

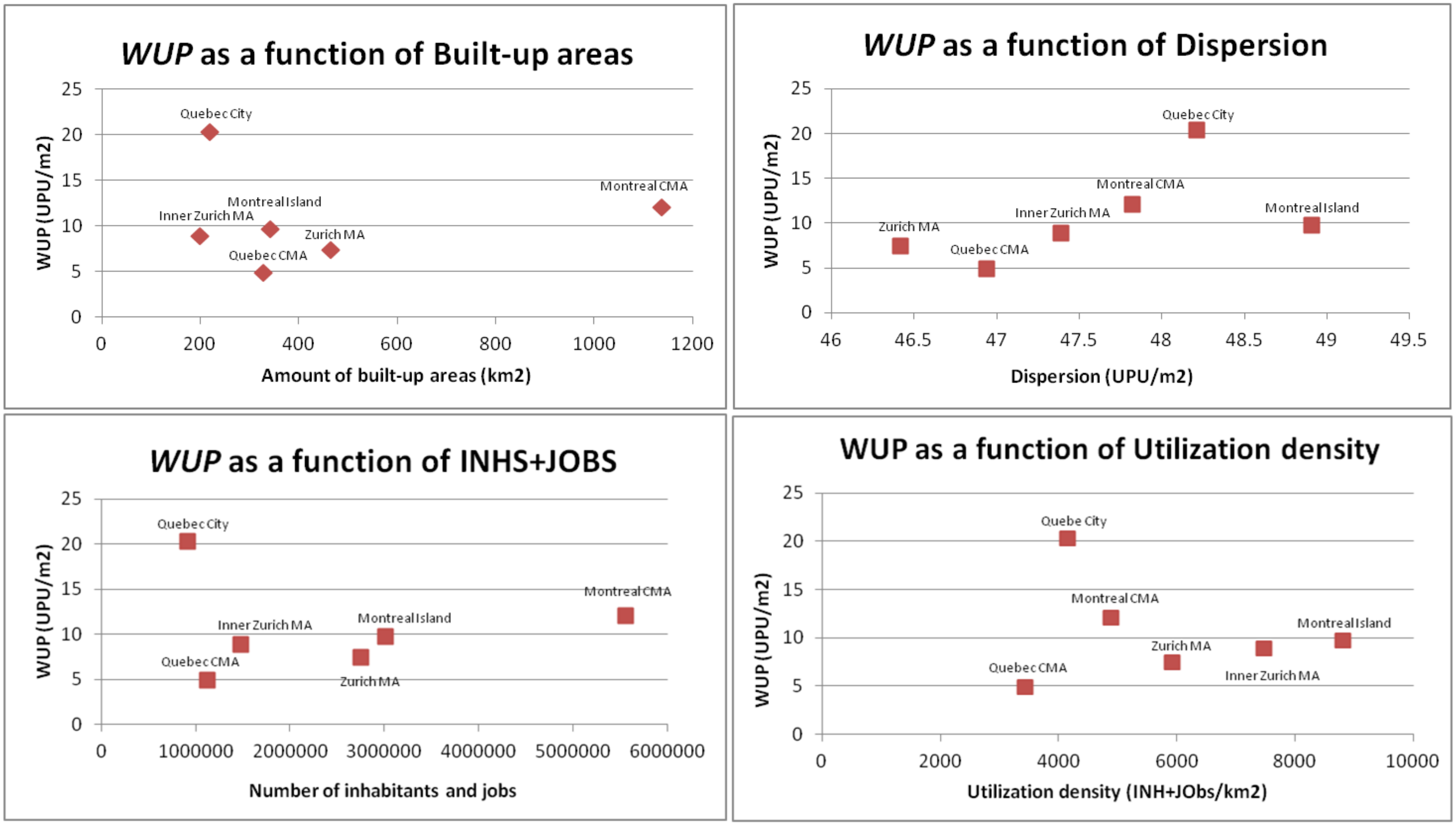


Figure 5-5: Relationships between the current values of weighted urban proliferation (*WUP*) and the four metrics of amount of built-up area, *DIS*, number of inhabitants and jobs and *UD* for six reporting units: Montreal Island, Montreal CMA, Quebec City, Quebec CMA (2011 data), inner Zurich MA and Zurich MA (2010 data).

Districts of Hampstead, Beaconsfield, Baie D'urfe, Dollard-Des-Ormeaux, Kirkland and Dorval located in the west of the Montreal Island (with the exception of Hampstead district) are the top six districts that demonstrated the highest levels of urban sprawl in 2011. In spite of the fact that these districts encompass large amounts of built-up areas they are all among the least densely populated areas (*UD* less than 4900 inhabitants and jobs per km^2). High values of *DIS* in the districts located in the west of the Island were mostly due to the presence of industrial areas with a low density of jobs. Many of the industrial sites in Montreal are located in the west of the main Island. For example, one third of the land in the district of Baie-D'urfe is covered by industrial parks, and 60% of the land in Dorval is covered by the Pierre-Elliot-Trudeau airport.

On the other end of the spectrum, Ville Marie, Le Plateau, Côte-des-Neiges, Rosemont and Outremont are the five districts with the lowest levels of *WUP*. These districts are all located in the center of the Island and constitute downtown Montreal. Downtown Montreal is the most densely populated space in Montreal and accordingly, the lowest values of *WUP* were found in this area.

The *WUP* values in districts that are located in the outskirts of the Island (i.e., Laval, Deux-Montagnes, Les Moulins, L'assomption, etc.) were always higher than 8 UPU/m^2, with the exception of Mirable and Rouville, where the values of *WUP* were 3.04 and 3.84 UPU/m^2, respectively. The obtained *WUP* value in Laval for the year 2011 was 26.31 UPU/m^2.

In Quebec City, the district of L`Ancienne Lorette exhibited the highest level of *WUP* and the district La Cité-Limoilou showed the lowest value of *WUP*. This can be explained by the high value of *UD* (12415 Inhabitants and jobs per km^2) in this district which constitutes the downtown of Quebec City. In the Zurich MA the same pattern was observed.

The highest values of *WUP* in the Zurich MA were found in the municipalities that constitute the suburbs of the city of Zurich (e.g., Zollikon, Kilchberg, Rüschlikon and Erlenbach with WUP values above 20 UPU/m^2). Also municipalities that are located north of the city of Zürich are found very sprawled (> 15 UPU/m^2). These municipalities are covered by large built-up areas that are mostly mixture of residential and industrial areas with relatively low values of utilization densities.

Low to relatively low values of sprawl in the Zurich MA were found in municipalities that are located outskirt of ZMA. The city of Zürich has a *WUP* value of 1.32 UPU/m^2 in 2010 and the city of Zug 1.71 UPU/m^2 are among the areas that have lowest values of sprawl in Zurich MA. Although these cities have large built-up areas they have high to very high utilization densities and therefore low value of sprawl. All the other municipalities with *WUP* values of below 2 UPU/m^2 in the year 2010 are rural and located in hilly terrains.

5.3.2 Historic development

Urban sprawl in all the three studied areas has been continuously increasing over time. Until 1971 the degree of urban sprawl in the Montreal and Quebec CMAs was close to each other, but very lower than degree of urban sprawl in the Zurich MA. But, since 1971 urban sprawl in Montreal CMA increased more sharply compared to Quebec CMA (Figure 5-6).

Until 1997, the Zurich MA had the highest value of *WUP* among the three metropolitan areas, and only then was surpassed by the Montreal CMA. The Zurich MA clearly has a longer history of urban sprawl, and exhibited a much higher level of 3.7 UPU/m^2 in 1960 than in the Montreal and Quebec CMAs, where it was still less than 1 UPU/m^2 at this time. Some may think Zurich is less sprawled in 1960 than Montreal and Quebec. However, one of the important findings of this study is that sprawl in Montreal and Quebec is a more recent phenomenon and the highest sprawl increases have happened since 1980.

What is similar in both Quebec and Montreal CMAs, is that the sharpest increases of sprawl in this two regions occurred during the past 25 years, whereas, the sharpest increases of sprawl in the Zurich MA happened between the years 1960 to 1980 and urban sprawl in the Zurich MA during the past 25 years increased less strongly compared to earlier times.

We also calculated the value of utilization density according to number of inhabitants (excluding the factor of jobs) and then we calculated *WUP'* for two CMAs of Montreal and Quebec for all time steps (dashed lines in figure 5-6). As expected values of *WUP'* was always higher than *WUP* in each time step for both CMAs since the utilization density using only inhabitants is lower than utilization density using inhabitants and jobs (refer to Appendix 3 for more detailed information).

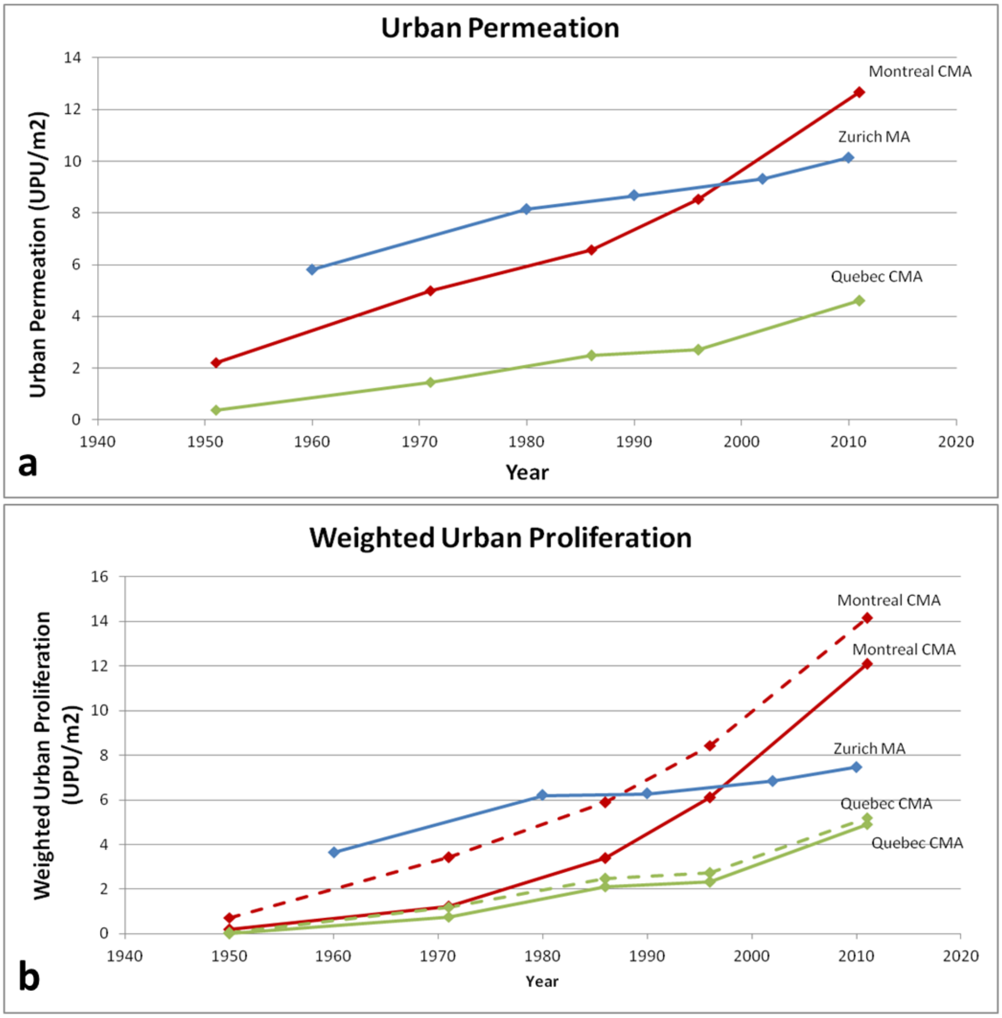


Figure 5-6: a) Increase in the value of urban permeation (*UP*) since 1951in Montreal CMA, Quebec CMA and Zurich MA; b) increase in the value of weighted urban proliferation (*WUP*) in Montreal CMA, Quebec CMA and Zurich MA. Calculation of average *WUP* for the years 1951-1996 and the use of correction factor for the calculation of *UD* values for the years 1951-1986 for the Montreal and Quebec CMAs are presented in Appendix 3. The dashed lines indicate the values of *WUP'* for the five time steps in Montreal and Quebec (*UD'* = number of inhabitants per square kilometer was used for the calculation of *WUP'*).

However, the comparison of values of urban sprawl in study areas with different sizes should be done with caution to correctly consider the influence of the sizes of the reporting units. It is more straightforward to compare the inner areas (Montreal Island, Quebec City and Inner Zurich MA) as their extents are very close to each other, about 500 km^2 (Figure 5-7).

Utilization density has decreased significantly on the Montreal Island and in Quebec City. *UD* in Montreal Island decreased by about 50% (from 18000 to 8800 inhabitants and jobs per km^2) and now is close to *UD* in Inner Zurich MA (7476 inhabitants and jobs per km^2). *UD* in Quebec City, also decreased by about 50%, but starting in 1970 already from a level of 8713 inhabitants and jobs per km^2 that Montreal has arrived at today, down to 4156 inhabitants and jobs per km^2 today. In contrast, *UD* in the Inner Zurich MA has been almost stable, and even increased slightly in the periods of 1980 to 1990 and 2002 to 2010. It is almost equals the current *UD* in Montreal and the *UD* of Quebec City of 1971.

Urban dispersion has been increasing in all three study areas, most pronounced in Quebec City, and the least in Zurich. Montreal Island has always exhibited the highest values of dispersion. The strongest increases in Montreal occurred between 1951 and 1971. In Quebec, the increase in dispersion was more or less equally strong at all times. In the Inner Zurich MA, the sharpest increases in the value of *DIS* took place in the period of 1960 to 1980. Approximately in the year 1987, *DIS* in Quebec City and the Inner Zurich MA were similar but it increased faster in Quebec City.

Urban permeation also has increased in all three study areas. As an example, *UP* in Montreal Island increased by a factor of three from 10.78 UPU/m^2 in 1951 to 33.45 UPU/m^2 in 2011. It has always been higher than in Quebec City and in the Inner Zurich MA. Between 1951 and 1996, the most rapid increase in *UP* was observed in Montreal. However, since 1996, *UP* has increased even faster in Quebec City.

Weighted urban proliferation has increased steadily and very strongly in all three study areas. While the value of *WUP* for Montreal Island was 0.01 UPU/m^2 in the year 1951, it increased at a faster and faster rate and reached a value of 9.74 UPU/m^2 in 2011. The value of urban sprawl in Quebec City has also increased enormously. In the year 1971 it was 1.81 UPU/m^2, and in 2011 it was eleven times as high with 20.33 UPU/m^2. In the Inner Zurich MA, *WUP* increased almost 3-fold from 3.11 UPU/m^2 in 1960 to 8.90 UPU/m^2 in 2010. While it was the highest in Zurich before 1985, Zurich has been surpassed by Quebec City by 1996 and Montreal by 2002.

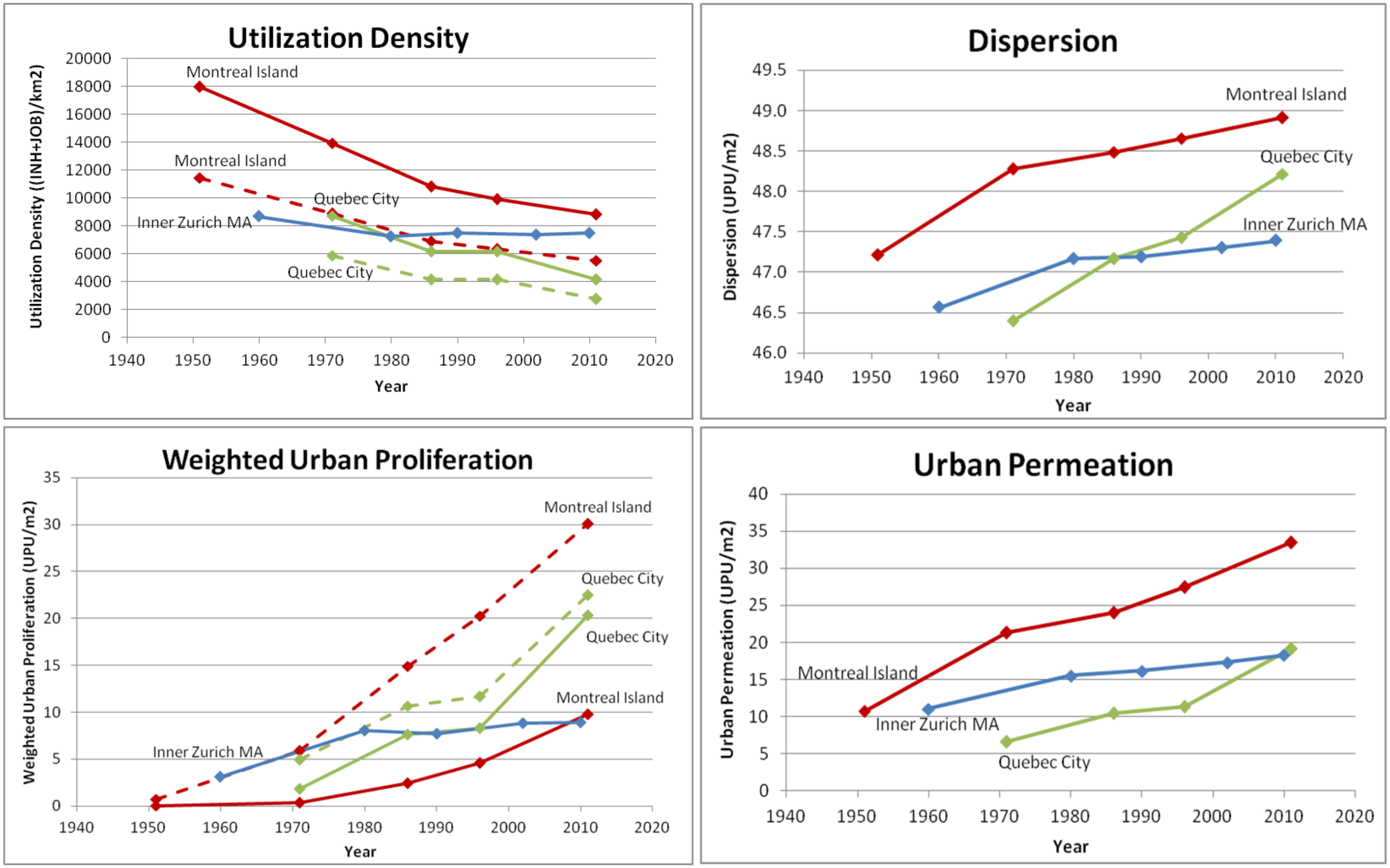
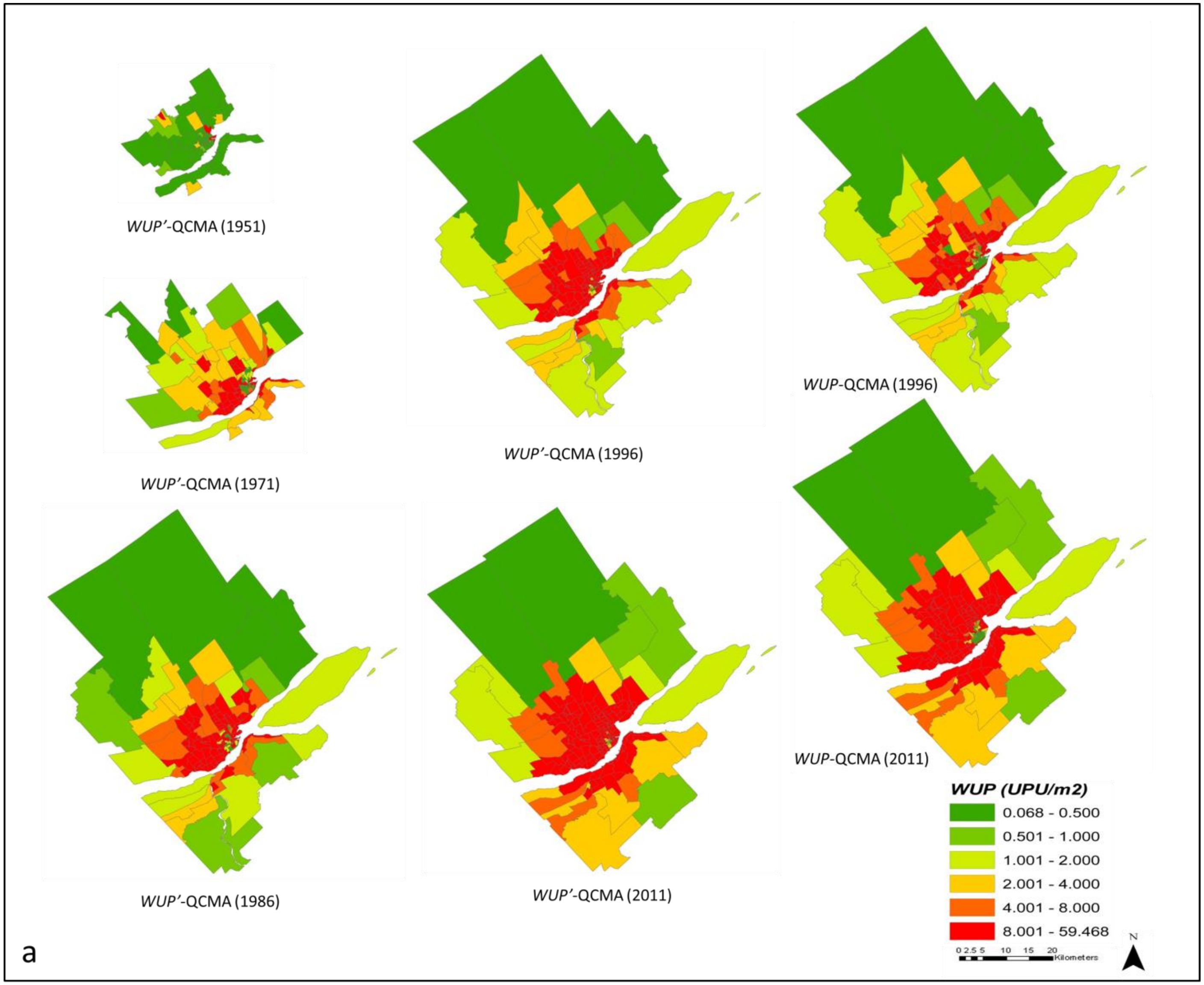
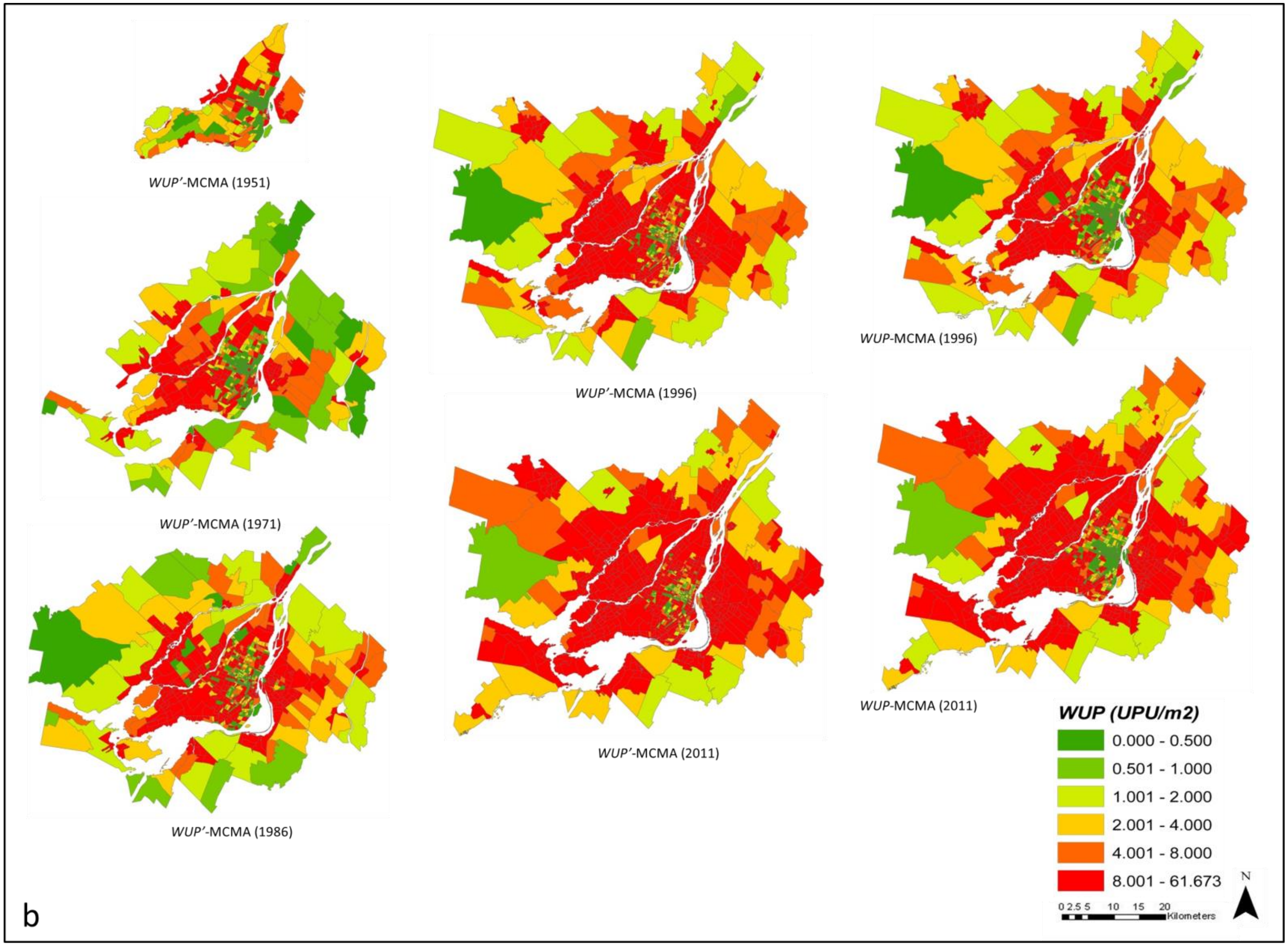


Figure 5-7: Values of *UD*, *DIS*, *WUP* and *UP* between 1951 and 2011 in the three reporting units of Quebec City, inner Zurich MA, and Island of Montreal. The dashed lines indicate the values of *UD'* and *WUP'* for the five time steps in Montreal and Quebec.

The value of *WUP* in Quebec City was always higher than this value on Montreal Island . The strongest increases in the value of urban sprawl in Quebec City happened in the period of 1986 to 2011. In the Inner Zurich MA the sharpest increase in the value of *WUP* occurred between 1960 and 1980. *WUP* in Montreal increased more steadily over time compared to the other two cities. The higher value of *WUP* in Quebec City in the most recent time steps (1996 and 2011) can be explained by the low value of *UD* in this City compared to Montreal Island and the Inner Zurich MA in combination with the strong increases in *DIS* and *UP*. Although dispersion and urban permeation in Montreal Island was always higher than in Quebec City, the higher value of *UD* on Montreal Island and in Inner Zurich MA resulted the lower value of urban sprawl in these two cities than in Quebec City.

Considering the degree of urban sprawl at smaller geographic regions such as census tract or district, help urban planners to conduct more detailed analysis of this phenomenon. Figure 5-8 present the values of *WUP* at census tract level for the Quebec and Montreal CMAs in five points in time (1951 to 2011), and for the Zurich MA at municipality level in three years (1960, 1980 and 2010).


WUP'-QCMA (1951)
WUP'-QCMA (1971)
WUP'-QCMA (1996)
WUP-QCMA (1996)
WUP'-QCMA (1986)
WUP'-QCMA (2011)
WUP-QCMA (2011)
WUP (UPU/m2)
0.068 - 0.500
0.501 - 1.000
1.001 - 2.000
2.001 - 4.000
4.001 - 8.000
8.001 - 59.468
N
Kilometers
a


WUP'-MCMA (1951)
WUP'-MCMA (1971)
WUP'-MCMA (1986)
WUP'-MCMA (1996)
WUP'-MCMA (2011)
WUP-MCMA (1996)
WUP-MCMA (2011)
WUP (UPU/m2)
0.000 - 0.500
0.501 - 1.000
1.001 - 2.000
2.001 - 4.000
4.001 - 8.000
8.001 - 61.673
N
0 2.5 5 10 15 20
Kilometers
b

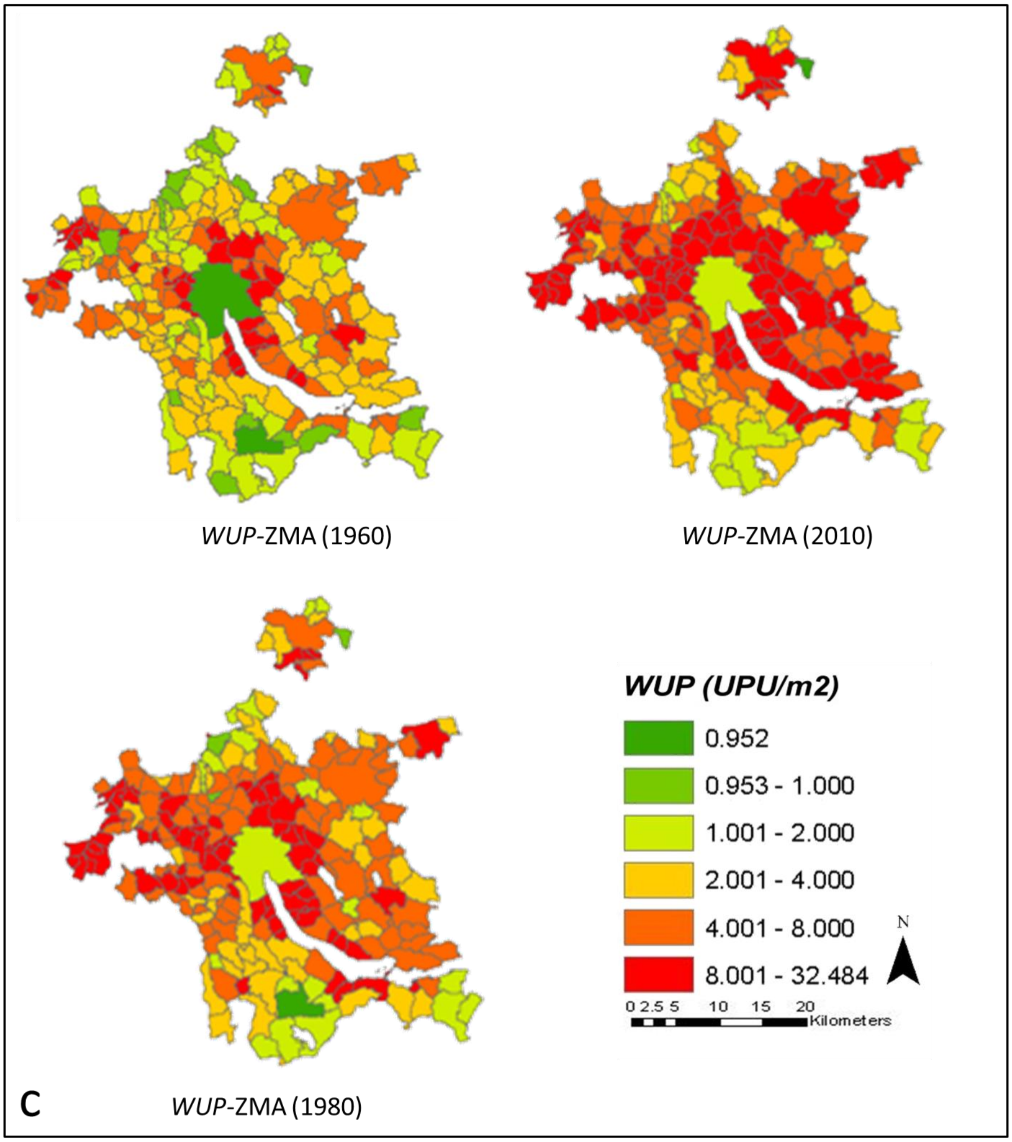
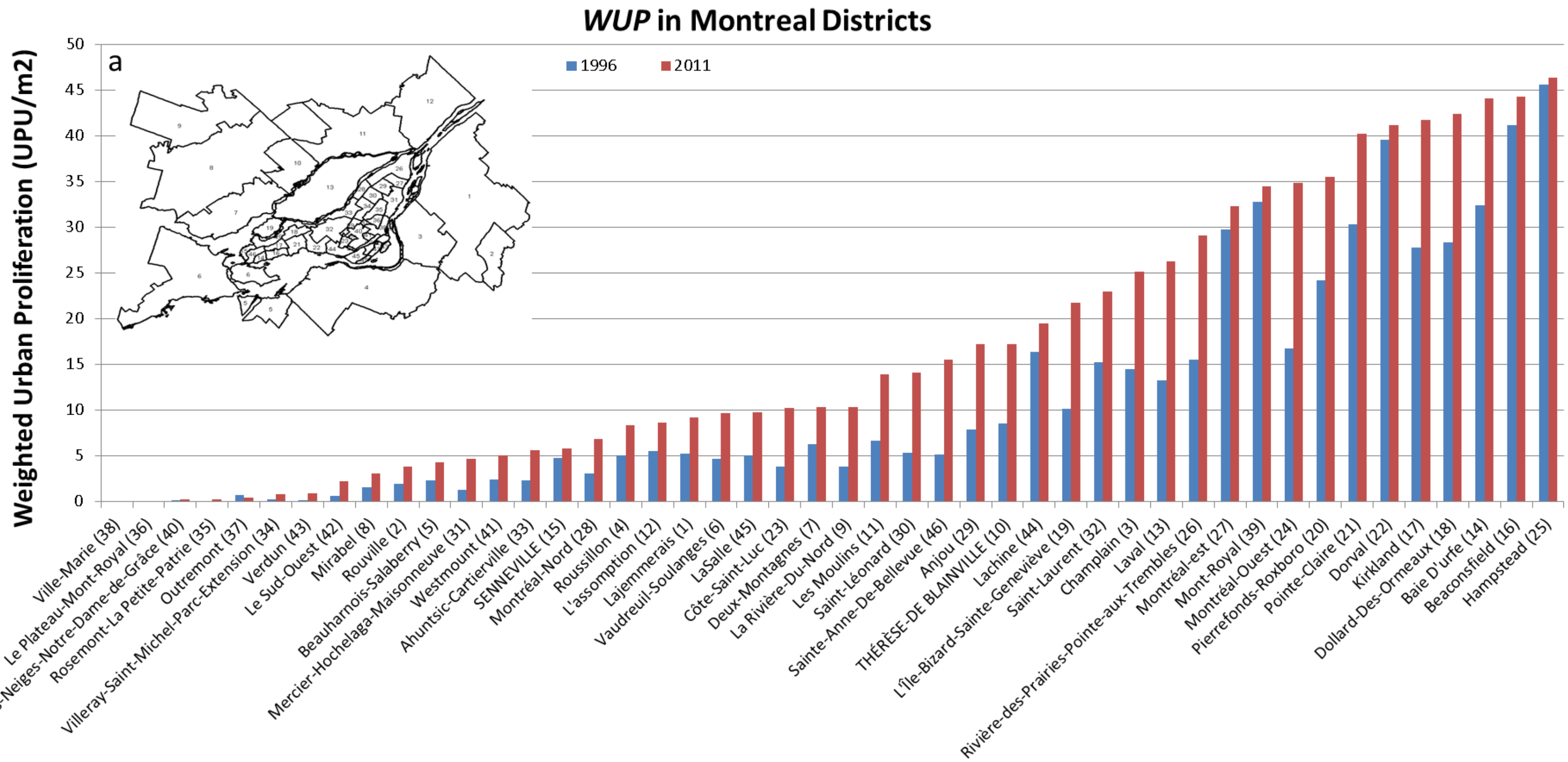


Figure 5-8: Urban sprawl (*WUP*) at the census tract level in the Montreal CMA from 1951-2011(a), in the Quebec CMA from 1951- 2011(b) and at the municipality level in the Zurich MA in 1960, 1980 and 2010 (c). Source: own data. Note that over time, the sizes of the CMAs expanded in Montreal and Quebec CMAs.

In most census tracts, urban sprawl increased in all time steps. However, there are a few census tracts in which sprawl decreased over the 25-year period between 1971 and 1996 or over the10-year period between 1986 and 1996. In areas where there was an increase in the value of utilization density, while the amount of urban areas remained constant or was slightly reduced, a decrease in the value of WUP is observed.

In general at the districts level urban sprawl has increased in most districts; however, there are some exceptions here as well. Figures 5-9 and 5-10 present the values of *WUP* for 1996 and 2011 and *WUP'* for all points in time at the district level for the Montreal and Quebec CMAs.


WUP in Montreal Districts
Weighted Urban Proliferation (UPU/m2)
a
1996
2011
50
45
40
35
30
25
20
15
10
5
0
Ville-Marie (38)
Le Plateau-Mont-Royal (36)
Côte-des-Neiges-Notre-Dame-de-Grâce (40)
Rosemont-La Petite-Patrie (35)
Outremont (37)
Villeray-Saint-Michel-Parc-Extension (34)
Verdun (43)
Le Sud-Ouest (42)
Mirabel (8)
Rouville (2)
Beauharnois-Salaberry (5)
Mercier-Hochelaga-Maisonneuve (31)
Westmount (41)
Ahuntsic-Cartierville (33)
SENNEVILLE (15)
Montréal-Nord (28)
Roussillon (4)
L'assomption (12)
Lajemmerais (1)
Vaudreuil-Soulanges (6)
LaSalle (45)
Côte-Saint-Luc (23)
Deux-Montagnes (7)
La Rivière-Du-Nord (9)
Les Moulins (11)
Saint-Léonard (30)
Sainte-Anne-De-Bellevue (46)
Anjou (29)
THÉRÈSE-DE BLAINVILLE (10)
Lachine (44)
L'Île-Bizard-Sainte-Geneviève (19)
Saint-Laurent (32)
Champlain (3)
Laval (13)
Rivière-des-Prairies-Pointe-aux-Trembles (26)
Montréal-est (27)
Mont-Royal (39)
Montréal-Ouest (24)
Pierrefonds-Roxboro (20)
Pointe-Claire (21)
Dorval (22)
Kirkland (17)
Dollard-Des-Ormeaux (18)
Baie D'urfe (14)
Beaconsfield (16)
Hampstead (25)

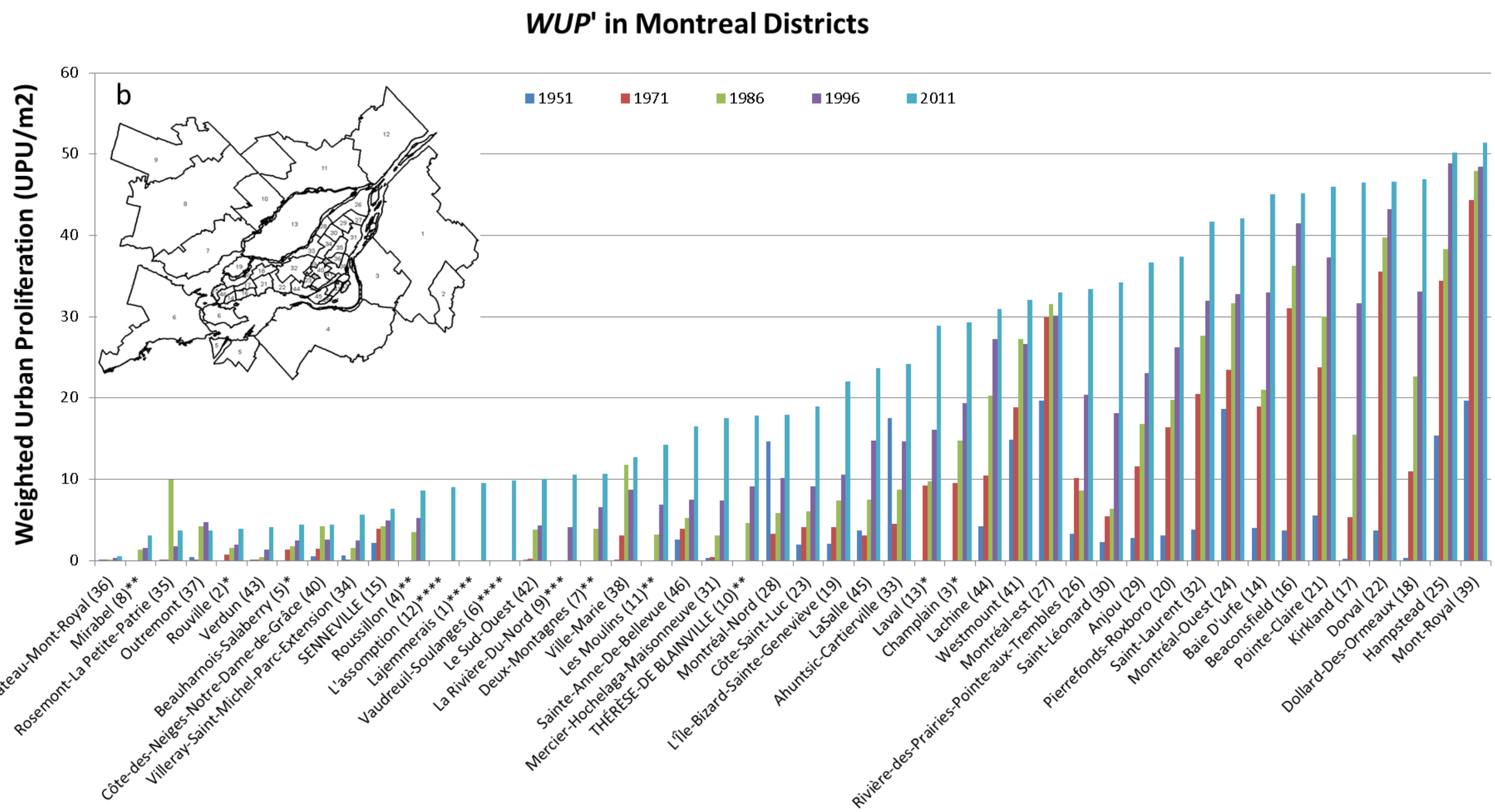
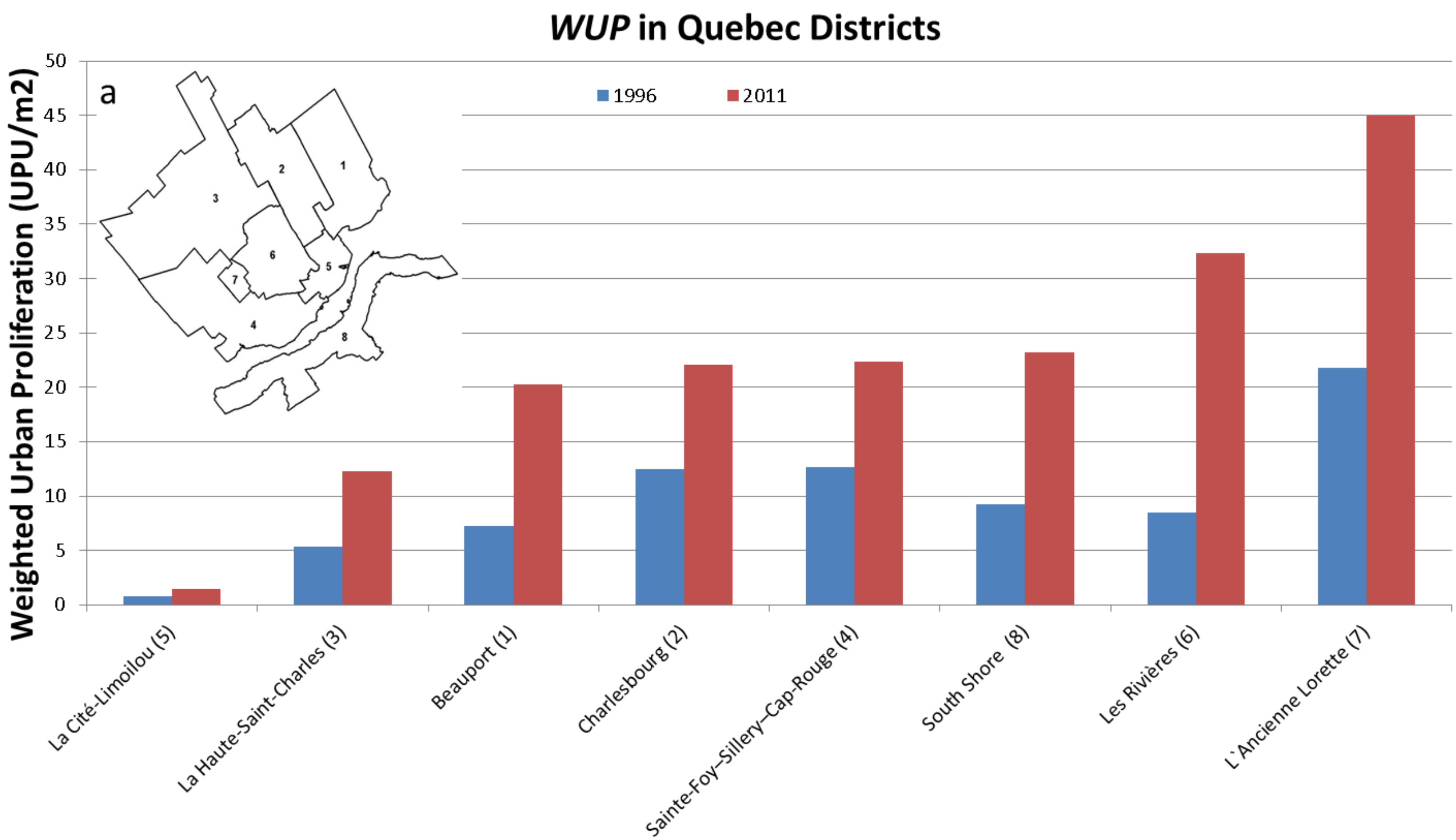


Figure 5-9: a) urban sprawl (*WUP*) in the Montreal CMA at district level in two points in time (1996 and 2011). b) urban sprawl (*WUP'*) in the Montreal CMA at district level in five points in time from 1951 to 2011, * indicates missing data in one time step, and **** indicates missing data in four time steps, respectively.



WUP in Quebec Districts
Weighted Urban Proliferation (UPU/m2)
a
1996
2011
0
5
10
15
20
25
30
35
40
45
50
1
2
3
4
5
6
7
8
La Cité-Limoilou (5)
La Haute-Saint-Charles (3)
Beauport (1)
Charlesbourg (2)
Sainte-Foy–Sillery–Cap-Rouge (4)
South Shore (8)
Les Rivières (6)
L`Ancienne Lorette (7)

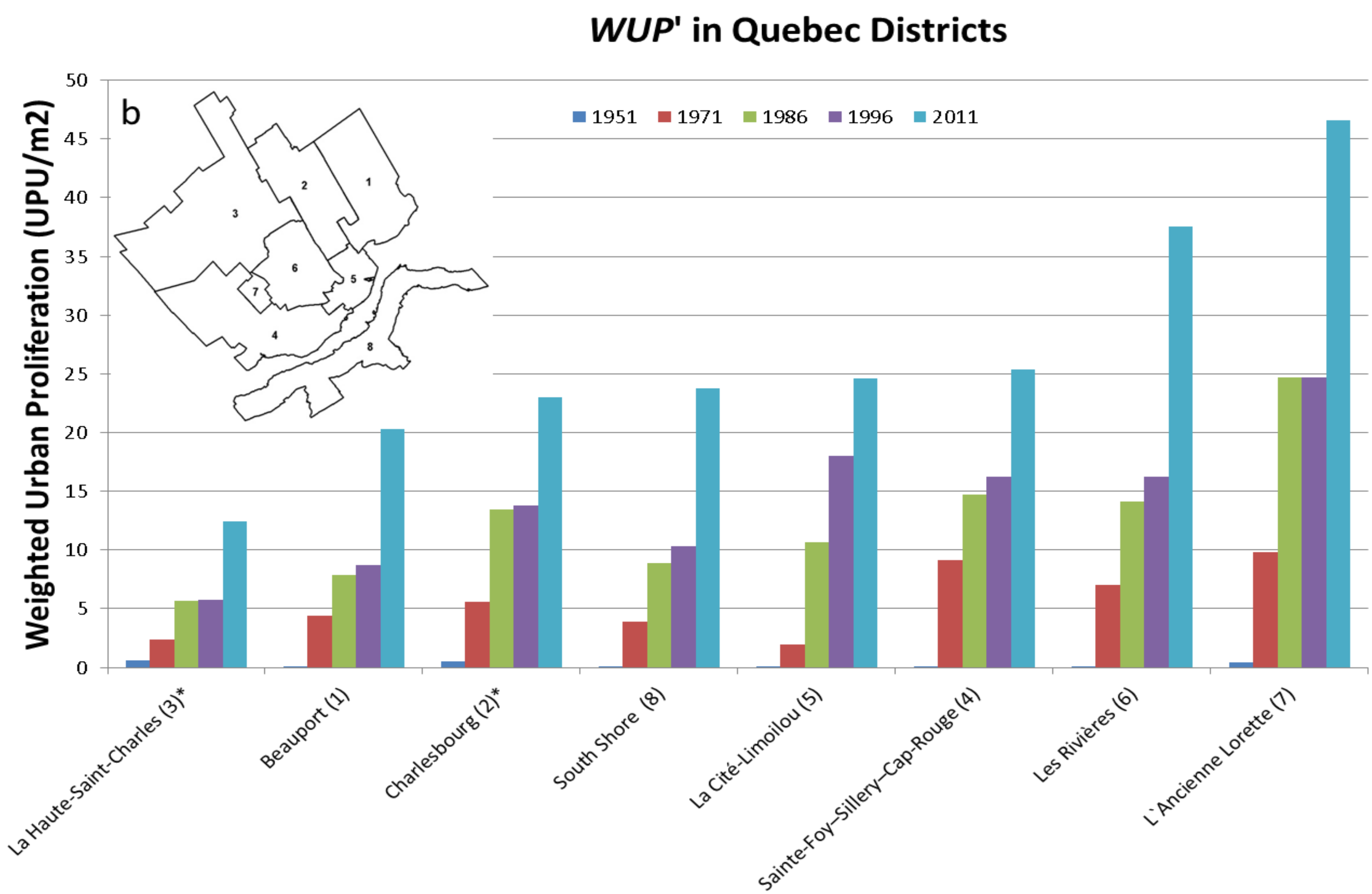


Figure 5-10: a) urban sprawl (*WUP*) in the Quebec CMA at district level in two points in time (1996 and 2011). b) urban sprawl (*WUP'*) in the Quebec CMA at district level in five points in time from 1951 to 2011,* indicates missing data for one point in time.

5.4. Discussion

5.4.1 Current level of sprawl

Inner Zurich MA differs from Montreal Island and Quebec City in several regards: Inner Zurich MA has a polycentric settlement structure whereas Montreal Island and Quebec City are monocentric. However, Inner Zurich MA is located along a lake which makes it similar to Montreal Island and Quebec City that are both along water. Just based on the amount of built-up area and the size of the reporting units, we had expected that the value of urban sprawl in the Inner Zurich MA should be higher than in Quebec City and lower than in the Montreal Island. However, Quebec City exhibited the highest value of *WUP* in 2011 followed by the Montreal Island.

WUP in Quebec City in 2011 was more than twice as high as in the Inner Zurich MA in 2010 (20 UPU/m^2) vs. (9 UPU/m^2), even though the amounts of settlement area in Quebec City (220 km^2) and in the Inner Zurich MA (199 km^2) are close to each other. However, Quebec City showed a lower value of *UD*, and it suffers from a higher dispersion than the Inner Zurich MA. The Inner Zurich MA had the lowest value of dispersion (47.3 UPU/m^2) compared to Quebec (48.2 UPU/m^2) and Montreal (48.9 UPU/m^2). Montreal Island still has the highest *UD* (8823 inhabitants and jobs per km^2). Although it is more dispersed than Quebec City and has more built-up areas it is less sprawled. This is mainly due to the much higher value of *UD* (4156 inhabitants and jobs per km^2 in Quebec City).

Various factors can explain the lower level of urban sprawl in Zurich. Firstly, Switzerland has a stronger regional planning legislation than Montreal and Quebec, e.g. the Spatial Planning Act of 1979 and the Richtpläne (structure plans) of the cantons. For example, there are a number of limitations for new designated building zones in Switzerland and only zones with relatively high population densities and almost always good connection to public transport are permitted. Factors such as the scarcity of suitable land in the Zurich MA, higher use of public transportation by inhabitants from all social classes, continuous expansion of the public transport system as well as the higher level of utilization density also contribute to explaining the slower increase of urban sprawl in Zurich. Moreover, the direct democracy, in Switzerland has favored stronger legislation and stricter regulations for regional planning that are usually accepted by the population's voting, e.g., Kulturlandinitiative that was a referendum to protect farmlands and the revision of the Spatial Planning Act in March 2012 that made this law more restrictive. In the City of Zurich, the motorized private traffic is scheduled to decrease from 36% to 26% in the next 10 years. This was decided by the population on September 2011. The area of the city of Zurich is 92 km^2, i.e., it covers about 20% of the Inner Zurich MA.

We found that larger cities are usually more sprawled than smaller ones, but at the city level of similar size (about 500 km^2), e.g. Montreal Island, Quebec City and Inner Zurich MA, cities with higher levels of availability of public transport use (modal share) and higher utilization density have a lower value of urban sprawl. Our results also suggest that a polycentric settlement structure does not necessarily lead to a higher level of sprawl. On the contrary, rather than contributing to urban sprawl, a polycentric settlement structure may indeed be suitable for reducing urban sprawl when efficient public transportation is implemented between the centers, which makes the use of cars unnecessary for travelling between the centers. In any case, it is certainly not the most important factor as compared to other factors to explain the differences between the Inner

Zurich MA and Montreal Island and Quebec City. A more detailed analysis may be needed to compare urban sprawl between polycentric and monocentric urbanization patterns.

5.4.2 Historic development since 1951

Urban sprawl in Montreal and Quebec has been rapidly increasing and most drastically in the last 25 years. The high value of urban sprawl can be explained by the large amount of built-up areas along with their high dispersion in the landscape as well as the decreasing utilization density in both study areas. Neither in Quebec City nor in Montreal did the strongest increase in sprawl occur during the time of classic suburbanization (neither in the City nor in the CMA), but only in the last 20 to 30 years, and it did at an increasing rate.

In contrast, the increase of sprawl in Zurich (both in the Inner MA and in the MA) was significantly slower in the years after 1980 than before 1980, and clearly slower than in Montreal and Quebec since the 1980s. This may give hope for further slowing down its increase and even advancing a decrease if appropriate measures are taken, even though it exhibited higher sprawl in the 1960s and 1970s. However, in Montreal and Quebec, the current increase has been strikingly faster since the 1980s, faster than ever before, with no slowdown in sight.

The value of utilization density on the Montreal Island has always been higher than in Quebec City and the Inner Zurich MA. Since 1980, *UD* in the Inner Zurich MA has stabilized at about 7300 inhabitants and jobs (7275 inhabitants and jobs in 1980 and 7476 in 2010), and similarly in the Zurich MA.

In contrast, *UD* on the Montreal Island has continuously decreased from 17959 inhabitants and jobs per km^2 in 1951 to 8823 inhabitants and jobs per km^2 in 2011, but this value is still slightly higher than in the Inner Zurich MA. However, utilization density in the larger Montreal CMA is now as low as 4896 inhabitants and jobs per km^2, and also has decreased strikingly, while it always has been between 5900 and 6400 inhabitants and jobs per km^2 in the Zurich MA. In Quebec City *UD* lost 52% of its value of 1971 and in the Quebec CMA 83% of its value of 1951 (from 20888 in 1951 to 3431 inhabitants and jobs per km^2 in 2011).

These results may be reflective of the differences in sprawl patterns between North America and Europe more generally. Montreal is a prime example of a concentric city surrounded by suburbs, i.e., it is typical of sprawl, whereas in the Zurich MA, several centers are growing towards each other, which is also contributing to an increase in the level of urban sprawl. However, even though Zurich MA is polycentric, it still has a lower degree of sprawl, and has almost been able to stabilize the level of sprawl.

In the beginning, we had expected that both monocentric and polycentric settlement patterns would lead to sprawl to a similar extent (and that the remaining differences would be caused by the topography, number of inhabitants and size of the regions), but that the main differences would be explained by the stronger regional planning legislation in Switzerland. How then does the almost exponential increase in sprawl in Montreal and the stabilization of sprawl in the Zurich MA relate to Zurich's polycentric settlement structure? Regional planning and public transport between the various centers in the Zurich MA are very strong, so there is no need for using cars when moving between these centers, whereas in Montreal and Quebec, most parts of the regions can only be accessed reasonably well (or at all) by car.

There are three levels of government in Canada (federal, provincial and municipal). According to Section 92(8) of the Constitution Act (1867), in each province, "the legislature may exclusively make laws in relation to municipal institutions in the Province". The rights and duties of municipalities in Quebec can be found in "cities and towns act", "municipal code" as well as the act respecting "land use planning and development (established in 1979)". However, planning laws in Quebec are not as strict as in Switzerland, and there is no common law between municipalities with the aim of controlling sprawl or densification of urban development.

As both Montreal and Quebec are monocentric, the difference in their level of sprawl, utilization density and dispersion can only be explained by the difference in their size, modal share, history and planning policies, but not by their settlement structure.

During the last decades, the Montreal Urban Community has coordinated certain plans, but, their effects on land-use planning were not very useful (Filion et al. 2010 cite Germain and Rose, 2000). In 1978, agricultural zoning or urban growth boundaries were established for Montreal. However, they were not very effective since most of the requests regarding rezoning of agricultural lands have often been accepted by the provincial governments who are responsible for this policy (Filion et al. 2010 cite Fischler and Wolfe, 2000; Germain and Rose, 2000).

Montreal's inhabitants use public transport more often than Quebec's inhabitants (with a modal share of 21.7% vs. 9.8% in Quebec). This is mostly due to the higher availability of public transport in Montreal which favored a higher utilization density in

Montreal. Montreal has an extensive bus system, an underground metro system and numerous commuter trains. However, the growth in the capacity and the extent of the metro in this city was not sufficient compared to the 72% increase in the population from 1961 to 2011. According to the census of 1961, the population of the Montreal CMA was about 2,215,600 people when the first inauguration of the metro Montreal took place (today 3,824,200 people).

Contrary to Montreal, public transport in Quebec only includes a bus system. Low availability of public transportation in addition to a lower price of gasoline in Quebec (annual average price of gasoline per liter in Quebec is 3% less than in Montreal) facilitated a higher use of the automobile in Quebec and the construction of freeways and highways.

5.4.3 Comparison with other studies

A study on the process of urbanization in the former county of Laprairie in Montreal CMA showed that 72% of the remaining open lands in 1988 became developed by 2000 (Murshid 2002). Using more land per person which is mostly due to the reduction in household size has been a major reason for the conversion of agricultural lands into urban areas in this county (Murshid 2002). Our results showed that the former county of Laprairie which is located in the municipality of Roussillon (district 4), exhibited a *WUP* value of 8.40 UPU/m^2 in 2011 and 5.06 UPU/m^2 in 1996, demonstrating a continuous increase of urban sprawl over the past 15 years. A recent study of Calgary proposed by Sun et al. (2007) used Shannon's Entropy to measure the degree of urban sprawl and its changes over time. Shannon's Entropy increased continuously from 0.850 in 1985 to 0.905 in 2001 in Calgary. The authors compared their result to the results of the study by Yeh and Li (2001) that used the same method for the measurement of urban sprawl in Dongguan City, China. Entropy was higher in Calgary for all time steps than in Dongguan City in 1990 (Sun et al. 2007).

However, although Shannon's Entropy measures urban sprawl as a continuous variable, it seems that it is not a reliable approach to quantify urban sprawl, since it does not meet the most of the suitability criteria for the measurement of urban sprawl suggested by Jaeger et al. (2010a). Moreover, the Entropy method is challenged with some limitations that have disabled us to compare the outcomes of the present study with the study of urban sprawl in Calgary and discussing these limitations is beyond the scope of this chapter.

Between 1971 and 2006 inner city densities in major metropolitan areas of Canada including Montreal declined sharply (Filion et al. 2010). A similar trend was observed in our results. Absence of planning agencies during the past decades of development is the main reason for the administrative fragmentation in Montreal and therefore the formation of numerous political institutions in this city (Filion et al. 2010). We also believe that the lack of efficient planning strategies and existence of many non-coordinated institutions was the main reason for the current high degree of urban dispersion and therefore high degree of urban sprawl in Montreal and Quebec.

5.4.4 Advantages and disadvantages of the method

The main and most important advantage of the method I used in my study is that it meets all 13 suitability criteria for measuring urban sprawl proposed by Jaeger et al. (2010a). Moreover, it does not require a large number of datasets to analyze urban sprawl (only a map of built-up areas and information about inhabitants and jobs is required), making it convenient for comparative analysis of urban sprawl at cross-national levels. It can also be applied at any scale and for different kinds of reporting unit (e.g., census tracts, districts, municipalities, *etc*.).

This method allows urban and environmental planners to conduct quantitative assessments of urban sprawl and compare potential future scenarios. Accordingly, Switzerland has already implemented *WUP* in various monitoring systems since 2010 for example, in the Swiss Landscape Monitoring System LABES, which includes more than 20 indicators about the state and development of the Swiss landscape (Roth et al. 2010).

When calculating sprawl using *WUP*, the first fundamental step that needs to be done is delineating the landscape or reporting unit. This might be difficult to understand or raise questions for people who want to compare different-sized cities without delineating the landscape for which they are measuring sprawl. This could result in sprawl analysis for the small city being done in a much smaller landscape than that for a large city. Of course, one can measure sprawl in a city with a small landscape and compare it with sprawl metrics for a larger one (located in a larger landscape inevitably); but, landscape size needs to be considered in result interpretation.

In fact, comparing two landscapes with different reporting unit sizes regarding the value of *WUP* is not advisable, since the size of the reporting unit and the amount of open space directly influence sprawl values. This is the reason that, for comparing urban sprawl at CMA levels for different points in time, I conducted all calculations and data analysis according CMA extent in 2011. (Recall that the MCMA and QCMA extent changed over time and estimated *UD* values to calculate sprawl at 2011 extent were used).

The values that were obtained by calculating WUP at CMA and city levels might look counter intuitive when CMA is compared to city (e.g. the obtained WUP value in 2011 for Quebec CMA was 4.91 UPU/m^2, whereas WUP in Quebec City was 20.33 UPU/m^2), but this is due mostly due to the area of reporting unit, which acts as a denominator when calculating UP (the bigger the reporting area unit, the smaller the UP value, if the amount of built-up area and dispersion remain constant). The area of built-up areas within the QCMA boundary is larger than the amount within the Quebec City boundary. However, the UP value for the QCMA was 4.6 UPU/m^2 (versus 19.12 UPU/m^2 in Quebec City).

The lower UP and WUP value at QCMA is due mostly to large amounts of open space left within the CMA boundary (about 90% of QCMA is open space), whereas, in Quebec City, built-up areas cover 40% of land.

The alternative way of comparing two different-sized cities is to eliminate the effect of size of the reporting unit by calculating total sprawl in each city. In fact, Jaeger et al. (2010b) introduced the total sprawl (TS) metric. TS, which is the product of total amount of built-up areas and built-up areas dispersion ($TS = \text{Settlement area} \cdot DIS$), is an extensive metric (5-11) (Jaeger et al. 2010b). In fact TS, calculates sprawl without considering landscape size.

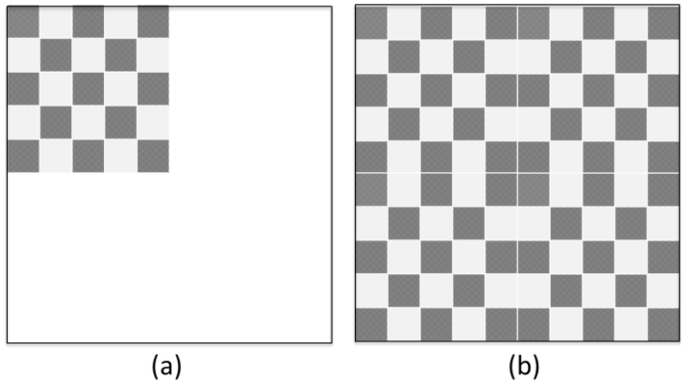


Figure 5-11: *TS* is an extensive metric, if calculated value of *TS* for landscape a is x UPU, *TS* for landscape b which has settlement structure and dispersion pattern similar to landscape a is 4 times more (4x UPU).

One limitation with *TS* is that it does not consider the third dimension of sprawl, utilization density. Also weighted dispersion (w_1 (*DIS*)) and weighted utilization density (w_2 (*UD*)) are not considered in the *TS* calculation, I recommend adding these two factors to the original equation and use TS', ($TS' = \text{Settlement area} \cdot DIS \cdot w_1(DIS) \cdot w_2(UD)$). This equation is, in fact, equal to ($WUP \cdot \text{area of reporting unit}$). Table 5-2 presents the value of *TS*, TS', *WUP* and *UP* for the six study areas – Montreal CMA, Quebec CMA, Zurich MA, Montreal Island, Quebec City, and Inner Zurich MA.

Table 5-2: Values of TS', *TS*, WUP and *UP* for six reporting units: Montreal CMA, Quebec CMA, Montreal Island, Quebec City (2011 results) and Zurich MA and Inner Zurich MA (2010 results). *TS'* could be use to compare sprawl in landscapes with different sizes (e.g., *WUP* which is the indicator of sprawl is higher in Quebec City than in Quebec CMA, however, *TS'* which is the indicator of total sprawl is higher in QCMA compared to Quebec City).

Sprawl metric	MCMA	Montreal Island	QCMA	Quebec City	Zurich MA	Inner Zurich MA
TS	54,376,416,388	16,726,422,728	15,391,842,059	10,598,994,270	21,607,113,500	9,414,402,620
TS'	51,914,784,581	4,874,256,475	16,425,487,662	11,270,762,376	15,898,325,500	4,580,647,860
WUP	12.0966	9.7486	4.9126	20.3337	7.4605	8.9083
UP	12.6702	33.4531	4.6034	19.1218	10.1402	18.3089
Area of reporting unit	4,291,690,185	499,996,791	3,343,560,257	554,289,339	2,131,000,000	514,200,000

Although *WUP* is an appropriate metric for quantifying the degree of sprawl, it does not include all aspects associated with urban sprawl (e.g., transportation aspects). "For urban sprawl, the ideal case would be that one indicator quantifies the degree of urban sprawl, while a set of additional indicators measure relevant causes, consequences, and attributes of urban sprawl" (Jaeger et al. 2010a, p 405).

One suggestion for potentially improving *WUP* could be the inclusion of a third weighting function (in addition to weighted *DIS* and weighted *UD*) that describes a transportation indicator, such as car dependency or mileage traveled per person. The bigger car dependency or mileage traveled per person value, the higher the weighting function value and the bigger the value of sprawl.

Utilization density could also be improved. Its significant advantage, which distinguishes it from other metrics that aim to measure density, is including the number of jobs in addition to the number of inhabitants when calculating density. However, it should be noted that the average work day is eight hours and the remaining 16 hours is dedicated to time spent at home or traveling to and from work. Therefore, decreasing the influence of number of jobs by a factor of 2 would result in a more accurate utilization density analysis. Including a usage indicator when calculating *UD*, such as the number of people that use a specific complex (e.g., number of students in a school), could also improve this metric.

Conclusion

The methodology used in this study can be applied as a tool for identifying the levels of sprawl and urban permeation and their change over time as well as the amount and dispersion of the urbanised areas at the metropolitan scale and at smaller scales (such as boroughs and census tracts). All these are important characteristics of the landscape. The results can then be used for the classification of metropolitan areas regarding urban sprawl and the identification of lands that are most in danger from sprawl and areas with higher potential for future urban developments and for reduction of urban sprawl in particular.

WUP can be used to investigate relationships between sprawl and its impact (such as on car ownership). It can also be used as an indicator to monitor urban development or conservation and protection of high-valued lands. For example, it can be used as to achieve goal 6 of the federal sustainable development strategy, which aims to “Maintain productive and resilient ecosystems with the capacity to recover and adapt; and protect areas in ways that leave them unimpaired for present and future generations” (Sustainable Development Office & Environment Canada, 2010, p 27). It can also be used to check the effectiveness of the new regulations for urban development (e.g., the development of TOD zones in Montreal CMA).

Controlling the dispersion of built-up areas with the aim of reducing the spread of urban settlements over the landscape and protection of agricultural lands and areas with a lower value of urban sprawl are actions that can be taken to limit urban sprawl. Limitation of sprawl might also be possible by determining environmentally friendly policies such as increasing the taxation for urban development in areas that are more in danger from urban sprawl. These policies along with better education of the public about the negative consequences of urban sprawl may promote consumers to decrease the level of land uptake per inhabitant and therefore decrease the level of urban sprawl.

Which factors could be changed to reduce the rate of increase of sprawl in Montreal and Quebec? The comparison with the Zurich MA provides an indication of the potential of how much sprawl could be reduced. The culture and the level of lifestyle are similar, but compared to Switzerland there is ample room in Montreal and Quebec for change in public transport, the regional planning legislation, the settlement pattern (creation of sub-centres with higher densities), and the utilisation density. For example, Laval should be densified as a centre and included in the metro system.

The comparison shows that factors such as the public transport system, regional planning legislation, settlement pattern (polycentric/monomocentric) and the general utilization density play the most important roles in the value of urban sprawl and its change over time.

In Montreal and Quebec, urban sprawl has gotten out of control and turned into a serious and fast growing problem since late 1980s. The last 25 years have made urban sprawl in Montreal and Quebec worse than ever before, and have done so faster than ever before. Quebec City is a prime example of urban sprawl today, in particular in its rapid increase since 1970. The fastest increases were observed in L'Acienne Lorette, Les Rivières and Sainte-Foy-Sillery-Cap-Rouge in Quebec, and in Hampstead, Beaconsfield, Baie D'urfe Dollard-Des-Ormeaux and Kirkland in Montreal.

The results of this study showed that sprawl had an increasing trend and its rate of increase is getting higher and higher. Therefore, we expect that this trend will continue in future. The steps planned right now for Montreal and Quebec such as the intensification of urban areas or development of TOD zones in Montreal (PMAD 2011) are so little compared to Switzerland (that itself suffers from sprawl) that much stronger effort are needed to discontinue these unsustainable growth patterns. Switzerland should continue on its way to limit the increasing trend of urban sprawl or at least stabilize the level of sprawl over all its cantons, including Zurich. However, in Montreal and Quebec rigorous measures and long term plans such as massive expansion of public transport are required. Montreal and Quebec are still investing large amounts of money in more roads and almost nothing in the expansion of public transport, even though it is known that this path is unsustainable. As an example, in 2012 Quebec used $705 million from the Building Canada fund for the completion of the second phase of highway 30 that connects Vaudreuil- Dorion to Chateauguay.

In the Zurich MA, every vote about suggested expansions or improvements of public transport has been accepted by the population, while many suggested road construction projects were rejected. This indicates that more sustainable patterns of development need a consensus in the society and long-term planning to put in place with a 20 to 30 years planning horizon. Elements of direct democracy seem to be very helpful in the case of Switzerland in this regard.

Increasing the modal share of public transport in Montreal from 21.7% to 40% would be much easier to achieve than increasing it from 68% to 78% as is currently done in Zurich. These numbers indicate the order of magnitude of the effort that is needed for the increase of metro connections between the sub-centres in Montreal and Quebec. The official inauguration of the Montreal metro took place in 1966 and from that time the metro system has been expanded here and there. However, this expansion has been far less significant than the expansions of the tramway and S-Bahn in Zurich. Without a strong increase in utilization density and a massive expansion of public transport, urban sprawl in Montreal and Quebec will continue to increase at a fast rate and will result in even more traffic problems and an increase in the associated negative effects that are typical of unsuitable development.

6. Overall discussion and conclusion

In spite of the many debates on sustainable development, smart growth policies, and acceptance of sustainable development as the best form of development for the future, there is still no agreement on how to monitor and control urban sprawl. Therefore, further research are needed to measure and control urban sprawl and to find the best solutions for avoiding negative consequences of sprawl at all administrative levels.

The preceding chapters of this thesis address the importance of the study of urban sprawl and monitoring it over time, and introduce different causes and consequences of urban sprawl as well as various methods for measurement of this phenomenon.

Major limitations with most of the proposed methods for the measurement of urban sprawl are the use of a high number of indices and difficulties with integrating different datasets for comparison of sprawl in different case studies or within one case study in different points in time. Most of the indicators used in these methods measure variables that are mostly causes or consequences of urban sprawl and are not capable of measuring dimensions of sprawl itself. Indeed the phenomenon of sprawl itself is distinct from its drivers or consequences. Therefore, measures of variables that are basically causes or effects of sprawl cannot be used directly to describe the quantity of this phenomenon, since factors other than sprawl may represent any potential variation or transformation in these variables.

Difficulties in interpreting results due to the lack of a threshold to distinguish sprawled from non-sprawled areas are another common problem with these metrics.

In chapter 5 of this thesis the method of Weighted Urban Proliferation and Urban Permeation (Schwick et al. 2012 and Jaeger et al. 2010b) was used to measure the level of urban sprawl in the two metropolitan areas of Montreal and Quebec. This study, for the first time, presents a quantitative assessment of urban sprawl in these two major metropolitan areas of Canada and compares the results with a European example (Zurich metropolitan area). Vector data of the Montreal and Quebec urban areas were created using a Geographic Information System and historic topographic maps for five time steps going back to 1951. The results of the quantification of urban sprawl were presented at different scales, from census tracts to metropolitan scale.

At the city level, Quebec City exhibited the highest level of urban sprawl, following by Montreal Island and the Inner Zurich MA. However, at the metropolitan level, larger metropolitan areas showed a higher level of urban sprawl, so that the Montreal CMA, Quebec CMA and Zurich MA ranked 1^{st}, 2^{nd} and 3^{rd}, respectively. The strikingly high value of sprawl in Quebec City is mainly due to the low level of utilization density and the high level of dispersion of built-up areas in this region. Although, the amount of urban area in Zurich and Quebec are very close to each other, the level of sprawl in Quebec City is more than twice as high than in Zurich. The amount of built-up areas on the Island of Montreal is higher than in Quebec City, However, Quebec City is more sprawled compared to the Island of Montreal because the level of utilization density is much smaller in Quebec City.

The strong regional planning legislation in Switzerland puts limits to new designated building zones in Zurich. This policy, together with the extensive expansion of public transport all over the Zurich metropolitan area and the high level of modal share explains the lower level of urban sprawl in Zurich.

While Zurich has a polycentric settlement structure, Montreal and Quebec are more monocentric. Contrary to the common expectations that regions with a polycentric settlement structure exhibit higher level of urban sprawl, our results for the Zurich MA showed that in fact the level of urban sprawl is lower here. This is mostly due to implementation of more efficient public transportation between the centers and therefore, a lower level of dispersion within built-up areas.

In the Zurich MA the highest increases of urban sprawl happened before 1980. Between1980 and 2011, sprawl increased at a lower speed. In contrast, the fastest increase in sprawl in Montreal and Quebec happened in the last 25 years. This may be due to the much more relaxed planning laws in Montreal and Quebec, whereas the spatial planning statute of 1979 in Switzerland has lowered the speed of increase in the level of sprawl. The planning laws in Quebec are by far not as strict as in Switzerland in terms of sustainability. This along with less efficient public transportation and a low transit modal share in Montreal and Quebec compared to Zurich is the main cause of sprawl in these two regions. Indeed, cars and sprawl are codependent (Wright and Boorse, 2013).

The outputs of the study of urban sprawl can be used as a tool for identifying the characteristics of the lands and their potential for urban developments in future as well as developing limitations for the fast increasing trend of sprawl that happens almost all over the world in developed and developing countries. However, measurement of sprawl should be done with caution, many metrics for measurement of sprawl measure relevant variables of sprawl than the sprawl itself (e.g., Entropy method which only measures the dispersion of built-up areas).

As an alternative, I recommended the method of Weighted Urban Proliferation introduced by Schwick et al. (2010) which unlike many of the methods that are proposed for measurement of urban sprawl, meets all of the fundamental suitability criteria for the measurement of urban sprawl. This method, in addition to other characteristics of sprawl enable urban planners and professionals to identify characteristics of lands such as the amount of land that is permeated by buildings and the amount of dispersion of the urbanised areas at different scales.

The results of the study of urban sprawl in Montreal and Quebec and comparison of them with Zurich (using *WUP* metric) indicate that the lack of effective planning strategies is the main reason for the current high degree of sprawl and its rapid increase over time. But in the recent years, especially since 2011 some new land use and development plans which have limitation of urbanized areas as one of their main objectives have been developed.

In Montreal, the Council of the Communauté métropolitaine de Montréal (CMM), took the first step and adopted the Metropolitan Land Use and Development Plan (PMAD), in December 2011. The PMAD suggests a framework for the land use planning of the Montréal metropolitan area. The PMAD has sustainable objectives such as development of transit oriented neighborhoods, promoting strategies to increase the area of agricultural land by 6% and adopting limits for future urbanization.

Following the release of PMAD, within the period of two years (by the end of 2013) the Montréal urban agglomeration must release the land use planning and development plan (SAD) for Montreal agglomeration in accordance to PMAD. One of the objectives of SAD is to make a constant plan in the 16 municipalities of Montreal agglomeration, and to provide some limits for development of urbanized areas. But, these plans are all newly developed, and their effects on urban sprawl have not yet been observed.

In Montreal and Quebec, the sharpest increases of sprawl happened over the past 25 years and with an alarming speed, meaning that urban sprawl in these areas is not an old form of development that was only happening 50 or 60 years ago, but it is happening right now. Therefore more rigorous measures to limit sprawl and long term strategic plans such as the expansion of public transport and developing TOD zones with the aim of reducing the dispersion of built-up areas and increasing utilization density within the urban areas are needed. Protecting fertile agricultural lands and areas that have lower level of urban sprawl are other essential steps that should be taken into consideration immediately.

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Appendices

Appendix 1

How reliable is the Entropy method as a measure of urban sprawl?

Abstract

During the past two decades, the phenomenon of urban sprawl got widespread attention among scholars in the field of urban planning. Urban sprawl has been defined and measured in different disciplines to help land-use and city planners in their vital decision making for the future. However, there is still no universal agreement on how to measure and control urban sprawl and to overcome its many negative effects on the environment, the economy and social communities.

Entropy is one of the most often used metrics for the measurement of urban sprawl since 2001. This study examines the behavior of Entropy and its reliability as a measure of urban sprawl, by applying it for the measurement of urban sprawl in seven theoretic landscapes and in six Canadian cities. We also tested the behavior of Entropy with regard to the choice of the city center and associated translocation of zones used in the calculation of Entropy and checked it against the 13 suitability criteria for the measures of urban sprawl. Entropy is often not sensitive to the dispersion of built-up areas that are distributed between different study zones or within a single zone of a landscape. In addition, changes in the designation of the zones within a landscape will usually change the value of Entropy for that landscape. Our results indicate that Entropy is not a reliable measure of urban sprawl since it does not meet fundamental suitability criteria for the measurement of urban sprawl.

Keywords: spatial metrics, suitability criteria, distribution, dispersion, compactness, urban development, urban growth, configuration.

Introduction

Even though urban sprawl has been a topic of great debate for several decades, it has been defined in different and often inconsistent ways in the academic literature. In most definitions, different sets of indicators of urban sprawl are used to define this phenomenon (Theobald, 2001) and there is still no commonly accepted definition of this phenomenon. Therefore, as urban sprawl has been defined in different disciplines, there is no agreement upon the measurement of this phenomenon (Bhatta et al. 2010, Jaeger et al. 2010a).

There are many studies that present a method for the measurement of urban sprawl and its impact. In fact monitoring the degree of urban sprawl would greatly help in controlling this phenomenon ant its many negative effects. However, most methods measured urban sprawl based on various indicators that are basically causes or consequences of this phenomenon and few convincing and reliable metrics have been developed for measuring this phenomenon (Jaeger et al. 2010b).

In this study, we use the definition of urban sprawl by Schwick et al. (2012): Urban sprawl is a phenomenon that can visually perceived in the landscape, sprawl "denotes the extent of the area that is built-up and its dispersion in the landscape in relation to the utilization of built-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" (Schwick et al. 2012 p.115). Accordingly urban sprawl is calculated with regard to three dimensions: the amount of land that is built up, the dispersion of built-up areas over the landscape, and the number of people living or working in the urban areas.

The main objective of this study is to examine the reliability of a commonly used method that is called Shannon's Entropy (Yeh and Li in 2001). To achieve this goal, we used the Entropy method to measure urban sprawl in seven simple examples of spatial distribution of urban areas and in six real-world case studies and compared the results with regard to 13 suitability criteria for measures of urban sprawl (Jaeger et al. 2010a). We also examined the behavior of the Entropy method with regard to the choice of the city center around which the zones required for the calculation of Entropy are located. This investigation shows how the degree of sprawl depends on the location of the city center that is used for the creation of zones.

The Shannon's Entropy method as a measure of urban sprawl

Yeh and Li (2001) declared that Shannon's Entropy (H_n) is capable of measuring "the degree of spatial concentration or dispersion of a geographical variable (x_i)" (Yeh and Li, 2001, p.84). They overlaid the urban land use images to measure the density of land development in a set of buffer zones that were created around city centers and along roads. Then they calculated the value of Entropy which indicates the density of the land development among n zones. Therefore, Entropy is used "to indicate the degree of urban sprawl by examining whether land development in a city or town is dispersed or compact" (Yeh and Li, 2001, p. 84). The value of Entropy is always between 0 and log (n) and is calculated by the following equation:

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

where p_i denotes the proportion to which the phenomenon is located in the i^{th} zone ($p_i = \frac{x_i}{\sum_j^n x_j}$), n is the number of zones, and x_i is the observed value of the phenomenon in the i^{th} zone.

Relative Entropy (H_n') can be used to scale the Entropy to a value between zero and 1 (Yeh and Li 2001) by dividing H_n by $\log(n)$. If the phenomenon is concentrated in one zone; the lowest value of relative Entropy (zero) will be obtained. At the other end of spectrum, if the value of relative Entropy has a large value (maxim of 1), this would indicate urban sprawl (Yeh and Li 2001).

$$H_n^{`} = \sum_i^n p_i \log \frac{1}{p_i} / \log\ (n)$$

One limitation of Entropy is that it is "sensitive to the variations in the the shapes and sizes of the regions used to calculate the observed proportions" (Yeh and Li, 2001, p 88). For example, if two different scales of analysis are used for the calculation of urban sprawl (e.g. when regions are divided into smaller sub-regions); different values will be obtained.

Yeh and Li (2001) suggested that decomposition theory can solve this problem because it can quantify the influence of the difference in the scales when larger zones are divided into smaller zones. The following equation for Entropy should be used in such cases.

$$H_n = \sum_{j=1}^m p_j \log\left(\frac{1}{p_j}\right) + \sum_{j=1}^m \left[p_j \sum_{i\in j}^{n_j} \left(\frac{p_{j(i)}}{p_j}\right) \log\left(\frac{p_j}{p_{j(i)}}\right)\right],$$

"where j is the j^{th} zone at the region scale, m is the total number of zones at the region scale, p_i is the proportion at the j^{th} zone at the region scale, $p_j(i)$ is the proportion at the i^{th} sub-region within the j^{th} region, and n_j is the total number of zones of sub-region at the j^{th} region" (Yeh and Li 2001, p. 88).

In this equation, Entropy is decomposed into two parts. The first part (H_m) calculates the variation of the phenomenon between regions and the second part ($H_{n/m}$) measures the variation of the phenomenon within regions ($H_n = H_m + H_{n/m}$) (Yeh and Li 2001). According to the equation, "the increse in the number of zones (with a smaller size) will cause the increase in the Entropy value because of gain of information within smaller sub-regions" (Yeh and Li 2001, p. 88).

Many scholars have used the Entropy method to measure the level of urban sprawl (e.g. Bhatta 2009a; Saraswati and Bandyopadhyay 2010; Kumar et al. 2007; Lata et al. 2001; Li & Yeh, 2004; Sudhira et al. 2004;). Indeed, Bhatta et al. (2010) concluded that Entropy is "perhaps the most widely used technique to measure the extent of urban sprawl" (Bhatta et al. 2010, p. 737), and that it "is proved to be the most strongest measurement tool among the available sprawl measurement techniques"(Bhatta et al. 2010, p.738). However, they stated that even though "it is not free from all nuisances", it "is preferred for its minimal limitations" and "future researches to develop some more reliable sprawl measurement techniques are highly demanded" (Bhatta et al. 2010, p. 738).

Problems with the Entropy method

Many landscape metrics have been used for the quantification of urban sprawl (Galster 2001, Angel et al. 2007, Jiang et al. 2007, Tsai 3005, etc.). All these metrics have their particular strengths and weaknesses. It is important is to choose the most reliable method for producing time series or for monitoring the state of a landscape and its changes over time. Therefore, the behavior of every proposed metric needs to be carefully studied and compared with existing metrics before they are applied in any study (Li and Wu 2004). An examination of the Entropy method and its behavior when applying it to measure the degree of urban sprawl in simple examples and in real case studies as well as an investigation of its behavior regarding 13 suitability criteria for the measurement of urban sprawl and the choice of the city center can help determine the reliability of this method.

Some simple examples to illustrate the behavior of Entropy

Figure A1-1 presents some simple examples of the distribution of built up areas in a landscape. Imagine there are several landscapes of the same size (for instance 6 km by 6 km) that all consist of four zones of the same size (3 km by 3 km). Each landscape has the same amount of built-up area but in different dispersion patterns.

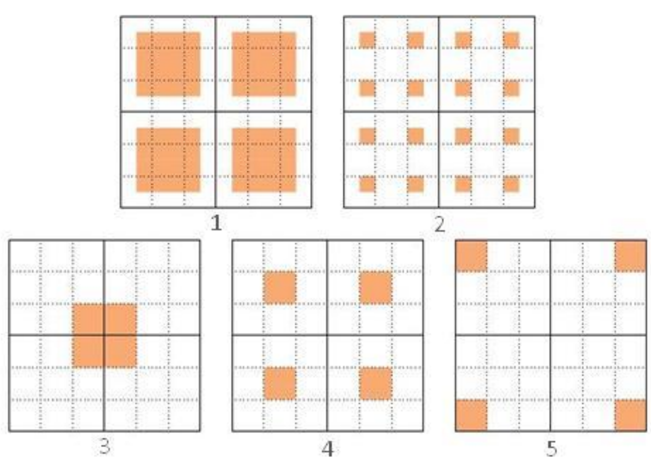

Figure A1-1: Illustration of the distribution of built-up areas in five different configurations. Each configuration consists of four zones of the same size (3 km by 3 km), and each zone is covered by 9 square of 1 km by 1 km (dotted lines).

The maximum value of relative Entropy (max value =1) was obtained for all five configurations. For instance, in figure A.1-1, the amount of p_i with the equation of ($p_i = \frac{x_i}{\sum_j^n x_j}$) within each zone is ¼, therefore relative Entropy ($H_n^{`} = \sum_i^n p_i log \frac{1}{p_i} / \log(n)$) is 1.

Similarly, the value of relative Entropy for the landscapes 2, 3, 4 and 5 is also 1, because the value of p_i for each zone of these landscapes is ¼ as well, even though the distribution and dispersion of the built-up areas is completely different in each landscape.

The value of sprawl should not be the same for different distributions of built-up areas within same-sized landscapes with similar zonings. Therefore, the first problem with the Entropy method is that it is not sensitive to how built-up areas are spatially distributed within the zones.

To further illustrate this point, we also calculated relative Entropy for two landscapes with the same size and same form of zoning, but this time it is imagined that in each landscape, all the built-up areas is located in a single zone (Figure A1-2).

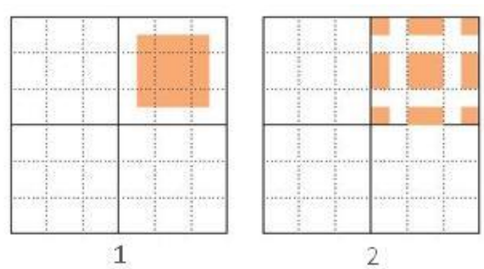

Figure A1-2: Illustration of the distribution of built-up areas in one single zone of two different alternatives with the same size and same form of zoning.

The obtained value of relative Entropy for both configurations was same. The value of relative Entropy for both landscapes was the minimum value, which is zero. This shows that Entropy is not sensitive to the changes in the distances between urban patches that are distributed in a single zone of a landscape. Therefore, relative Entropy is not capable of measuring the true value of dispersion between built-up areas either they are distributed between several zones or when they are all gathered in a single zone.

Six real-world case studies

We used six real-world case studies (Quebec, Montreal, Sherbrook, Toronto, Drummondville and Trois Rivières) to investigate the sensitivity of Entropy to the variation in the size and number of zones (Figure A1-3). Geobase vector data was used for the measurement of Entropy in all the six case studies.

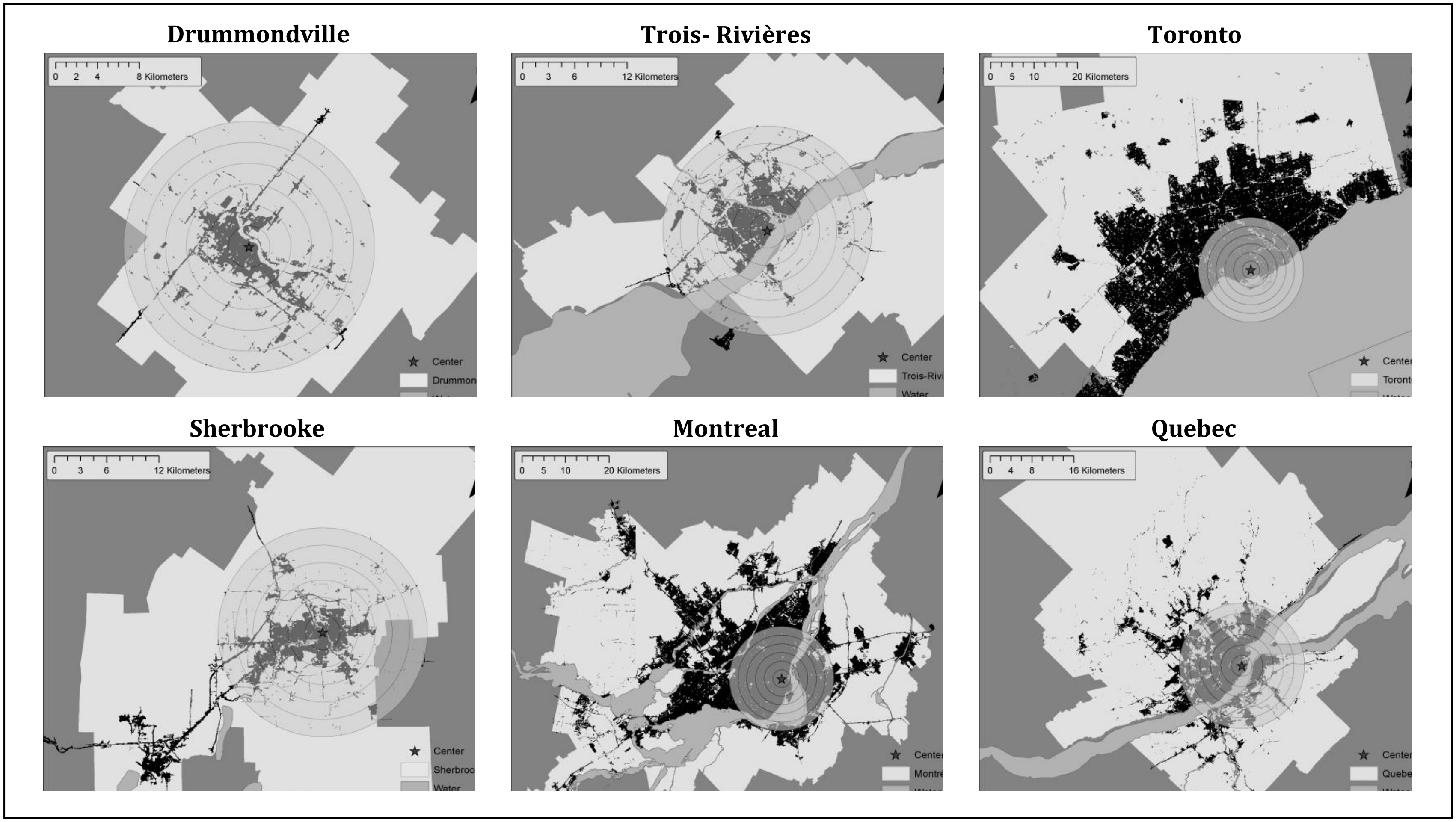

Figure A1-3: Spatial patterns of urban development in the cities of Drummondville, Trois Rivières, Toronto, Sherbrooke, Montreal and Quebec City. The 6 zones shown are each 2 km wide, located around the city center. Source: Geobase.

First, the start point that represents the city center was chosen. Then, 6 buffers with the width of 2 km were created around the city center. These buffers that represent the scale of analysis with the radius of 12 kilometers; were divided into 12 zones by adding 6 other buffers within equal distance from one another. This division of zones continued until we had a total of 48 zones. Accordingly the four sets of buffers zones that were created, divided each case study into 6, 12, 24 and 48 zones (Figure A1-4). In this approach, decision about number of zones and the distance between buffers was made according to the example presented in the study of Yeh and Li (2001).

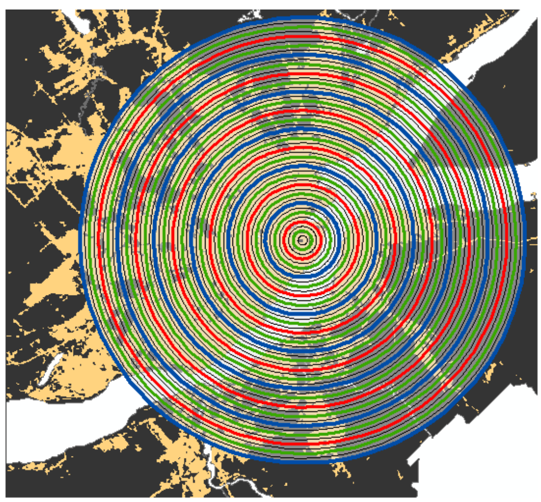

Figure A1-4: Dividing total scale of analysis into sub-zones for Quebec City. Blue buffers divided the whole region into 6 zones, red buffers divided these 6 zones to 12 zones, green buffers divided the 12 zones into 24 zones, and black buffers divided the whole region into 48 zones.

According to Yeh and Li (2001) when regions are divided into sub-regions, the relative Entropy can be calculated based on decomposition theorem. Table A1-1 presents the results of calculation of relative Entropy, using the decomposition theorem.

Table A1-1: Entropy for the six cities of Sherbrooke, Quebec, Trois Rivières, Toronto, Montreal, and Drummondville based on four sets of zones.

1.	Sherbrooke				Quebec			
Zones	H_m	$H_{n/m}$	H_n	H_n'	H_m	$H_{n/m}$	H_n	H_n'
6	1.711	-	1.711	0.955	1.701	-	1.701	0.949
12	1.711	0.672	2.383	0.959	1.701	0.688	2.388	0.961
24	1.711	1.357	3.069	0.966	1.701	1.377	3.078	0.969
48	1.711	2.047	3.758	0.971	1.701	2.070	3.770	0.974
	Trois-Rivières				Toronto			
Zones	H_m	$H_{n/m}$	H_n	H_n'	H_m	$H_{n/m}$	H_n	H_n'
6	1.685	-	1.685	0.940	1.678	-	1.678	0.936
12	1.685	0.677	2.362	0.951	1.678	0.685	2.363	0.951
24	1.685	1.364	3.048	0.959	1.678	1.376	3.054	0.961
48	1.685	2.052	3.737	0.965	1.678	2.068	3.746	0.968
	Montreal				Drummondville			
Zones	H_m	$H_{n/m}$	H_n	H_n'	H_m	$H_{n/m}$	H_n	H_n'
6	1.633	-	1.633	0.912	1.666	-	1.666	0.930
12	1.633	0.687	2.320	0.934	1.666	0.671	2.337	0.940
24	1.633	1.378	3.012	0.948	1.666	1.354	3.020	0.950
48	1.633	2.071	3.704	0.957	1.666	2.039	3.705	0.957

The results indicate that the method is not reliable since the trend of increase in the value of relative Entropy versus the number of zones is not logical. For example, for 6 zones the value of urban sprawl is 0.949 in Quebec City and 0.955 in Sherbrooke, indicating that Sherbrooke is more sprawled. However, this relation changed strangely when 12, 24 or 48 zones were used. By the increase in the number of zones, the value of urban sprawl in Quebec City surpassed the value of urban sprawl in Sherbrooke.

The same problem was also observed when Toronto and Trois-Rivieres were compared. Using 6 number zones, the value of urban sprawl in Toronto (0.936) was lower than in Trois-Rivieres (0.941). However, it surpassed the value of sprawl in Trois-Rivieres when 12, 24 or 48 sub-regions were used (Figure A1-5)

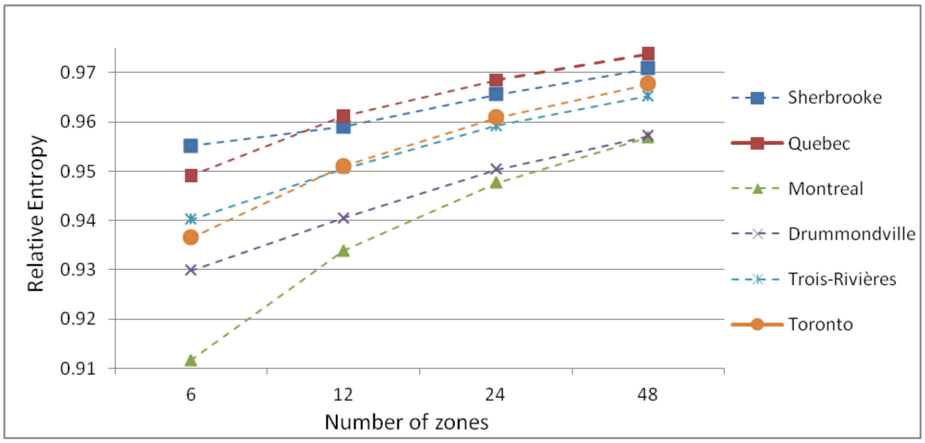

Figure A1-5: The Entropy values for the six selected cities as a function of the number of zones.

Entropy increased as the number of zones increased. However, this increase is not logical when different cities are compared together. Our results are in contradiction with the similar investigation on the three case studies of Tangsha, Dalang and Hongmei (Yeh and Li 2001). The effect of increase in the value of Entropy versus number of zones was also investigated in the study of Yeh and Li (2001). However, they concluded that increase of relative Entropy in the three mentioned cities is logical and ranking of cities regarding sprawl stays constant as the number of sub zones increases.

Problems related to the choice of the location of the city center

In the third step, we examined the behavior of the Entropy method based on the location of the city center and the translocation of zones. Two different points within a distance of 3 km were selected as the two reasonable city centers in Quebec City.

Relative Entropy was calculated for a landscape with the size of 14 km by 14 km divided into 6 zones, using the first city center and for the same landscape and same number of zones but using the second city center (Figure A1-6).

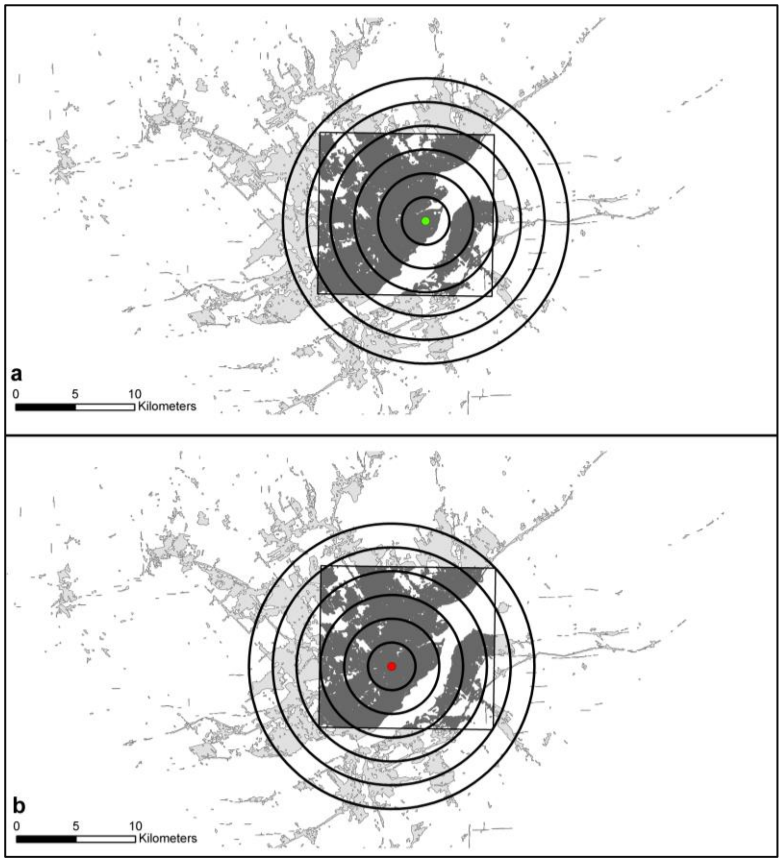

Figure A1-6: Examination of the behavior of the Entropy method with regard to the choice of the city center. a) The obtained value of relative Entropy using city center 1 was 0.88, b) the value of relative Entropy using city center 2 was 0.86.

When the first city center was used, the value of relative Entropy was 0.88 (figure A1-6a). However, this value decreased to 0.86 when the location of the city center changed (figure A1-6b). This result revealed that Entropy is sensitive to the choice of the city center, and therefore, the translocation of the zones will change the value of Entropy for a landscape with a certain amount of built-up area. However, the degree of sprawl that is measured should not depend on the choice of the city center because this can lead to disagreement between studies using different city centers.

Suitability criteria for the measurement of urban sprawl

For the creation and use of every landscape metric several specific requirements must be considered depending on its purpose (Jaeger et al. 2010a). The 13 suitability criteria for the measurement of urban sprawl introduced by Jaeger et al. (2010a) help better understand the behavior and reliability of those metrics that aim to quantify the degree of urban sprawl (Table A1-2). The importance of these criteria differs. Some of them are essential and every method for measuring sprawl must meet them. Others are additional characteristics that only an ideal metric for measurement of sprawl meet them (Jaeger et al. 2010a).

Moreover, for some criteria there may be different views. Criterion 5 (Monotonous reaction to increases in urban areas) is one of these criteria. One view is that an increase in the amount of urban areas always results in a higher level of sprawl. However, the other view is that the degree of sprawl may decrease when the land is covered with more buildings in a way that the dispersion of the urban areas decreases. In our definition for urban sprawl, the amount of urban areas is one of the three main dimensions of urban sprawl and we believe that as the amount of land that is built up increases urban sprawl would usually increases even when dispersion decreases, except for extreme cases when dispersion strongly decreases. Table A1-2 presents examination of the Entropy method regarding these criteria.

Table A1-2: Examination of the Entropy method regarding 13 suitability criteria for the measurement of urban sprawl, suggested by Jaeger et al. (2010a).

Suitability criteria	**Mandatory (M)/ Highly desirable (HD)/ Desirable (D)**	**Assessment of the Entropy method**	**Suitability of Entropy**
Intuitive interpretation	HD	Entropy is easy to understand	+
Mathematical simplicity	HD	Calculation of Entropy is easy	+
Modest data requirements	HD	Entropy has low data needs (map of built-up areas)	+
Low sensitivity to very small patches of urban area	M	The contribution of each patch of built-up area is proportional to its contribution to the total size of urban patches in a region, so smaller patches have less influence on the value of the metric	+
Monotonous reaction to increases in urban areas: a) while the dispersion of built-up areas stays constant, b) while their dispersion changes	a) M, b) D	Entropy is in many cases not sensitive to this criterion, e.g. when the urban areas in all zones increase by the same percentage (e.g. by 10%) all pi will be the same	-
Monotonous reaction to increasing distance between two urban patches when within the scale of analysis	M	Entropy is in many cases not sensitive to the change of distance between two urban patches, e.g. when the built-up areas are located and stayed in one single zone or when they are distributed in two different zones and stayed in these zones	-

Suitability criteria	**Mandatory (M)/ Highly desirable (HD)/ Desirable (D)**	**Assessment of the Entropy method**	**Suitability of Entropy**
Monotonous reaction to increased spreading of three urban patches	M	Entropy is in many cases not sensitive to this change, e.g. when all the built-up areas are distributed in one single zone or when they are distributed in number of zones	-
Same direction of the metric's responses to the processes in criteria 5, 6 and 7	M	Entropy does not meet this criterion, since it does not meet criteria 5 to7	-
Continuous reaction to the merging of two urban patches	M	Entropy is in many cases not sensitive to this change e.g. when the two urban patches are located with a single zone	-
Independence of the metric from the location of the pattern of urban patches within the reporting unit	M	The value of Entropy in many cases depends on the location of the zones e.g. when they are created around the city center for the analysis and the city center may be chosen at different locations	-
Continuous reaction to increasing distance between two urban patches when they move beyond the scale of analysis	HD	Entropy is not sensitive to this change in the landscape and does not have any parameter to represent the scale of analysis. Even if we interpret that zones are representing the scale of analysis, Entropy does not meet this criteria	-
Mathematical homogeneity (i.e., intensive or extensive	D	Entropy is not an extensive metric, since it is not additive for non interacting landscapes	-

Suitability criteria	Mandatory (M)/ Highly desirable (HD)/ Desirable (D)	Assessment of the Entropy method	Suitability of Entropy
measures)			
Additivity (i.e., additive or area-proportionately additive measure)	D	Entropy is not an additive or area proportionately additive measure. Simple theoretic examples showed that when a landscapes (landscape 1) with n (e.g. n = 4) number of zones and evenly distributed built-up areas is added to a similar landscape (e.g. landscape 2) with m (e.g. m = 4) number of zones, the value of the Entropy in the new landscape with n+m = 8 zones is not sum of the two values of Entropy for landscape 1 and landscape 2	-

Among the 13 suitability criteria, Entropy only meets criteria 1 to 4. Entropy is easy to calculate. Also the Entropy method does not need a lot of datasets. However, Entropy does not meet mandatory criteria 5-10 and it does not meet criteria 11, 12 and 13 which are highly desirable.

Simple examples from section 8.1.3.1 showed that Entropy is not sensitive to the increase or decrease of distances between urban patches in these cases. Therefore, for landscapes with similar amount of urban area but different levels of dispersion of the built-up areas we obtained the same amount of Entropy. Accordingly, Entropy does not meet criteria 5, 6, 7, 8 and 9. The Entropy also depends on the choice of the city center.

Therefore, for a certain landscape; different values of Entropy may be obtained as the location of city center changes. Therefore, Entropy does not meet criterion number 10.

As the Entropy does not have any parameter to represent the scale of analysis of it is not possible to investigate its behavior in relation with criterion number 11. However, if we assume that the size of the zones represents the scale of analysis Entropy would not meet criterion number 11. Entropy is not an extensive or additive metric and therefore, it does not meet criteria of 12 and 13.

Discussion and conclusion

The objective of this paper was to suggest that not all existing metrics for measurement of urban sprawl are reliable. Our result demonstrated that Entropy method is not suitable for measurement of urban sprawl even though many researchers have used it over the past years. The main problem of the Entropy is that it does not meet the fundamental suitability criteria for the measurement of urban sprawl. According to the Table A1-2 the Entropy method does not meet 9 out of 13 criteria.

The second problem with the Entropy method is that it is not sensitive to the spatial distribution of the built-up areas between different zones or within a single zone of a landscape with similar configurations. This means that Entropy is in many cases not sensitive to how compact or dispersed the built-up areas are.

One might argue that Entropy measures only the dispersion of built-up areas as one important dimension of sprawl but not other important dimensions of sprawl such as total amount of built-up areas or their utilization density. However, the first set of examples (figure A1-1 and A1-2) demonstrated that Entropy is not suitable measure of dispersion.

A third problem is that the value of Entropy strongly depends on the choice of the zones. The results will change regarding how the zones in the built-up areas are defined. The criteria that are used to define the zones or the city center in one study may not be applicable to other studies. Therefore, a comparison of cities or even one city at different points in time will often not be possible. We recommend choosing those metrics that are independent from any kind of zoning or choice of city center. The decomposition theorem does not eliminate any of these limitations.

Considering these problems, we conclude that Shannon's Entropy is not a trustworthy method for the study of urban sprawl that its use will create misleading results. An alternative suggestion could be the method of "Weighted Urban Proliferation" and "Urban Permeation" that introduced by Schwick et al. (2012) and Jaeger et al. (2010b). Both metrics meet all 13 suitability criteria for the measurement of urban sprawl and the studies which have used this method for the quantification of urban sprawl have the reliability of these metrics (Jaeger and Schwick subm).

Appendix 2

The following two tables present the layers (including point and polygons) that represent urban areas. Table A2-1 presents the features of CanVec dataset, used for the delineation of built-up areas for the year 1996 and previous time step and table A2-2 presents the features of CanMap dataset used for delineation of built-up areas of the year 2011.

Table A2-1: Entities form the CanVec dataset that were used for the delineation of urban areas (abbreviations: BS: building and structures, LX: Places of interest, IC: Industrial and commercial areas, EN: Energy, TR: Transportation)

Entity	Entity description	Theme	Name (Point)	Name (Surface)
Building	Arena	BS	2010009 0	2010009 2
Building	Other	BS	2010009 0	2010009 2
Building	Community centre	BS	2010009 0	2010009 2
Building	Highway service centre	BS	2010009 0	2010009 2
Building	Medical centre	BS	2010009 0	2010009 2
Building	Sportsplex	BS	2010009 0	2010009 2
Building	Gas and oil facilities building	BS		2010009 2
Building	Parliament building	BS	2010009 0	2010009 2
Building	Educational building	BS	2010009 0	2010009 2
Building	Penal building	BS	2010009 0	2010009 2
Building	Industrial building	BS		2010009 2
Building	Religious building	BS	2010009 0	2010009 2
Building	Railway station	BS	2010009 0	2010009 2
Building	Hospital	BS	2010009 0	2010009 2
Building	City hall	BS	2010009 0	2010009 2
Building	Unknown	BS	2010009 0	2010009 2
Building	Armoury	BS	2010009 0	2010009 2
Building	Courthouse	BS	2010009 0	2010009 2
Building	Customs post	BS	2010009 0	2010009 2
Building	Police station	BS	2010009 0	2010009 2
Building	Fire station	BS	2010009 0	2010009 2
Building	Electric power station	BS	2010009 0	2010009 2
Building	Municipal hall	BS	2010009 0	2010009 2
Building	Satellite-tracking station	BS	2010009 0	2010009 2
Building	Coast guard station	BS	2010009 0	2010009 2
Chimney	Burner	BS	2060009 0	
Chimney	Unknown	BS	2060009 0	
Chimney	Industrial	BS	2060009 0	
Chimney	Flare stack	BS	2060009 0	
Tank	Horizontal, unknown	BS	2080009 0	2080009 2
Tank	Unknown, unknown	BS	2080009 0	
Tank	Vertical, other	BS	2080009 0	2080009 2
Tank	Vertical, water	BS	2080009 0	2080009 2
Tank	Vertical, unknown	BS	2080009 0	2080009 2

Entity	Entity description	Theme	Name (Point)	Name (Surface)
Cross	Cross	BS	2120009 0	
Navigational aid	Navigation beacon	BS	1250009 0	
Navigational aid	Navigation light	BS	1250009 0	
Navigational aid	Unknown	BS	1250009 0	
Silo	Silo	BS	2440009 0	
Tower	Communication	BS	2530009 0	
Tower	Control	BS	2530009 0	
Tower	Clearance	BS	2530009 0	
Tower	Firebreak	BS	2530009 0	
Tower	Lookout	BS	2530009 0	
Residential area	Residential area	BS		1370009 2
Cemetery	Cemetery	LX	1000039 0	1000039 2
Drive-in theatre	Drive-in theatre	LX	2070009 0	2070009 2
Domestic waste	Domestic waste	IC		1360019 2
Industrial solid	Industrial solid depot	IC	1360029 0	1360029 2
Gas and oil	Gas and oil facilities	EN	1360049 0	1360049 2
Runway	Airport, indefinite	TR	1190009 0	1190009 2
Runway	Airport, nonofficial	TR	1190009 0	1190009 2
Runway	Airport, official	TR	1190009 0	1190009 2
Runway	Heliport, indefinite	TR	1190009 0	
Runway	Heliport, nonofficial	TR	1190009 0	
Runway	Heliport, official	TR	1190009 0	
Runway	Hospital heliport, nonofficial	TR	1190009 0	
Runway	Hospital heliport, official	TR	1190009 0	
Runway	Water aerodrome, indefinite	TR	1190009 0	
Runway	Water aerodrome, official	TR	1190009 0	

Table A2-2: Entities form the CanMap dataset that were considered for the delineation of urban areas (abbreviations: BFR: building footprints, LUR: land use)

Entity description	Theme	Code	Shape file type
ARENA	BFR	106	Region
ARMOURY	BFR	107	Region
AUTOMOBILE PLANT	BFR	108	Region
BARN/MACHINERY SHED	BFR	109	Region
CEMENT PLANT	BFR	111	Region
CHEMICAL PLANT	BFR	112	Region
CHURCH	BFR	113	Region
CITY HALL	BFR	114	Region
COAST GUARD STATION	BFR	115	Region
COLLEGE	BFR	116	Region
COMMUNITY CENTRE	BFR	117	Region
CONVENT	BFR	118	Region
CORRECTIONAL INSTITUTE	BFR	119	Region
COURTHOUSE	BFR	120	Region
COURT HOUSE	BFR	120	Region
CUSTOMS POST	BFR	121	Region
DOME	BFR	122	Region
ELECTRIC POWER STATION	BFR	123	Region
FACTORY	BFR	124	Region
FILTRATION PLANT	BFR	125	Region
FIRE STATION	BFR	126	Region

Entity description	Theme	Code	Shape file type
FIRE/POLICE STATION	BFR	127	Region
FISH HATCHERY	BFR	128	Region
FISH PROCESSING PLANT	BFR	129	Region
GRAIN ELEVATOR	BFR	130	Region
HALL	BFR	131	Region
HIGHWAY SERVICE CENTRE	BFR	132	Region
HOSPITAL	BFR	133	Region
HOSTEL	BFR	134	Region
HOTEL	BFR	135	Region
KILN (TOBACCO)	BFR	136	Region
LUMBER MILL	BFR	137	Region
MEDICAL CENTRE	BFR	139	Region
MONASTERY	BFR	140	Region
MOTEL	BFR	141	Region
MUNICIPAL HALL	BFR	142	Region
MUSEUM	BFR	143	Region
NON-CHRISTIAN PLACE OF WORSHIP	BFR	144	Region
OBSERVATORY	BFR	145	Region
OIL/GAS FACILITIES BUILDING	BFR	146	Region
GAS AND OIL FACILITIES	BFR	146	Region
OTHER	BFR	147	Region
PARLIAMENT BUILDING	BFR	149	Region
PENITENTIARY	BFR	150	Region
PETROLEUM REFINERY	BFR	151	Region
PLANT	BFR	152	Region
POLICE STATION	BFR	153	Region
PULP/PAPER MILL	BFR	154	Region
RAILWAY STATION	BFR	155	Region
REFORMATORY	BFR	156	Region
SANATORIUM	BFR	157	Region
SATELLITE-TRACKING STATION	BFR	158	Region
SAWMILL	BFR	159	Region
SCHOOL	BFR	160	Region
SEMINARY	BFR	161	Region
SENIOR CITIZENS HOME	BFR	162	Region
SEWAGE TREATMENT PLANT	BFR	163	Region
SHIPYARD	BFR	164	Region
SHOPPING CENTRE	BFR	165	Region
SPORTSPLEX	BFR	166	Region
STEEL MILL	BFR	167	Region
TRADING POST	BFR	168	Region
UNIVERSITY	BFR	169	Region
WARDEN/RANGER STATION	BFR	170	Region
WATER TREATMENT PLANT	BFR	171	Region
WEIGH SCALE (HIGHWAY)	BFR	172	Region
WEIGHT SCALE	BFR	172	Region
GREENHOUSE	BFR	174	Region
PENAL BUILDING	BFR	175	Region
LODGING FACILITIES	BFR	176	Region
INDUSTRIAL BUILDING	BFR	177	Region
RELIGIOUS BUILDING	BFR	178	Region
EDUCATIONAL BUILDING	BFR	179	Region
FORT: GENERIC/UNKNOWN	BFR	585	Region
FORT	BFR	585	Region
GREENHOUSE	BFR	618	Region
STADIUM	BFR	1220	Region

Entity description	Theme	Code	Shape file type
COMMERCIAL	LUR	-	Region
RESIDENTIAL	LUR	-	Region

Appendix 3

1) Calculation of *WUP* for the Montreal and Quebec CMAs for the years 1951, 1971, 1986 and 1996

The extent of the CMAs of Montreal and Quebec changed between 1951 and 2011. Basically CMA boundary extended over time; therefore, some parts of the current CMA (2011 delineation) are not included in the 1951, 1971, 1986 or even 1996 CMAs delineation.

Accordingly, the information about inhabitants and jobs for some built-up areas that are distributed within the 2011 CMA, were not available for the years 1951, 1971, 1986 and 1996. Therefore, in order to compare the results of sprawl within the constant boundary of 2011 CMA in different points in time, we used the average value of weighted urban proliferation.

For all the time steps except 2011, we came up with two different values for inhabitants and jobs: first value is the exact value within the true extent of CMA in each time step, and second value is the estimated value within the 2011 CMA. Estimated values are calculated by using the available information for the closest time step (e.g., for some parts which data was not available in 1986, we used the inhabitants and job counts of 1996).

Using these two different values, we calculated urban sprawl twice: first, using the exact value of inhabitants and jobs for each time steps (we called it maximum value for sprawl), meaning that we assumed that there were no people living or working within the built-up areas that are beyond the CMA of each year, and second, using the estimated value (we called it minimum value of sprawl). Then, we used the average of these two values (we called it average value of sprawl) for each time step in order to compare the results of sprawl in different points in time. Table A3-1 presents the true and estimated values of inhabitants and jobs as well as associated values of *WUP*.

Table A3-1: Calculation of average value of weighted urban proliferation for the Montreal and Quebec CMAs: using true and estimated value of utilization density. Min *WUP*: minimum value of weighted urban proliferation (using true value of inhabitants and jobs), max *WUP*: maximum value of weighted urban proliferation (using estimated value of inhabitants and jobs for each CMA). Average *WUP*: average of minimum and maximum *WUP*.

CMA	Year	*WUP (MIN)*	*WUP (MAX)*	*WUP* (Average)	Exact *UD*	Estimated *UD*
Montreal	1951	0.0086	0.3754	0.1920	9547.101	15970.060
Montreal	1971	0.9686	1.4772	1.2229	8580.069	9445.059
Montreal	1986	3.0727	3.7173	3.3950	6972.377	7517.174
Montreal	1996	6.0171	6.1746	6.0959	6172.554	6274.059
Montreal	2011	12.0966	12.097	12.0966	4896.244	4896.244
Quebec	1951	0.0006	0.0105	0.0055	12267.250	17056.925
Quebec	1971	0.6599	0.8616	0.7608	6383.177	7244.926
Quebec	1986	2.1179	2.1300	2.1240	4806.792	4846.815
Quebec	1996	2.3046	2.3168	2.3107	4939.257	4974.263
Quebec	2011	4.9126	4.9126	4.9126	3431.297	3431.297

2) Calculation of UD for the Montreal and Quebec CMAs for the years 1951, 1971 and 1986

Since the information about job counts was not available for the years 1951-1986 we used a correction factor to calculate the value of *UD* in these years at CMA level and at city level. The correction factor is *UD* of 1996 divided by *UD'* of 1996 (where *UD* is inhabitants+jobs/km^2 in 1996 and *UD'* is inhabitants/km^2 in 1996).

$$\text{Correction factor} = \frac{UD\ ((Inh + Jobs)/km^2))\ \text{in 1996}}{UD'\left(\frac{Inh}{km^2}\right)\text{in1996}}$$

In order to see the difference in the value of sprawl when *UD* is calculated only based on inhabitants or based on inhabitants plus jobs per area of land, we calculated *WUP'* which indicates the value of sprawl when utilization density is measured only based on number of inhabitants. As expected value of *WUP'* for all reporting units in all time steps was higher than value of *WUP*. Table A3-2 presents the values of *WUP, WUP'*, *UD*, *UD'* and the correction factor used four calculation of urban sprawl for four reporting units of Montreal Island, Montreal CMA, Quebec City and Quebec CMA.

Table A3- 2: *WUP, WUP'*, *UD*, *UD'* and the correction factor for four reporting units of Montreal CMA, Montreal Island, Quebec CMA and Quebec City.

Montreal Census Metropolitan Area					
Sprawl Metric	1951	1971	1986	1996	2011
WUP (MIN)	0.0086	0.9686	3.0727	6.0171	12.0966
WUP (MAX)	0.3754	1.4772	3.7173	6.1746	12.097
WUP (Average)	0.1920	1.2229	3.3950	6.0959	12.0966
Exact *UD*	9547.1	8580.1	6972.4	6172.6	4896.2
Estimated *UD*	15970.1	9445.1	7517.2	6274.1	4896.2
WUP' (MIN)	0.160	3.161	5.701	8.3220	14.1607
WUP' (MAX)	1.2654	3.6921	6.0492	8.5653	14.1607
WUP' (Average)	0.7130	3.4269	5.8754	8.44361	5.87541
Exact UD'	6633.0	5961.1	4844.1	4288.5	3363.2
Estimated UD'	11095.4	6562.1	5222.6	4536.4	3363.2
Correction Factor	1.4393	1.4393	1.4393	-	-
Montreal Island					
Sprawl Metric	1951	1971	1986	1996	2011
WUP	0.0139	0.3357	2.4003	4.5486	9.7486
WUP'	0.7072	5.8625	14.8902	20.2608	30.0720
UD	17959.0	13931.4	10821.5	9915.4	8823.3
UD'	11461.3	8890.9	6906.2	6328.0	5504.5
Correction Factor	1.56692	1.56692	1.56692	-	-
Quebec Census Metropolitan Area					
Sprawl Metric	1951	1971	1986	1996	2011
WUP (MIN)	0.0006	0.6599	2.1179	2.3046	4.9126
WUP (MAX)	0.0105	0.8616	2.1300	2.3168	4.9126
WUP (Average)	0.0055	0.7608	2.1240	2.3107	4.9126
Exact *UD*	12267.3	6383.2	4806.8	4939.3	3431.3
Estimated *UD*	17056.9	7244.9	4846.8	4974.3	3431.3
WUP' (MIN)	0.0139	1.1494	2.4640	2.7156	5.2039
WUP' (MAX)	0.0820	1.2452	2.4686	2.7205	5.2039
WUP' (Average)	0.0480	1.1973	2.4663	2.71805	5.20387
Exact UD'	8474.4	4409.6	3320.6	3412.1	2323.3
Estimated UD'	11783.2	5004.9	3348.3	3437.6	2323.3
Correction Factor	1.44756	1.44756	1.44756	-	-
Quebec City					
Sprawl Metric	1951	1971	1986	1996	2011

WUP	-	1.8177	7.6135	8.3078	20.3337
WUP’	-	4.9410	10.6540	11.6676	22.4899
UD	-	8713.8	6142.6	6162.7	4156.2
UD’	-	5865.0	4134.4	4147.9	2757.2
Correction Factor	-	1.48573	1.48573	-	-