Exponential increase of urban sprawl in Montreal in the last 60 years should be taken into consideration in decisions about future urban development

Brief regarding the proposed development in Pierrefonds West, Montreal

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1. Introduction

To be able to make informed and responsible decisions, decision makers need to be aware of the history of urban development in Montreal in the last few decades.

Work in our lab at Concordia University has documented patterns of urban development in Montreal for the time period between 1951 and 2011and has compared the results with Quebec City and Zurich (Switzerland). Please find our study attached to this brief (Annex 1). It was published in the international peer-reviewed journal *Ecological Indicators* (Nazarnia et al. 2016).

Our study addressed two questions:
1) How quickly has the level of urban sprawl increased in Montreal and Quebec City since the 1950s, and what are their current degrees and spatial patterns of sprawl?
2) What are the similarities and differences between Montreal and Quebec (Canada) and Zurich (Switzerland) in their level of urban sprawl in the past six decades?

The results of our study should be taken into consideration in decisions about future urban development in Montreal. Therefore, this brief summarizes some important results.

Highlights:

(1) Urban sprawl is a serious threat to sustainability.

(2) Urban sprawl has increased exponentially in Montreal since 1951.

(3) Urban sprawl in Montreal is a more recent phenomenon than in Zurich. The strongest increases in sprawl have happened since the early 1980s. Urban sprawl has accelerated continuously in Montreal and Quebec since 1951. Here, the fastest increases in sprawl have been observed in the last 25 years, whereas in Zurich the strongest acceleration was in the 1960s.

(4) The current trends in urban sprawl in Montreal clearly contradict the goals and the spirit of sustainable development.

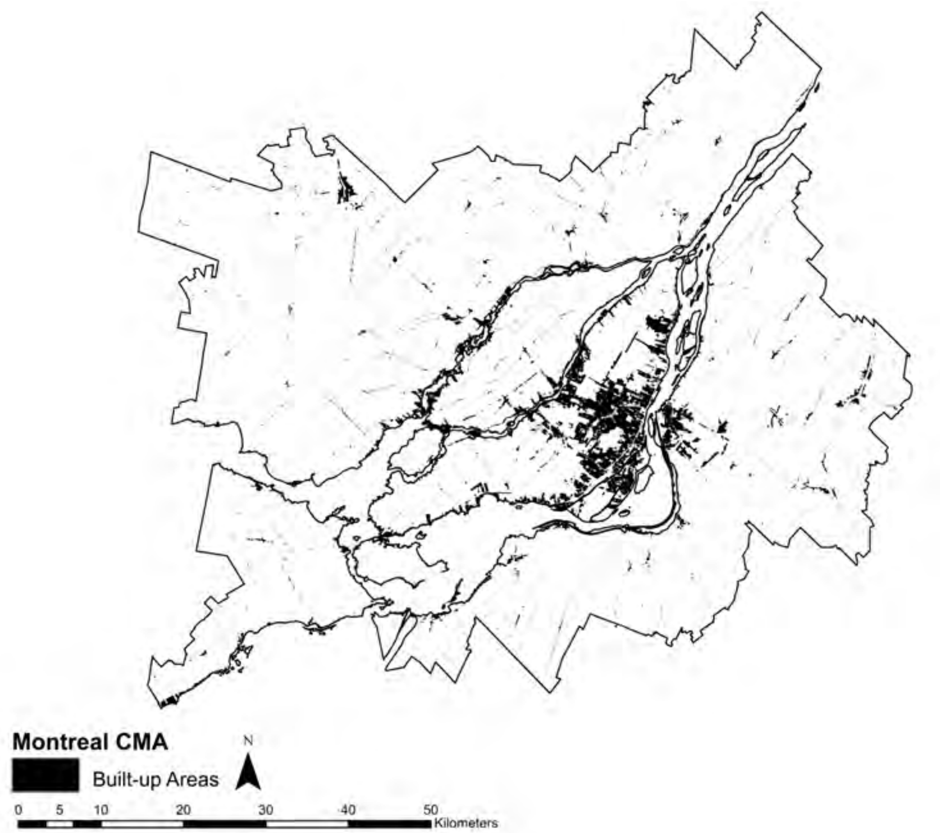
(5) Pierrefonds-Roxboro is among the 10 most highly sprawled districts of the Montreal Census Metropolitan Area (CMA).

(6) The most effective approach to keeping further sprawl to a minimum consists in the reduction of land-uptake per inhabitant and the concentration of settlement areas (i.e., without extending the borders of each settlement), i.e., in **using land sparingly.**

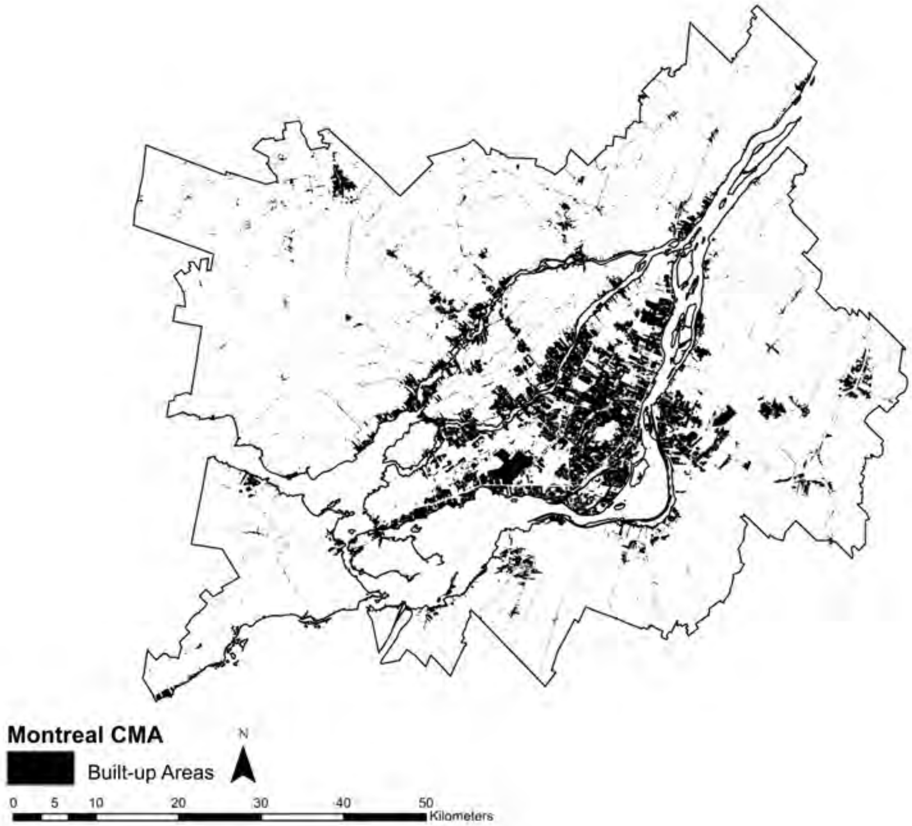
Data sources: The calculation of the sprawl metrics (according to the *WUP* method by Jaeger and Schwick (2014)) requires two datasets: A map of built-up areas and information about inhabitants and jobs. For the calculation of urban sprawl in Montreal and Quebec, we used the CanVec dataset provided in vector format in 2007 by Natural Resource Canada and updated in 2011 and CanMap Route Logistics (version 2011.3, a product of DMTI spatial). For the earlier years, historic datasets were not available in digital format. Therefore, we geo-referenced and digitized national topographic maps of Montreal and Quebec at the scale of 1:50,000 backwards in time, starting from the base layer of 1996 using ArcGIS 10.1.

2. Results: Accelerated increase of urban sprawl in Montreal in the last 60 years

Figure 1 shows the development of built-up areas in Montreal for the years 1951 - 2011.

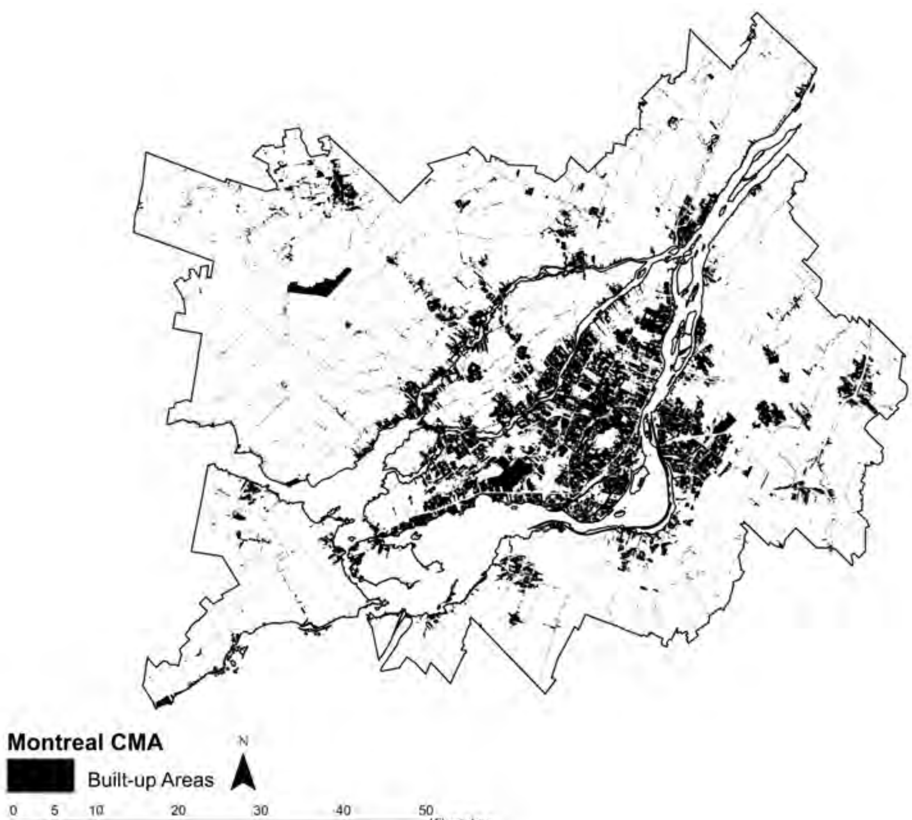


(a) 1951



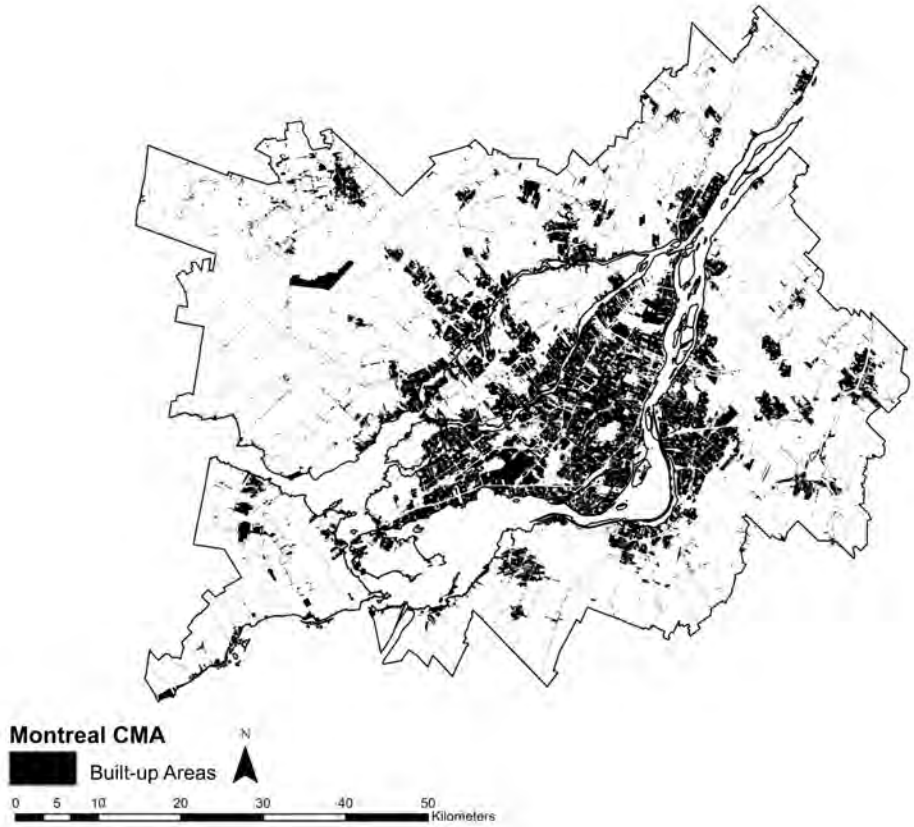
Montreal CMA
Built-up Areas
N
0 5 10 20 30 40 50
Kilometers

(b) 1971

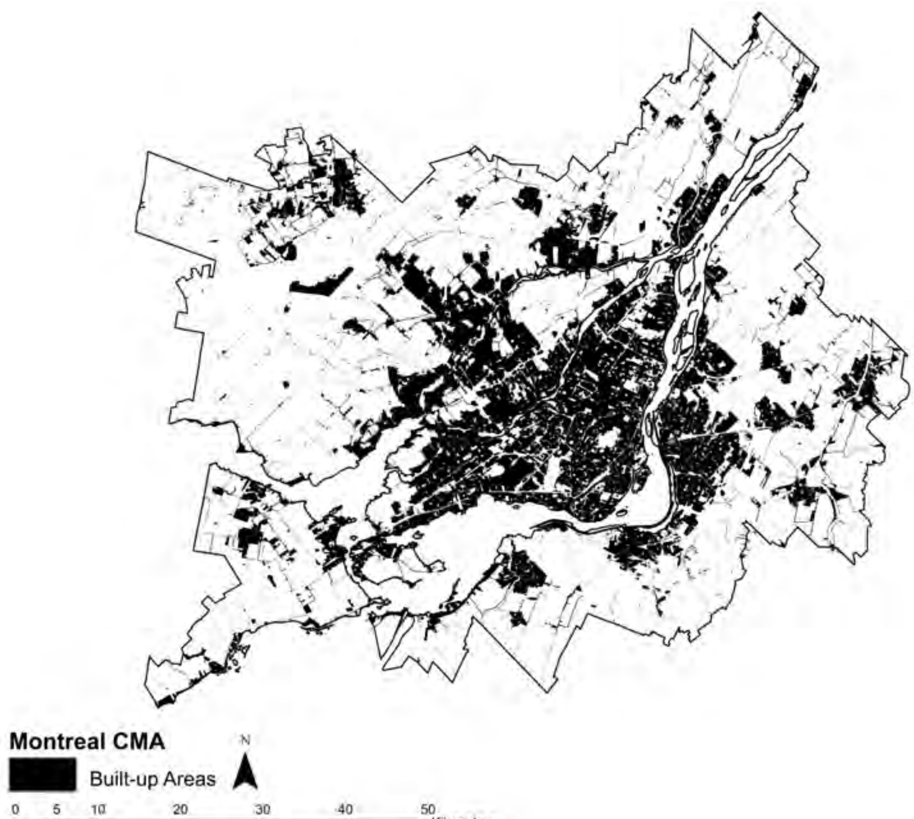


Montreal CMA
Built-up Areas
N
0 5 10 20 30 40 50
Kilometers

(c) 1986



(d) 1996



(e) 2011

Fig. 1: Built-up areas in Montreal in the years 1951 - 2011 (Source: Nazarnia et al. 2016).

What is urban sprawl?

Urban sprawl can be visually perceived in a landscape. A landscape is the more sprawled, the more it is permeated by buildings. Urban sprawl has three components (Fig. 2): The degree of sprawl is higher when

- more area in the landscape is built up,
- the buildings are more dispersed in the landscape,
- the amount of built-up areas per inhabitant or job is higher (i.e., the utilization density of the built-up areas is lower).

Causes and consequences of sprawl are distinguished from the phenomenon of sprawl itself.

We measured urban sprawl using the *WUP* method by Jaeger and Schwick (2014).

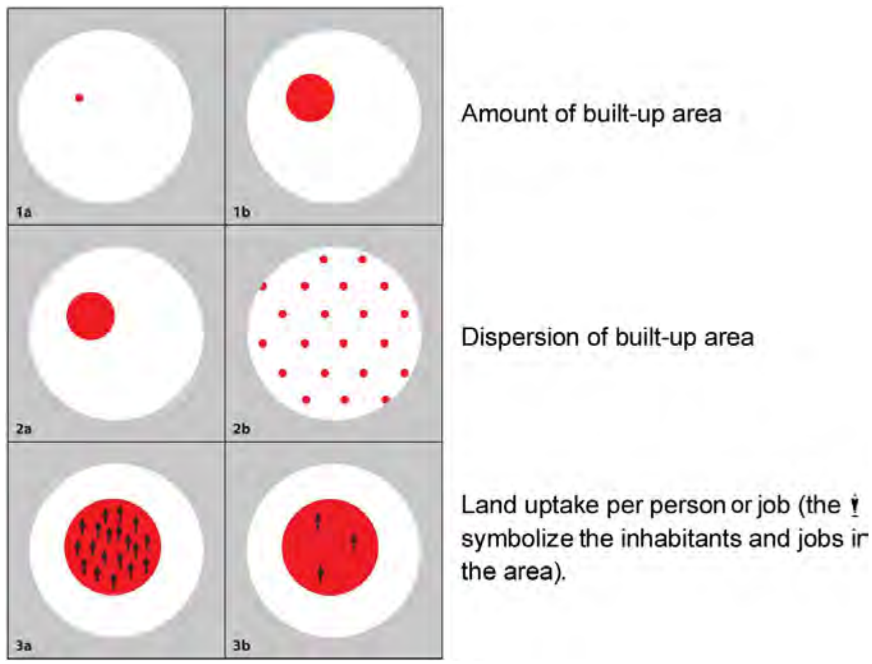


Fig. 2: The three components of urban sprawl: In a landscape (white), urban sprawl increases when (1) the built-up area grows (top row), (2) the built-up area becomes more dispersed (middle row), or (3) the amount of built-up area per inhabitant or job increases, i.e., the utilization density of the built-up area decreases (bottom row) (Source: Jaeger and Schwick 2014).

Current level of urban sprawl: The current *WUP* value (2011) in the Montreal CMA is 12.6 UPU/m^2. It is much lower in the Quebec CMA with 4.98 UPU/m^2, and between these two is the value of the Zurich MA with 7.46 UPU/m^2 (Fig. 3). Montreal has the largest proportion of built-up area (26.5%) and the highest dispersion (*DIS* = 47.82 UPU/m^2). The Zurich MA has a proportion of built-up area of 21.8% and a *DIS* of 46.42 UPU/m^2, lower than the Montreal CMA. The proportion of built-up area in Quebec CMA amounts to 9.8%, with a somewhat higher *DIS* (46.94 UPU/m^2) than in Zurich (see details in Nazarnia et al. 2016).

Urban sprawl in all three study areas has increased continuously since the 1950s. Until 1971, the degrees of urban sprawl in the Montreal and Quebec CMAs were close to each other, and much lower than in the Zurich MA. However, since 1971, urban sprawl in Montreal CMA has increased more sharply compared to Quebec CMA (Fig. 3).

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 3.65 UPU/m^2 in 1960 than the Montreal and Quebec CMAs, where it was still less than 1 UPU/m^2 at this time. Some may have expected that Zurich were less sprawled in 1960 than Montreal and Quebec. However, an important finding of our study is that sprawl in Montreal and Quebec is a **more recent phenomenon** than in Zurich, and the strongest increases in sprawl have happened **since the early 1980s**.

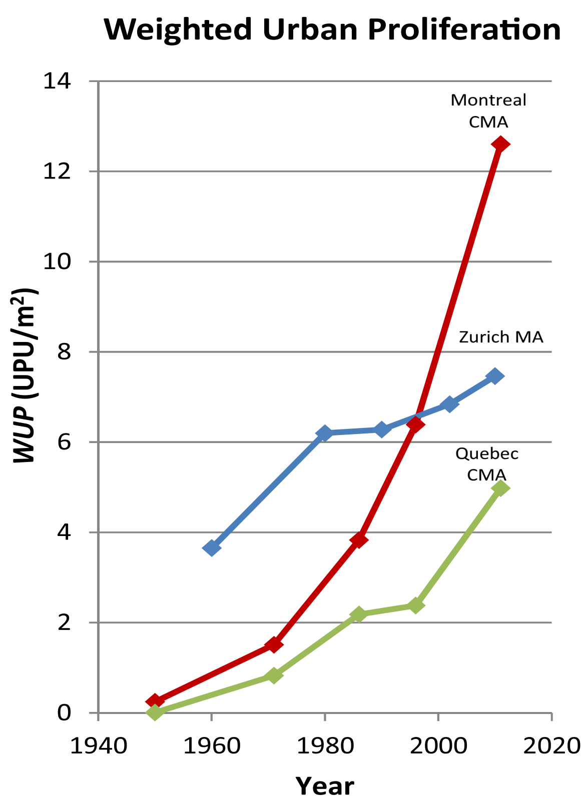


Fig. 3: Values of urban sprawl (*WUP*) between 1951 and 2011 in the Quebec Census Metropolitan Area (green), Zurich Metropolitan Area (blue) and the Montreal Census Metropolitan Area (red) (source: Nazarnia et al. 2016).

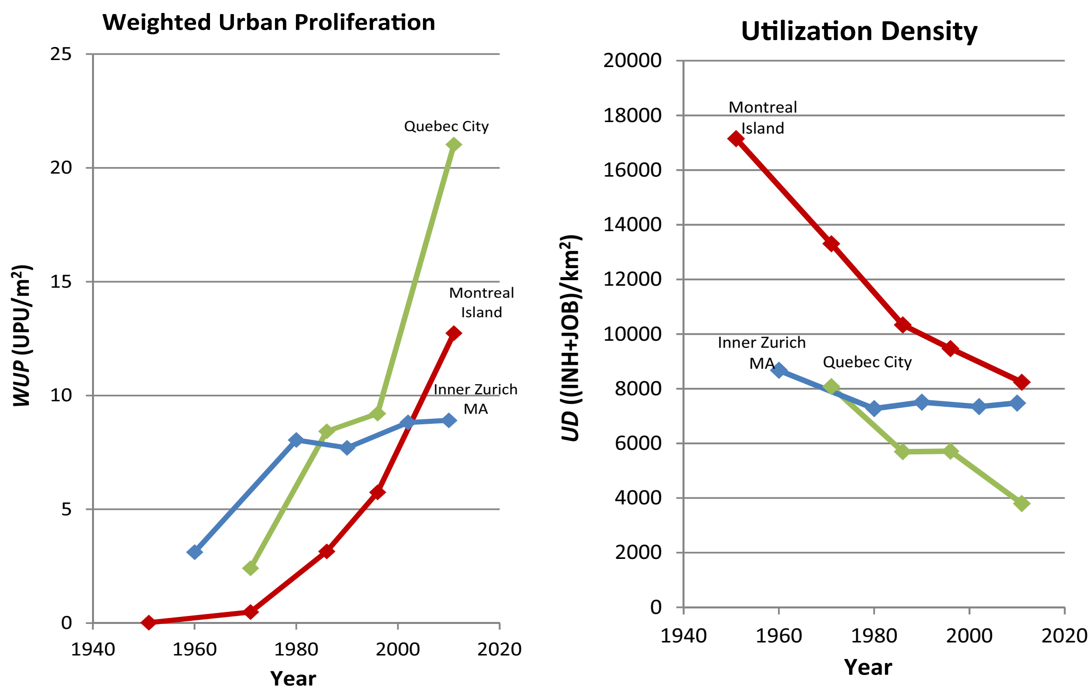


Fig. 4: Values of urban sprawl (*WUP*) and utilization density (UD) between 1951 and 2011 in Quebec City (green), Inner Zurich Metropolitan Area (blue) and the Island of Montreal (red) (source: Nazarnia et al. 2016).

Urban sprawl in the districts of Montreal: In Montreal, the top six districts of highest levels of urban sprawl in 2011 are Hampstead, Beaconsfield, Baie D'urfe, Dollard-Des-Ormeaux, Kirkland, and Dorval (Fig. 6), located in the west of the Montreal Island (with the exception of Hampstead). These districts encompass large amounts of built-up areas and are among the least densely populated areas (UD < 4800 inhabitants and jobs per km^2). High values of *WUP* in the districts located in the west of the Island were mostly due to the presence of industrial areas with a rather 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 sprawl (< 0.7 UPU/m^2). These districts are all located in the center of the Island and constitute downtown Montreal, which is the most densely populated space in Montreal.

The *WUP* values in districts 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 Mirabel and Rouville (3.05 and 3.84 UPU/m^2, respectively).

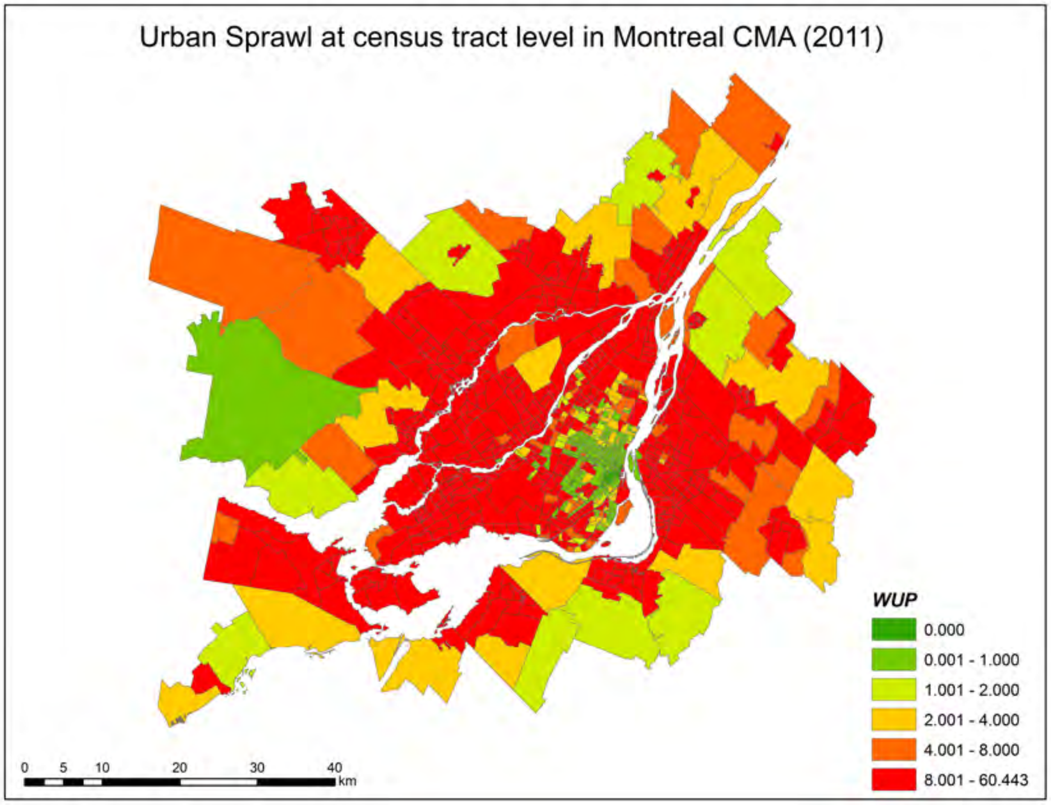


Fig. 5: Map of urban sprawl (*WUP*) in the Montreal CMA at census tract level in 2011.

The district of **Pierrefonds-Roxboro is among the 10 most highly sprawled areas** of the Montreal CMA (Fig. 6). The proposed development would significantly increase the degree of urban sprawl in Pierrefonds-Roxboro.

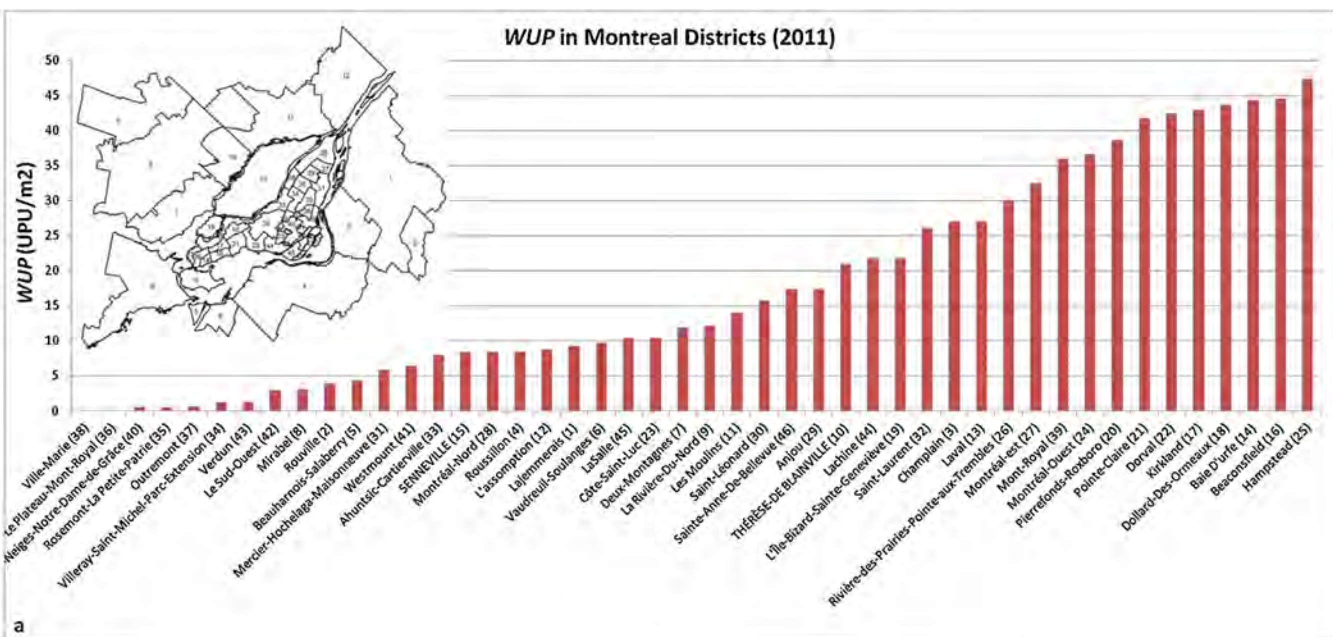


Fig. 6: Urban sprawl (WUP) in the Montreal CMA at district level in 2011. Pierrefonds-Roxboro (20) is the eighth most sprawled district in the Montreal CMA.

3. Effects of urban sprawl

Urban sprawl has manifold consequences, and some of them are desired (otherwise there would be no sprawl). For example, affordable single family homes with ample space between the houses, a classic example of sprawl, are preferred by many people because they offer more privacy and a larger degree of freedom to do what they want than apartment buildings. People appreciate a green surrounding around their single-family homes and their job locations, they often prefer to have more space for themselves, a larger garden, and more possibilities for playing outside for small children.

However, urban sprawl has **a large number of long-term negative environmental, economic, and social impacts**. The European Environment Agency has summarized the effects of urban sprawl in their recent report "*Urban Sprawl in Europe*" (EEA & FOEN 2016). For example, urban sprawl causes conflicts with conservation targets, agriculture, and social development and therefore **is a serious threat to sustainability** (Haber 2007). Urban sprawl is a prime example of the *tragedy of the commons* where the benefits of the use of a common pool resource – the landscape – go to single citizens, while the detrimental effects are shared among all of the society (Hardin 1968).
Table 1 provides an overview. More detailed information about these effects is given in the report by the European Environment Agency (EEA & FOEN 2016). The report is available online at: www.eea.europa.eu/publications/urban-sprawl-in-europe.

These consequences should be taken into consideration in decisions about future urban development in Montreal.

Table 1: Environmental, economic, and social effects of urban sprawl and/or urban growth. (Source: EEA & FOEN 2016, see there for a complete list of the sources cited)

Theme	Consequences of urban sprawl	Sources (examples)
Environmental impacts		
Land cover	• Land uptake for buildings and related infrastructure facilities, loss of farmland	Camagni et al. (2002), Pauleit et al. (2005), Eigenbrod et al. (2011), Wilson and Chakraborty (2013)
	• Removal and alteration of vegetation over larger areas	Pauleit et al. (2005)
	• Soil compaction, sealing of soil surface, loss of ecological soil functions, loss of water permeability, reduction of groundwater regeneration, reduced evapo-transpiration	Ewing (1994/2008), Scalenghe and Marsan (2009), Siedentop and Fina (2010)
Geomorphology	• Local alterations to geomorphology (e.g., cuts, stabilisation of slopes) over larger areas	Rivas et al. (2006)
Local climate	• Change of micro-climate conditions due to urban heat island effect: reduced vegetation cover, reduced albedo, warming of surface temperature, increased variability in temperature	Zhou et al. (2004), Taha (1997), Stone et al. (2010)
	• Modification of humidity conditions, e.g., reduced	Taha (1997)

	evapo-transpiration due to vegetation removal and soil sealing, lower moisture content in the air due to higher solar radiation, stagnant moisture due to soil compaction, increased variability in moisture • Climatic thresholds, modification of wind conditions due to removal of vegetation and construction of buildings	 Song (2005), Stone et al. (2010)
Energy and climate change	• Higher energy consumption and higher greenhouse gas emissions per person • Reduced carbon dioxide uptake due to removal of vegetation over larger areas, e.g., forest, grassland • Reduction of the capacity of the soil to act as a carbon sink	Kenworthy et al. (1999), Borrego et al. (2006), Waitt and Harada (2012), Jones and Kammen (2014), Duffy (2009) Hutyra et al. (2011) Lal (2003)
Air pollution, noise, light	• Higher air pollution per capita: vehicle exhaust, fertilising substances, dust, particles, road salt, oil, fuel, and other substances leading to air and water pollution and eutrophication • Higher noise pollution (causing insomnia and other health effects) • Higher light pollution, modification of light conditions, and other visual stimuli • Decoupling of material cycles in waste treatment (longer distances for waste transport and treatment counterbalances the positive effects of material recycling)	Navara and Nelson (2007), Rich and Loncore (2006), Bart (2010), Borrego et al. (2006), Tu et al. (2007) Slabbekoorn and Peet (2003), Moudon (2009) Bennie et al. (2014) EEA (2006)
Water	• Hydrological alterations of watersheds: reduced quantity and quality of groundwater, lifting or lowering of groundwater table • Modification of surface water courses • Water pollution, e.g., pollution of rainwater by tire abrasion, dust, and heavy metals, washed into rivers • Higher risk of leakages per capita: more leakages as the network of pipes is longer • Drainage, faster removal of water and increased risk of flooding (e.g., due to sealed surfaces) • Diminished hydrological dynamics of wetlands around sprawled cities • Increased water consumption per capita • Competition between agricultural irrigation and water use by city dwellers (e.g., in dry summers)	Jat et al. (2009), Wilson and Chakraborty (2013) Haase (2009), Feyen et al. (2009) Tu et al. (2007) Pauliuk et al. (2014), EEA (2014) Haase (2009), Wilson and Chakraborty (2013) EEA (2006) March and Sauri (2010) EEA (2006)
Flora and fauna	• Loss of habitats for native species; sometimes creation of new habitats with special conditions • Loss of soil biodiversity • Reduction of habitat below required minimal areas, loss of species, loss of biodiversity • Habitat alteration and higher disturbance rates • Higher numbers of invasive species, stronger spread of invasive species due to changes in climatic conditions • Reduced resilience of ecosystems	Alberti (2005) Alberti (2005) EEA (2006) Nobis et al. (2009), Scalenghe and Marsan (2009), Shochat et al. (2010) Scalenghe and Marsan

		(2009), Shochat et al. (2010)
	• Impoverishment or alteration of species communities	McKinney (2006), McKinney (2008), Raupp et al. (2010)
	• Modification of food-webs due to altered food-availability	Faeth et al. (2005)
	• Increased fragmentation of the landscape: Barrier effect, habitat fragmentation, disruption of migration pathways, impediment of dispersal, increased road mortality of wildlife, isolation of populations, degradation of ecological networks, loss of existing green infrastructure	EEA (2006), EEA & FOEN (2011), Alberti (2005)
	• Genetic isolation and increased inbreeding, disruption of meta-population dynamics	EEA (2006), Alberti (2005)
	• Restriction of re-colonization of empty habitat patches	McKinney (2008)
Landscape scenery	• Visual stimuli, noise	Bennie et al. (2014), Slabbekoorn and Peet (2003), Moudon (2009)
	• Increasing penetration of the landscape by built-up areas	Pauleit et al. (2005)
	• Landscapes can be read and interpreted less because of visual breaks, contrasts between nature and technology	Ewald and Klaus (2009)
	• Changes of landscape character and identity	Marull et al. (2010), Ewald and Klaus (2009), Müller et al. (2010)
	• Increased exploitation of river beds and expansion of quarries for construction material	EEA (2006)
Land use	• Loss of agricultural land and highly fertile soils (non-renewable resource)	Wilson and Chakraborty (2013)
	• Uptake of agricultural land leads to intensification of agricultural production elsewhere and encourages mass production	Pena et al. (2007), Eigenbrod et al. (2011)
	• Reduced recreational quality of natural and semi-natural areas	White et al. (2013)
	• Increased conflicts with other land-use interests, decreased availability of land for agriculture, renewable energy supply and industrial purposes, higher pressure on protected areas, conflicts with conservation management due to light and noise pollution and recreational activities	Haber (2007)
Economic impacts		
	• Higher costs of transportation for households for commuting	Camagni et al. (2002); Bento et al. (2005), Travisia et al. (2010)
	• Higher demand for transport, increased car use, higher cost for public transportation infrastructure	Kenworthy et al. (1999), Ewing 1997
	• Higher costs due to dealing with traffic congestion and the extension of urban infrastructure in newly developed regions	Hortas-Rico and Sole-Olle (2010), Klug and Hayashi (2010), Cinyabuguma and McConnell (2013)
	• Higher costs due to higher energy consumption per person	Kenworthy et al. (1999)
	• Higher public service costs and higher expenditure for construction and maintenance of infrastructure per capita (roads, electricity, water provision pipes, waste	Kenworthy et al. (1999), Ewing (1997), Pauliuk et al. (2014)

	water collection pipes, municipal garbage collection, snow removal, etc.)	
	• Higher material use for construction per housing unit	Roy et al. (2015)
	• Reduction in food production and reduced self-sufficiency, higher dependence on imported food	Haber (2007), Wilson and Chakraborty (2013)
	• Increased demand for raw materials, e.g., concrete, expansion of quarries, over-extraction of gravel from river beds	EEA (2006)
	• Changes in the distribution of populations relative to locations of ecosystem service supplies can reduce the per capita supply and increase the costs of service provision.	Eigenbrod et al. (2011)
	• Degradation or loss of various ecosystem services, higher costs for their substitution or restoration by technology	Cumming et al. (2014)
	• Environmentally degraded urban areas are less attractive to new investors and new highly qualified employees	EEA (2006)
	• Economic losses in touristic areas when the landscape scenery is degraded.	EEA (2006)
Social impacts and on quality of life		
	• Desired place to live for many people because low density housing offers more privacy and garden area than in densely built-up parts of cities	Bruegmann (2005)
	• Higher proportion of single households leading to a more resource-intensive living style	Dura-Guimera (2003), Howley (2009)
	• Greater segregation of residential development based on income	Thurston and Yezer (1994), Power (2001), Brade et al. (2009), Cassiers and Kesteloot (2012)
	• Longer commuting times, reduction of social interaction	Putnam, R.D. (2000)
	• Respiratory problems (e.g., asthma) due to higher air pollution	Frumkin et al. (2004)
	• Insomnia and other health effects due to higher noise pollution and heat island effect	Frumkin et al. (2004)
	• Increased obesity, stress, and decreased physical activity	Costal et al. (1988), Ewing et al. (2003), Garden and Jalaludin (2009)
	• Reduced human benefits from groundwater, conflicts due to competition for groundwater	EEA (2006)

5. Conclusions

In Montreal and Quebec, urban sprawl has gotten out of control and has turned into a serious and fast growing problem since the late 1980s (Nazarnia et al. 2016). **In the last 25 years, urban sprawl in Montreal and Quebec has become worse than ever before and has done so faster than ever before.** Quebec City is a prime example of urban sprawl today, in particular regarding its rapid increase since 1970. The steepest 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.

Montreal and Quebec City are still investing large amounts of money in more roads and almost nothing in the expansion of public transport, even though this path is considered as being unsustainable. Therefore, it is likely that this trend will continue in the future. The steps planned currently for Montreal and Quebec such as the intensification of urban areas or the development of TOD zones in Montreal (CMM, 2011) are so little compared to Switzerland (that itself suffers from sprawl) that much stronger efforts are needed to discontinue these unsustainable growth patterns. Switzerland is continuing on its way to limit 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.

Our study provides an indication of the potential of how much sprawl could be reduced and what factors could be changed in Montreal and Quebec. There is ample room in Montreal and Quebec for improvements in public transport, in the regional planning legislation, in the settlement pattern (creation of sub-centres with higher densities), and in utilization density.

The *WUP* method can be applied for measuring the levels of sprawl and dispersion of the urbanized areas and their temporal changes at any scale and for the classification of regions regarding urban sprawl and the identification of areas that are most in danger from sprawl, and areas with higher potential for future urban developments and for reduction of urban sprawl in particular. The *WUP* can be used to investigate relationships between sprawl and its impacts (e.g., relation with car ownership), as an indicator to monitor urban development, to evaluate the effectiveness of new regulations for urban development (e.g., development of TOD zones in Montreal CMA) and the effectiveness of the protection of high-value lands. For example, goal 6 of the federal sustainable development strategy 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).

Various measures to limit urban sprawl have been proposed in the literature (summarized by Schwick et al. 2012 and EEA&FOEN 2016), e.g., controlling the dispersion of built-up areas and stronger protection of agricultural lands. Better education of the public about the negative consequences of urban sprawl may encourage consumers to decrease land uptake per inhabitant and help decrease the level of urban sprawl.

In the Zurich MA, every vote about suggested expansions or improvements of public transport has been accepted by the population, while many proposed road construction projects were rejected. This indicates that more sustainable patterns of development require strong support in the society and long-term planning with a 20 to 30 year 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 22.2% to 40% would be much easier to achieve than increasing it from 63% to 78% as is currently being 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. Since the inauguration of the Montreal metro in 1966 its expansion has been far less significant than the expansions of the tramways and S-Bahns (rapid urban railway) in Zurich. Without a strong increase in utilization density and a massive expansion of public transport, urban sprawl in Montreal and Quebec City will continue to increase at a fast rate and will result in even more serious traffic congestion problems than today and growing negative effects that are typical of unsustainable development.

6. Measures to stop or reduce urban sprawl

> *"He who wants to act responsibly needs to know what he does. He needs to be able to see the potential consequences of his actions. (...) An enlightened reason would be a reason that recognizes its own possibilities and limitations. It would be a reason that does not do everything that one can do, but has recognized that only such an acting is sensible that sees its own consequences within our given limitations, and can only in this way become responsible acting"*
>
> *(Georg Picht[1] 1967)*

The current trends in urban sprawl in Montreal clearly contradict the goal of sustainable development, and they cannot continue in the long term. Thus, sustainability will become more and more difficult to achieve as urban sprawl advances (Haber 2007). However, it still seems realistic today to significantly slow down the increase of the problem using appropriate countermeasures.

Awareness of the issue among decision makers and the public is important for addressing the problem effectively. Decision-makers and the general public should therefore be made more aware of the long-term consequences of urban sprawl and loss of agricultural soils and habitats such as wetlands etc., and need to be informed about suitable measures. For example, urban sprawl is hotly debated in Switzerland. The **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 public recognition of the problem by politicians is a useful first step. The Federal Statute on Regional Planning of 1979 already included a responsibility to avoid sprawl by ensuring that land is used economically and that the extension of settlements is limited (LAT, 1979). It strengthened the role of the designated building zones and clearly reduced the number of new buildings constructed outside of these zones.
The Alternative Bank of Switzerland (ABS) is using the *WUP* method to avoid urban sprawl, i.e., they assess the contribution of new construction projects and mortgage lending to sprawl, in addition to economic criteria (www.abs.ch; ABS, 2012). It serves to evaluate potential new buildings regarding their contribution to urban sprawl as a basis for the decision about granting of mortgages. The bank does not give mortgages for buildings that would contribute strongly to urban sprawl. This could be called *divestment from urban sprawl*.

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[1] *German Philosopher (1913-1982)*

Such evaluation can also be the basis for the awarding of *energy labels*: The *WUP* indicator is part of a new assessment system for sustainable construction in Switzerland (*Standard Nachhaltiges Bauen Schweiz*, SNBS) which aims at reducing the negative impacts of new constructions in society, economy, and in the environment. The *WUP* method serves as an indicator to assess the loss of soils, effects on biodiversity, and landscape consumption (http://www.nnbs.ch/fr/standard-snbs/).

The most effective approach to keeping further sprawl to a minimum consists in the reduction of land-uptake per inhabitant and the concentration of settlement areas (i.e., without extending the borders of each settlement), i.e., **use land sparingly.** Consequently, the following five general guidelines are essential in supporting efforts for controlling urban sprawl (EEA&FOEN 2016):

(1) Clear separation of building zones and non-building zones, and long-term settlement restriction: The building zones and non-building zones are clearly distinguished from each other. The built-up areas are compact, and do not fray at the fringe. The sizes of the building zones are determined in a rigorous way that does not easily allow for extension of their boundaries. These boundaries are fixed on a long-term basis.

(2) Building only in the designated building zones: Construction outside of the designated building zones creates considerable sprawl because it badly affects dispersion values and land-uptake per person. Exceptions are permitted only if the new buildings are bound to a particular location due to their function, e.g., water supply facilities.

(3) Preventing dispersed expansion of built-up areas: New built-up areas and individual buildings are only allowed at locations where dispersion values are low (compact configuration). This can be done by in-filling, i.e., use of gaps inside of existing built-up areas such as unused lots or brownfields. If such in-filling is not possible, then in-fills can be done on the edge of existing built-up areas or at other places with low dispersion values. For example, in the Netherlands, 34% of residential developments between 2001 and 2005 took place in existing urban areas (Buitelaar et al., 2008). In England, the national government successfully introduced a brownfield housing target of 60% in 1998, implying that 60% of all residential developments must take place on previously development land and through the conversion of existing buildings. Since 2000, this target has been achieved every year (Adams et al., 2010).

(4) Densification of existing built-up areas and minimum densities in new built-up areas: Not all built-up areas have the same potential for densification, but even moderate densification is desirable because sprawl is reduced at the location where densification takes place and further sprawl elsewhere is prevented (fewer new built-up areas needed any more). When construction of new built-up areas is unavoidable, the land uptake per person is at least as low as the average land-uptake per person in the region surrounding the new built-up areas. Densification is done in a way that the quality of the built-up areas is increased. An important part of this is that green spaces in built-up areas are preserved and improved in their quality for recreation. The required levels of densification do not imply that urban areas will be dominated by highrises in the future. For example, the canton of Zurich (Switzerland) is planning to densify the existing built-up areas by about 20% by

2040. Therefore, urban sprawl will be significantly reduced in the canton of Zurich. Almost no further expansion of the built-up areas is allowed in the canton of Zurich. Therefore, the new population needs to be accommodated mostly in the existing built-up areas. The necessary densifications are relatively modest (average of less than 20% of the existing density). The densification takes into account the existing settlement types: The rural areas will keep their rural character (densification < 10%). Densification of the suburban areas is the strongest (> 20%). The suburban areas shown in red are supposed to transition from a suburban character to an urban character (Regierungsrat Kanton Zürich 2014). This is in accordance with the results of the Swiss National Research Programme 65 "New Urban Quality" that concluded that the urbanization of suburban areas is one of the main tasks of society in the 21st century (Sulzer and Desax 2015).

(5) Integrated planning of transport and settlement development: The relation between built-up areas and public transport is important to consider because the density of built-up areas is related to the attractiveness (level of service) and cost effectiveness of public transport. Therefore, planning of settlement development and transport infrastructure are integrated. This requires a planning process that transcends administrative boundaries and integrates various sectors to control the development of compact settlements and ensures a well-functioning transport infrastructure. A central condition for breaking the vicious circle of transport and sprawl (Fig. 7) is that infrastructure, mobility, and regional development are coordinated comprehensively (Matthey 2012).

Many more examples of suitable and inspiring measures are presented in the report "*Urban sprawl in Europe*" (EEA & FOEN 2016).

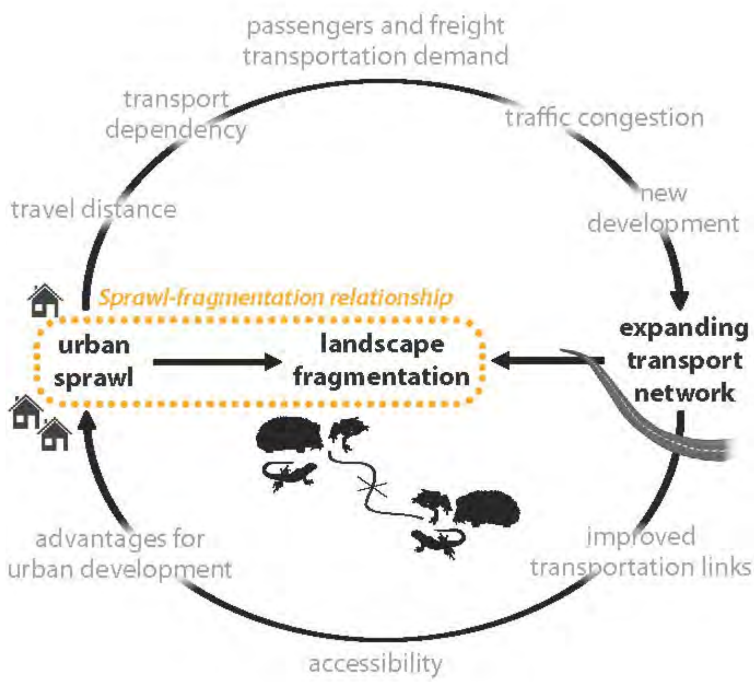

Fig. 7: The expansion of road networks and urban sprawl are interlinked through a feedback loop, illustrating the danger of a lock-in effect: Areas of high land-uptake per person cannot be served efficiently by public transport, and people will depend on using cars (Source: Torres et al. 2016).

Annex 1: "***Accelerated urban sprawl in Montreal, Quebec City, and Zurich: Investigating the differences using time series 1951-2011***"
Paper by Nazarnia et al. (2016).

Annex 2: "***Mesurer et éviter l'étalement urbain***"
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Accelerated urban sprawl in Montreal, Quebec City, and Zurich: Investigating the differences using time series 1951–2011

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ABSTRACT

Increasing awareness of the negative effects of urban sprawl has made sprawl a topic of great debate. However, higher efforts are needed to protect forests, agricultural lands, and other open spaces from urban sprawl. This study compares patterns of accelerated increase in sprawl in the Montreal and Quebec Census Metropolitan Areas in Canada with the Zurich metropolitan area in Switzerland between 1951 and 2011. We applied the recent metrics of urban permeation (*UP*) and weighted urban proliferation (*WUP*) to measure urban sprawl. Urban sprawl has accelerated continuously in Montreal and Quebec since 1951. Here, the fastest increases in sprawl have been observed in the last 25 years, whereas in Zurich the strongest acceleration was in the 1960s. Urban sprawl has increased exponentially in Montreal since 1951. On the Island of Montreal, the degree of urban sprawl (*WUP*) increased 26-fold from 0.49 UPU/m^2 in 1971 to 12.74 UPU/m^2 in 2011, while in Quebec City it increased 9-fold from 2.41 UPU/m^2 to 21.02 UPU/m^2 from 1971 to 2011. In contrast, the level of sprawl (*WUP*) in the Inner Zurich metropolitan area increased almost 3-fold from 3.12 UPU/m^2 in 1960 to 8.91 UPU/m^2 in 2010, i.e., it was higher before 1980, but then was surpassed by Montreal and Quebec City. The strongest increases in land uptake per person were observed in Quebec City and on the Island of Montreal, while it increased only slightly in Zurich. Two major reasons for this striking difference in sprawl dynamics are Switzerland's stronger planning legislation since 1979 and a much higher level of public transportation availability in Zurich. The comparative analysis of urban sprawl presented in this study can greatly help land-use planners critically assess projected plans and control urban sprawl and its negative consequences. The *WUP* method can also be used to establish targets and limits to urban sprawl and to evaluate the effectiveness of measures to control sprawl.

1. Introduction

More than half of the world's human population has been living in urban areas since about 2008 as a consequence of population growth and a movement of people from rural to urban areas (UNFPA, 2007). For example, while only 50% of Americans lived in cities in 1950, 80% lived in metropolitan areas by the 1990s (Putnam, 2000). In many cases, this has resulted in urban sprawl, in particular in North America where low-density suburban development and automobile dependency have been prevalent, but also in many other places all over the world for similar reasons (Irwin and Bockstael, 2002; Batisani and Yarnal, 2011; Hennig et al., 2015).

1.1. Causes and consequences of urban sprawl

Many factors contribute to the particular pattern of urban development known as urban sprawl, e.g., consumer preferences for inexpensive lots, single-family detached housing, and for living in green low-density neighbourhoods, and the wish for second homes. Telecommunication improvements and low gasoline prices have made human choices of dwelling locations more independent of their distances from central facilities (Ewing, 1997). Unorganized patterns of growth have resulted from planning activities without

Abbreviations: CMA, Census Metropolitan Area; CMM, Communauté Métropolitaine de Montréal; *DIS*, dispersion; FSO, Federal Statistical Office of Switzerland; *LUP*, land uptake per person; MA, metropolitan area; NTDB, National Topographic Database; PMAD, Plan Métropolitain d'Aménagement et de Développement; RCM, regional county municipalities; TLM, topographic landscape model; TOD, transit-oriented development; *UD*, utilization density; *UP*, urban permeation; URSMEC, URban Sprawl MEtrics Calculation (tool); *WUP*, weighted urban proliferation.

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a clear vision for the future (Wright and Boorse, 2013). Public policies, such as taxation systems, subsidies, and road construction, may contribute to, or moderate, the drivers of urban sprawl.

However, sprawl is an unsustainable form of development due to its many harmful environmental, economic and social effects. Soil sealing, increasing scarcity of land for renewable energy and food production, increase in greenhouse gas emissions and water pollution, loss of habitats and valuable ecosystem services, lower infrastructure and public transportation efficiency, long commuting times, and reduced civic involvement in the society are widespread consequences of urban sprawl (Haber, 2007; Frumkin, 2002; Forys and Allen, 2005; Siedentop and Fina, 2010; Ewing, 1997; Putnam, 2000).

In Canada, urbanization is the second most important human activity causing habitat loss, which in turn is the most prevalent threat to endangered species in this country (Venter et al., 2006). The effects of urban sprawl are cumulative, i.e., they result from the combination of all development projects, and most are irreversible in human time spans. Therefore, effective efforts are needed to better apprehend, measure, and control sprawl.

1.2. Definition of urban sprawl

The wide variety of definitions of “urban sprawl” have rendered the term fuzzy (Audirac et al., 1990). Three main reasons for this confusion are that (1) sprawl has been defined differently by different disciplines (Bhatta et al., 2010); (2) it is difficult to distinguish “sprawl” from similar terms such as “suburbanization” or “suburban development” (Maier et al., 2006); and (3) causes and consequences of sprawl are often confused with the phenomenon of sprawl itself (Jaeger et al., 2010a). Hence, a reliable definition of urban sprawl is needed, and this study uses the following: “The more area built over in a given landscape (amount of built-up area) and the more dispersed this built-up area in the landscape (spatial configuration), and the higher the uptake of built-up area per inhabitant or job (lower utilization intensity in the built-up area), the higher the degree of urban sprawl” (Jaeger and Schwick, 2014). This definition is based on a comparison of definitions in the literature (Jaeger et al., 2010a) and served to develop a recent metric of sprawl according to 13 suitability criteria (Section 2.2).

1.3. Comparing urban sprawl in Canada to Switzerland

There is increasing consensus among scholars, decision makers, and the general public that most Canadian cities are severely affected by urban sprawl. However, most studies in Canada focus on the consequences and other aspects of sprawl rather than the degree of sprawl itself. Examples are the investigation of direct and indirect impacts of urban development on land conversion by Pond and Yeates (1993) and the comparison of residential density between four major metropolitan areas of Canada by Filion et al. (2010). The latter study identified Montreal as a more administratively fragmented and decentralizing metropolitan area compared to Toronto, Vancouver and Ottawa. A study about the relation between municipal fragmentation and suburban sprawl in North American cities identified Montreal and Quebec City as the most municipally fragmented metropolitan areas in Canada (Razin and Rosentraub, 2000). When comparing 96 cities in North America, Montreal and Quebec City were found to be more similar to US metropolitan areas than most other Canadian metropolitan areas (since five of the ten least fragmented metropolitan areas were Canadian: Toronto, Calgary, Hamilton, Winnipeg, Vancouver and Ottawa; Razin and Rosentraub, 2000). Municipal fragmentation was measured based on the number of local governments in relation to the number of residents, the existence of multi-purpose metropolitan governments, and the proportion of population in the cities of more than 100,000 residents in the metropolitan area. A low level of municipal fragmentation did not directly correlate with compact urban development. However, a low level of municipal fragmentation could be a precondition for less dispersed urban development because the existence of numerous local governments may encourage sprawl through less coordinated planning (Razin and Rosentraub, 2000).

Few studies have measured urban sprawl in Canada. Sun et al. (2007) used Shannon’s Entropy to measure the level of urban sprawl in Calgary for six points in time: Shannon’s Entropy increased continuously from 0.850 in 1985 to 0.905 in 2001 indicating an increase in urban sprawl.

The Montreal and Quebec Census Metropolitan Areas (CMAs) lack a quantitative assessment of urban sprawl. About half of the population of the Province of Quebec lives in the Montreal CMA, and one-tenth lives in the Quebec CMA. Located on the north bank of the Saint Lawrence River, Quebec City is among the oldest settlements in North America and is the political capital of the Province. The Montreal and Quebec CMAs comprise lands that are among the most fertile in Canada. However, many fertile areas have been converted to urban land use during the past few decades. In Montreal, population growth in combination with a continuous reduction in population densities in the central zones of the city since 1950 can partly explain the current level of urban sprawl. In the 1960s, the population spread towards the Eastern and the Western parts of the Montreal Island and to Laval (north of Montreal Island), which resulted in a high increase in urban sprawl. Since 1996, migration to suburbs located further from the Island of Montreal has also risen strongly (Linteau, 2013). In Quebec City, population growth along with the extensive growth in the amount of built-up areas are among the main drivers of urban sprawl. Between the years 1971 and 2006, the population of the Quebec CMA increased by 62%, where during the same period of time, the built-up areas increased by 261% (CMQ, 2006).

The Communauté Métropolitaine de Montréal (CMM) council published a metropolitan land use and development plan in 2011, entitled “Plan Métropolitain d’Aménagement et de Développement” (PMAD), that presents 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. The CMM proposed 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. The PMAD also suggested that the densification of the urban areas between the vacant lands outside of TOD zones should be considered in projected developments (CMM, 2011).

We wanted to compare Montreal and Quebec with a contrasting region that (1) has a significantly higher modal share for public transport, (2) has a longer history of development with a significant level of sprawl in the 1960s, and (3) has a stronger regional planning legislation than Canada, while (4) it is part of the Western culture and has a comparable lifestyle. Therefore, we selected a region from Europe: Zurich metropolitan area (MA). The cantonal government of Zurich created a Specialist Department for Spatial Planning (Fachstelle für Raumplanung) in 1942, which is the Office for Spatial Development (Amt für Raumentwicklung) today. Sensitive areas were protected from construction activities by regulations in the canton of Zurich for the first time in 1942. The canton has implemented Regional Comprehensive Plans (regionale Gesamtpläne) on a regular basis since 1948. The revision of the Construction Act in 1959 distinguished designated building zones from non-building zones. The designated building zones of the years between 1964 and 1973 were rather large, based on the predicted increase in population and employment, and they were significantly reduced in

1978 and again in 1995, when large parts of them were re-zoned as agricultural land. According to the most recent cantonal Richtplan (structure plan) of 2014, new building zones will be designated only in exceptional cases. Additional reasons for choosing Zurich were the availability of high-quality data (Jaeger and Schwick, 2014) and the similar size of the Inner Zurich MA as Montreal Island and Quebec City. Similar to Montreal and Quebec City, which are located on the shore of the St-Laurence river, Zurich is located along the shore of Lake Zurich. Zurich contrasts with the selected Canadian cities in its historic development. Montreal was founded as a city in 1642 and Quebec in 1608, whereas Zurich has been settled for about 2000 years. Zurich has more rigorous regional planning legislation. The Zurich MA is distributed among seven cantons (Zurich, Aargau, Schwyz, Zug, Schaffhausen, Thurgau and St. Gallen), and its settlement structure is polycentric. Modal share of public transport in the Zurich MA is 63% (Statistisches Amt Kanton Zürich, 2012), whereas it is only 22.2% for work trips in Montreal CMA and 11.3% for work trips in Quebec CMA (StatCan, 2011a).

In Switzerland, urban sprawl is hotly debated. The 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 a responsibility to avoid sprawl by ensuring that land is used economically and that the extension of settlements is limited (LAT, 1979). It strengthened the role of the designated building zones and clearly reduced the number of new buildings constructed outside of these zones. However, the municipalities can designate new building zones almost entirely autonomously, and both the building zones and the built-up areas in Switzerland have grown apace since (FSO, 2012), i.e., the Federal Statute has not succeeded in preventing 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 requires that (1) the designation of new building zones must be limited according to the anticipated need based on predicted population growth in the next 15 years, and (2) levies must be introduced 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 clear majority of 62.9%.

1.4. Research questions

This study addresses two research questions:

1) How quickly has the level of sprawl increased in the Montreal and Quebec CMAs since the 1950s, and what are their current degree and spatial pattern of sprawl?
2) What are the similarities and differences between Montreal and Quebec (representing Canada) and Zurich (representing Switzerland) in their level of sprawl in the last six decades?

We compared these three examples to illustrate the differences between North-American and European metropolitan areas of similar size and lifestyle and to look for contrasts between patterns of urban sprawl and change over time. We also explored potential reasons for the differences. We use the terms built-up area, settlement area, and urban area synonymously in this paper.

2. Methods

2.1. Study areas

The three regions studied are the Montreal and Quebec CMAs in Canada and the Zurich MA in Switzerland; nested in them are the three inner areas: the Island of Montreal, the City of Quebec, and the Inner Zurich MA (Fig. 1). The Montreal CMA is Canada's second most densely populated metropolitan area (StatCan, 2011b), located in the southwest of the province of Quebec, where the St-Lawrence and Ottawa Rivers meet, with a land area of 4260 km^2 and a population of 3,824,200 inhabitants (StatCan, 2012a). The Island of Montreal has a population of 1,886,500 and a land area of 500 km^2 (StatCan, 2012b). The Quebec CMA is the second most populous area in the province of Quebec, with a land area of 3350 km^2 and a population of 765,700 inhabitants (StatCan, 2012c). Quebec City has a land area of 454 km^2 and a population of 516,620 inhabitants and is the capital of the Province (StatCan, 2012d). Our definition of Quebec City includes parts of the south shore as a part of the City as it is highly urbanized, 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 its population is 612,092 inhabitants).

The Zurich MA has a population of 1,820,000 and a land area of 2131 km^2 (FSO, 2011). It is located in the north of Switzerland (Fig. 1b). Inner Zurich MA has a population of 929,000 inhabitants (2010) and a land area of 514 km^2 and is the largest continuously urbanized area of Switzerland (own calculation based on FSO, 2011).

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 (calculation of estimated values is described in Appendix B).

2.2. Metrics of urban sprawl

We used the metric of weighted urban proliferation (*WUP*) to quantify the degree of urban sprawl of a landscape (or reporting unit) (Jaeger and Schwick, 2014). *WUP* is a combination of urban permeation (*UP*), urban dispersion (*DIS*), and utilization density (*UD*) according to the three dimensions of our definition of urban sprawl (Section 1.2) (Fig. 2).

DIS measures the dispersion of built-up areas based on the distances between any two points within the built-up areas, expressed in urban permeation units per square metre of built-up area (UPU/m^2) (Jaeger et al., 2010b). Its calculation requires the specification of the scale of analysis, which is denoted by the horizon of perception (*HP*). People with an eye height of 180 cm can see the surrounding area within a radius of 4.8 km due to the curvature of the Earth (assuming there are no obstacles obstructing their view); therefore, distances between 1 km and 5 km are suitable choices for *HP* (Jaeger et al., 2010b). This study uses an *HP* of 2 km. Accordingly, the maximum distance between any two points considered within built-up area was 2 km. The value of dispersion increases when the *HP* increases; for example, the values of *DIS* for an *HP* of 5 km are about 55–80% higher than for an *HP* of 2 km, and about 100–160% higher for an *HP* of 10 km. The ranking order of reporting units according to their *DIS* value can change when a different *HP* is used, but this does not happen in most cases, as the sensitivity analysis by Orlitová et al. (2012) has shown. The *DIS* is an intensive metric, i.e., its value is invariant when the study area is enlarged over an invariant spatial pattern. In the calculation of *WUP*, dispersion is weighted with a weighting function $w_1(DIS)$, which assumes values between 0.5 and 1.5 to give higher weights to the more dispersed parts of the built-up areas (Jaeger and Schwick, 2014). We used the URban Sprawl MEtrics Calculation (URSMEC) tool for the calculation of the dispersion metric (Jaeger et al., 2008). The input for the tool was a binary map of built-up areas (15 m cells). The output of the tool was a map of so-called S_i values that are assigned to

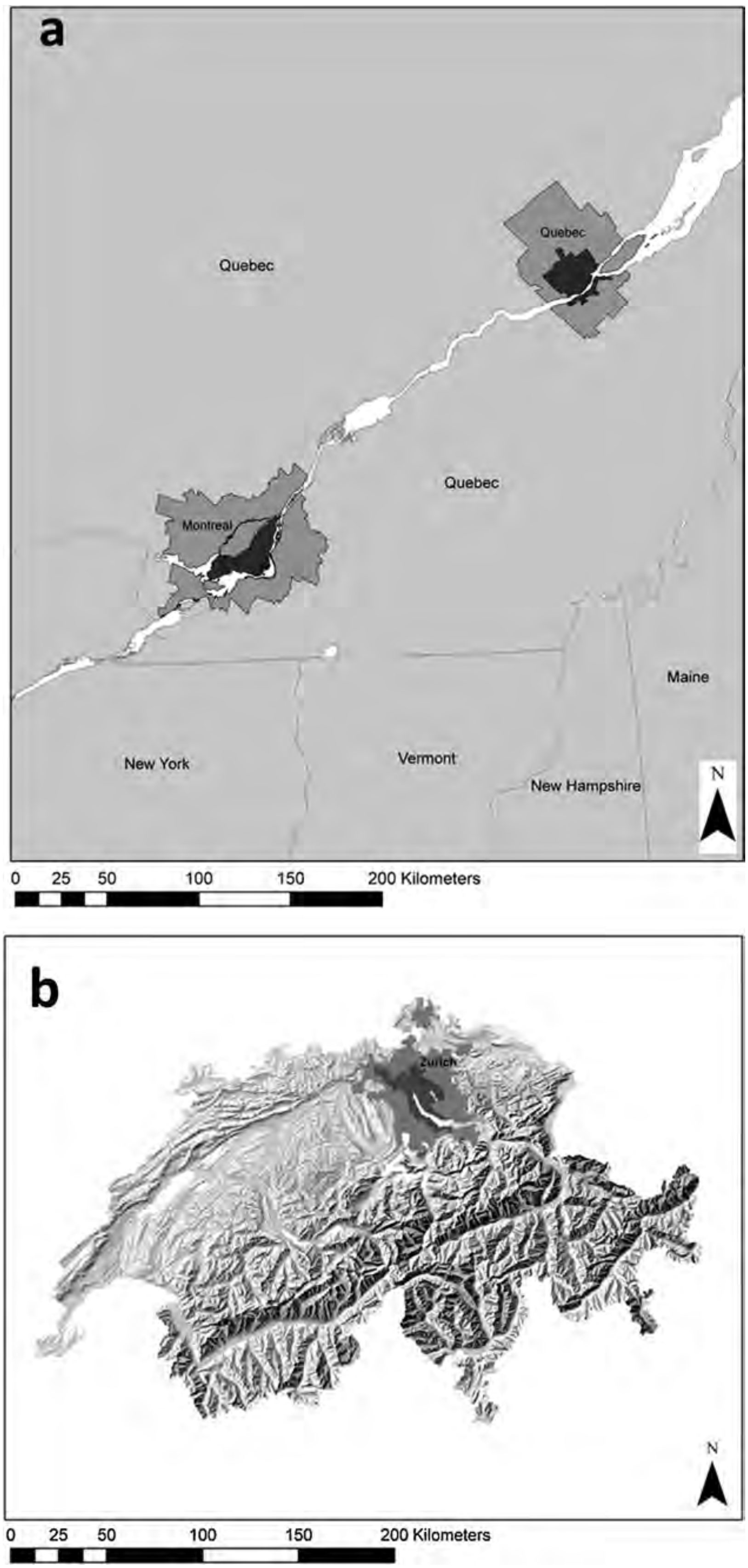

Fig. 1. Study areas: (a) Montreal and Quebec CMAs (medium grey, delineation of 2011). The inner areas (Montreal Island and Quebec City) are shown in dark (*Source*: Statistics Canada, 2011 boundary files. Scale: 1:2,000,000); (b) Zurich MA (medium grey) and the Inner Zurich MA (dark area) in Switzerland.

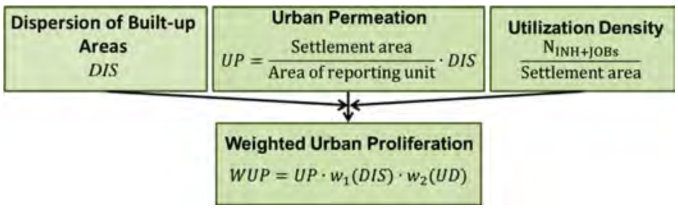

Fig. 2. Relationships between the metrics of urban sprawl used in this paper. *WUP* = weighted urban proliferation, *DIS* = dispersion of built-up areas, *UP* = urban permeation, *UD* = utilization density, w_1 and w_2 = weighting functions for *DIS* and *UD* (modified after Jaeger and Schwick, 2014).

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.

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 metre 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 a weighting function $w_2(UD)$, which assumes values between 0 and 1 to give lower weights to more intensively utilized urban areas, i.e., those that have more inhabitants and jobs. 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, 2014).

WUP is the result of the combination of all three dimensions of sprawl (Fig. 2).

2.3. Data sources

The calculation of the metrics requires only two datasets: a map of built-up areas and information about inhabitants and jobs. For the calculation of urban sprawl in Montreal and Quebec, we used the CanVec dataset provided in vector format in 2007 by Natural Resource Canada and updated in 2011, CanMap Route Logistics (version 2011.3, a product of DMTI spatial), and national topographic maps (see Tables A1 and A2 in Appendix A for complete list of all layers and features considered in the delineation of built-up areas).

We used the same method to calculate the area of single buildings in the Canadian case studies as in the study of urban sprawl in Switzerland by Jaeger and Schwick (2014). After gathering all relevant entities from CanVec and CanMap datasets some limitations were identified in these layers and suitable modifications were applied. The main modification was the manual delineation of the settlement areas based on the solitary buildings provided in point format. 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 built-up areas. Wherever four or more buildings were closer to each other than 100 m, a new settlement area was delineated (examples in Fig. 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. Therefore, around all the points representing solitary buildings, buffers of a radius of 15 m were created (assumed area of each building was $\pi r^2 = 706.5\,m^2$).

Another modification was related to building footprints. The datasets represent some urban features as building footprints, but other industrial areas and residential areas as 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 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 always included in the settlement areas (Fig. 3b), similar to the study from Switzerland (Jaeger and Schwick, 2014).

For the earlier years, historic datasets were not available in digital format. Therefore, we geo-referenced and digitized national topographic maps of Montreal and Quebec at the scale of 1:50,000 backwards in time, starting from the base layer of 1996 (CanVec data) (Fig. 4) using ArcGIS 10.1 (ESRI, 2011).

Lack of homogeneous data has been a common challenge for studies of urban growth over time. Although the source data of the CanVec and CanMap datasets are very similar, there are some minor differences. For example, the same solitary buildings presented as points in CanVec are shown as building footprints in CanMap. To reduce potential errors resulting from such differences, data of 1996 (CanVec) were used together with 2011 data (CanMap) to produce built-up areas for 2011, i.e. all features of the 1996 built-up areas are part of the 2011 layer, resulting in a neglect of the (small number of) built-up areas that may have been removed between 1996 and 2011. In addition, assigning an average area (of 706.5 m^2) to solitary buildings and potential digitization errors of topographic maps may have led to errors (potentially up to 10% in the final results).

The information about inhabitants in Montreal and Quebec came from the Canadian census for 1951, 1971, 1986, 1996 and 2011 (StatCan, 1951, 1971, 1986, 1996, 2011c). Job data in Montreal and Quebec for 2011 were from the census of workplace of 2006 (StatCan, 2006). Canadian censuses have been conducted every five years by Statistics Canada and are the main source of socio-economic and demographic information. However, at census tract level, the census of workplaces was not available for 1951–1996. Therefore, we used a correction factor for the calculation of utilization density for these years (Appendix B).

The base data for Zurich for 2010 were provided by Swisstopo's digital topographic landscape model TLM VECTOR25 at a scale of 1:25,000 (Federal Office of Topography swisstopo, 2013). Its settlement areas were manually captured along their borders. Larger open spaces within settlements were not recorded as urban areas (if they covered 2–4 ha or more). However, this data acquisition method is a little imprecise: in widely scattered settlements it can be difficult to draw a clear distinction between closed urban areas and single buildings. Despite this drawback, the TLM is still the best available for delimiting settlements in Switzerland. Data for 2002 were obtained from the digital landscape model VECTOR25 (predecessor of the TLM) (Federal Office of Topography swisstopo, 2002). On this basis, settlement areas of 1960, 1980 and 1990 were digitized using 1:100,000 maps. Urban areas were delimited using the same criteria as TLM and VECTOR25 (Jaeger and Schwick, 2014). Single buildings outside closed urban areas were manually digitized using the same maps, and were assigned spaces based on existing data (VECTOR25, National Register of Buildings and Dwellings).

Data about inhabitants in Zurich were drawn from the censuses of 2010 (FSO, 2011), 2000, 1990, 1980 and 1960 (FSO, 1850–2000), and jobs for 2010 and 2002 from the federal business census of 2008 and 2001 (FSO, 2002, 2009). For earlier times, we used commuter statistics from the censuses.

2.4. Reporting units

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

A CMA consists of one or more neighbouring municipalities located around a core that has a total population of at least 100,000 people (StatCan, 2011d). A disadvantage of using CMAs is that their

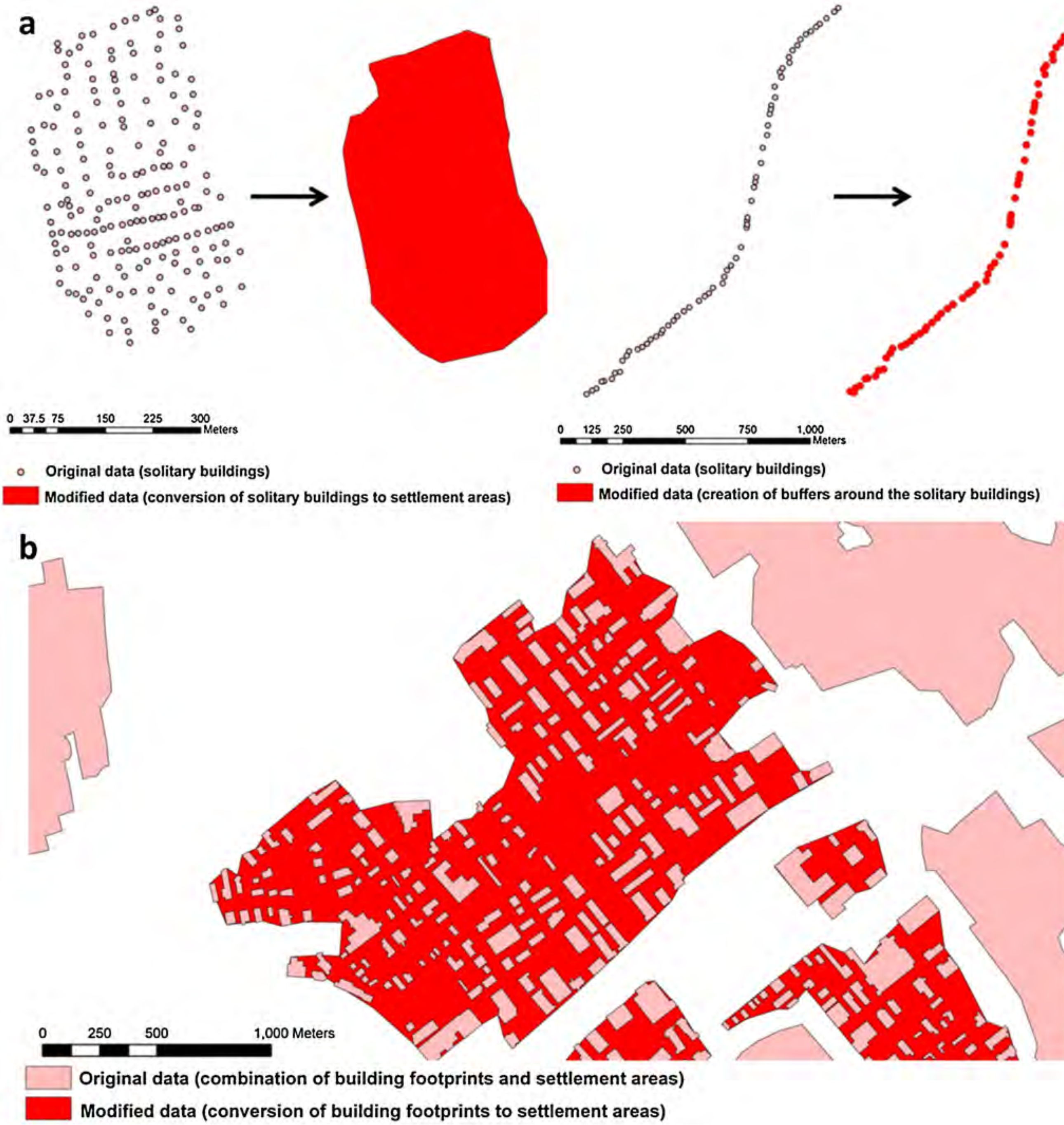

Fig. 3. Delineation of built-up areas: (a) delineation around building footprints located at distances less than 100 m from one another (left); solitary buildings located in a row were kept in their original pattern using a buffer of a radius of 15 m (right). (b) Delineation by converting building footprints to settlement areas: vacant areas between building footprints are part of urban areas and should be considered in the measurement of urban sprawl (both the pink and the red areas are considered as built-up areas). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

extension has changed significantly between 1951 (when the term CMA was used for the first time) and 2011. As a consequence, the suitability of CMAs as reporting units to assess urban sprawl over time is limited. Therefore, to be able to directly compare the three regions (without the effect of growing reporting units) we also studied the central, most densely populated zones of similar size (Montreal Island size of 500 km^2, Quebec City size of 554 km^2, Inner Zurich MA size of 514 km^2).

The Zurich MA was defined by the Swiss Federal Statistical Office (FSO). Any municipality is part of the MA 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 MA of Zurich. Zurich MA consists of 226 municipalities from seven cantons.

The Inner Zurich MA is not officially defined. Our delineation is based on the objective that its size be similar to 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 (Zurich, Argau, Schwyz).

The existence of a wide range of census data at the scale of census tracts has made census tracts one of the most important reporting

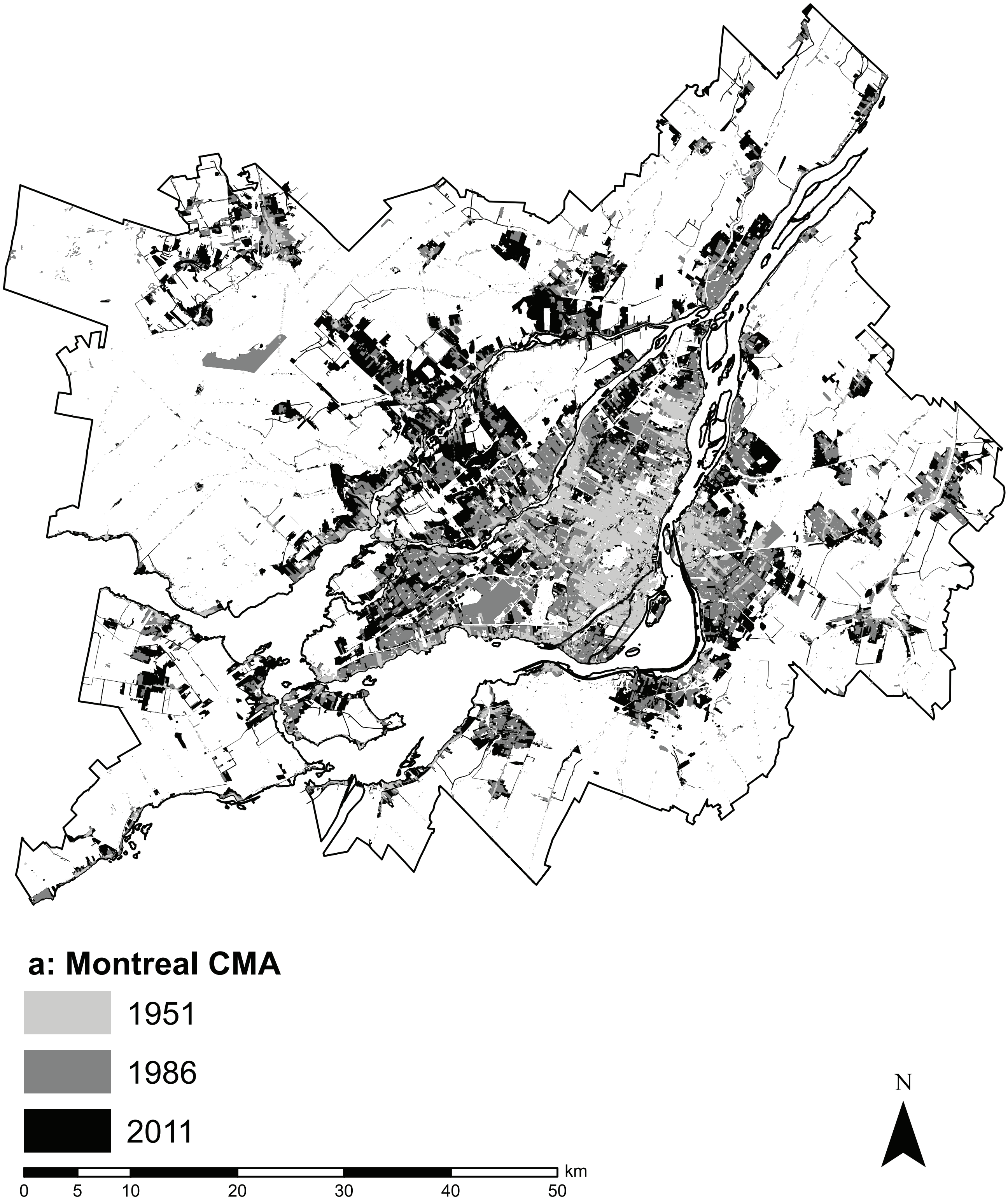

Fig. 4. Built-up areas in the three study areas at three points in time: (a) Montreal CMA in 1951, 1986 and 2011 (*Source*: built-up areas in 2011: CanVec (2011) and CanMap (2011) vector datasets, built-up areas in 1986 and 1951: own digitization based on national topographic maps at the scale of 1:50,000 product of National Resource Canada); (b) Quebec CMA in 1951, 1986 and 2011 (*Source*: built-up areas in 2011: CanVec (2011) and CanMap (2011) vector datasets, built-up areas in 1986 and 1951: own digitization based on national topographic maps at the scale of 1:50,000 product of National Resource Canada.); (c) Zurich MA in 1960, 1980 and 2010.

units in urban studies. In Canada, census tracts usually have a population between 2500 and 8000 people (StatCan, 2011e), e.g., the Montreal CMA of 2011 consists of 921census tracts. One potential (but usually negligible) limitation of census tracts is the change in their delineation over time due to neighbourhood growth, community reformation, and municipal integration (StatCan, 2011e). However, in most cases, these changes consist in the split of census tracts into two or more new census tracts (StatCan, 2011e), and usually users can reaggregate the new census tracts to the original census tract for historical comparison.

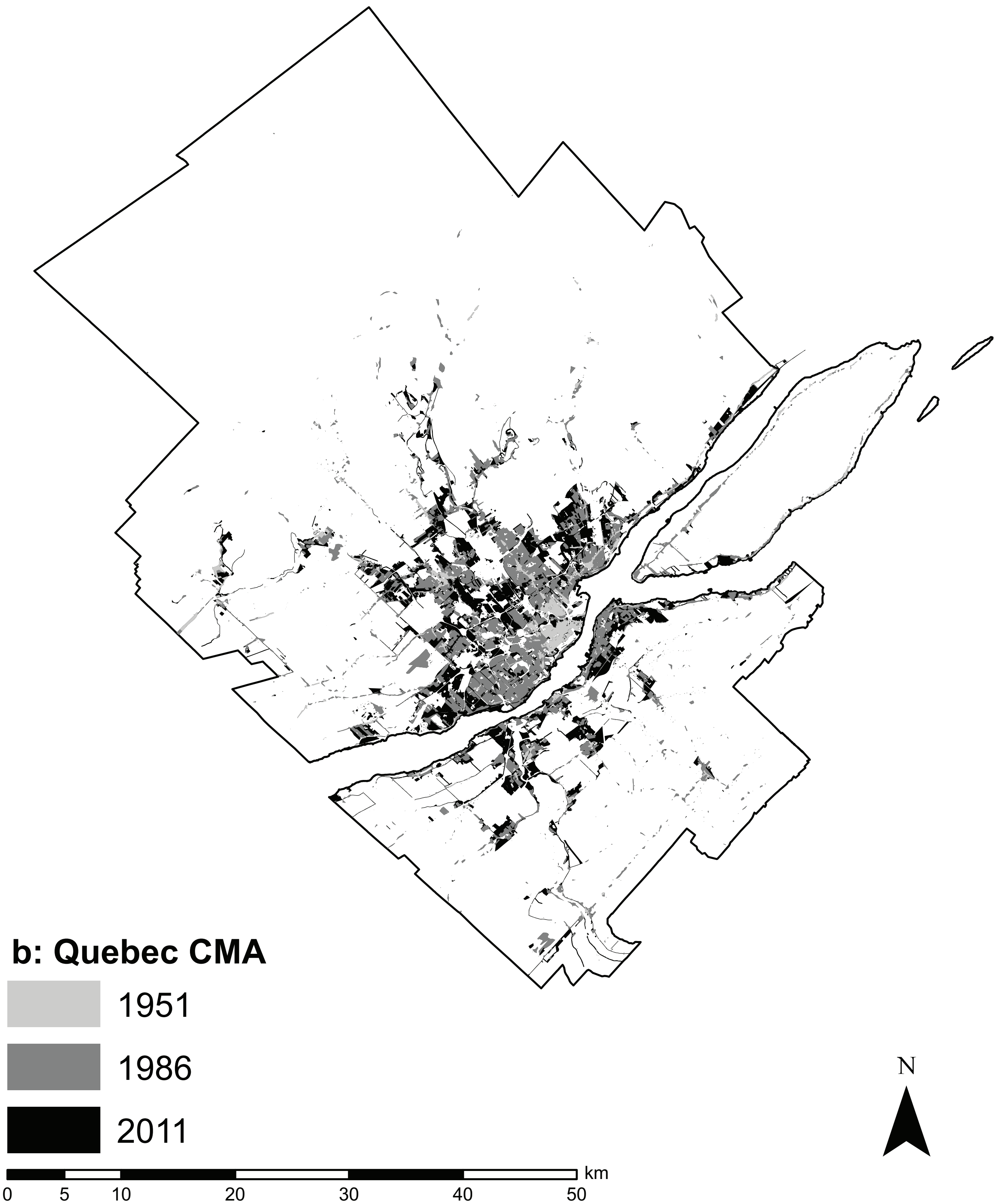

Fig. 4. (*Continued*).

The degree of urban sprawl at the district and municipality level provides a more aggregated picture of similarities and differences among study areas. Districts are a combination of boroughs and municipalities. We delineated them based on census tract boundaries of 2011 (and kept them constant for all points in time). We calculated population and job information at the district level by aggregating the information of groups of census tracts. The six districts of Quebec City are a combination of six boroughs of Quebec, the south shore and the L'Ancienne Lorette region. Montreal CMA contains 46 districts, which are a combination of 19 boroughs, 15 municipalities, and 12 regional county municipalities (RCMs).

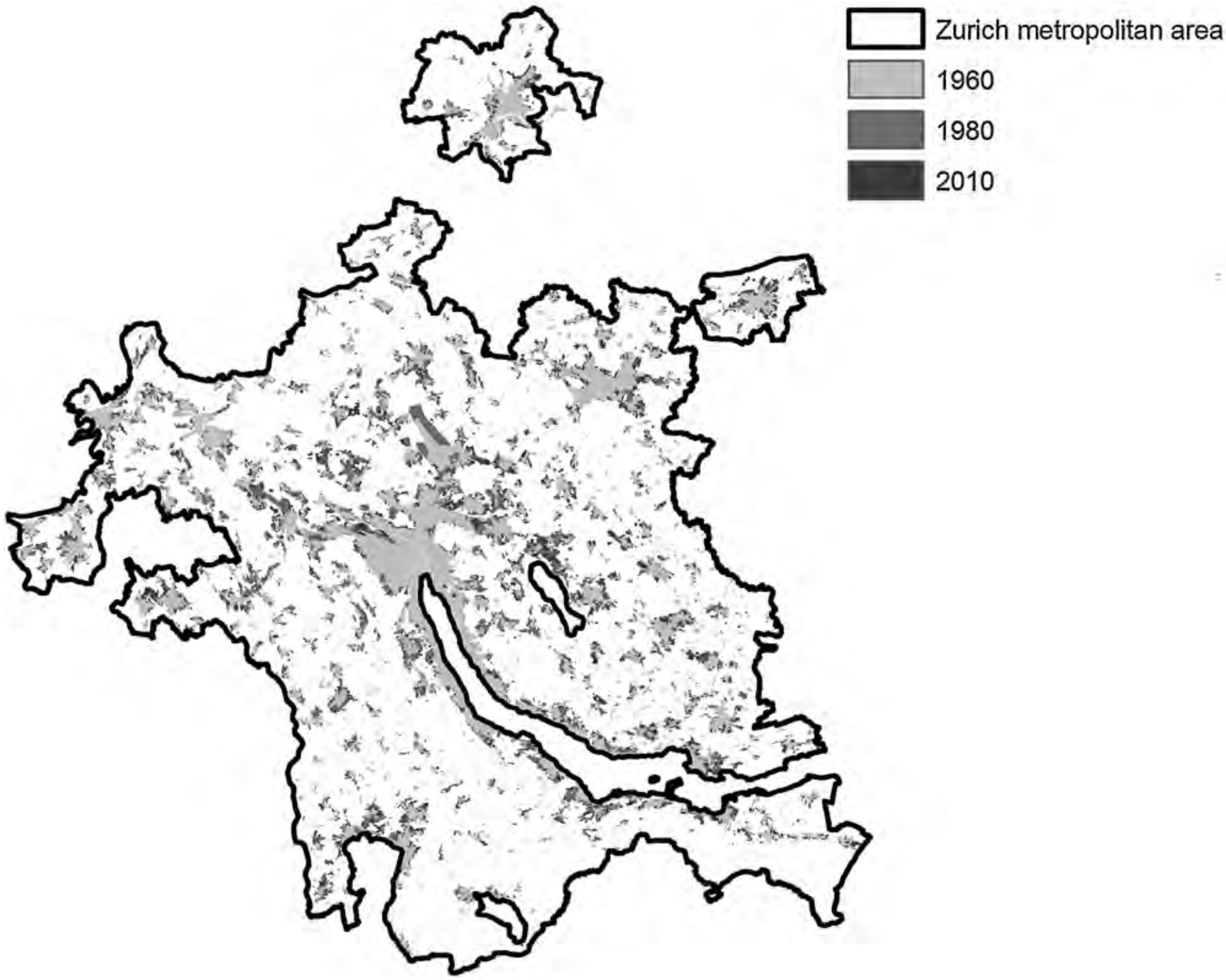

Fig. 4. (*Continued*).

All other reporting units follow the official definitions that have been used by the administrative institutions and therefore are relevant for their planning efforts and policy making, while they allow for temporal comparisons. (The only exceptions are that our definition of Quebec City included the south shore and our delineation of Inner Zurich MA.)

3. Results

3.1. Current level of urban sprawl

The current *WUP* value (2011) in the Montreal CMA is 12.6 UPU/m^2, much lower in the Quebec CMA with 4.98 UPU/m^2, and between these two in the Zurich MA with 7.46 UPU/m^2 (Table 1). Montreal has the largest proportion of built-up area (26.5%) and the highest *DIS* (47.82 UPU/m^2). The Zurich MA has a proportion of built-up area of 21.8% and a *DIS* of 46.42 UPU/m^2, lower than the Montreal CMA. The proportion of built-up area in Quebec CMA amounts to 9.8%, with a somewhat higher *DIS* (46.94 UPU/m^2) than in Zurich.

Even though *UD* in Quebec CMA (3224 inhabitants and jobs per km^2) is much lower than in Zurich MA (5927 inh. and jobs per km^2), the value of *WUP* in Quebec CMA is clearly lower than in the Zurich MA, due to the lower proportion of settlement area in Quebec CMA, which is 45% of Zurich's. The Quebec CMA is much larger (by 57%) (3344 km^2) than the Zurich MA (2131 km^2).

The areas in the Montreal CMA exhibiting the highest levels of sprawl are located in the west of the main Island, in Laval, in Longueuil and its surroundings, and along the shoreline north of Laval (Fig. 8). Highly sprawled areas in the Quebec CMA include L'Acienne Lorette, Les Rivières, and Sainte-Foy-Sillery-Cap-Rouge. 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 (high *UD* values) and in the regions that are located in the outskirts of the CMA such as Mirabel and Rouville which have lower amounts of built-up area compared to suburbs located closer to the city centre. Similarly, the lowest values of *WUP* in the Quebec CMA were found in the downtown area and in areas with large open lands that are located far from the city centre.

The results of *WUP* for the three inner study areas are directly comparable. The *WUP* value on the Montreal Island is 12.74 UPU/m^2, whereas it is significantly higher in Quebec City with 21.02 UPU/m^2, and lower in the Inner Zurich MA with 8.91 UPU/m^2. The strikingly high value in Quebec City is mostly caused by the low *UD* of only 3798 inhabitants and jobs per km^2, whereas both the built-up area and *DIS* are high. In contrast, both Montreal Island and the Inner Zurich MA have a much higher *UD* of 8237 and 7476

Table 1
Values of the urban sprawl metrics in the Montreal CMA, Quebec CMA, Montreal Island, Quebec City, Zurich MA and Inner Zurich MA. 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 (Fig. 8). *UD* = utilization density, *DIS* = urban dispersion, *UP* = urban permeation, *WUP* = weighted urban proliferation, UD' = utilization density (where only number of inhabitants was considered in the calculations), WUP' = weighted urban proliferation where UD' was used. For information on UD', WUP' and the correction factor please refer to Appendix B.

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	–	–	–	–	2,816,900
UD ((inh + jobs)/km^2)	17,150.86	13,304.48	10,334.55	9469.26	8236.96
Inhabitants	1,308,989	1,959,145	1,709,465	1,783,315	1,882,440
UD' (inh/km^2)	11,461.35	8890.94	6906.23	6327.99	5504.48
DIS (UPU/m^2)	47.21	48.28	48.49	48.66	48.91
UP (UPU/m^2)	10.78	21.28	24.00	27.43	33.45
WUP (UPU/m^2)	0.02	0.49	3.15	5.75	12.74
WUP' (UPU/m^2)	0.71	5.86	14.89	20.26	30.07
Correction factor	1.496	1.496	1.496	1.496	–

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	–	–	–	–	5,227,186
UD ((inh + jobs)/km^2)	14,619.557	8993.816	7236.831	5953.652	4597.026
Inhabitants	1,395,436	2,737,250	2,921,352	3,326,452	3,824,221
UD' (inh/km^2)	10,695.7	6579.9	5294.48	4355.71	3363.19
DIS (UPU/m^2)	47.19	47.077	47.08	47.32	47.82
UP (UPU/m^2)	10.84	7.27	7.32	8.88	12.67
WUP (UPU/m^2)	0.11	1.81	3.83	6.8	12.60
WUP' (UPU/m^2)	1.1	4.68	6.34	8.88	14.16
Correction factor	1.367	1.367	1.367	1.367	–

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)	–	79.21	123.12	132.58	219.83
Inhabitants + Jobs	–	–	–	–	834,958
UD ((inh + jobs)/km^2)	–	8079.47	5695.44	5714.02	3798.29
Inhabitants	–	464,594	509,036	549,944	606,108
UD' (inh/km^2)	–	5865.01	4134.40	4147.89	2757.23
DIS (UPU/m^2)	–	46.4	47.16	47.43	48.22
UP (UPU/m^2)	–	6.63	10.48	11.34	19.12
WUP (UPU/m^2)	–	2.41	8.43	9.21	21.02
WUP' (UPU/m^2)		4.94	10.65	11.67	22.49
Correction factor	–	1.378	1.378	1.378	–

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	–	–	–	–	1,057,317
UD ((inh + jobs)/km^2)	20,027.37	7645.42	4744.63	4880.18	3224.45
Inhabitants	264,924	480,500	603,267	671,889	761,818
UD' (inh/km^2)	14,430.12	5508.68	3418.60	3516.27	2323.28
DIS (UPU/m^2)	43.69	45.99	45.68	45.96	46.94
UP (UPU/m^2)	2.07	4.25	2.51	2.73	4.60
WUP (UPU/m^2)	0.0006	1.80	2.19	2.38	4.98
WUP' (UPU/m^2)	0.019	3.33	2.5	2.75	5.20
Correction factor	1.388	1.388	1.388	1.388	–

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	198.66
Inhabitants + Jobs	1,060,962	1,232,296	1,323,668	1,384,210	1,485,220
UD ((inh + jobs)/km^2)	8675.1	7274.5	7508	7343.3	7476.3
DIS (UPU/m^2)	46.56	47.17	47.19	47.3	47.39
UP (UPU/m^2)	11.07	15.54	16.18	17.34	18.31
WUP (UPU/m^2)	3.12	8.04	7.70	8.82	8.91

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 ((inh + jobs)/km^2)	6316.7	5684.2	5923.5	5892.8	5926.7
DIS (UPU/m^2)	45.42	46.08	46.12	46.26	46.42
UP (UPU/m^2)	5.8	8.15	8.67	9.31	10.14
WUP (UPU/m^2)	3.65	6.2	6.28	6.84	7.46

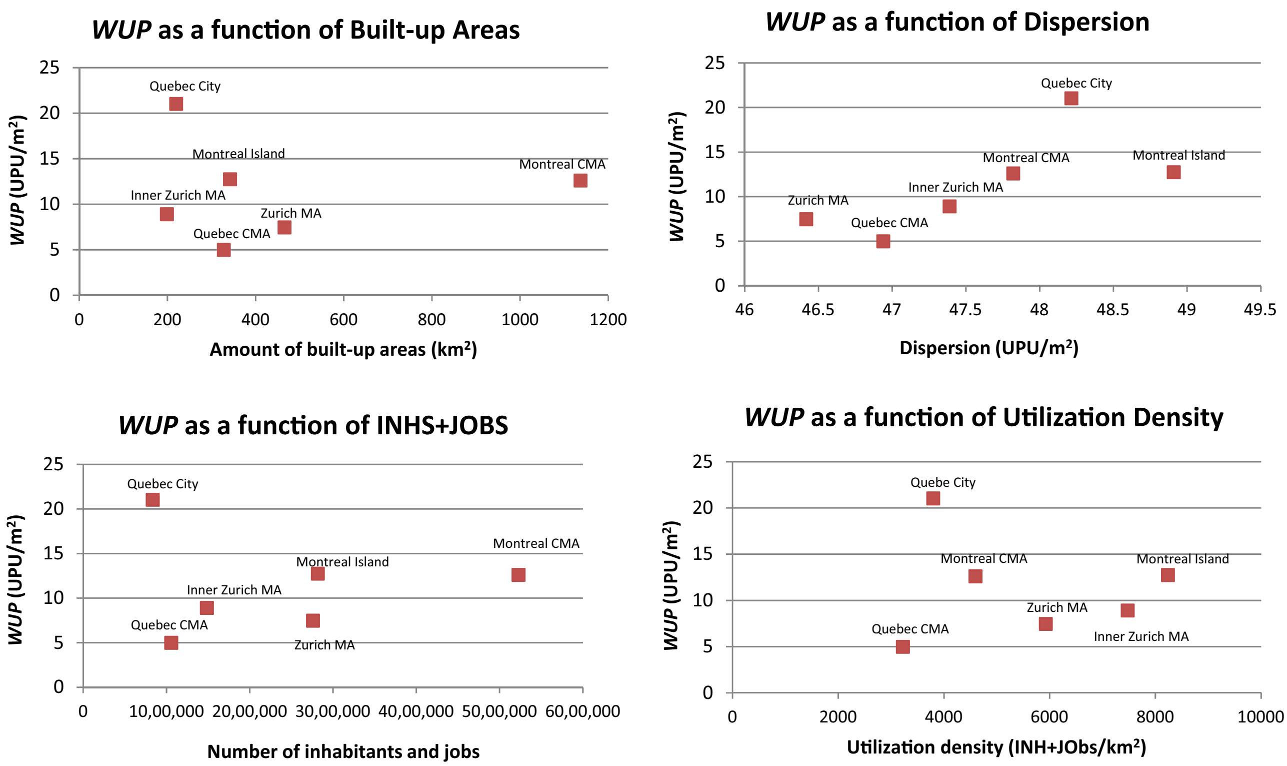

Fig. 5. Relationships between the current values of weighted urban proliferation (*WUP*) and the four metrics of amount of built-up area, dispersion, number of inhabitants and jobs, and utilization density for six reporting units: Montreal Island, Montreal CMA, Quebec City, Quebec CMA (2011 data), Inner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

inhabitants and jobs per km^2, respectively. As a consequence, large parts of the 342 km^2 of built-up areas on the Montreal Island are 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 (199 km^2 of built-up area with about 1,485,000 inhabitants and jobs vs. 220 km^2 with only 835,000 inhabitants and jobs in Quebec City).

The *UD* values on the Montreal Island and in the Inner Zurich MA are close to each other. Even though *UD* is slightly higher in Montreal, *WUP* is lower in Zurich because *UP* is much lower in Zurich (18.31 UPU/m^2) than in Montreal (33.45 UPU/m^2) due to a lower proportion of urban area. The value of *UP* in Quebec City (19.12 UPU/m^2) is close to the value for the Inner Zurich MA. The higher *UD* values in Montreal (Island) than in Inner Zurich are related to the fact that the Inner Zurich MA is not an official political unit. We defined it to select an area of similar size as the Island of Montreal for the comparison. It is not identical to the City of Zurich, but also includes suburban and periurban areas. The urban densities in the neighbourhoods of the City of Zurich are mostly higher than 40,000 inhabitants and jobs per km^2, while the suburban and periurban densities range between 2000 and 20,000 inhabitants and jobs per km^2. The inner city of Montreal has been larger than the inner city of Zurich during the study period. Therefore, the Inner Zurich MA has a larger proportion of suburban and periurban densities than the Island of Montreal. Montreal is the second most densely populated metropolitan area in Canada after Toronto (StatCan, 2011b) and has a higher population density than most other North American cities (Filion et al., 2004, p. 54; calculations based on 2010/11 census data by Townsend and Ellis-Young, pers. comm.).

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 (21.02 UPU/m^2) and Quebec CMA (4.98 UPU/m^2).

The relationships between the values of *WUP*, *DIS*, *UD*, the number of inhabitants and jobs, and the amount of built-up areas provide additional insight about the sprawl patterns (Fig. 5). The amount of built-up area in the Montreal CMA is more than 3 times as high as on the Montreal Island. Similarly, the amount of built-up area in the Zurich MA is more than twice as large as in the Inner Zurich MA. In contrast, 67% of the built-up area of the Quebec CMA are located in Quebec City. Similarly, the number of inhabitants and jobs in the Montreal CMA is 86% higher than on the Montreal Island, and also 86% higher in the Zurich MA than in the Inner Zurich MA. However, in the QCMA it is only slightly higher than in Quebec City (by 27%). Moreover, *DIS* in each CMA/MA is lower than in its respective inner areas; the biggest difference in its value is observed between Quebec City (48.22 UPU/m^2) and the Quebec CMA (46.94 UPU/m^2). The *UD* at the city level is higher than at the metropolitan scale in Montreal and Zurich. However, *UD* in Quebec City (3798 inhabitants and jobs per km^2) is only 18% higher than in the Quebec CMA (3224 inhabitants and jobs per km^2). As a result, the high value of *WUP* in Quebec City can be explained by its large value of *DIS*, along with its low value of *UD*.

The top six districts of highest levels of urban sprawl in 2011 are Hampstead, Beaconsfield, Baie D'urfe, Dollard-Des-Ormeaux, Kirkland, and Dorval, located in the west of the Montreal Island (with the exception of Hampstead) (Fig. 9a). These districts encompass large amounts of built-up areas and are among the least densely populated areas ($UD < 4800$ inhabitants and jobs per km^2). High values of *WUP* 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-Mont-Royal, Côte-des-Neiges, Rosemont, and Outremont are the five

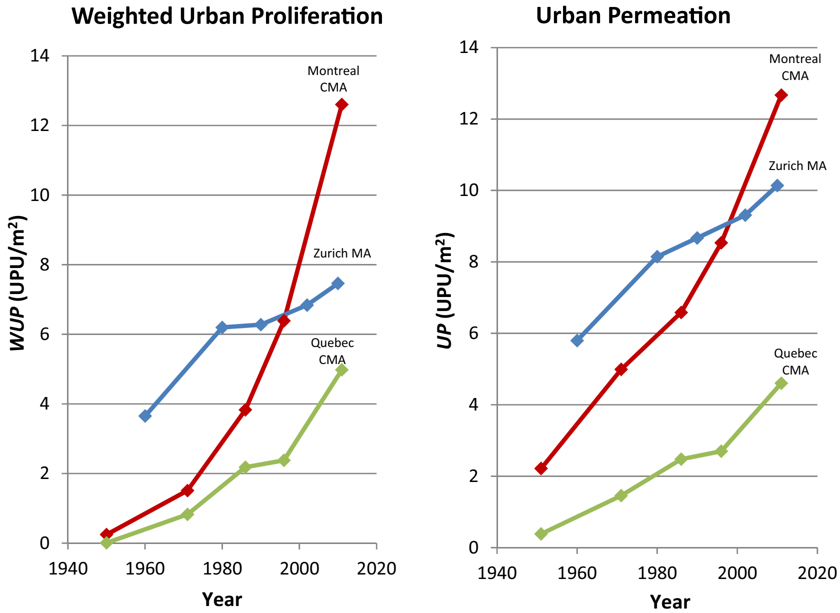

Fig. 6. Increase in the values of weighted urban proliferation (*WUP*) and urban permeation (*UP*) in Montreal CMA (always for the 2011 delineation), Quebec CMA (2011 delineation) and Zurich MA since 1951 (using average *WUP* for Montreal and Quebec CMAs). Calculation of average *WUP* used for the years 1951–1996 and the use of correction factors for the calculation of *UD* for these years for the Montreal and Quebec CMAs are presented in Appendix B.

districts with the lowest levels of sprawl (<0.7 UPU/m^2). These districts are all located in the centre of the Island and constitute the city core of Montreal, which is the most densely populated space in Montreal.

The *WUP* values in districts off the Island of Montreal (i.e., Laval, Deux-Montagnes, Les Moulins, L'assomption, etc.) were always higher than 8 UPU/m^2, with the exception of Mirabel and Rouville (3.05 and 3.84 UPU/m^2, respectively), while *WUP* is 27.07 UPU/m^2 in Laval.

In Quebec City, the district of L'Ancienne Lorette exhibits the highest and La Cité-Limoilou the lowest level of sprawl. The latter can be explained by the high value of *UD* (11,398 inhabitants and jobs per km^2) in this district which constitutes the downtown of Quebec City (Fig. 10a).

In the Zurich MA, a similar pattern is observed. The highest values of sprawl were found in the municipalities that constitute the suburbs (e.g., Zollikon, Kilchberg, Rüschlikon, and Erlenbach with *WUP* > 20 UPU/m^2). Municipalities located north of the city of Zurich are also highly sprawled (>15 UPU/m^2). They are covered by large built-up areas that are mostly a mixture of residential and industrial areas with relatively low values of *UD*. Low to relatively low values of sprawl are found in the outskirts of the Zurich MA. The city of Zurich (1.32 UPU/m^2 in 2010) and the city of Zug (1.71 UPU/m^2) are also among the areas that have lowest values of sprawl. Although these cities have large built-up areas, their *UD* is high to very high. All the other municipalities with *WUP* values of below 2 UPU/m^2 in 2010 are rural and located in hilly terrains.

3.2. Historic development

Urban sprawl in all three study areas has been continuously increasing. Until 1971, the degrees of urban sprawl in the Montreal and Quebec CMAs were close to each other, and much lower than in the Zurich MA. However, since 1971, urban sprawl in Montreal CMA has increased more sharply compared to Quebec CMA (Fig. 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 3.65 UPU/m^2 in 1960 than the Montreal and Quebec CMAs, where it was still less than 1 UPU/m^2 at this time. Some may have expected that Zurich was less sprawled in 1960 than Montreal and Quebec. However, an important finding of our study is that sprawl in Montreal and Quebec is a more recent phenomenon than in Zurich, and the strongest increases in sprawl have happened since the early 1980s. Both Quebec and Montreal have exhibited their sharpest increases in sprawl during the past 25 years, whereas the sharpest increases of sprawl in the Zurich MA happened between the years 1960 and 1980, while urban sprawl in the Zurich MA increased less strongly during the past 25 years than in earlier times.

Since the comparison of values of urban sprawl in study areas of different sizes needs to be done with caution, to correctly consider the influence of the sizes of the reporting units, we also compared the three inner areas as their extents are very similar and their comparison is more straightforward (Fig. 7).

Utilization density has decreased significantly on the Montreal Island and in Quebec City. *UD* in Montreal Island decreased by about 50% (from 17,151 to 8237 inhabitants and jobs per km^2) and is now close to *UD* of 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 8079 inhabitants and jobs per km^2 which Montreal has arrived at today, down to 3798 inhabitants and jobs per km^2. In contrast, *UD* in the Inner Zurich MA has been almost stable, and even increased slightly in the periods of 1980–1990 and 2002–2010. It almost equals the current *UD* in Montreal and the *UD* of Quebec City in 1971.

Urban dispersion has been increasing in all three study areas, most pronouncedly 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 was more or less equally strong at all times. In the Inner Zurich MA, the sharpest increases took place in 1960–1980. Approximately in 1987, *DIS* values in Quebec and Zurich were similar, but *DIS* continued to increase faster in Quebec City.

Urban permeation also has increased; for example, *UP* in Montreal increased by a factor of three from 10.78 UPU/m^2 in 1951 to

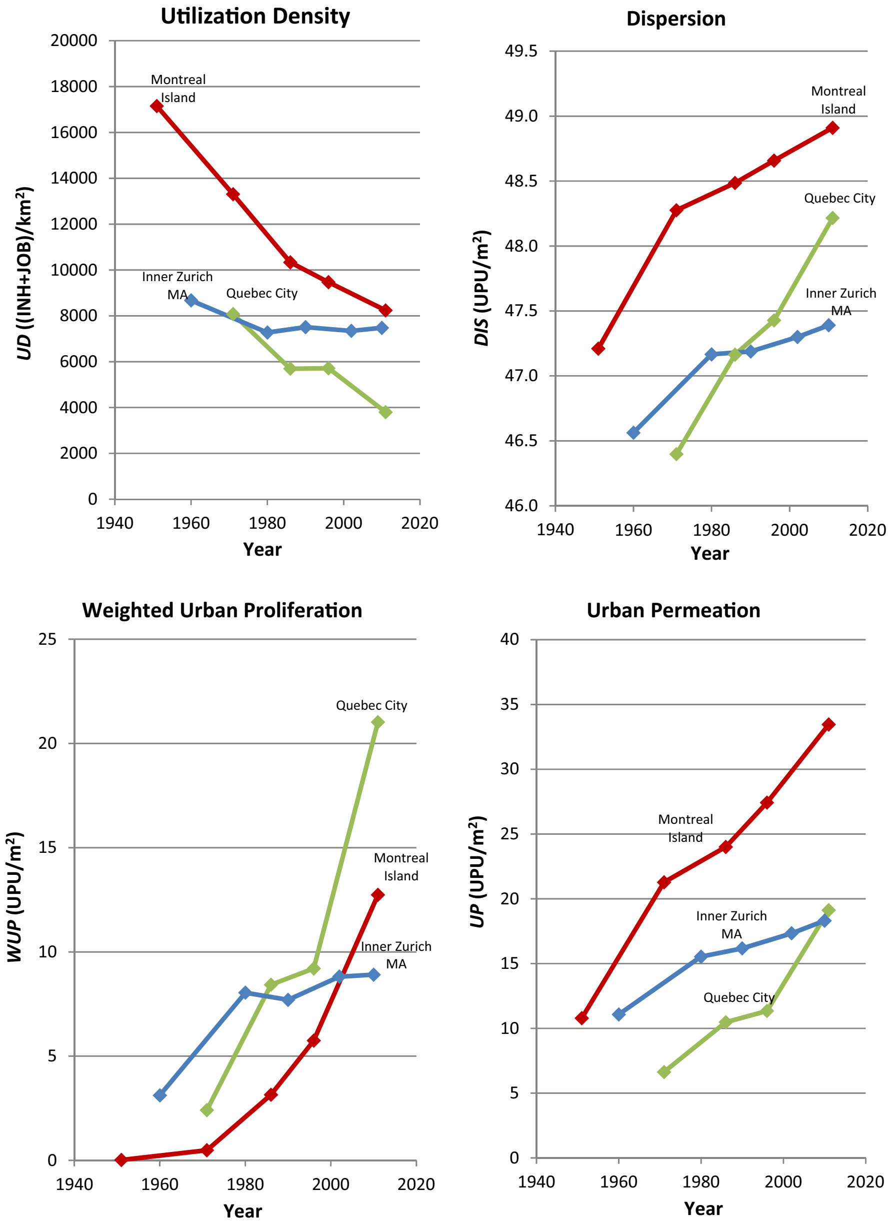

Fig. 7. Values of *UD*, *DIS*, *WUP* and *UP* between 1951 and 2011 in Quebec City, Inner Zurich MA and Island of Montreal.

33.45 UPU/m^2 in 2011. It has always been higher than in Quebec City and Zurich. 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 very strongly in all three study areas. The increase has accelerated in Montreal and Quebec. While *WUP* for Montreal Island was 0.02 UPU/m^2 in 1951, it reached 12.74 UPU/m^2 in 2011. Urban sprawl in Quebec City in 1971 was 2.41 UPU/m^2, and in 2011 it was nine times as high with 21.02 UPU/m^2. In the Inner Zurich MA, *WUP* increased almost 3-fold from 3.12 UPU/m^2 in 1960 to 8.91 UPU/m^2 in 2010. While sprawl was the highest in the Inner Zurich MA before 1985, it has been surpassed by Quebec City by 1984 and Montreal Island by 2002.

The value of *WUP* in Quebec City was always higher than on Montreal Island. The strongest increase in urban sprawl in Quebec City happened in 1986–2011. The higher value of *WUP* in Quebec City in the most recent time can be explained by its very low value of *UD* in combination with strong increases in *DIS* and *UP*. In the Inner Zurich MA, the sharpest increase in *WUP* occurred between 1960 and 1980. Sprawl in Montreal has accelerated more steadily compared to the other two cities. Although dispersion and urban permeation on the Montreal Island were always higher than in Quebec City, the higher values of *UD* on the Montreal Island and in Inner Zurich MA resulted in a lower value of urban sprawl than in Quebec City.

Considering urban sprawl at smaller geographic regions (census tracts and districts) helps urban planners conduct more detailed analysis of this phenomenon. Fig. 8 presents the values of *WUP* at the census tract level for the Quebec and Montreal CMAs in five points in time (1951–2011), and for the Zurich MA at the municipality level in three points in time (1960, 1980 and 2010).

In most census tracts, urban sprawl increased at all times. However, there are a few census tracts in which sprawl decreased between 1971 and 1996 or between 1986 and 1996. In these areas, an increase in *UD*, while the amount of urban areas remained constant or was slightly reduced, resulted in a decrease in the value of *WUP*.

At district level, urban sprawl has increased in most districts; however, there are some exceptions here as well. Figs. 9 and 10 present the values of *WUP* for 2011 and of *WUP*′ (based on inhabitants only, i.e., not including jobs) for all points in time at the district level in the Montreal and Quebec CMAs.

4. Discussion

4.1. Current level of sprawl

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 would be higher than in Quebec City and lower than on the Montreal Island. However, Quebec City exhibits the highest value of *WUP* in 2011, followed by Montreal Island.

The *WUP* in Quebec City in 2011 is more than twice as high as in the Inner Zurich MA in 2010 (21 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 shows a lower value of *UD*, and it suffers from a higher dispersion than the Inner Zurich MA. The Inner Zurich MA has a lower dispersion (47.39 UPU/m^2) than Quebec (48.22 UPU/m^2) and Montreal (48.91 UPU/m^2). Although Montreal Island is more dispersed than Quebec City and has more built-up areas it is less sprawled since it has a much higher *UD* (8237 vs. 3798 inhabitants and jobs per km^2 in Quebec City).

Various factors such as the scarcity of suitable land in the Zurich MA, much higher use of public transportation by inhabitants from all social classes, continuous expansion of the public transport system and the higher level of utilization density explain the lower level of urban sprawl in Zurich. Switzerland also 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. 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 for designation. The direct democracy in Switzerland has favoured stronger legislation and stricter regulations for regional planning that are commonly accepted by the population's voting, e.g., Kulturlandinitiative was a referendum that aimed at protecting farmlands, and the revision of the Spatial Planning Act in March 2012 made this law more restrictive. In the city of Zurich, motorized private traffic is scheduled to decrease from 36 to 26% in the next 10 years according to a decision by the population in September 2011. The area of the city of Zurich is 92 km^2 and covers about 20% of the Inner Zurich MA.

Fig. 8. Urban sprawl (*WUP*) at the census tract level in the Montreal CMA from 1951 to 2011 (a), in the Quebec CMA from 1951 to 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. *WUP*′ indicates the value of urban sprawl in accordance with *UD*′ (*UD*′ = inhabitants/settlement area).

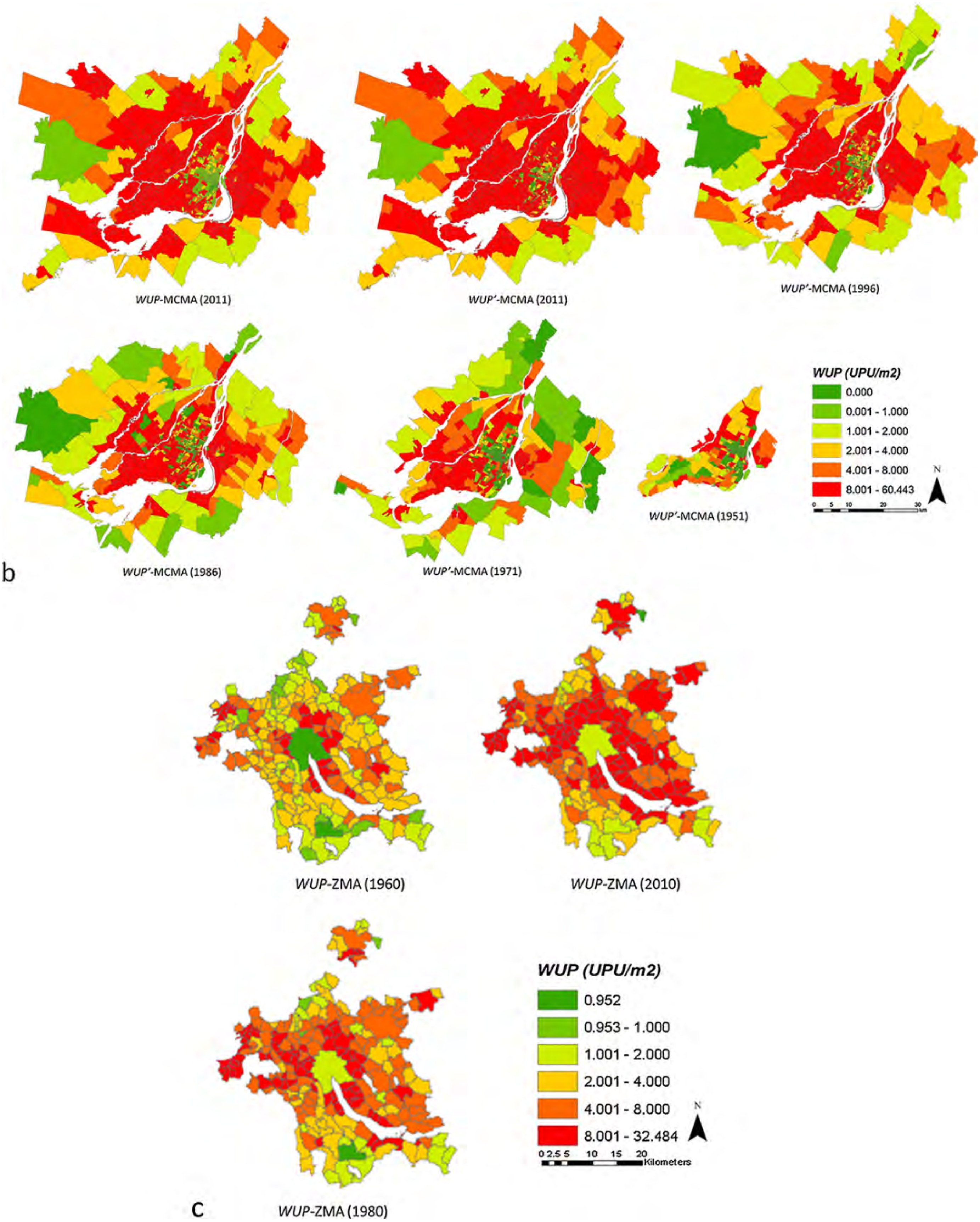

Fig. 8. (*Continued*).

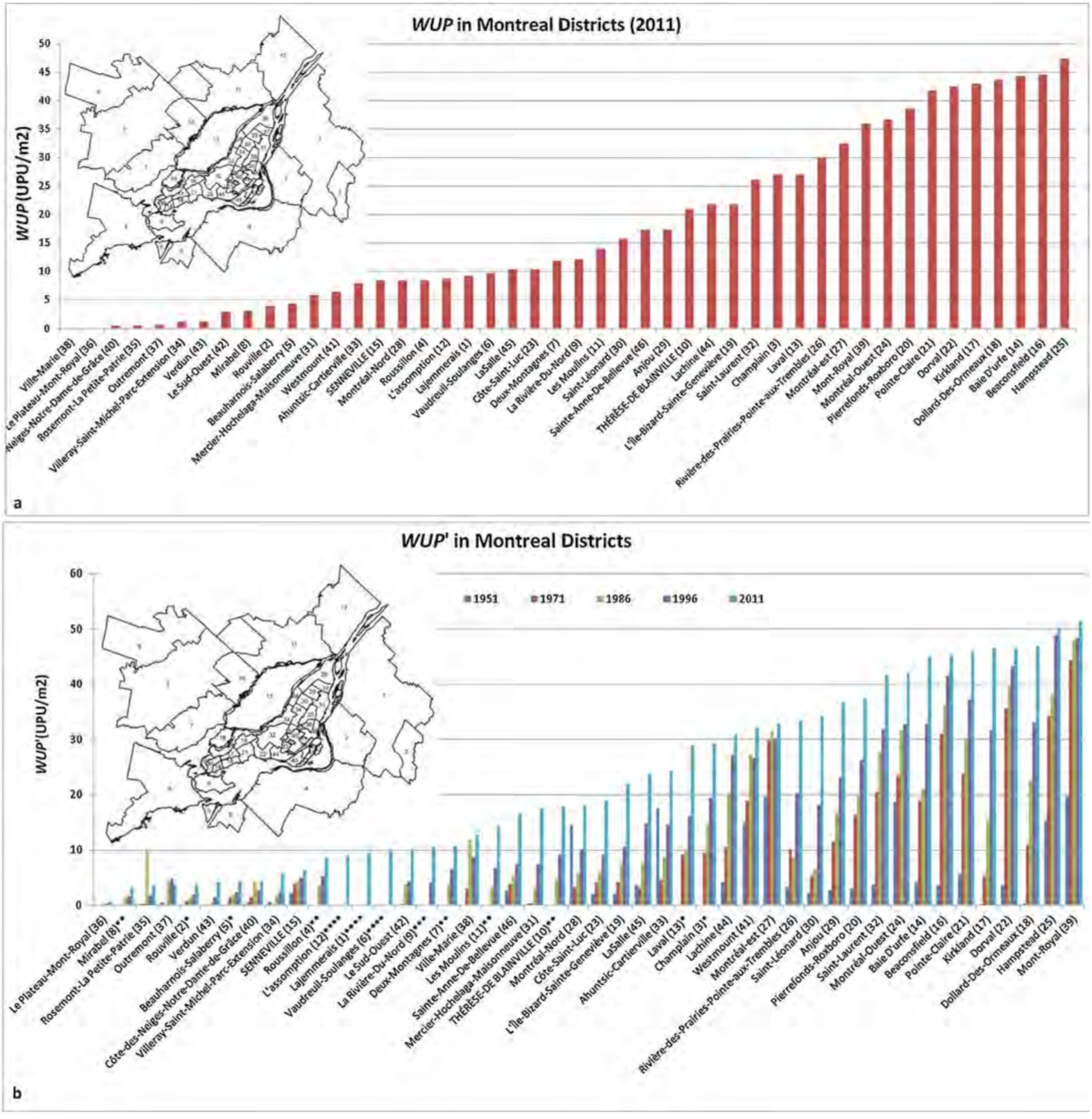

Fig. 9. (a) Urban sprawl (*WUP*) in the Montreal CMA at district level in 2011. (b) Urban sprawl (*WUP'*) in the Montreal CMA at district level at five points in time from 1951 to 2011, * indicates missing data in one time step, and **** indicates missing data in four time steps, respectively.

At the city level of similar size (about 500 km^2), i.e., Montreal Island, Quebec City and Inner Zurich MA, we found that cities with higher levels of public transport (higher modal share) and higher utilization density are less sprawled. Montreal and Quebec are examples of concentric cities surrounded by suburbs, i.e., they are typical of sprawl, whereas in the Zurich MA, several centres are growing towards each other. However, even though Zurich MA is more polycentric compared to Montreal and Quebec, it still has a lower degree of sprawl, and has almost stabilized the level of sprawl. Our results suggest that a polycentric settlement structure does not necessarily lead to a higher level of sprawl, but a polycentric settlement structure may indeed be suitable for reducing urban sprawl when efficient public transportation is implemented, which makes the use of cars unnecessary for travelling between the centres. It is certainly not as important as other factors to explain the differences between the Inner Zurich MA and Montreal Island

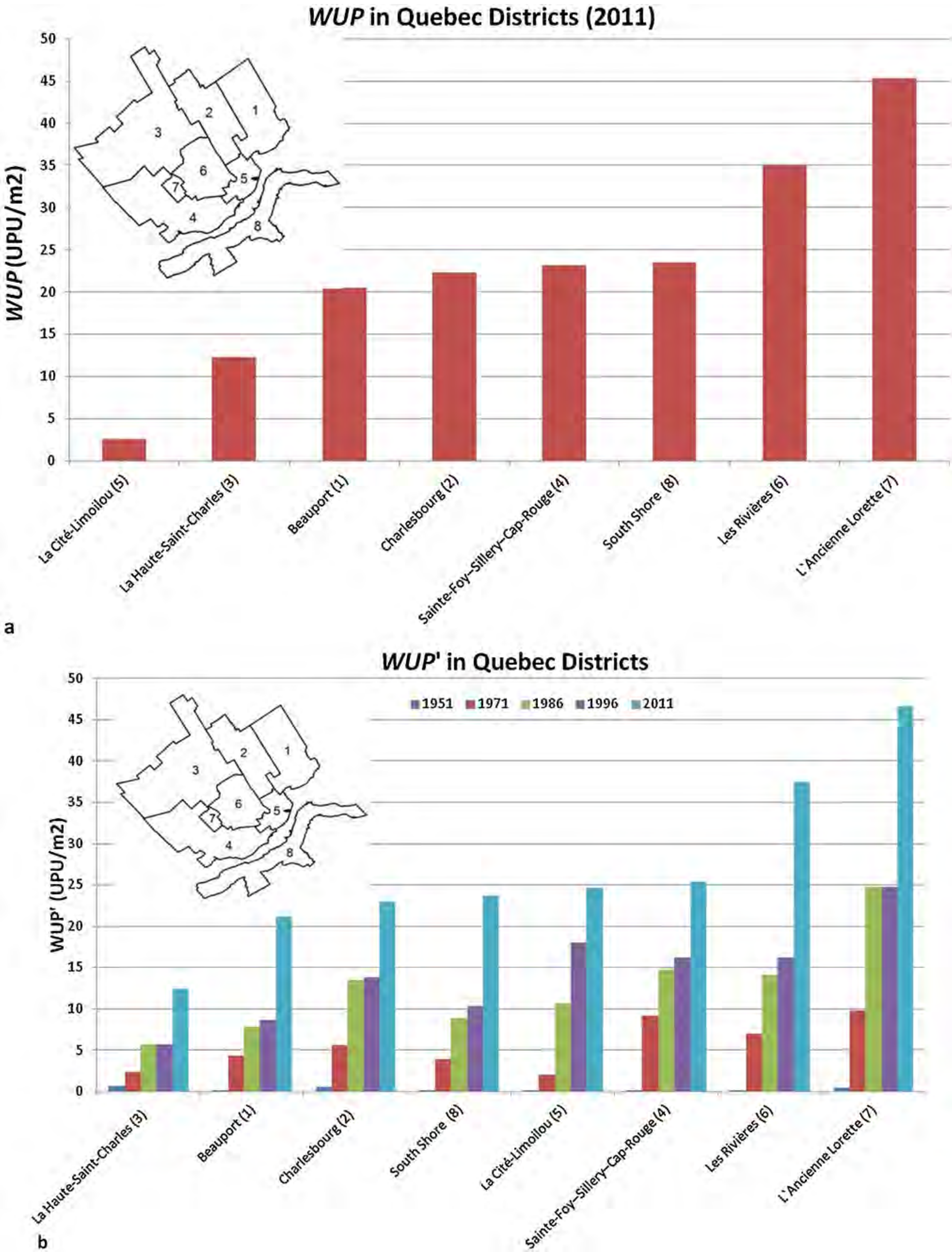

Fig. 10. (a) Urban sprawl (*WUP*) in the Quebec CMA at district level in 2011. (b) Urban sprawl (*WUP*′) in the Quebec CMA at district level at five points in time from 1951 to 2011.

and Quebec City. A more detailed analysis is needed to compare urban sprawl between polycentric and monocentric urbanization patterns.

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 20–30 years, and 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 increase has become strikingly faster since the 1980s, faster than ever before, with no slowdown in sight. These results may reflect the differences in sprawl patterns between North America and Europe more generally.

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 17,151 inhabitants and jobs per km^2 in 1951 to 8237 inhabitants and jobs per km^2 in 2011, but this value is still slightly higher than in the Inner Zurich MA. However, *UD* in the larger Montreal CMA is now as low as 4597 inhabitants and jobs per km^2, and also has decreased strikingly, while it has always been between 5900 and 6400 inhabitants and jobs per km^2 in the Zurich MA. In Quebec City, *UD* lost 53% of its value of 1971, and in the Quebec CMA, 83% of its value of 1951 (from 20,027 in 1951 to 3224 inhabitants and jobs per km^2 in 2011).

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" (Constitution Act, 1867). The rights and duties of municipalities in Quebec can be found in the "cities and towns act", the "municipal code", and 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 City have a similar settlement structure, the difference in sprawl, *UD*, and dispersion can only be explained by the difference in their size, modal share, history, and planning policies.

Since 1971, the Montreal Urban Community has coordinated certain plans, but their effects on land-use planning were weak (Filion et al., 2010; Germain and Rose, 2000). In 1978, agricultural zoning and urban growth boundaries were established for Montreal. However, they were not effective since most of the requests regarding rezoning of agricultural lands have been accepted by the provincial governments who are responsible for this policy (Filion et al., 2010; Germain and Rose, 2000).

Montreal's inhabitants use public transport more often than Quebec's (with a modal share of 22.2% vs. 11.3% in Quebec). Montreal has an extensive bus system, an underground metro system and numerous commuter trains. However, the growth in the capacity of the metro was much less (almost none) than the 72% increase in population between 1961 (when the Montreal metro was built) and 2011 (from 2,215,600 to 3,824,200 in the Montreal CMA).

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

4.3. Comparison with other studies

A study about the former county of Laprairie in Montreal CMA showed that 72% of the remaining open lands in 1988 became developed by 2000 (Murshid, 2002). Use of more land per person, 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). The former county of Laprairie, located in the municipality of Roussillon (district 4), exhibited a *WUP* value of 8.46 UPU/m^2 in 2011, demonstrating a drastic increase in sprawl in the past 15 years.

Between 1971 and 2006, inner city density in Montreal declined sharply (Filion et al., 2010). A similar trend was observed in our results, since 1951. Absence of metropolitan-wide planning agencies and the formation of numerous jurisdictional institutions has made Montreal one of the most administratively fragmented urban areas in Canada (Filion et al., 2010; Razin and Rosentraub, 2000). The lack of efficient planning strategies and the lack of coordination between too many existing institutions were major reasons for the high degree of urban dispersion and urban sprawl in Montreal and Quebec City. For Montreal, Dupras and Alam (2015) have recently shown that this increase in built-up areas has reduced the amount of croplands, grasslands, and forest, and has had negative impacts on ecosystem services.

4.4. Advantages and disadvantages of the WUP method

The main advantage of the *WUP* method is that it meets all 13 suitability criteria for measuring urban sprawl proposed by Jaeger et al. (2010a). It does not require many datasets to analyze urban sprawl (only a map of built-up areas and information about inhabitants and jobs). It can be applied at any scale and for different kinds of reporting unit (e.g., census tracts, districts, municipalities) and allows planners to conduct quantitative assessments of urban sprawl and to compare potential future scenarios. Switzerland has already implemented *WUP* in various monitoring systems since 2010, e.g., the Swiss Landscape Monitoring System LABES (Kienast et al., 2015).

The first step in calculating *WUP* delineates the reporting unit. It is not possible to compare cities without delineating the landscapes for which sprawl is measured. If the analysis of sprawl for a small city is done using a smaller landscape than for a large city, the interpretation of the results needs to consider that the sprawl values refer to the respective landscapes studied. For example, the 2011 value of *WUP* for the Quebec CMA was 4.98 UPU/m^2 and 21.02 UPU/m^2 in Quebec City. The difference is largely due to the larger CMA area used as reporting unit in the denominator when calculating *UP* (the larger the area, the smaller the *UP* value, if the amount of built-up area and dispersion remain constant), while the amount of built-up areas within the QCMA is only slightly larger than the amount in Quebec City (about 90% of the QCMA is open space, whereas built-up areas cover 40% of land in Quebec City). For monitoring temporal changes, the reporting unit should be kept the same. Since we applied the same CMA (extent of 2011) in Fig. 6 for all points in time, all values can be compared directly.

We used the number of full-time equivalents for the calculation of *UD*, but these numbers may not always be available. The raw number of jobs can then be used instead as a good approximation: the value of *UD* will then usually be a few percent higher (3–8%), and rarely more than 10%. The differences in the resulting (lower) *WUP* values depend on the value of *UD* in the weighting function $w_2(UD)$, i.e., the differences can be small or rather large. For example, the decreases in *WUP* are 23.5% in Montreal Island (from 12.74 to 9.74 UPU/m^2), 3.3% in Quebec City (from 21.02 to 20.33 UPU/m^2), and 19.4% in Inner Zurich MA (from 8.91 to 7.18 UPU/m^2). One option to avoid this difficulty is to use a general conversion factor between jobs and full-time equivalents, which can be applied when no other value is available for the region studied. In Switzerland this factor is: 1 job = 0.85 fulltime equivalents. Alternatively, one can use the raw number of jobs (+inhabitants) for time series, but then the results cannot be directly compared to regions where full-time equivalents (+inhabitants) were used.

Future refinements of the *UD* metric are possible by also including the number of people using specific buildings (e.g., number of students in a school or visitors of theatres) in addition to the number of jobs, but such data may not be easily available.

5. Conclusion

In Montreal and Quebec, urban sprawl has gotten out of control and has turned into a serious and fast growing problem since the late 1980s. In the last 25 years, urban sprawl in Montreal and Quebec has become worse than ever before and has done so faster than ever before. Quebec City is a prime example of urban sprawl today, in particular regarding its rapid increase since 1970. The steepest 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. Montreal and Quebec City are still investing large amounts of money in more roads and almost nothing in the expansion of public transport, even though this path is considered as being unsustainable. For 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. Another example is the ongoing reconstruction of the Turcot Intersection in Montreal for 3 billion dollars (Thompson et al., 2013). Therefore, we expect that this trend will continue in the future. The steps planned currently for Montreal and Quebec such as the intensification of urban areas or the development of TOD zones in Montreal (CMM, 2011) are so little compared to Switzerland (that itself suffers from sprawl) that much stronger efforts are needed to discontinue these unsustainable growth patterns. Switzerland should continue on its way to limit 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.

Our study provides an indication of the potential of how much sprawl could be reduced and what factors could be changed in Montreal and Quebec. There is ample room in Montreal and Quebec for improvements in public transport, in the regional planning legislation, in the settlement pattern (creation of sub-centres with higher densities), and in *UD*. For example, Laval should be densified and covered by the metro system.

The *WUP* method can be applied for measuring the levels of sprawl and dispersion of the urbanized areas and their temporal changes at any scale and for the classification of regions regarding urban sprawl and the identification of areas that are most in danger from sprawl, and areas with higher potential for future urban developments and for reduction of urban sprawl in particular. The *WUP* can be used to investigate relationships between sprawl and its impacts (e.g., relation with car ownership), as an indicator to monitor urban development, to evaluate the effectiveness of new regulations for urban development (e.g., development of TOD zones in Montreal CMA) and the effectiveness of the protection of high-value lands. For example, goal 6 of the federal sustainable development strategy 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). Various measures to limit urban sprawl have been proposed in the literature (summarized by Schwick et al., 2012), e.g., controlling the dispersion of built-up areas and stronger protection of agricultural lands. Better education of the public about the negative consequences of urban sprawl may encourage consumers to decrease land uptake per inhabitant and help decrease the level of urban sprawl.

In the Zurich MA, every vote about suggested expansions or improvements of public transport has been accepted by the population, while many proposed road construction projects were rejected. This indicates that more sustainable patterns of development require strong support in the society and long-term planning with a 20–30 year 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 22.2 to 40% would be easier to achieve than increasing it from 63 to 78% as is currently being 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. Since the inauguration of the Montreal metro in 1966 its expansion has been far less significant than the expansions of the tramways and S-Bahns (rapid (sub-)urban railways) in Zurich. Without a strong increase in *UD* 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 serious traffic problems than today and growing negative effects that are typical of unsustainable development.

Acknowledgements

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Appendix A. Data used for the delineation of built-up areas

Tables A1 and A2 present the layers (including point and polygons) that represent urban areas. Table A1 presents the features of CanVec dataset, used for the delineation of built-up areas for the year 1996 and previous time steps (1951, 1971 and 1986), and Table A2 presents the features of the CanMap dataset used for the delineation of built-up areas of the year 2011. CanVec was produced from three main sources: the National Topographic Database (NTDB), Landsat 7 imagery coverage, and Geobase data. CanVec contains 11 themes, one of which is the layer of buildings and urban structures that includes all types of buildings and urban structures defined as "permanent walled and roofed constructions". This layer consists of 41 types of buildings as areas or points. Some other relevant 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 we also considered them as urban areas.

Table A1
Entities from the CanVec dataset that were used for the delineation of urban areas (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
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 depot	Industrial solid depot	IC	1360029 0	1360029 2
Gas and oil facilities	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	

Although the latest update of the CanVec dataset was in 2011, the most recent actual date of update for the buildings and urban structures is 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 for 1996 and were modified for the earlier points in time according to historic topographic maps. For the calculation of urban sprawl in 2011, the CanVec layers were used along with CanMap Route Logistics (version 2011.3, a product of DMTI spatial). Being consistent with the CanVec dataset, those features of CanMap that represent urban areas were used.

Appendix B. Calculation of *WUP* and *UD* for the Montreal and Quebec CMAs

(1) Calculation of *WUP*

The extent of the CMAs of Montreal and Quebec changed between 1951 and 2011. The CMA boundary extended over time;

Table A2
Entities from the CanMap dataset that were considered for the delineation of urban areas (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
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
Commercial	LUR	–	Region
Residential	LUR	–	Region

therefore, some parts of the current CMA (2011 delineation) are not included in the 1951, 1971, 1986 or even 1996 CMA 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, which is calculated in the following steps:

For all the time steps except 2011, we determined two values for inhabitants and jobs: the first value is the exact value within the true extent of CMA in each time step, and the second value is the estimated value within the 2011 CMA boundary. Estimated values were calculated by using the available information for the closest time step. For example, in the calculation of inhabitants and jobs for 1986, for those urban areas that were not included in the delineation of the 1986 CMA boundary, but were included in the delineation of 2011 boundary, we used the inhabitants and jobs of the closest time step (which is 1996 in this case) of the respective areas and called it the "estimated inhabitants and jobs of 1986".

Using these two different values, we calculated urban sprawl twice: first, we used the exact value of inhabitants and jobs for each time steps, and we called it the maximum value of sprawl, meaning that it is assumed that there were no people living or working within those built-up areas that are not in the delineation of the CMA of corresponding year, but are part of the 2011 CMA. The *WUP* will be higher compared to the situation when we consider the people living and working in the respective areas. Therefore, we called it WUP_{max}. The second time, we used the estimated value of *UD*, and we called it the minimum value of sprawl because when we consider there are people living and working in all areas of the CMA (using the available population values for the closest point in time, and estimating the number of job using a correction factor, see below), the value of *UD* will be higher, and the value of *WUP* will be lower. Therefore, we called it WUP_{min}. Then, we used the average of these two values WUP_{max} and WUP_{min} (we called it the average value of sprawl) for each time step in order to compare the results of sprawl in different points in time. Table B1 presents the true and estimated values of inhabitants and jobs and the associated values of *WUP*.

(2) Calculation of *UD*

Since the information about job counts was not available for the years 1951–1996, 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 2011 divided by *UD′* of 2011 (where *UD* is the number of inhabitants and jobs per km^2 of built-up area in 2011 and *UD′* is the number of inhabitants per km^2 of built-up area in 2011).

$$\text{Correction factor} = \frac{UD((\text{Inh} + \text{jobs})/\text{km}^2)\,\text{in 2011}}{UD'(\text{Inh}/\text{km}^2)\,\text{in 2011}}$$

UD of 1996 = *UD′* (inhabitants/km^2) in 1996*correction factor. This estimation of the number of jobs is correct when this ratio is constant over time. However, regionally specific changes of this ratio are possible (for example a region may be affected by de-industrialization and loss of jobs more than other regions), which are not captured by our approach.

In order to see the differences in the values of sprawl when *UD* is calculated only based on inhabitants or based on inhabitants plus jobs per area of land, we calculated *WUP′* indicating the value of sprawl when utilization density is measured only based on number of inhabitants. As expected, the value of *WUP′* for all reporting units in all time steps was higher than value of *WUP*. Table B1 presents the values of *WUP*, *WUP′*, *UD*, *UD′* and the correction factor used for the calculation of urban sprawl for the reporting units of Montreal CMA and Quebec CMA.

Table B1
WUP, *WUP′*, *UD*, *UD′* and the correction factors for the reporting units of Montreal CMA and Quebec CMA.

Montreal Census Metropolitan Area (in the delineation of 2011)					
Sprawl metric	1951	1971	1986	1996	2011
Area of reporting unit (km^2)	4291.69	4291.69	4291.69	4291.69	4291.69
Built-up area (km^2)	210.38	459.19	603.07	775.68	1137.08
Inhabitants + jobs	–	–	–	–	5,227,186
Estimated inhabitants + jobs	–	–	–	–	–
Exact *UD* ((inh + jobs)/km^2)	9066.35	8148.01	6621.28	5861.73	4597.03
Estimated *UD* ((inh + jobs)/km^2)	15,165.89	8969.45	7138.64	6200.71	4597.03
Inhabitants	1,395,436	2,737,250	2,921,352	3,326,452	3,824,221
Estimated inhabitants	2,334,237	3013,203	3,149,616	3,518,815	–
Exact *UD′* (inh/km^2)	6633	5961.1	4844.1	4288.5	3363.2
Estimated *UD′* (inh/km^2)	11,095.4	6562.1	5222.6	4536.4	3363.2
DIS (UPU/m^2)	45.25	46.66	46.85	47.22	47.82
UP (UPU/m^2)	2.22	4.99	6.58	8.54	12.67
WUP_{min} (UPU/m^2)	0.01	1.23	3.52	6.13	12.6
WUP_{max} (UPU/m^2)	0.48	1.79	4.14	6.64	12.60
$WUP_{Average}$ (UPU/m^2)	0.25	1.51	3.83	6.39	12.60
WUP'_{min} (UPU/m^2)	0.16	3.16	5.70	8.32	14.16
WUP'_{max} (UPU/m^2)	1.27	3.69	6.05	8.57	14.16
$WUP'_{Average}$ (UPU/m^2)	0.71	3.43	5.88	8.44	14.16
Correction factor	1.367	1.367	1.367	1.367	–
Quebec Census Metropolitan Area (in the delineation of 2011)					
Sprawl metric	1951	1971	1986	1996	2011
Area of reporting unit (km^2)	3343.56	3343.56	3343.56	3343.56	3343.56
Built-up area (km^2)	31.26	108.97	181.67	196.91	327.91
Inhabitants + jobs	–	–	–	–	1,057,317
Estimated inhabitants + jobs	–	–	–	–	–
Exact *UD* ((inh + jobs)/km^2)	11,761.50	6120.01	4608.62	4735.62	3224.45
Estimated *UD* ((inh + jobs)/km^2)	16,353.71	6946.23	4646.99	4771.03	3224.45
Inhabitants	264,924	480,500	603,267	671,889	761,818
Estimated inhabitants	368,362	545,369	608,290	676,912	–
Exact *UD′* (inh/km^2)	8474.4	4409.6	3320.6	3412.1	2323.3
Estimated *UD′* (inh/km^2)	11,783.2	5004.9	3348.3	3437.6	2323.3
DIS (UPU/m^2)	41.30	44.73	45.60	45.87	46.94
UP (UPU/m^2)	0.39	1.46	2.48	2.70	4.60
WUP_{min} (UPU/m^2)	0.001	0.73	2.18	2.37	4.98
WUP_{max} (UPU/m^2)	0.01	0.92	2.19	2.39	4.98
$WUP_{Average}$ (UPU/m^2)	0.01	0.83	2.18	2.38	4.98
WUP'_{min} (UPU/m^2)	0.01	1.15	2.46	2.72	5.2
WUP'_{max} (UPU/m^2)	0.08	1.25	2.47	2.72	5.2
$WUP'_{Average}$ (UPU/m^2)	0.05	1.20	2.47	2.72	5.2
Correction factor	1.388	1.388	1.388	1.388	–

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Mesurer et éviter l'étalement urbain

Christian Schwick, Jochen Jaeger et Felix Kienast

En Suisse, l'étalement urbain augmente à une vitesse effrayante. Il a plus que doublé depuis 1950 et ses conséquences à long terme sont alarmantes. Une nouvelle méthode pour le mesurer confère aux planificateurs et aux politiciens un instrument susceptible de donner aux discussions une note plus objective, d'évaluer les scénarios de planification, de définir les objectifs pour l'avenir et de vérifier le succès des mesures qui visent à le réduire.

Fig. 1. L'étalement urbain gagne également les vallées alpines. Vue depuis la Cima della Trosa en direction du Centovalli. (Photo: Die Geographen schwick+spichtig, 2011)

Consommation de paysage vertigineuse en Suisse

La croissance des surfaces bâties et des voies de communication, le remembrement rural et l'agriculture intensive ont provoqué un changement radical des paysages en Europe au cours des cinquante dernières années. À maints endroits, le paysage d'autrefois ne se reconnaît quasiment plus (Ewald et Klaus 2009; Fig. 1).

En 1955, dans un mince opuscule rouge intitulé «achtung: die Schweiz» («attention: la Suisse»), Lucius Burckhard, Max Frisch et Markus Kutter mettaient déjà en garde contre la croissance incontrôlée du paysage urbain. Ils proposaient alors de respecter la limitation des surfaces comme défi à se donner et de bien considérer les conséquences à long terme. La loi sur l'aménagement du territoire (LAT) de 1979 prescrit une utilisation mesurée du sol en vue d'éviter le mitage. L'étalement du milieu bâti doit donc être limité. En renforçant le rôle des zones à bâtir, la LAT a permis, au cours des trente dernières années, un recul marqué de la construction de nouveaux bâtiments en dehors de ces zones. Toutefois, depuis lors, la surface bâtie et à bâtir n'a pas cessé de croître de façon considérable en Suisse. Avec les conséquences suivantes: perte de terres agricoles, d'habitats pour la faune sauvage et de biodiversité, dissémination d'espèces de plantes invasives, grandes distances spatiales entre l'habitat, le travail et les loisirs, de même que formation de cités-dortoirs.

Un problème majeur est l'utilisation souvent faible des surfaces bâties (Fig. 2). Ce phénomène a des répercussions économiques, écologiques et sociales négatives, notamment à cause des coûts élevés de viabilisation et de services (voirie, eau, électricité, collecte de déchets), d'une plus grande consommation d'énergie et d'un taux supérieur de dépenses non couvertes dans les transports publics.

À ce jour, l'aménagement du territoire n'a pas réussi à endiguer l'étalement urbain. Le développement effectif est en contradiction avec les principes du développement durable tels qu'ils sont inscrits depuis 1992 dans l'Agenda 21 issu de la conférence de l'ONU à Rio, et depuis 1999 dans la Constitution suisse. «L'étalement urbain et la destruction des terres agricoles sont des problèmes non résolus de l'aménagement du territoire» (citation de Doris Leuthard, Présidente de la Confédération et de Corinne Casanova, Chancelière de la Confédération en 2010). Or le renforcement du mitage est dû en grande partie à de fausses incitations. En effet, de mauvais signaux donnent à l'habitat à la campagne une attractivité démesurée: application trop limitée du principe pollueur/payeur dans l'imputation des coûts d'équipement liés aux nouvelles constructions; internalisation insuffisante des coûts externes pour les transports publics et privés; manque d'imposition conséquente lors de plus-values générées par les mesures d'aménagement, de viabilisation et d'infrastructure (Frey et Zimmermann 2005).

Le développement durable exige l'arrêt de l'étalement urbain

Les tendances actuelles du développement de l'urbanisation en Suisse vont à l'encontre de l'objectif d'un développement territorial durable qui est de plus en plus difficile à atteindre au fur et à mesure que le mitage progresse (Fig. 3 et 4). À l'aide de mesures appropriées, il semble toutefois encore possible d'éviter celui-ci afin qu'à l'avenir la Suisse s'éloigne plus lentement de l'objectif de la gestion durable qu'au cours des dernières décennies. Certes, depuis longtemps, nombre de mesures nécessaires ont fait l'objet de discussions, mais leur absence d'application ou la timidité de leur mise en œuvre ont rendu leur impact quasiment nul.

Les facteurs suivants favorisent la progression de l'étalement urbain:

1. Maintien, voire accroissement, d'une surface bâtie importante par habitant;
2. Augmentation du nombre d'habitants;
3. Développement urbain à forte dispersion;
4. Suburbanisation;
5. Construction en dehors des zones à bâtir, notamment dans les zones de protection des paysages;
6. Mode de construction dispersé plutôt que regroupé;
7. Développement urbain décentralisé et non pas centralisé.

De cette liste peuvent être déduites des mesures fondamentales susceptibles de réduire à l'avenir l'étalement urbain. Il en ressort l'ordre de priorités suivant:

1. La mesure la plus efficace, et donc essentielle, consiste à éviter l'ajout de surfaces bâties supplémentaires. La construction dense, en particulier en comblant les terrains vagues, l'édification de bâtiments de remplacement présentant une utilisation accrue et la réutilisation de friches industrielles («recyclage des surfaces») sont toujours possibles. Le tissu bâti cesse alors de gagner du terrain.
2. Là où la première mesure est irréalisable, il importe de viser autant que possible la concentration à l'intérieur des zones à bâtir, c'est-à-dire de ne pas créer de nouvelles zones bâties ni de nouveaux bâtiments individuels à l'extérieur de ces zones. Les nouvelles constructions sont édifiées directement en bordure du bâti existant.
3. Si cela n'est toujours pas possible, les nouveaux édifices nécessaires doivent au moins ne pas être implantés dans des paysages, sites et monuments naturels d'importance nationale et dignes d'être protégés (zones IFP), des paysages de marais ou des corridors pour la faune sauvage, etc.
4. L'étendue et la position des zones à bâtir doivent être considérées et adaptées conformément aux points 1 à 3. La taille des zones à bâtir doit être réduite à long terme dans la mesure du possible.

Fig. 2. Comment mesurer le degré de mitage de ce paysage? Vue depuis le Säli-Schlössli près d'Olten en direction d'Aarburg/Rothrist. (Photo: Klaus Ewald, 1999)

Les trois pièges écologiques selon Haber (2007)

Le sol fertile est une ressource limitée dont la destruction est irréversible à long terme. La production alimentaire nécessite des terres arables et des prairies aux sols appropriés. L'approvisionnement accru en énergie renouvelable exigera également des terres de vaste étendue. De surcroît, l'être humain ne cesse de revendiquer la terre pour la transformer en zones d'habitat, d'industrie, de transports, en zones de décharges, mais aussi en zones de détente et de protection de la nature. Ces trois formes de demande croissante de surfaces sont en concurrence les unes avec les autres. C'est la raison pour laquelle Haber (2007) les a caractérisées de «pièges écologiques» menaçant probablement l'humanité encore plus que tout autre problème environnemental pris de façon isolée. D'où sa mise en garde, Haber faisant remarquer que la terre et les sols fertiles se raréfient de façon alarmante et que ce phénomène continue d'être sous-estimé.

Au vu de l'objectif du développement durable du paysage, il faudrait mettre fin à la croissance des zones bâties et démanteler partiellement celles qui sont situées dans des espaces d'intérêt écologique ou agricole reconnu. Afin de limiter l'étalement urbain, des prescriptions légales claires s'avèrent indispensables comme cadre de référence fiable. Il serait ainsi possible d'instaurer une sécurité juridique, de mettre un terme à la concurrence entre des communes qui se disputent emplois, contribuables et habitants, et de favoriser de meilleures coopérations dans l'optique d'un développement durable. Sur la base de connaissances écologiques fiables, d'un monitoring et d'une planification, il faudrait déployer des efforts bien plus grands qu'aujourd'hui pour préserver les terres et le sol et les utiliser avec parcimonie et mesure (HABER 2007).

D'où un besoin urgent de données chiffrées afin de comparer les différentes régions et d'identifier les tendances de développement, les paramètres satisfaisants faisant encore actuellement défaut.

Nouvelle méthode de mesure: prolifération urbaine pondérée

Jusqu'à présent, les définitions de l'étalement urbain étaient trop imprécises pour servir de base à sa mesure. Un projet dans le cadre du Programme national de recherche 54 est venu remédier à ce manque (JAEGER *et al.* 2008; SCHWICK *et al.* 2011).

Une définition qui décrit le phénomène en tant que tel et distingue ses causes de ses effets est nécessaire (JAEGER *et al.* 2010a):

> L'étalement urbain est un phénomène perceptible visuellement dans le paysage. Un paysage sera d'autant plus mité qu'il comportera de surfaces bâties, que celles-ci seront dispersées et que leur utilisation à des fins d'habitation ou d'emploi sera faible.

Ainsi les critères mesurables suivants: taille de la surface bâtie, dispersion et utilisation de celle-ci viennent compléter l'évaluation intuitive. L'impact sur le mitage de toute modification de l'urbanisation peut, sur la base de cette définition, être déjà analysé dans la phase de planification.

Surface bâtie, dispersion et utilisation

La définition de l'étalement urbain convient pour l'élaboration d'un modèle applicable mathématiquement (JAEGER

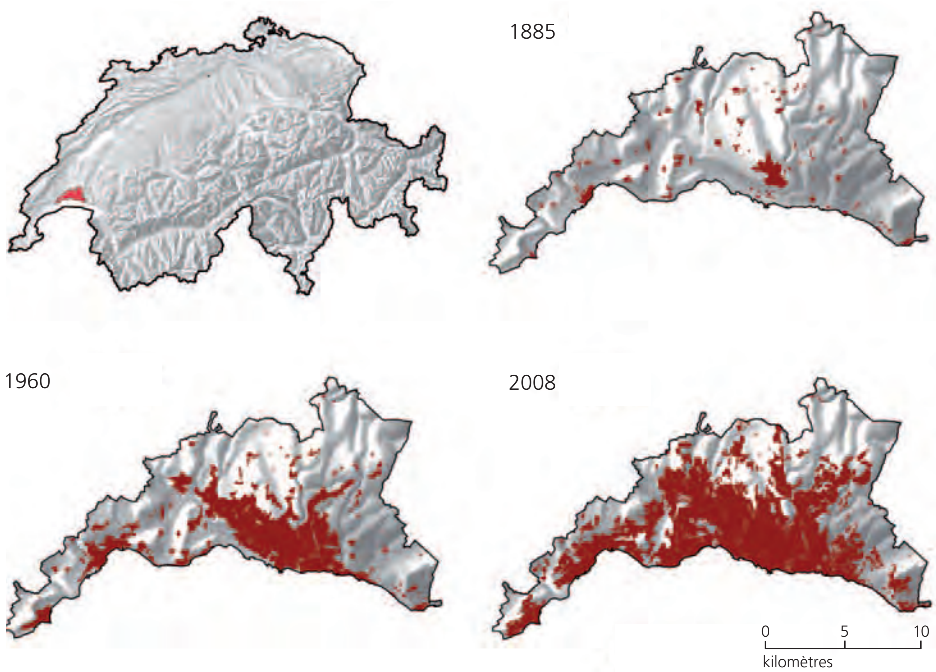


Fig. 3. Évolution des zones bâties dans la région de Lausanne entre 1885 et 2008.

Fig. 4. Entre 1909 (photo du haut) et 1999 (photo du bas) – environ la durée d'une vie humaine –, l'étalement urbain a considérablement augmenté à Frenkendorf. (Photo: Frenkendorf 1909: K. Lüdin, Fotoarchiv Druckerei Lüdin AG, Liestal. Frenkendorf 1999: Karl Martin Tanner, Seltisberg)

et al. 2010b). La formule qui en résulte comporte trois parties:

> *PUP = PU* * p_1*(DIS)* * p_2*(OT)*
>
> ou pour le traduire en mots:
>
> *Prolifération urbaine pondérée = Perméation urbaine * Pondération*$_1$*(Dispersion) * Pondération*$_2$*(Occupation du territoire par personne ou par emploi)*

Les trois paramètres utilisés sont définis comme suit:

1. La *perméation urbaine (PU = urban permeation)* est exprimée en unités de perméation urbaine (UPU) par m^2 de paysage [UPU/m^2]. *PU* mesure non seulement la taille de la surface bâtie (Fig. 5, rangée supérieure), mais aussi son degré de dispersion (*PU = DIS* * surface bâtie / aire de la région).
2. L'éparpillement des surfaces bâties est qualifié de *dispersion (DIS)*. L'unité *DIS* correspond aux unités de perméation par m^2 de surface bâtie [UPU/m^2]. L'idée principale est que le mitage augmente lorsque la dispersion des surfaces bâties est plus forte (Fig. 5, rangée du milieu). Ce paramètre recourt aux distances comprises entre tous les points qui se situent à l'intérieur des zones bâties (la moyenne de toutes les paires de points possibles est ensuite calculée; pour de plus amples détails, voir JAEGER *et al.* 2010b). Plus les points sont éloignés les uns des autres, plus ils contribuent à la dispersion.
3. *Occupation du territoire (OT):* Plus la surface bâtie occupée par habitant ou par emploi est faible, meilleure est l'utilisation de la surface (Fig. 5, rangée inférieure). L'occupation du territoire est mesurée en m^2 de surface bâtie par habitant ou par emploi [m^2/(H+E)].

La dispersion et l'occupation du territoire sont pondérées par les fonctions de pondération p_1*(DIS)* et p_2*(OT)* pour mieux faire ressortir les différences entre une faible et une forte dispersion d'une part, et une utilisation faible ou forte de la surface bâtie d'autre part (Fig. 6). Lorsque la dispersion des surfaces bâties se situe au niveau de la moyenne suisse de l'année 1960, le facteur de pondération p_1*(DIS)* est de 1; en présence de valeurs supérieures de dispersion, le facteur s'élève jusqu'à 1,5, et en présence de valeurs inférieures, il descend au plus bas jusqu'à 0,5. Lorsque l'occupation du territoire par personne est très faible – par exemple dans les zones densément construites –, la valeur du facteur de pondération p_2*(OT)* est proche de 0. Cela correspond à la compréhension intuitive selon laquelle les centres-villes ne sont pas mités. Le facteur de pondération atteint 0,8 dans les zones où l'occupation du territoire est de 400 m^2 de surface bâtie par personne, ce qui coïncide avec l'objectif du Conseil fédéral. Lorsque le besoin d'espace par personne est supérieur, le facteur augmente jusqu'à 1 (Fig. 6).

En raison de ces deux fonctions de pondération, le paramètre est appelé *prolifération urbaine pondérée (PUP)* (Fig. 6).

En outre, l'horizon d'observation joue un rôle clé dans la perception de l'étalement urbain. Seuls les bâtiments situés dans ce rayon (librement choisi) participent au mitage d'un endroit donné (Fig. 7). Tous les résultats présentés dans cette Notice ont été calculés sur la base d'un horizon d'observation de deux kilomètres.

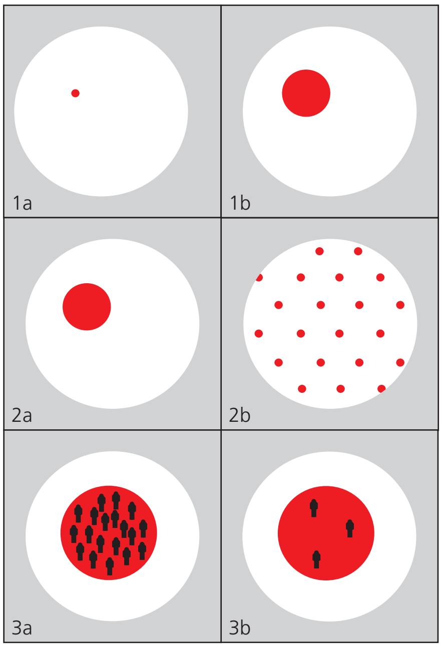


Fig. 5. Dans un paysage (en blanc), l'étalement urbain augmente quand 1) la surface bâtie s'accroît (série du haut), 2) la dispersion des zones bâties progresse (série du milieu) ou 3) l'occupation du territoire par personne (habitant ou emploi) est en hausse (série du bas).

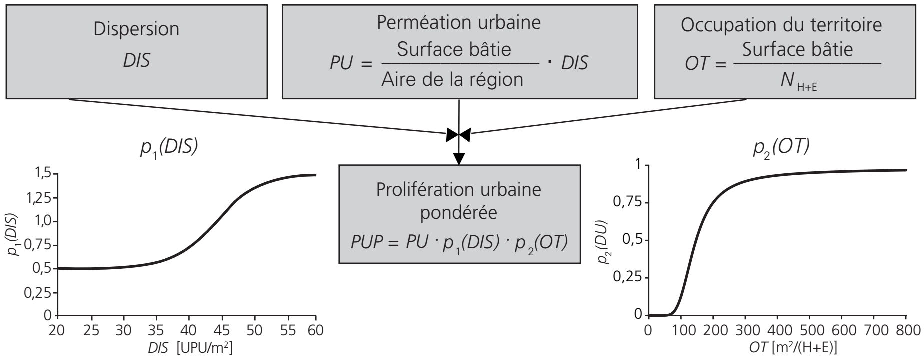


Fig. 6. Rapport entre les paramètres de l'étalement urbain. Avec: *DIS* = Dispersion = Éparpillement des zones bâties; *PU* = Perméation urbaine (urban permeation); N_{H+E} = Nombre d'habitants et d'emplois, p_1 et p_2 = Fonctions de pondération pour *DIS* et *OT*.

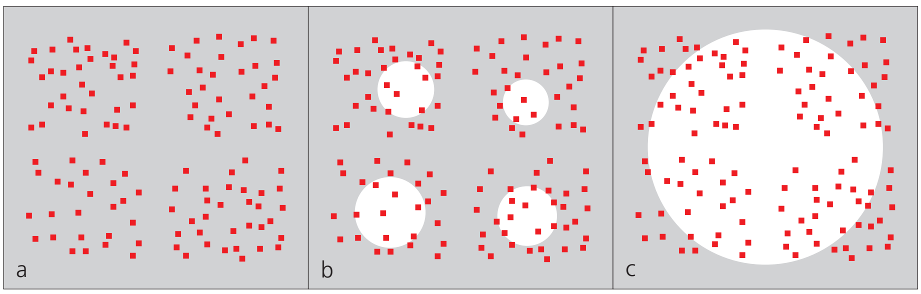


Fig. 7. Un paysage est ponctué de bâtiments individuels (a). Lorsque l'on choisit un horizon d'observation limité, (b) les bâtiments individuels semblent être répartis de façon presque régulière. Avec un plus grand horizon d'observation (c), on remarque que les bâtiments se regroupent dans quatre régions du paysage.

Trois exemples pour illustrer la méthode

Les régions de Sursee, Coire et Lugano (Fig. 8 et 9) ont été choisies comme exemples pour illustrer la méthode de mesure. Ces exemples démontrent que seule l'interaction des trois paramètres (perméation urbaine, dispersion et occupation du territoire par habitant ou par emploi) permet d'obtenir un tableau exhaustif de l'étalement urbain.

La région de Lugano présente la prolifération urbaine pondérée la plus élevée. De 1935 à 2002, celle-ci a augmenté de 416 %. Les surfaces bâties sont fortement dispersées. Depuis 1960, de nombreuses localités se sont rapprochées, ce qui accroît la valeur de la dispersion. L'occupation du territoire par habitant ou par emploi est – ce qui est caractéristique des agglomérations – légèrement inférieure à la moyenne suisse. La valeur de la prolifération urbaine pondérée est ainsi légèrement inférieure à celle de la perméation urbaine.

C'est dans la région de Coire que la prolifération urbaine pondérée est la plus faible. Elle a «seulement» progressé de 126 %. Entre 1935 et 1960, elle a même diminué car le nombre d'habitants et d'emplois a connu une hausse nettement supérieure à celle de la surface bâtie. L'occupation du territoire par habitant ou par emploi s'est par là même réduite de façon considérable. La faible valeur de l'occupation du territoire par habitant ou par emploi est typique des zones urbaines. Dans la région de Coire également, la dispersion s'est fortement accentuée entre 1935 et 1980. Mais elle n'a que peu augmenté de 1980 à 2002 car les nouvelles surfaces bâties se sont surtout établies dans les espaces vides ou en bordure du bâti déjà existant.

Dans la région de Sursee, la valeur de la prolifération urbaine pondérée se situe entre celles des deux exemples précédents. En 2002, elle était de 175 % supérieure à celle de 1935. Cette région connaît les valeurs de dispersion les plus faibles des trois régions sélectionnées. Entre 1935 et 1960, la dispersion a même légèrement reculé. En effet, les zones bâties qui se sont alors développées se trouvaient à proximité des anciens cœurs des villages, et leurs limites étaient à plus de deux kilomètres de celles des autres villages, c'est-à-dire au-delà de l'horizon d'observation. À partir de 1960, ces zones se sont étendues et rapprochées les unes des autres à

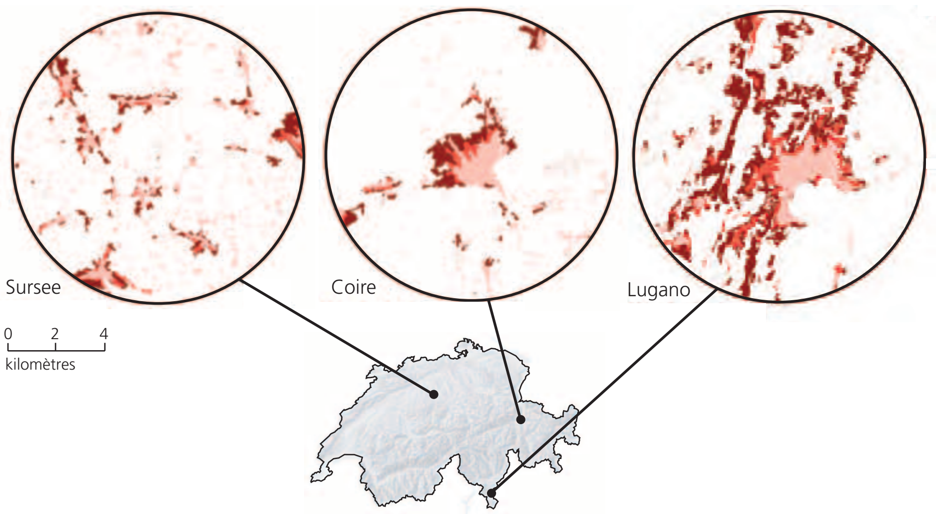


Fig. 8. Évolution des zones bâties dans les trois régions de Sursee, de Coire et de Lugano. Le diamètre de chaque région est de 12 kilomètres. Les cartes montrent l'évolution des zones bâties en 1935 (rose), 1960 (rouge) et 2002 (rouge foncé).

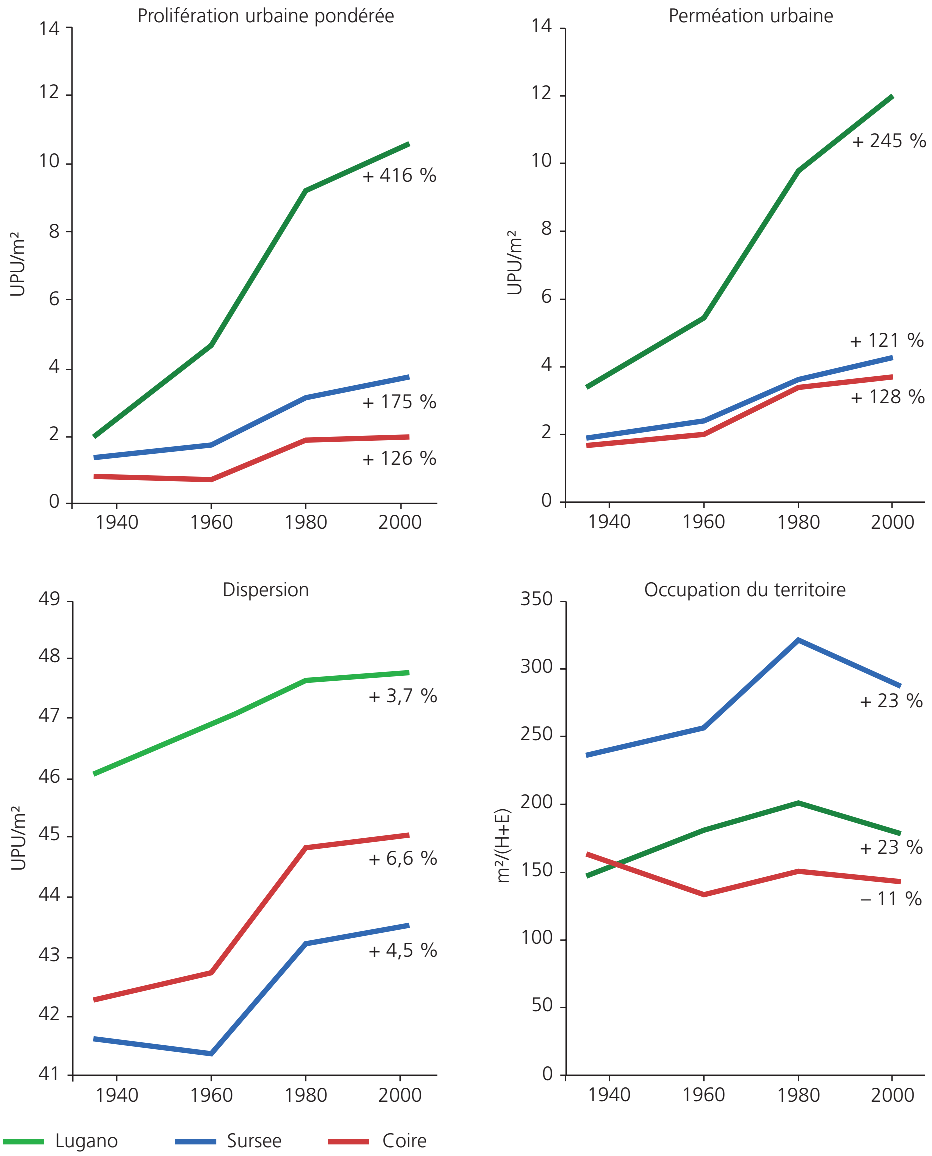


Fig. 9. Évolution de la prolifération urbaine pondérée, de la perméation urbaine, de la dispersion et de l'occupation du territoire par habitant ou par emploi dans les trois régions de Lugano, Sursee et Coire. Quatre années sont représentées: 1935, 1960, 1980 et 2002.

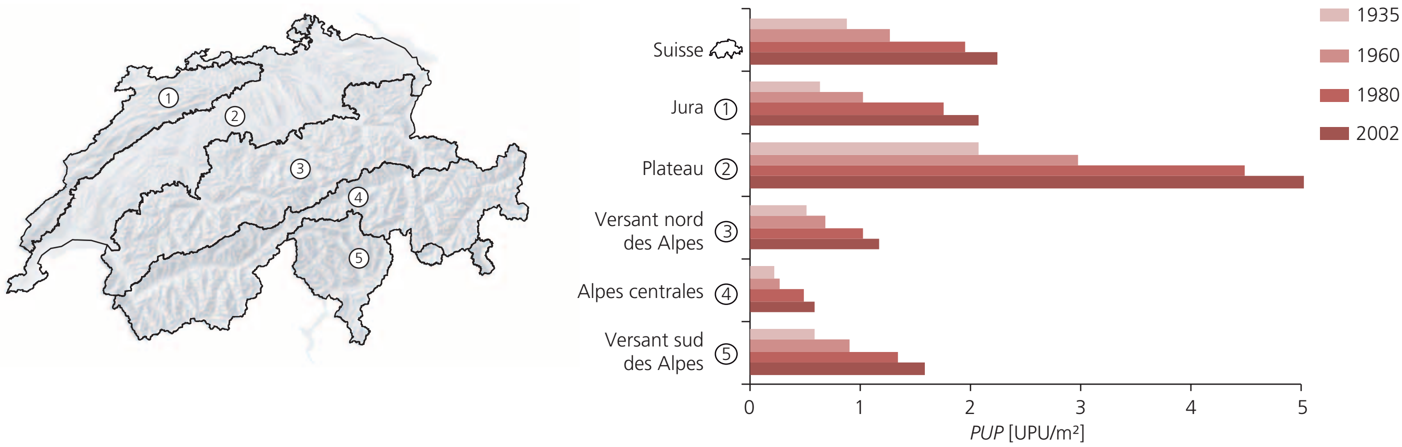


Fig. 10. Évolution de la prolifération urbaine pondérée en Suisse et dans les cinq régions biogéographiques entre 1935 et 2002.

moins de deux kilomètres par endroits, c'est-à-dire en deçà de l'horizon d'observation. La dispersion de la région de Sursee s'est pour cette raison fortement accrue. L'occupation du territoire par habitant ou par emploi y est élevée. Une telle situation est caractéristique des nombreuses régions rurales à la densité de construction relativement faible.

Applications de la méthode de la prolifération urbaine pondérée

La prolifération urbaine pondérée s'applique à toutes les échelles, du monitoring national à la planification de quartiers. Elle s'avère utile pour débattre de façon objective des questions liées à l'étalement urbain. Des données quantitatives sur la vitesse de changement du paysage sont importantes pour effectuer des comparaisons temporelles et spatiales, reconnaître les modifications de tendances et définir des objectifs vérifiables. Il est possible de comparer différentes variantes de planification en fonction de leur impact sur l'étalement urbain et de fixer – et contrôler – des valeurs maximales. Les différents projets de planification sont alors non seulement considérés séparément, mais aussi tous ensemble afin de prendre en compte l'effet global de tous ces projets. En voici l'illustration par quatre exemples:

Exemple 1:
Utilisation dans l'observation nationale du territoire et du paysage

Il existe en Suisse divers systèmes de monitoring sur les questions spatiales et environnementales. L'Observation du paysage suisse (OPS) de l'Office fédéral de l'environnement est spécifiquement axée sur une utilisation durable du territoire (Roth *et al.* 2010). Dans ce système de monitoring, la mesure de la prolifération urbaine pondérée est présente depuis le premier relevé de 2010.

L'étalement urbain n'a cessé d'augmenter de façon continue en Suisse de 1935 (0,87 UPU/m²) à 2002 (2,22 UPU/m²), soit 155 % d'accroissement (Fig. 10). En 1951, sa valeur correspondait à la moitié de celle calculée en 2002, ce qui signifie que l'étalement urbain a doublé en 51 ans. La plus forte augmentation, de 0,69 UPU/m², a eu lieu entre 1960 et 1980, époque de la suburbanisation à grande échelle en Suisse. Également dans les cinq régions biogéographiques du pays – Jura, Plateau, versant nord des Alpes, Alpes centrales et versant sud des Alpes –, cet étalement a plus que doublé depuis 1935. En valeurs absolues, celui-ci a connu la plus forte hausse sur le Plateau jusqu'en 2002 pour atteindre à cette date 5,02 UPU/m². Sa progression dans les trois régions alpines est aussi préoccupante, d'autant plus que l'urbanisation se développe essentiellement dans les vallées qui se heurtent à des limites spatiales.

Dans tout le pays, de même que dans les régions biogéographiques, l'étalement urbain s'est ralenti après 1980. Il importe toutefois de rester vigilant: selon des données provisoires et comme l'indique la croissance des zones bâties depuis 2002, son augmentation s'est de nouveau accélérée au cours de la dernière décennie.

Exemple 2:
Étude de régions délimitées sur le plan fonctionnel

La méthode de la prolifération urbaine pondérée ne s'arrête pas aux frontières administratives. Deux exemples l'illustrent: les fonds des vallées des cantons de montagne et les agglomérations.

Valais central

Le paysage du Valais central se divise en trois parties. Dans la vallée du Rhône, plate et sillonnée de zones bâties, est pratiquée une agriculture intensive. Les versants et les vallées latérales des Alpes valaisannes et bernoises qui jouxtent ensuite la vallée sont en grande partie boisés et recouverts de zones bâties, pour la plupart touristiques. Plus en altitude se situent des zones exploitées par l'économie alpine ainsi que les hautes Alpes. En 1935, la vallée abritait des milieux bâtis nettement séparés les uns des autres, tandis que les versants accueillaient des zones isolées exploitées elles aussi par l'économie alpine. Entre 1935 et 2002, dans toute la région, les zones bâties se sont fortement étendues et se sont rejointes par endroits. De nouvelles zones d'habitation sans lien avec les anciens centres sont également apparues (Fig. 11).

En 1935, la prolifération urbaine pondérée en Valais central s'élevait à 0,4 UPU/m², ce qui équivaut à la moitié environ de la valeur au niveau national (Fig. 13, courbe rouge). Jusqu'en 2002, cette valeur s'est accrue de façon impressionnante, plus précisément de 703 %, pour atteindre 3,2 UPU/m² et dépasser alors de 44 % la valeur comparative pour l'ensemble de la Suisse. L'éparpillement des zones bâties (dispersion) est passé de 43,23 UPU/m² à 45,9 UPU/m². Cette valeur excède également la moyenne du pays (44,95 UPU/m²). Le besoin de surface par habitant ou par emploi s'est considérablement accentué: de 163 m² en 1935 à 302 m² en 2002, il a quasiment doublé; il est de 36 % supérieur à la valeur comparative pour toute la Suisse.

La représentation de la prolifération urbaine pondérée sur une carte raster montre la forte augmentation du mitage dans le Valais central (Fig. 14, en haut). En 1935, les zones non bâties ou faiblement mitées prédominaient. La surface bâtie a plus que triplé depuis 1935, couvrant 4262 ha en 2002. Jusqu'à cette date, de grandes parties du Valais central connurent un étalement urbain important (>15 UPU/m²). Les régions aux alentours des deux centres de Sion et de Sierre furent alors particulièrement concernées.

Dans la mesure où aucune zone bâtie n'est démantelée, diminuer l'étalement urbain dans la région du Valais central n'est possible qu'en réduisant considérablement l'occupation du territoire par habitant ou par emploi. Cela signifie que l'occupation du territoire devrait nettement baisser afin de descendre sous la barre des 200 m²/(H+E). La région devrait ainsi gagner plus de 100 000 habitants ou emplois sans élargir l'espace bâti pour autant. Cependant, vu les grandes zones à bâtir non construites que l'on observe déjà aujourd'hui, une forte poursuite de l'étalement urbain est plus que probable en l'absence de contre-mesures radicales.

Il convient aussi de noter que de grandes parties du Valais central ne sont pas du tout constructibles. Il apparaît ainsi clairement que dans de telles évaluations, il importe non seulement de considérer la valeur absolue de la prolifération urbaine pondérée, mais aussi son augmentation relative et la taille des surfaces non constructibles.

Fig. 11. La plaine du Rhône dans la région du Valais central, vue depuis Vercorin en direction de Saint-Léonard: des zones bâties dispersées à vaste échelle marquent le paysage de leur empreinte. (Photo: Yves Maurer, 2003)

Fig. 12. Densités élevées de construction et séparation nette avec la zone non constructible. Construction «Feldhof» à Zoug. (Photo: Die Geographen schwick+spichtig 2011)

Région de Zoug

La région de Zoug se situe sur le Plateau, entre les deux grandes villes de Zurich et Lucerne, au bord du Lac de Zoug. Elle est extrêmement dynamique par son site, notamment grâce aux avantages liés à ses faibles taux d'imposition et à sa proximité avec la métropole de Zurich (Fig. 12).

Vers 1935, les zones bâties des communes se distinguaient clairement les unes des autres ainsi que de leur environnement (Fig. 14, en bas). Jusqu'en 2002, le milieu bâti s'est fortement étendu, de nombreuses surfaces jadis séparées ayant fusionné. Le nombre d'habitants et d'emplois a augmenté de 241 %, mais la surface bâtie seulement de 121 %. Il en a résulté de façon générale une densification des zones bâties qui s'est traduite par une élévation relativement faible de la valeur de la prolifération urbaine pondérée (+26 %) (Fig. 13, courbe bleue). Exemple rare: la valeur de la prolifération urbaine pondérée pour Zoug a même nettement baissé de 1980 à 2002 (–34 %). Deux objectifs de planification définis dans le plan directeur du canton de Zoug jouent un rôle déterminant dans cette évolution:

– «Le canton et les communes séparent les zones constructibles des zones non constructibles. Des lignes limitent l'étalement du milieu bâti.»
– «Les cantons et les communes renforcent les zones centrales des communes ainsi que les importants nœuds du transport public. Les communes … autorisent des densités de construction élevées.»

Ces deux dispositions évitent une forte progression de la surface bâtie, de la perméation urbaine et de la dispersion, tandis que l'occupation du territoire par habitant ou par emploi diminue par là même. Effectivement, cette dernière a chuté entre 1980 et 2002. Malgré l'augmentation de la surface bâtie, une réduction de l'étalement urbain est ainsi possible en densifiant les constructions et en comblant les espaces vides dans les zones bâties déjà existantes.

La région de Zoug est un exemple modèle qui illustre la façon dont l'étalement urbain peut être non seulement ralenti, mais aussi réduit. Toutefois, du fait de la limitation conséquente des zones de nouvelles constructions, les appartements de la région de Zoug se font rares et chers.

Exemple 3:
Scénarios – dans quel paysage voulons-nous vivre à l'avenir?

Les scénarios sur l'étalement urbain en Suisse montrent quelles peuvent être sur le paysage les répercussions à long terme des décisions prises dans la politique d'urbanisme, et quels développements alternatifs sont réalisables. Les trois scénarios présentés ici s'appuient sur les chiffres de population du recensement suisse de l'année 2000 et sur les zones bâties de l'année 2002 (Fig. 15). Le *scénario minimal* table sur une croissance de la population à hauteur de 341 000 habitants jusqu'en 2050, et sur le fait que les zones d'habitat nouvellement construites seront compactes et toujours situées en bordure directe des zones bâties déjà existantes. Le *scénario maximal* prévoit quant à lui une augmentation de 2 455 000 habitants avec de nouvelles zones d'habitat dispersées dans la zone constructible. Le scénario *densification* projette aussi une croissance de la population de près de 2,5 millions jusqu'en 2050. Contrairement au scénario maximal, la zone bâtie ne croît pas dans ce cas de figure car les nouveaux habitants vivent et travaillent dans le milieu bâti déjà existant.

Les scénarios mettent en évidence la forte influence que l'augmentation de la population et du bâti, ainsi que la situation spatiale des zones bâties supplémentaires (regroupées ou dispersées), auront sur le développement futur de l'étalement urbain en Suisse. D'où les déductions que l'on peut en faire pour les décennies à venir:

– l'étalement urbain continuera fortement de gagner du terrain en l'absence de contre-mesures;
– il existe toutefois des différences considérables entre les scénarios;
– toute croissance de la population, sans modification de l'occupation du territoire par habitant ou par emploi, renforcera la poursuite de l'étalement urbain;
– lors d'une augmentation donnée de la population et de l'absence de modification de l'occupation du territoire par personne, la progression de l'étalement urbain peut être freinée de façon sensible si les zones bâties nouvellement érigées sont regroupées et non pas dispersées;
– lors d'une augmentation donnée de la population, la progression de l'étalement urbain peut être freinée de façon sensible si l'urbanisation s'effectue de façon concentrée sans qu'aucune autre suburbanisation du paysage n'ait lieu;
– l'étalement urbain, en présence d'une croissance de population donnée, peut être non seulement freiné fortement par une diminution de l'occupation du territoire par habitant ou par emploi, mais également réduit.

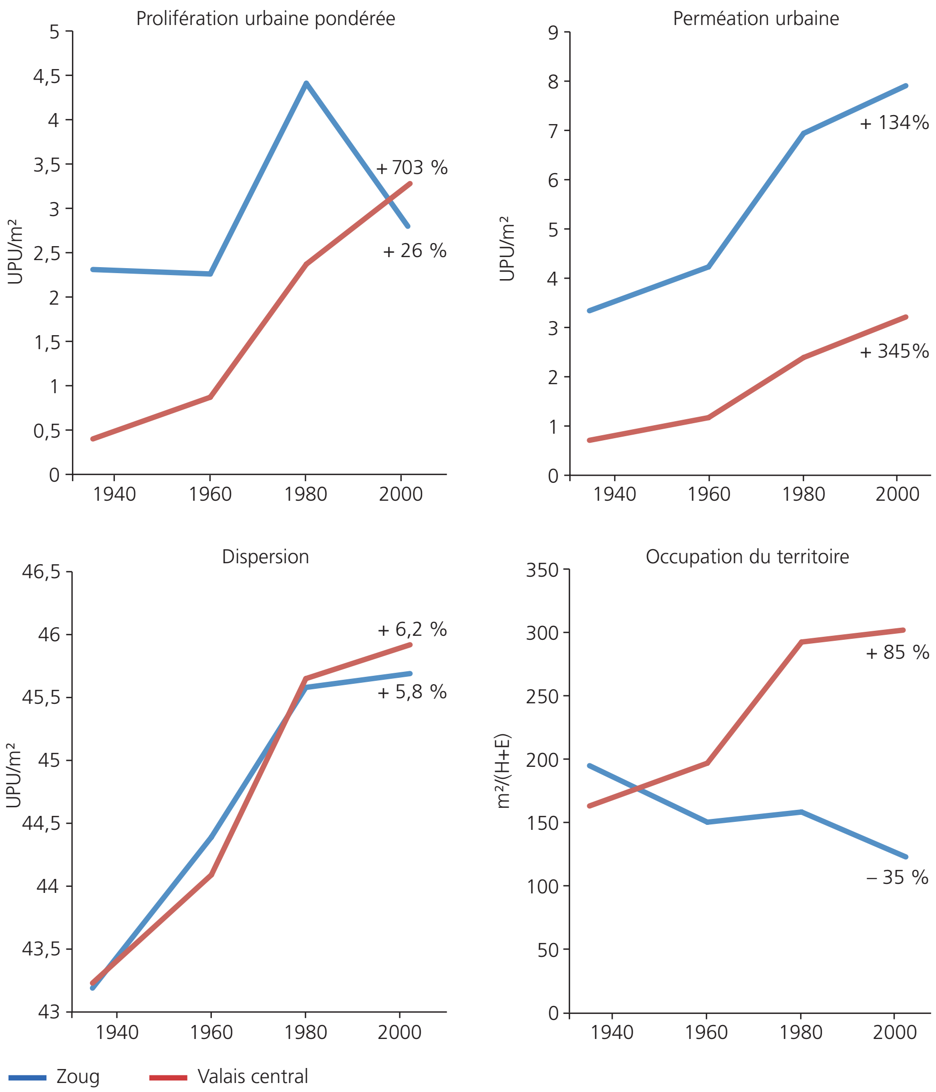


Fig. 13. Évolution de la prolifération urbaine pondérée dans les régions du Valais central et de Zoug pendant la période comprise entre 1935 et 2002.

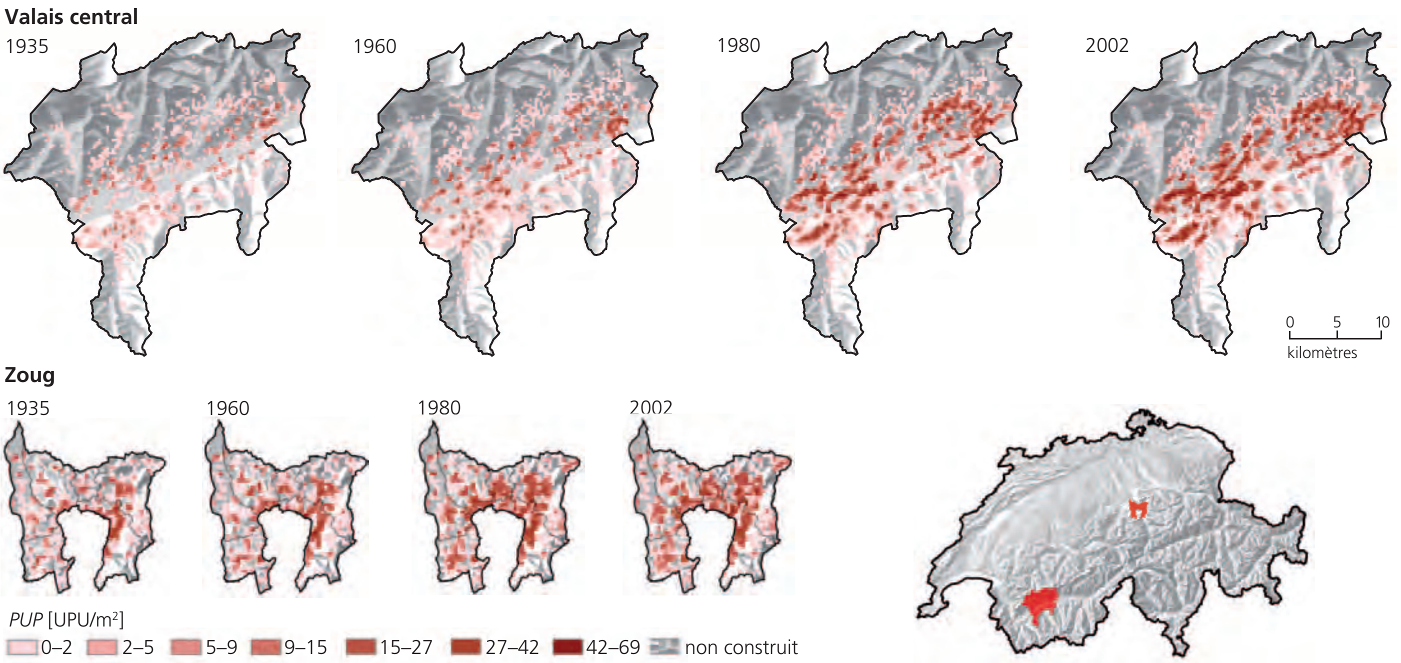


Fig. 14. Évolution de la prolifération urbaine pondérée *PUP* dans les régions du Valais central (en haut) et de Zoug (en bas) entre 1935 et 2002. La taille de chacune des cellules raster est de 300 m * 300 m.

Pour 2050, le scénario minimal prévoit que la Suisse comptera près de 7,5 millions d'habitants. En réalité, cette valeur a déjà été dépassée de 400 000 habitants en 2010. Par conséquent, l'étalement urbain se développera très probablement selon le scénario maximal si ne sont effectuées aucune correction nette de l'occupation du territoire par personne ni aucune concentration des nouvelles zones bâties. Il est à craindre qu'à l'avenir, l'augmentation ne se fasse au niveau supérieur de la fourchette envisagée.

Exemple 4: Application dans la planification

Lors de la délimitation de nouvelles zones à bâtir, la méthode de la prolifération urbaine pondérée est un instrument qui sert à analyser l'impact de ces surfaces devenues constructibles sur l'étalement urbain futur. L'emplacement et la densité des constructions dans ces nouvelles zones influencent grandement la valeur de la prolifération urbaine pondérée (Fig. 16).

Soit dans un paysage de 9 ha quatre parcelles construites, chacune de 900 m² et de quatre habitants (Fig. 16, cas A). Dans ce cas, la valeur de la prolifération urbaine pondérée est de 0,13 UPU/m². Dans les cas B et C, une parcelle supplémentaire est construite, d'une même superficie et d'un même nombre d'habitants. Si cette parcelle supplémentaire se situe au centre de la surface déjà bâtie (cas B), la prolifération urbaine pondérée s'élève de 18 % et la dispersion diminue de 6 %. Si la nouvelle parcelle se trouve à l'extérieur de la zone d'habitat existante, c'est-à-dire dans un paysage vierge, l'augmentation de la valeur de la prolifération urbaine pondérée est nettement supérieure (+60 % par rapport au cas A, +36 % par rapport au cas B); elle s'accompagne également d'une nette hausse de la dispersion.

Si la directive politique stipulant que l'étalement urbain ne devrait plus s'accentuer prévaut, la méthode de la prolifération urbaine pondérée fournit des données exactes indiquant les moyens d'atteindre cet objectif. Dans le cas B, l'occupation du territoire par habitant devrait être réduite de 20 %, ce qui nécessite la présence d'une personne supplémentaire

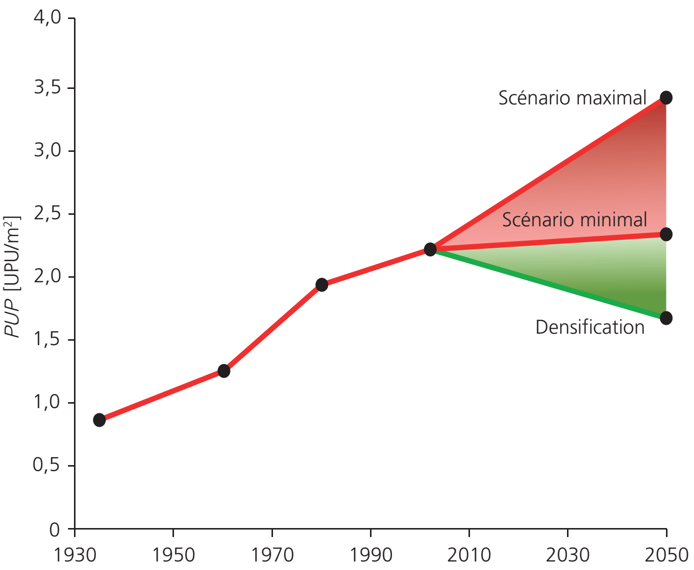


Fig. 15. Augmentation de la prolifération urbaine pondérée depuis 1935 en Suisse et évolution projetée entre 2002 et 2050.

dans chaque parcelle. Dans le cas C, elle devrait même être réduite de 33 %, ce qui correspond à deux habitants de plus par parcelle.

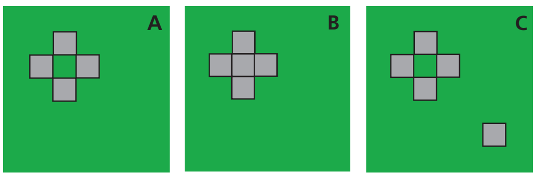
Mesures pour endiguer l'étalement urbain futur

De façon plus précise, nous proposons les mesures suivantes pour limiter la progression de l'étalement urbain en Suisse ou la stopper complètement. Selon la région, un paquet différent conviendra. Dans certaines zones, il est même possible de diminuer ainsi cet étalement. Les mesures sont en lien direct avec la méthode et les paramètres de la prolifération urbaine pondérée.

Densifier les zones bâties existantes
La mesure principale consiste à ne pas construire de zones supplémentaires. Les zones bâties cessent dès lors de s'étendre. Des constructions permettant de densifier les zones bâties fermées demeurent possibles. Les valeurs des paramètres de la perméation urbaine et de la dispersion restent alors inchangées, et l'occupation du territoire par personne diminue si le nombre d'habitants ou d'emplois augmente.

Arrêter la croissance dispersée du milieu bâti
Cette mesure signifie que la construction de nouvelles zones bâties (et de bâtiments individuels) n'est pas autorisée à l'intérieur de zones à bâtir qui seraient sans contact avec les frontières du milieu bâti existant. Seuls les espaces vides à l'intérieur ou le long des zones d'habitat existantes sont comblés, et de préférence à des endroits à faible dispersion (développement regroupé des zones bâties).

Protéger efficacement les espaces libres de construction
Les rares zones restantes non gagnées par le mitage ou l'étant faiblement devraient être protégées efficacement. Sans que cette liste ait la prétention d'être exhaustive, ces zones comprennent les sites IFP, les espaces non morcelés à faible circulation, les sites naturels à l'écart des axes routiers, les sites marécageux, les réserves de biosphère, les ceintures vertes et les corridors pour la faune sauvage. Toutes les zones en dehors de celles à bâtir font partie des espaces libres de construction. Les terres agricoles restantes, de même que les forêts, doivent être protégées efficacement au niveau juridique afin d'éviter qu'elles ne soient utilisées à d'autres fins.



	A	B	C
Perméation urbaine [UPU/m²]	0,3	0,4	0,5
Dispersion [UPU/m²]	7,8	7,3	10
Occupation du territoire [m²/(H+E)]	225	225	225
Prolifération urbaine pondérée [UPU/m²]	0,13	0,15	0,2

Fig. 16. Illustration de la méthode de la prolifération urbaine pondérée en tant qu'instrument d'analyse lors de la mise en zone constructible. A) Situation initiale du développement avec quatre parcelles construites. B) La nouvelle parcelle construite se trouve au centre des zones bâties déjà existantes. C) La nouvelle parcelle construite se situe dans la campagne, sans lien avec la zone bâtie déjà existante.

Épargner les zones sensibles au mitage
Les régions particulièrement sensibles à la progression du mitage devraient être épargnées par les constructions. Dans des endroits à grande dispersion, il suffit parfois de quelques nouveaux bâtiments pour entraîner une détérioration notable. Les zones sensibles au mitage comprennent notamment les zones d'habitat dispersé et les espaces en bord de vallée.

Délimiter le milieu bâti
La démarcation des zones bâties au moyen de lignes, la désignation de ceintures vertes lors de l'établissement des plans directeurs et des plans d'affectation, ainsi que les mesures favorisant le développement du milieu bâti vers l'intérieur, sont des contributions essentielles pour endiguer le mitage (Gennaio *et al.* 2009).

Respecter la loi exigeant la construction à l'intérieur des zones à bâtir
La construction à l'extérieur des zones à bâtir participe fortement au mitage. De telles constructions dégradent en particulier la valeur de la dispersion et, en règle générale, l'occupation du territoire par personne également.

Les quatre mesures suivantes portent sur la collaboration entre plusieurs communes ou cantons et sur le développement d'objectifs pour l'avenir.

Plafonner la surface des zones à bâtir et prélever la plus-value
S'il est impossible d'empêcher la croissance des zones bâties, contingenter les zones à bâtir s'avère une mesure pertinente. Toutefois, cela ne suffit pas pour ralentir l'étalement urbain car les zones à bâtir existantes sont de très grande taille. Il importe d'exploiter la plus-value des surfaces liée à leur transformation en terrain à bâtir et à la viabilisation de ce dernier.

Aménager au niveau interrégional
La concurrence que se livrent communes, régions et cantons pour les emplois, les contribuables et les habitants est en partie responsable de l'étalement urbain. Une planification interrégionale est nécessaire pour limiter au strict minimum le nombre et la superficie des zones industrielles et des quartiers résidentiels, et pour maintenir le plus bas possible leur degré de dispersion.

Fig. 17. Quel sera le visage de la Suisse en 2050? Münsingen en 1981 (à gauche) et en 2004 (à droite). Reproduit avec l'autorisation de swissimage © swisstopo (BA110467).

Établir des valeurs cibles, des valeurs limites et des valeurs indicatives pour l'étalement urbain
La formulation de valeurs cibles, de valeurs limites et de valeurs indicatives est une démarche importante pour la gestion mesurée d'une ressource rare. Que des problèmes à ce niveau aient été surmontés dans d'autres domaines environnementaux (notamment ceux de la protection de l'air ou de la protection des eaux) est de bon augure. Des valeurs limites doivent être déterminées lors d'un processus décisionnel politique sur la base de données scientifiques, dont les valeurs de la prolifération urbaine pondérée.

Aménager à long terme le milieu bâti à partir de principes directeurs
Il convient de définir des objectifs à long terme pour l'aménagement souhaité des systèmes de zones bâties et de transport durables, et d'en déduire des scénarios en vue des transformations nécessaires à cet effet (Baccini et Oswald 1998). La planification de cet aménagement devrait passer d'un modèle centré sur la demande à un modèle axé sur les objectifs, et de ce fait synonyme de durabilité.

Si ces mesures sont combinées adéquatement et appliquées de façon conséquente, elles auront des répercussions positives sur le paysage en Suisse: des limites plus claires seront de nouveau reconnaissables entre zones constructibles et zones non constructibles. Les bordures des zones bâties ne seront plus effilochées, mais au contraire plutôt arrondies. Le milieu bâti sera de façon générale plus dense, ce qui conférera aux espaces peu peuplés un caractère urbain plus prononcé. À l'intérieur des zones bâties, les friches industrielles et les zones à bâtir inutilisées seront densément construites. La relocalisation des zones à bâtir entraînera à long terme une diminution de la dispersion dans les zones industrielles et commerciales qui deviendront ainsi plus concentrées et plus compactes (zones à plusieurs étages). Les nouveaux espaces bâtis seront avant tout implantés dans des endroits bien desservis par les transports publics et non plus établis sur des terrains bon marché difficilement accessibles par ces transports. Cela se traduira par une séparation plus nette entre le milieu bâti urbain, les espaces ruraux, les zones historiques et le paysage naturel. Lors de ces considérations, il ne faut pas perdre de vue ce qui se produirait sans ces mesures (Fig. 17): la construction de bâtiments dispersés sur de vastes étendues du sol suisse, et de ce fait le mitage et toutes ses conséquences fâcheuses, continueraient d'augmenter rapidement.

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