Urban Sprawl and Climate Change:

A Survey of the Pertinent Literature on Physical Planning and Transportation Drivers

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Abstract

Urban sprawl has previously been extensively researched in urban literature, but there are still ambiguities, controversies, and debates around its definitions, characterizations, measurements, causes, and consequences. This study is not aiming to resolve the numerous debates about and around urban sprawl. Rather, we are exploring, reviewing, and collecting the pertinent literature on physical planning and transportation drivers linking urban sprawl and climate change. Given the unprecedented urbanization rates, accelerating population growth, the over-exploitation of resources, and environmental degradation, a deeper and updated understating of urban sprawl is urgently needed in the current context of climate change and other environmental crises. The three intertwined sets of characteristics concerning urban sprawl are low residential densities, low intensity and segregated land-use, and generalized dependence on the automobile. These have all been established as criteria to investigate the relationship between urban sprawl and climate change. We consider sprawled environments from a morphological perspective, which is concerned with the artifacts and spatial forms within their broader geographical contexts and conceives the built environment as a dynamic system. This study wishes to bring some light on the planning debates on the links between urban sprawl, sustainable development, and climate change more generally.

Key Words:

Urban Sprawl, Quantifying Sprawl, Climate Change, Physical Planning Drivers, Urban GHG/CO2 Emissions, Urban Sustainability, Urban Morphology.

1. Introduction

Urbanization has been regarded as one of the most striking phenomena of the 20th century (Baklanov, Molina, and Gauss, 2016; Wang et al., 2012; Taylor and Lang, 2004). The portion of the world population living in cities has reached 50% at the turn of the 20th century, and it is estimated that urbanites will represent 66% of the population by 2050 (United Nations, 2012). In different parts of the world, urbanization has assumed the form of low-density development at the periphery of the city. Urban sprawl, as this was called, used to be considered “an American zeitgeist” (Burchell et al., 1998), but it is now becoming an international, and perhaps even global, phenomenon. Even though the latter has previously been extensively researched in urban literature, there are still ambiguities, fuzziness, and debates surrounding the definition of urban sprawl as well as its characterization, measurement, causes, and consequences. Sprawl is multifaceted. The term has been used as a noun, a verb, and an adjective (Gaslter et al., 2001). Sprawl has been described as a situation, a process, an outcome, a phenomenon, a fact, a consequence, a pattern, etc. Meanwhile, the physical and spatial structures of our cities are changing dramatically (Arribas-Bel and Schmidt, 2013; Brueckner, 2000). Moreover, a deeper and updated understating of sprawl is urgently needed in the context of climate change and other environmental crises. There is a strong consensus in the applied planning literature to the effect that urban sprawl is detrimental to the environment and that, inversely, compact forms of development produce a lighter environmental footprint. Such contentions are globally supported by science. Yet, the empirical research results do not translate easily into evidence-based planning and design (i.e. physical planning). A number of reasons can explain this state of affairs.

While planning is, by definition, an integrated approach to urban development, fundamental research is fragmented by nature. Research is constrained by disciplinary boundaries and the specificity of its methods of inquiry. Fragmented, and at times, seemingly contradictory results, are difficult to translate into planning terms. Furthermore, the links between the forms of urban development, climate change, and the environment more broadly, are complex and intricate. Causes and consequences are often difficult to untangle; some development practices take a direct environment toll, whereas other such costs are incurred indirectly. Finally, as alluded to earlier, the concepts used to describe and define forms of urban development are often elusive. Sprawl and compactness offer cases in point. While seemingly evocative, these labels refer to polar opposite conditions found at both ends of a spectrum (Ewing and Shima, 2015; Ewing, 1997).

Each term fails to capture the variety of forms in which either sprawl or compactness can manifest. Furthermore, there is no terminology to describe intermediate conditions that belong to neither of those categories. This study wishes to bring some clarity to the planning debates on the links between urban material and spatial forms, climate change, and sustainability more generally. The research on sprawl has been the “ground zero” of such debates. Accordingly, our investigation starts by revisiting the literature on sprawl. It is not aiming, per se, at resolving the numerous debates about and around urban sprawl. Rather, it is exploring, first, how sprawl has been problematized, defined, characterized, and measured. We engage in this exercise while acknowledging that the concept is problematic. A review, however, of some pertinent literature can advance our knowledge on sprawl, and from there, on the links between urban forms and the environment more generally. Our second goal is hence to collect recent scientific contributions, to survey their methods, and summarize the evidences they gathered in order to compare results across different approaches and to cautiously generalize some of their conclusions while highlighting some ambiguities and controversies. In this study though, only a small cross-section of the literature concerned with the definitions, characteristics, causes, and consequences of sprawl has been reviewed. The selection has been subjected to “biases,” totally assumed by the researchers. Firstly, we privileged studies concerned with the material and spatial manifestations of sprawl in coherence with the tenets of urban morphology. This approach is concerned with the artefacts and spatial forms within their broader geographical contexts, which conceives the built environment as a dynamic system. Such a choice eliminates studies on economic, social, and cultural causes and consequences of sprawl. Secondly, we gave precedence to quantitative research on sprawl and on the relationship between sprawl and climate change.

Those criteria are opportunistic. Conceiving sprawled environments from a material and systemic perspective opens up the possibility to assess them within their broader urban context, comprised of a natural substratum and all anthropogenic structures. Thus, privileging quantitative research favors comparative assessment of studies’ results. Yet, our approach to this analytical literature review is both inductive and deductive. While the aforementioned theoretical and methodological considerations, influenced by morphological approaches, inform the selection of sources, the literature itself points to important aspects of the problem that are also addressed in this report. For instance, there is abundant research on the links between urban form, transportation, and climate change that clearly belongs to this study. This material was included because the empirical research itself establishes a very strong relationship between transportation and the urban material and spatial forms.

Figure 1 offers a diagrammatic representation of the articulations between climate change (and other environmental crises) and human habitats. It aims at achieving some conceptual clarity while situating the themes addressed in this report within a broader framework. It seeks, in particular, at untangling key, yet intricate, relationships between environmental and urban settlements dynamics. Specifically, the left-hand side of the diagram details how the anthroposphere, or the humanized habitats including human settlements, is part of the broader geosphere. The right-hand side lists, in particular, the earth-systems that are currently in crises, including the climate, before highlighting some anthropic causes such as the "physical planning drivers." The central part of the diagram illustrates how anthropogenic and natural environments dynamics are intertwined and details the themes discussed in this report. The greyed boxes highlight aspects that are more specifically addressed. A good way to summarize the approach is to point out that it is centered on aspects of urban development and management that fall under the realm of physical planning (i.e. built forms, including infrastructures, land-use, and transportation).

Urban development in Québec has been globally consistent with the trends observed on the continent, in particular, since the end of the Second World War. Sprawl has prevailed in its largest cities. In the Québec context, the forms of urbanization and their associated transportation practices take center stage in climate change debates. Québec has committed to reducing its GHG emissions by 37,5% below the 1990 levels by 2030. In 2014, some 41% of the GHG emissions were attributable to the transportation sector in the province. Road transportation per se, accounted for 33,6% of the total (Ministère du développement durable, de l'environnement et de la lutte contre les changements climatiques, 2016). Whereas the total emissions went down to 81,7 M. of tons, from 89,5 between 1990 and 2015, unlike other sectors, transportation saw its emissions increasing by 21,3% over the same period (Gouvernement du Québec, 2018). Those increases are mainly due to a vehicle fleet that grows much faster than the population, an increase in the average number of kilometers traveled, and the rising popularity of larger vehicles. The total number of cars and light trucks in circulation, for instance, increased by 35% to 4,67M. between 2001 and 2016 (Société de l'assurance automobile du Québec, 2016). The number of cars on the road as well as the number of kilometers traveled are closely related to the modes of urbanization and the sprawling development at the periphery of Québec largest cities. Tellier and Gelb (2018) developed a synthetic index of urban sprawl based on the ratio density of outer suburbs/density of the central city. By such a measure, Québec City has experienced a 19,08% increase of sprawl between 2006 and 2016, whereas Montreal saw an increase of 11,00% for the same period (Tellier and Gelb, 2018).

The core of this report consists of an analytical literature review on topics relevant to urban sprawl and climate change. The ways in which urban sprawl is defined determine how it is measured. Similarly, the approaches used to measure sprawl impact on the interpretation that could be derived of its environmental costs. Section 2 details the methodology used to gather pertinent references. Section 3 provides background information by addressing sprawl definitions, characteristics, causes, and consequences. Section 4 focuses on quantitative research on urban sprawl. Section 5 seeks out empirical evidence regarding relationships between urban sprawl and climate change, and between sprawl and its other associated environmental tolls. Section 6 discusses initiatives for climate protection and for adaptation. Section 7 identifies some limitations and gaps in the research, and reconceptualizes urban sprawl from a morphologist's perspective, in order to address some of those. The section touches in particular to the problematic question of spatial partitioning, i.e., the delineation of geographical units of reference for the investigation of the environmental performance of urban forms.

2. Methodology

The initial step consisted in consulting literature review articles based on similar topics and objectives to ours. The said articles are:

Compactness versus Sprawl: A Review of Recent Evidence from the United States by Ewing and Hamidi (2015);

Investigating the interplay between transport, land use and the environment: a review of the literature by Yigitcanlar and Kamruzzaman (2014);

The Environmental Impacts of Sprawl: Emergent Themes from the Past Decade of Planning Research by Wilson and Chakraborty (2013);

The Costs of Sprawl—Revisited by Burchell et al. (2002);

Environmental impacts of urban sprawl: a survey of the literature and proposed research agenda by Johnson (2001);

The Costs of Sprawl-Revisited by Burchell et al. (1998), and;

Characteristics, Causes, and Effects of Sprawl: A Literature Review by Ewing (1994).

The exercise allowed us to constitute a preliminary bibliography, and more importantly, to survey the themes covered in the literature. Based on such a foundation, we conducted a systematic search for articles published in English language journals from 1979 until 2018, relying primarily on ISI's Web of Science® database. The search was conducted based on various iterations of the following string of keywords (and synonyms): (urban sprawl OR sprawl) AND (climate change or global warming or greenhouse gas emission* OR CO2) AND (transportation OR land use* OR land use*). This operation came up with 220 returns. The results include 187 articles, 25 proceedings papers, 5 editorials, and 9 reviews. Based on this result, we found that Environmental Sciences has contributed the most articles; 70 articles from Environmental sciences which accounts for 31.81% of the total. Followed by 53 from Environmental Studies (24.09%), 31 from Urban Studies (14.09%), 24 from Ecology (10.91%), 22 from Water Resources (10%), 22 from Green Sustainable Science Technology (10%), 17 from Geosciences Multidisciplinary (7.73%), 15 from Geography (6.82%), 15 from Economics (6.82%), 15 from Planning Development (6.82%). Among all returned articles, 218 were in English (99%), and two were outliers (in Italian and Turkish).

The initial search results were refined by carefully reviewing the abstracts and the key words supplied by the authors. Sixty articles were selected for thorough review. We then mainly focused on these 60 articles but did not limit ourselves to them. We also paid special attention to books and governmental reports referenced with some frequency in the scientific articles. Of key interest was material produced by the Intergovernmental Panel on Climate Change (IPCC), the European Environment Agency (EEA), the Transit Cooperative Research Program (TCRP), etc. Finally, we examined the bibliographies of the previous literature related to this topic to identify other pertinent studies that might have been skipped by the database search. Our final bibliography is comprised of a little less than 200 items.

Even though sprawl has been documented in other places, given the limited scope of this study, the primary focus is on North America. This paper aims at reviewing the concept of urban sprawl from an objective, balanced, and rational perspective. Existing sprawled environments are there to stay and such type of development will not disappear overnight (Barnes et al., 2001). A basic attitude implicit in this paper is that urban sprawl should be considered and treated as a manageable problem. Curtailing sprawl or mitigating its environmental impacts require better-informed planning and public policies. Unprecedented urbanization rates, accelerating population growth, over-exploitation of resources, and environmental degradation confers a sense of urgency to a better management of urban sprawl. In the context of climate change, sprawl needs to be tackled "up-stream" in order to reduce the direct and indirect contribution of sprawled environments to GHG emissions. It needs to be tackled "down-stream" as well, in order to adapt to cities and to increase their resilience against the effects of climate change.

Note: Readers can find more information on urban sprawl research in: *Urban Sprawl and Related Problems: Bibliometric Analysis and Refined Analysis from 1991 to 2011* by Zeng et al. (2014).

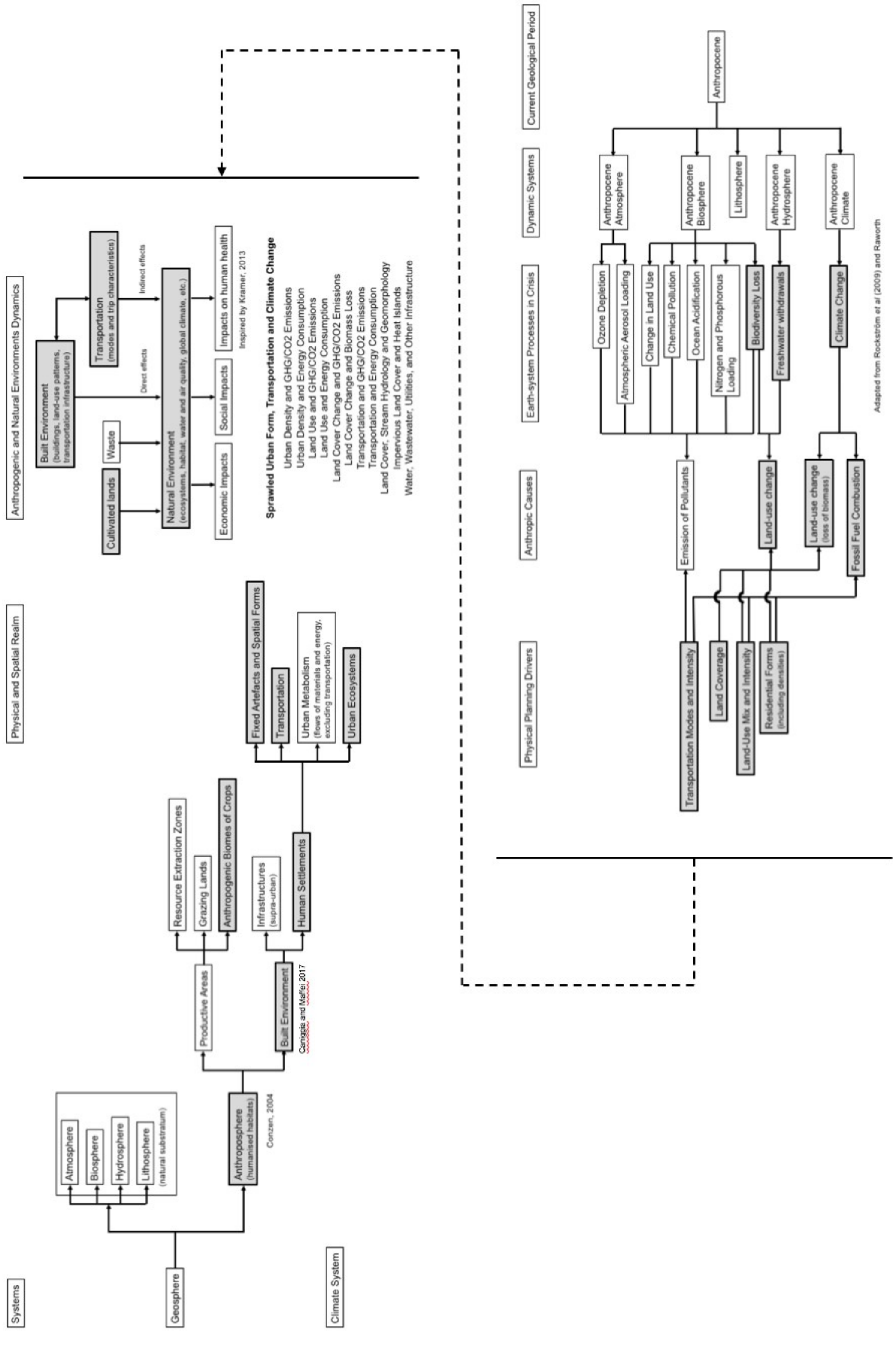

Figure 1. Diagram of the urbanization anthropogenic and natural environments dynamics

3. Better Understanding the Notion of Urban Sprawl

Urban sprawl is not a recent phenomenon. Many authors trace it back to the beginning of the twentieth century (Barrington-Leigh and Millard-Ball, 2015; Frenkel and Ashkenazi, 2008; Gillham, 2002; Mitchell, 2001; Burchell et al., 1998; Ewing, 1994; Harvey and Clark, 1965). Yet, the term "sprawl," per se, only appeared in the planning literature in the 1950s (Burchell et al., 1998).

In the United States since the turn of the twentieth century, two demographic trends combined to funnel the physical expansion of cities, i.e., sprawl. At times of rapid population growth and rampant urbanization, the country experienced continuing growth of its suburb populations, accompanied by a continuing decline of population in the centers of cities (Yin and Sun, 2007). These trends have prevailed until today and are generally seen as unlikely to change in the short term (Savitch and Kantor, 2002). In 1940, 15% of the population of the United States was living in suburbs (Burchell et al., 1998), whereas people residing in the suburbs outnumbered people lived in the central cities by the 1970s (USGAO, 1999; Mieszkowski and Mills, 1993; Masotti and Hadden, 1974). In 2007, for the first time in history, the world's urban population exceeded the rural population (Baklanov, Molina, and Gauss, 2016, p.235). As Torrens (2008) claims prosaically: "Urban growth has to go somewhere" (p.6). It is, however, worth noting that the spatial expansion of cities is only one of the modalities of absorption of population growth. Other modalities include a densification of the city "from within," by building up in open spaces, including within existing parcels, or through vertical deployment, by adding floors. Whereas the mere scale of urban population growth on the continent during the last century would justify in itself some physical expansion of cities, the development at the periphery has unfolded at a larger scale than population increases. The EPA notes that in the US, "[a]lthough the population has grown dramatically in census-defined urban areas, the trend has largely resulted in growth in suburbs rather than in central cities" (EPA, 2013, p.7). Moreover, the form assumed by the urbanization at the periphery of cities has translated in levels of consumption of land that population growth alone could not justify. One of the most dramatic trends in the built environment during the twentieth century has been the expansion of the geographic size of metropolitan regions. Such transformations were marked by decreasing residential densities at the periphery as the process unfolded. Those modes of urbanization were evidently enabled by transportation trends and, in particular, the generalization of automobility. The latter considerations bring us to the need to define sprawl. The term implies more than mere urbanization at the peripheries of cities. It denotes a certain form of development characterized by low-intensity occupation of the land. Most definitions convey such ideas more or less precisely, but no unified definition elicits a strong consensus. The problem stems largely from the difficulties to characterize and qualify the urban forms that sprawl assumes, and in particular, to quantify the intensity of land occupation.

3.1 Defining Urban Sprawl

A better understanding of the definitions, characteristics, causes, and consequences of urban sprawl must be presented before addressing how sprawl can be accurately measured and effectively managed. Vague, distorted, or biased definitions limit our ability to formulate appropriate public policies and planning initiatives. Further, Banai and DePriest (2014) claimed that how urban sprawl is defined will influence the way it is measured.

Many articles on urban sprawl deemed useful stress that there is no unitary definition of sprawl (Hamidi and Ewing, 2014; Hamidi et al., 2015; Zeng et al., 2014; Torrens, 2008; Cutsinger et al., 2005; Wilson et al., 2003; Barnes et al., 2001; Gaslter et al., 2001; Johnson, 2001; Burchell et al., 1998; Ewing, 1997). Moreover, a number of synonyms have been equated with sprawled contexts without further distinctions: suburban sprawl (Whyte, 1958), suburbanization, edge city (Garreau, 1992), edgeless city, etc. To better understand the concept of urban sprawl, one of the first tasks is to survey and decipher relevant definitions.

Sprawl has been defined in a variety of ways (Johnson, 2001). Barnes et al. (2001) suggest that the definition of sprawl ultimately depends on the perspective of the definers (p.3). Banai and DePriest (2014, p.1) echo that position: “[w]hile professionals from different specializations shed lights on various aspects of urban sprawl, the differences in language and perspectives (e.g. architects, planners, real estate agents, bankers, land-use regulators) contributes to the lack of a cohesive definition.” Many definitions have their limitations by focusing on certain aspects of development or certain types of development pattern. The confusion that stems from mixing causes and consequences associated with different manifestations of sprawl is also a major source of ambiguity in defining sprawl (Jaeger et al., 2014; Gaslter et al., 2001). Seeking to instill some order, Wilson and Chakraborty (2013) have identified three categories in which definitions of urban sprawl can be sorted. Sprawl is respectively portrayed as the consequence of a negative externality; as a particular pattern of development, or; as a phenomenon in itself. We selected several definitions of urban sprawl in the literature in order to portray the diversity of perspectives at play. Table 1 presents the said definitions while highlighting their respective particularities.

Authors and Year of Publication	Definition of Urban Sprawl	Particularity of the definition
Burchell et al., (1998)	“Density, or more specifically, low density, is one of the cardinal defining characteristics of sprawl. But density has to be set in context... Sprawl is not simply development at less than-maximum density; rather, it refers to development ... at a low relative density, and one that may be too costly to maintain.” (p.6)	By insisting on setting density “in context” and by pointing to the potential costs of low density, the definition stress that sprawl should be assessed in relative terms: i.e. relative to localised circumstances (cultural, geographical, etc.) and relative to a sound use of the resources in that particular context
Sierra Club, (1998)	“low-density, automobile-dependent development beyond the edge of service and employment areas”	The definition stresses some of sprawl’s spatial characteristics (density, position relative to service etc.) and effects (automobile dependence).
Nelson and Duncan, (1999)	“Unplanned, uncontrolled, and uncoordinated single-use development that does not provide for an attractive and functional mix of uses and/or is not functionally related to surrounding land uses and which variously appears as low density, ribbon or strip, scattered, leapfrog, or isolated development.” (p.1)	The definition mixes normative and affective criteria (functional, attractive), spatial attributes (scattered, isolated, etc.) and the characterization of development processes (uncontrolled, etc.).
Barners et al., (2001)	“sprawl as a pattern of land-use/land cover conversion in which the growth rate of urbanized land (land rendered impervious by development) significantly exceeds the rate of population growth over a specified time period, with a dominance of low-density impervious surfaces”. (p.4)	The definition refers to an urbanization processes (land cover conversion, ratio land urbanized/population growth) and the resulting spatial patterns (land-use) and spatial properties (density, impervious surfaces, etc.)
Gaslter et al., (2001)	“Sprawl (n.) is a pattern of land use in a UA that exhibits low levels of some combination of eight distinct dimensions: density, continuity, concentration, clustering, centrality, nuclearity, mixed uses, and proximity”. (p.685)	Sprawl is defined in purely spatial terms, as the pattern resulting from the combination of eight properties manifested at “low-levels” of intensity. The said properties allow quantification, hence inaugurating the “first multidimensional measures of sprawl by disaggregated land-use patterns into eight different dimensions” (Ewing and Hamidi, 2014). Intensity thresholds (“low”) are as per operational definitions

Jaeger et al., (2010)	"A landscape suffers from urban sprawl if it is permeated by urban development or solitary buildings. For a given total amount of build-up area, the degree of urban sprawl will depend on how strongly clumped or dispersed the patches of urban area and buildings are; the lowest degree of sprawl corresponds to the situation when all urban area is clumped together into the shape of a circle. The highest possible degree of sprawl is assumed in an area that is completely built over. Therefore, the more urban area present in a landscape and the more dispersed the urban patches, the higher the degree of urban sprawl". (p.400)	Sprawl is defined in spatial and topological terms and as a gradient, which take into consideration the developed, or "built" land cover.
Jaeger and Schwick, (2014)	"A landscape suffers from urban sprawl if it is permeated by urban development or solitary buildings and when land uptake per inhabitant or job is high. The more area built over and the more dispersed the build-up area, and the higher the land uptake per inhabitant or job (lower utilization intensity in the built-up area), the higher the degree of urban sprawl". (p.296)	Further from Jaeger et al. 2010 definition, sprawl is defined in spatial and topological terms and as a gradient, which takes into consideration the developed, or "built" land cover as well as land uptake (expressed in ratios inhabitants/land area and jobs/land area).
Ewing, Tian, and Lyons, (2018)	"sprawl is operationally defined as low density, single use, uncentered, or poorly connected development". (p.96)	This operational definition of sprawl centers on four spatial characters affecting the distribution of people and urban functions (land-use) and the configurational properties of the street network (connectivity).

Table 1. Different definitions of urban sprawl

The definitions of sprawl vary greatly depending on the disciplinary, theoretical, and methodological perspectives, as well as the heuristic objectives of their authors. Accordingly, these definitions are more or less expansive, comprehensive, refined, inclusive, complex, or multidimensional. As evidenced by the sample of definitions introduced in Table 1, no unitary definition can capture the full complexity of sprawl. Yet, most definitions revolve around a handful of recurring themes. Sprawl has temporal and spatial dimensions. It refers to both an urbanization process and to the resulting spatial forms. Spatially speaking, it pertains to the modalities of an occupation of the land, i.e., land-coverage and land-use patterns. Land-use refers to the spatial distribution of populations and activities as well as to the material structures that house and support those. Sprawl is associated with the low intensity of land use. In the absence of normative and operational definitions that specify the thresholds for low intensity, sprawl can only be understood in relative terms. More specifically, sprawl manifests a lower intensity of occupation of the land than other parts of the same urbanized area presenting similar geographical and spatial opportunities and constraints. Sprawl is a form of urban development that produces a suboptimal return on investment, environmentally, socially, and economically speaking, for the community.

More synthetically stated: the term sprawl denotes an urbanization process that produces low-intensity modes of an occupation of the land. This is characterized by built and spatial forms that are suboptimal in serving their purposes when taking into consideration their geographical, cultural, and technological contexts and local historical precedents.

This definition is purposefully vague on the spatial attributes and properties of sprawl, as well as on its processes and outcomes. The literature doesn't produce a unified portrait in these regards, but some common grounds can be noted. The next section centers on the spatial properties and characters of sprawl as per the contributions of influential and respected figures in the field. The following section will trace a rapid portrait of some causes and consequences of sprawl routinely invoked in the literature.

3.2 Spatial Characteristics of Urban Sprawl

Even though there is little unity in the definitions of urban sprawl, there is a general agreement that the latter is a land use development process that produces recognizable, and perhaps measurable, spatial patterns. Table 2 lists spatial characteristics routinely evoked by these and other authors. They are representative of what the literature on sprawl puts forth. Those characteristics are integral parts of the attempt to define and delineate sprawl as an operational concept for the analysis. Further, they open the possibility of quantitative measurements of the various manifestation of the phenomenon, an aspect that will be discussed in a subsequent section of this paper. Harvey and Clark (1965) remind us that "there is an important characteristic of sprawl which must be remembered. Sprawl, by any definition, refers to settled areas no matter what their characteristics may be" (p.8). Accordingly, the spatial characteristics and patterns listed in Table 2 refer to "built-up" i.e., urbanized areas as opposed to natural or agricultural landscapes.

Authors and Year of Publication	**Spatial characteristics of Urban Sprawl**
Harvey and Clark, (1965)	continuous low density, ribbon development extending out from the city, discontinuous or leap-frog development.
Ewing, (1997, 1994)	leapfrog or scattered, low-density, single-use development

Burchell et al., (1998)	low density, unlimited outward expansion, land uses spatially segregated, leapfrog development, widespread commercial strip development;
Squires 2002 in Stone and Frumkin, (2010)	geographic expansion over large areas, low-density land use, low land-use mix, low connectivity, [and heavy reliance on automobiles relative to other modes of travel]
Zhao, (2010)	Low density and dispersed development in physical aspect, and a low degree of local mixed land use in functional aspect.
Ewing and Hamidi, (2014)	leapfrog or scatted development, commercial strip development, expenses of low-density development, or expenses of single-use development. [one prominent functional indicator of sprawl: poor accessibility]
Jaeger et al., (2015)	spatial expansion of urban areas, scattering of settlements, i.e., how dispersed patches of built-up areas are, low-density development (i.e. area-intensive growth). (p.58)
Barrington-Leigh and Millard-Ball, (2015)	low densities, spatially segregated land uses, a street network with low connectivity. (p.8244)
Ewing, Tian, and Lyons, (2018)	[poor accessibility and automobile dependence].

Table 2. Spatial characteristics of urban sprawl commonly highlighted in the literature

References to automobile dependence were included in the table since they are stressing a functional characteristic of sprawled environments that derives directly from sprawl inherent spatial patterns. Leaving aside such functional considerations, the listed characteristics all fall into two broad categories. They are either geometrical or relative to the land-use composition.

When analyzing the system of the built environment, morphologists probe the artefacts and spatial forms through three sets of geometrical categories: configuration, i.e., shape (morphometric analysis); dimensions (metrological analysis), and; relative position, i.e. spatial syntactic relations and parthood relations (mereological analysis – i.e.: part to part and part to whole). Expressions such as *ribbon development, continuous, discontinuous, leap frog, and scattered* all refer to shape and open up the possibility to conduct morphometric analyses. The expressions *expanse, widespread, and low density* evidently refer to dimensional characters amenable to metrological analyses. Whereas the terms *spatially* *segregated or network connectivity* point to a relative position in space and to topological relations that can be subjected to mereological and spatial syntax analyses.

References to *single-use development, land-uses, commercial strips, land-use mix, and segregated land-uses* are all pertaining to a land-use composition in sprawled environments. They open up the possibility to analyze and characterize the land-use make-up and the levels of land-use homogeneity or heterogeneity in the urbanized environment.

3.3 Causes and Consequences of Urban Sprawl

3.3.1 Causes of Urban Sprawl

Regardless of how it is defined and conceptualized, there is no doubt that sprawl is induced by a variety of factors. The causes of urban sprawl are not all unequivocal and immediate. Some are direct; others are indirect. They are difficult to untangle, and the literature on the matter reflects those difficulties and ambiguities. Pendall (1999) argued that sprawl is a response to an array of fiscal, socio-economic, political, and physical forces. Yet, over the past several decades, some of these drivers have changed as a consequence of shifting realities in each of those realms.

A significant body of early studies links urban sprawl with strong consumer preference for suburban living and to the alleged 'flight from city blight' or a 'white collar' lifestyle (Echenique et al., 2012). Gordon and Richardson (1997) argue that "[l]ow-density settlement is the overwhelming choice for residential living" (p.96). The *National Housing Survey* (1996) conducted by the firm Fannie Mae (un-famous for its role in the 2008 mortgage subprime scandal) equates urban sprawl with the *American Dream*, epitomized in the enthusiasm for owing a big single-family detached house in the suburbs. Bruegmann (2006) connects suburban sprawl to the American Dream too. This explanation, however, has been questioned by others. Ewing (1997) argues that, if offering a more complete and broader list of housing options, suburbs ranked low relative to other residential alternatives. Besides, consumers' preferences shift over time (Ewing and Hamidi, 2015). Barrington-Leigh and Millard-Ball (2015) notice more recently that there is an apparent shift in consumer preferences toward urban living. Similarly, Newton et al. (2000) demonstrate that apartment living is becoming much more acceptable in Australia.

Other researchers have linked urban sprawl with government regulations (Hamidi and Ewing, 2014; Bart, 2007; Yin and Sun, 2007; Levine, 2006; Pendall, 1999; Burchell et al., 1998; Downs, 1998; Ewing, 1997, 1994; Gordon and Richardson, 1997a, 1997b; Harvey and Clark, 1965). To summarize some of their key findings, regulations have curtailed and inflected development by creating an imperfect land market that was not only distorted by externalities, but further deteriorated by stringent low-density regulation and imposed segregated land uses. Yin and Sun conclude that “[s]prawl has been caused by poor planning and fragmented governance on land use” (Yin and Sun, 2007, p. 150). Levine (2006) has tested how the current zoning regulations contribute to sprawl. He calls the opposition between planning and the market “an imaginary dichotomy,” (Levine, 2006, p. 107) and argues that low-density zoning is limiting the full exercise of the free market in real estate. Brueckner (2000) posits for his part that market failures have contributed to sprawl.

Public subsidies have been identified as another major driver of urban sprawl (Ewing and Hamidi, 2015). In the United States, infrastructure and transportation remain heavily subsidized (Ewing, 1994). Raup (1975) lists a number of public subsidies contributing to suburbanization, such as subsidized highways, tax policies, deductibility of property taxes, mortgage interest particularly beneficial for suburban residents, and public utility pricing policies.

Lastly, technological advancements in transportation, and in particular, the automobile (Hamidi and Ewing, 2014; Brueckner, 2000) and telecommunications (EEA, 2016b) have been invoked for their contribution to urban sprawl. The appearance of the automobile and the expansion of the automobile industry has fundamentally changed the way we build our cities. The sprawled urban forms stem from car-oriented development that thrived in the context of generalized automobility.

This short summary of the causes most frequently invoked to explain sprawl is useful in order to stress that there are systemic and structural factors driving sprawl (including some leveraging by planning policies). Sprawl is neither the product of master design nor the “natural” and inevitable outcome of civilizational evolution. Sprawl thrived because it served the economic interests of those involved in the auto industry and because the mode of production of housing was tweaked in its favor. Perhaps most importantly, sprawl thrived because a significant proportion of the costs of sprawl, either defined in economic or environmental terms, were not internalized. The latter aspect points to the impacts and consequences of sprawl.

3.3.2 Impacts and Consequences of Urban Sprawl

Discussions on the consequences or impacts associated with sprawl, good or bad, have been going on for decades (Burchell et al.,1998). Those evaluations are mainly based on the social, economic, and environmental outcomes of sprawl (Barnes et al., 2001, p.5; Burchell et al., 1998). A majority of studies conclude that sprawl is an unsound or suboptimal form of urban development (Bogart, 2006). Urban sprawl has been associated with a number of personal and social problems such as the loss of sense of community (Moe and Wilkie, 1997); obesity due to sedentary lifestyle and automobile dependence (Zhao and Kaestner, 2010; Salon, 2006; Lopez, 2004; Ewing et al., 2003); negative impacts on public health (Bray et al., 2005; Frumkin, Frank, and Jackson, 2004); housing affordability (Nelson et al., 2002); income and racial segregation (Ragusett, 2016; Galster and Cutsinger, 2007; Downs, 1998); unaesthetic and homogeneous environment (Burchell et al., 1998; Gordon and Richardson, 1997); central city and downtown decline (Downs, 1999); individual travel costs (Burchell et al., 2002, 2003), etc.

A thorough analysis of the social and economic consequences and implications of urban sprawl are way beyond the scope of this review. Yet, our characterization of sprawled environments, as marked by low-intensity modes of an occupation of the land and characterized by built and spatial forms that are suboptimal in serving their purposes, espouses the idea that sprawl doesn't make the best use of available resources, starting with the land. Such an argument can be made in economic terms, but we contend that it can be made also strictly in morphological terms, by evaluating how different physical and spatial arrangements compare and perform with regard to material resources, consumption, and transformation. Articulating the problem this way, in relation to the material realm, situates the human habitats within the broader context of the geosphere (as per the diagram of Figure 1). Further, the subject of resource consumption and transformation opens on the broader question of environmental transformations and their associated (environmental) costs.

Much of the literature focusing on sprawl and the natural environment indicates that the former causes numerous and serious environmental problems (Yin and Sun, 2007). A rich body of empirical evidences links sprawl with environmental degradations due to GHG emissions (associated mainly with greater vehicle travelling); energy inefficiency; air pollution (traffic, and traffic congestion); overabundance of infrastructure; loss of farmland, forests, prairies, and wetlands; resource depletion; etc. (Ewing and Hamidi, 2015; Bereitschaft and Debbage, 2013; Song, Popkin, and Gordon-Larsen, 2013; Stone, Hess, and Frumkin, 2010; Stone, 2008; Burchfiel et al., 2006; Burchell and Mukherji, 2003; Johnson, 2001; Sierra Club, 1998; Ewing, 1997; Landis, 1995). The links between urban sprawl, climate change, and other environmental problems will be explored at length in Section 5 of this report.

A minority of authors concludes to some benefits associated with urban sprawl. Burchell et al. (1998) state that "benefits of sprawl are mirror images of costs" (p. 8). Burchell et al. (2002) group the benefits of urban sprawl into four categories: housing; transportation; land planning, and; quality-of-life and social benefits. They argue that the sprawled city has the ability to deliver homeownership, as in the potential for real estate investment gains and life style satisfaction. Kahn (2001) points to increased housing affordability and greater equality of housing opportunity across racial lines in sprawled developments.

Note: More information on discussions and debates about urban sprawl and its effects, history can be found in: *Streetcar Suburbs: The Process of Growth in Boston (1870–1900)* by Warner (1978), *The Costs of Sprawl-Revisited* by Burchell et al. (1998), *Suburban Nation: The Rise of Sprawl and the Decline of the American Dream* by Duany, Plater-Zyberk, and Speck (2000), *The Costs of Sprawl—Revisited* by Burchell et al. (2002), *The limitless city: a primer on the urban sprawl debate* by Oliver (2002), *Conventional Development Versus Managed Growth: The Costs of Sprawl* by Burchell and Mukherji (2003), *The international faces of urban sprawl: lessons learned from North* America by Wagner and Cabana (2006), and *Toronto sprawls: a history* by Solomon (2007).

4. Quantitative Research on Urban Sprawl

This section investigates several of the most cited empirical quantitative research projects on urban sprawl in urban literature. Even if many scholars do not agree on the definitions, or on the costs and benefits of sprawl, there is a general agreement that in order to analyze its impacts, we must have valid and reliable measurements to assess it (Hamidi and Ewing, 2015; Barnes, 2001; Torrens and Alberti, 2000). Given the ambiguities pertaining to the definition of urban sprawl, it is not surprising that the topic of measuring urban sprawl is subject to debates and some controversies of its own. Yet, some debates have less to do with the nature of the phenomenon that one tries to measure than with methodological complexities and limitations, as will be seen.

4.1 The Measurement of Urban Sprawl

There are multiple ways to measure urban sprawl (Banai and DePriest, 2014, p.1; Jaret et al., 2009). A wide body of literature in recent years has tried to quantify sprawl by using a variety of sprawl indexes (Laidley, 2016; Barrington-Leigh and Millard-Ball, 2015; Ewing and Hamidi, 2014; Jaeger and Schwick, 2014; Kaczynski, Galster, and Stack, 2014; Song, Popkinb, and Gordon-Larsenb, 2013; Jaeger et al., 2010; Frenkel and Ashkenazi, 2008; Torren, 2008; Lee and Gordon, 2007; Cutsinger et al., 2005; Song and Knaap, 2004; Reid, Pendall, and Chen, 2003; Fulton et al, 2001; Pendall, 2001; Galster et al., 2001; Malpezzi and Guo, 2001; etc.). Comparing and evaluating these measures of urban sprawl can help us to see their strengths and weaknesses. Ewing and Hamidi (2015) propose a classification based on the evolution of approaches and methods according to three stages. The first stage covers the period prior to the year 2000 inclusively, the second stage is from 2001 to 2010, and the third stage is from 2011 until now. Table 3 introduces several methods that are representative of the stages in question.

The first stage documents early attempts to quantify urban sprawl. The methods remained crude and the results were typically coarse and unidimensional (Ewing and Hamidi, 2015, p.414). Early research mainly focuses on the rapid growth of suburbs relative to central cities (Chinitz, 1965). For example, Fulton et al. (2001) analyzed different sprawl patterns among U.S. metropolitan areas between 1982 and 1997 by calculating a metropolitan area's "density," which was defined "as the population of a metropolitan area divided by the amount of urbanized land in that metropolitan area" (p.3). Density has been used as one of the chief measurements or the sole indicator of urban sprawl in many early studies. As Churchman (1999) points out, however, density itself is a complex concept and requires "a more careful approach to its use" (p.389). Hitchcock (1994) reminds us that any discussion of density must beware the pitfalls of averages.

It is now widely understood that sprawl is a complex, multi-dimensional, multiple scalar, and temporal phenomenon (Hamidi and Ewing, 2014; Custinger et al., 2005; Ewing et al., 2002, Frenkel and Ashkenazi, 2008; Galster et al., 2001; Torren, 2008). A notable feature of studies on the matter is their acknowledgment that the measurement of one dimension of urban sprawl cannot fully capture its inherent complexity. The second and third stages mark the attempts to engage further with the multidimensionality of sprawl.

Since 2000, advances in Geographic Information System (GIS), the rising popularity of remote sensing techniques, and the proliferation of spatial data sources have enabled the development of multi-level, multi-dimensional, or multi-disciplinary approaches to tackle quantitatively various dimensions of sprawl by using multiple indicators (Ewing and Hamidi, 2014; Song, Popkin, and Gordon-Larsen, 2013; Torrens, 2008; Barnes et al., 2001).

Gaslter et al. (2001) developed one of the most widely cited and most complex multidimensional sprawl indexes to date (Laidley, 2016; Hamidi and Ewing, 2014). Their approach categorizes land use pattern into eight measurable dimensions: density, continuity, concentration, clustering, centrality, nuclearity, mixed uses (heterogeneity), and proximity. Similarly, Cutsinger et al. (2005) have further extended Gaslter's sprawl measures to twelve conceptually distinct dimensions of land use patterns.

Another article by Ewing, Pendall, and Chen (2003) explored similar territories by using multi-dimensional land use metrics to measure sprawl. It received considerable favorable attention. They took a slightly different approach, starting by specifying four separate sprawl indicators: development density, activity centrality, land use mix, and street accessibility, and then combined them into an overall compactness/sprawl index. This compactness/sprawl indices have since been widely used in a variety of fields, especially in research focused on the built environment and public health.

There are many additional approaches that can be used to measure the multiple dimensions of urban sprawl. We have to limit ourselves, however, to a few novel and innovative examples. Frenkel and Ashkenazi (2008) developed an innovative multi-disciplinary approach derived from landscape ecology. Unlike most of the sprawl studies which focus on one discipline, they measured urban sprawl in Israel by combining three disciplinary perspectives: urban research, fractal geometry, and ecological research. Torrens (2008) measured a range of sprawl characteristics by focusing on one US city: Austin, TX, but operated on multi-levels. His measurement of sprawl starts at the metropolitan level and moves at the local level before going down to the land parcel level.

Subsequent methods for the measurement of urban sprawl, associated with the third stage, were aiming to tackle changes in the degrees of urban sprawl. These methods also aimed to examine the patterns of urban sprawl associated with different periods of development. Even though the previous approaches offered more accurate measurements of urban sprawl as compared to earlier efforts, they generally focused on exploring urban sprawl in a single year (Hamid and Ewing, 2014), which made it hard to observe trends in changes (Barrington-Leigh and Millard-Ball, 2015).

In order to fill such a gap, Ewing and Hamidi (2014) developed new compactness/sprawl indices to measure changes in sprawl in 162 U.S. Urbanized Areas (UZAs) for the years 2000 and 2010, hence allowing for temporal comparisons. Following the same logic, Sarzynski, Galster, and Stack (2014) explored the multi-dimensional variations and changes in U.S. metropolitan land use patterns during the 1990s. Recently, Jaeger and Schwick (2014) have conducted analyses extending the time span considerably. They developed a Weighted Urban Proliferation (WUP) metric to assess urban sprawl in Switzerland and “present for the first-time quantitative figures about the development of sprawl for an entire country over a time period of more than a century” (p.295). Their method is suitable for studying changes in regional sprawl patterns over time and offers valuable tools for analyzing the changing nature of sprawl and urban development historically. Recently, Henning et al. (2015) and EEA & FOEN (2016) used UP and WUP as sprawl metrics for all European countries. Similarly, studies by Wissen et al. (2011) and Schwick et al. (2012) also capture changes in sprawl over time by focusing in Switzerland.

Barrington-Leigh and Millard-Ball (2015) presented “the first high resolution time series of sprawl from 1920 to 2012” in the U.S. They quantified sprawl through a reconstruction of the historical road networks for many subsets of US counties. Nazarnia, Schwick, and Jaeger’s 2016 comparative study includes a 60-year time frame for measuring the degree of urban sprawl while considering different territories in comparing patterns of urban sprawl. Their analysis studied the similarities and differences between patterns of accelerated increase in sprawl in Montréal, Québec City, and Zurich between 1951 and 2011 by applying urban permeation (UP) and weighted urban proliferation (WUP) indices. The results demonstrated that different areas exhibited different patterns and degrees of urban sprawl. This approach opens up possibilities for the cross-cultural investigation of sprawl measurement. More studies are needed to test the universal applicability of their sprawl metrics. Table 3 summarizes the evolution of methods used to measure sprawl.

Note: Scientific efforts on review the measurement of urban sprawl can be found in: *The Measurement of Suburban Sprawl: An Evaluation* by Jaret et al. (2009).

Stage	Author (s) and Year of publication	Method used	Significance of the study	Critiques
Stage 1 (before 2000) **Crude and One dimensional**	Chinitz, (1991)	The growth of suburbs relative to central cities	The urban development patterns in the United States have been shaped by a set of 'Locators'.	Measurements of a single dimension of urban sprawl cannot fully capture its complexity.
	Pendall, (1999)	Population divided by the amount of developed land to obtain density estimates for 1982 and 1992	Pendall's measure of sprawl is strictly related to density.	
Stage 2 (2001-2010) **Multi-level, Multidimensional, or Multi-Disciplinary Approaches**	Fulton et al., (2001)	Analyze different sprawl patterns among U.S. metropolitan areas between 1982 and 1997 by calculating a metropolitan area's "density", which was defined "as the population of a metropolitan area divided by the amount of urbanized land in that metropolitan area" (p.3).	Their concept of sprawl was strictly density-related; Sprawl occurred where land was consumed at a faster rate than population growth	There is a lack of consistency across different studies. Studies used different approaches have delivered very different results, sometimes even contradictory results for the same city by different methods (Ewing and Hamidi, 2015; Jaeger et al., 2010).
	Gaslter et al., (2001)	They first categorized land use pattern into eight dimensions: density, continuity, concentration, clustering, centrality, nuclearity, mixed uses (heterogeneity), and proximity.	One of the first multi-dimensional measures of urban sprawl	
	Ewing, Pendall, and Chen, (2003)	Four separate sprawl indicators: development density, activity centrality, land use mix, and street accessibility; and then combined into an overall compactness/sprawl index.	These compactness/sprawl indices have been widely used in many fields, especially in the built environment/health research.	
	Cutsinger et al., (2005)	Use twelve conceptually distinct dimensions of land use patterns to measure urban sprawl	Extended Gaslter's sprawl measures	
	Frenkel and Ashkenazi, (2008)	Combine three different disciplines: urban research, fractal geometry, and ecological research.	"urban sprawl is not necessarily expressed in terms of a decreasing tendency in density with time" (p.71).	
	Torrens, (2008)	Focuses on one US city: Austin, TX, but operated on multi-scales	Surprisingly, Torrens found that land-use became more mixed in the face of sprawl.	

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	Song, Popkin, and Gordon-Larsen, (2013)	A reduced set of neighborhood metrics	Quantify the physical form of neighborhoods with varying sizes in the U.S. and aiming to achieve national wide applicability	
Stage 3 (2011-now) **Longitudinal and Evolutionary Approaches**	Ewing and Hamidi, (2014)	A new compactness/sprawl index to measure changes in sprawl	Allowing multi-year comparisons	Sprawl measure should be context-sensitive, when measuring urban sprawl in different countries or regions, benchmarks set by different authors should be examined carefully because the precise meaning of urban sprawl varies enormously between areas.
	Jaeger and Schwick, (2014)	Weighted Urban Proliferation (WUP) metric	"present for the first-time quantitative figures about the development of sprawl for an entire country over a time period of more than a century" (p.295).	
	Sarzynski, Galster, and Stack, (2014)	The multi-dimensional variations and changes in U.S. metropolitan land use patterns	Study found that metropolitan areas became denser during the 1990s but developed in more sprawl-like patterns across all other dimensions.	
	Barrington-Leigh and Millard-Ball, (2015)	Quantify sprawl through a reconstruction of historical road networks for a substantial subsets of US counties.	"the first high resolution time series of sprawl from 1920 to 2012" in the U.S.	
	Nazarnia, Schwick, and Jaeger, (2016)	Apply urban permeation (UP) and weighted urban proliferation (WUP)	Not only enlarged the time frame for measuring degree of urban sprawl, but also expanded territories for comparing patterns of urban sprawl. This approach opens up possibilities for cross-cultural investigation of sprawl measurement.	

Table 3. Three stages in the measurement of urban sprawl

4.2 Challenges Facing Quantitative Research on Urban Sprawl

By reviewing a wide range of quantitative research on urban sprawl, we have noticed that the quantification of urban sprawl has evolved simultaneously with the progress of its definition. Pendall (1999, p.558) stresses that “the measurement of sprawl is not straightforward, partly because of the variation in how sprawl is defined.” Compared to the earlier stages of attempts at measurement, significant progress has been made toward a more accurate measure of urban sprawl. It is commonly accepted that urban sprawl is a multi-dimensional phenomenon that requires a different set of measures for each dimension. Studies using different methods, however, have delivered differing results in a sometimes-contradictory assessment of sprawl for the same city when measured by different methods (Ewing and Hamidi, 2015; Jaeger et al., 2010). One potential cause is pointed out by Torrens, who suggests that a lack of proper theoretical foundation might lead to an ill-defined interpretation of the data: “[m]ethodologies are highly variable and are often data driven rather than having a foundation in theory or practice” (Torrens, 2008, p.8). Schwarz (2010) concludes that the lack of consistency across different studies limits our ability to study and compare urban environments across cities, regions, or countries. Comparative studies are still rare among these categories.

Important limitations are clear and apparent. No measurement is perfect, obviously, yet each method has its own advantages and disadvantages, which should be carefully reviewed in accordance with the objectives of the empirical study considered. Future research will benefit from exploring the range of options currently available and taking a more comprehensive and systematic approach. Assessing quantitative research methods on urban sprawl would likewise benefit from greater theoretical clarity. We contend that the theoretical, methodological, and empirical contributions from the discipline of urban morphology can help us to develop a proper theoretical framework for the quantitative analysis of sprawl. In particular, by situating sprawled environments within their broader context, comprised of a variety of urban forms manifesting different densities and spatial compositions; and also, by helping to develop methods that characterize and quantitatively analyze the said diversity of conditions.

Note: Discussion on the challenge in measuring urban sprawl can be found in: *The Fundamental Challenge in Measuring Sprawl: Which Land Should Be Considered?* By Wolman et al. (2005).

5. Urban Sprawl and Climate Change

The progress toward more accurate measurements of urban sprawl has enhanced our ability to understand and measure its environmental consequences, including the relationship between sprawl and climate change. This section reviews some current research centered on the said relationship while focusing on trends in urban land use/land cover change and transportation. By definition, the environmental impacts need to be assessed dynamically, against some sort of balance sheet. The environmental costs incurred by development result from an alteration of pre-existing conditions that reduce the yield of natural systems or compromise their capacity to serve their ecological functions optimally. Not all anthropogenic transformations are detrimental to the natural systems. Pre-industrial agriculture, based on the principle of stewardship of the land, offers a case in point. Indigenous peoples have practiced silviculture and agriculture in the Saint-Lawrence River valley for hundreds of years with no apparent harm to the environment (Munoz et al., 2014). Similarly, incremental anthropogenic transformations over a long period of time allow natural systems to reach a new state of equilibrium, which Magnaghi calls neoecosystems (Magnaghi, 2014).

The difficulties that come with assessing the environmental costs of urbanization, including climate change, come from the fact that the interactions between anthropic and environmental transformations are extremely complex and intricate, as they unfold at multiple levels of spatial resolutions. For instance, a compact and densely populated urban organism alters the natural substratum drastically; yet, those alterations are highly concentrated in space in such a way that their impacts might be lessened at another spatial resolution. For their part, controlled access highways crisscrossing large territories are contributing to landscape fragmentation, and their environmental impacts on the fauna might be much bigger than their physical footprint would suggest at first. Further, some environmental impacts of urbanization and sprawl are directly felt, whether others are indirect. In each case, form matters. Heating a dwelling in winter entails the production and consumption of energy. Yet, compact inner-city residential forms are more energy efficient than spatially dispersed suburban ones. Similarly, low-density residential development will generate more numerous and longer trips that will translate in a significant, though indirect, environmental toll. The way we build and practice our cities has changed dramatically over the past decades. Sprawl has been a central feature of said development, which has come at colossal environmental costs. Some of those costs are drivers of climate change. Other costs come in the form of increased vulnerability to the already felt and anticipated impacts of climate change. Direct and indirect relationships between sprawled urbanization and its causes and consequences on the environment are difficult to untangle (re: the Diagram in Figure 1 of this report). As an example, sprawl reduces biomass, which produces a direct impact on climate change (by lessening the capacity to capture CO_2). Such reduction of the biomass also affects biodiversity. This, in turn, impacts insects and animals that are already vulnerable due to ongoing climate change itself. Some of those insects and animals might provide essential ecological services for the production of food for human consumption, hence contributing to what could be described as a perfect storm. This research approaches such conundrums in a pragmatic way. While being centered on climate change, it focuses on the physical planning drivers of change, including drivers that contribute to other unfolding environmental crises, or drivers that increase the urban vulnerabilities regarding the impacts of climate change. The following sections detail our approach.

5.1 On Causes and Consequences of Climate Change

The Intergovernmental Panel on Climate Change (IPCC, 2007a) has portrayed climate change in the following terms: "[w]arming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global mean sea level" (p.5). Climate change has become the leading environmental issue of our time, this includes the effects it has on urban planning (Ewing and Hamidi, 2015; Marsden and Rye, 2010). Curbing it and preparing for its consequences has become a top priority for nations around the world. Climate change impacts, directly and indirectly, every region and everyone living on our planet in a variety of ways. The effects of climate change include more frequent and severe weather, storm surge, flooding, heat waves, increased air pollution, higher wildlife extinction rates, adverse human health impacts, reduced agricultural/ecosystem productivity, increased vulnerability, more acidic oceans, disappearance of polar ice caps and glaciers, rising oceans and sea levels, etc. (IPCC, 2017). The long-term effects are potentially catastrophic (Alexander, 2014).

There are two main causes of climate change: natural and anthropogenic drivers (see Conceptual map 1). Volcanic activity and solar output are the two primary natural contributors to climate change. Within scientific communities, there is an overwhelming consensus that has existed for some time to the effect that the GHG emissions caused by human activities are the major cause of climate change (Hamin and Gurran 2009; De Coninck et al., 2008; Ewing et al., 2008; Bart, 2007; Bulkeley and Betsill, 2005; Hennicke, 2005). The connection between human-induced GHG emissions and climate change has been clearly articulated in the IPCC's 2001 report. There is also a consensus within the scientific community that among all of the GHGs, carbon dioxide (CO2) is the most detrimental contributor to global climate change (Yigitcanlar and Kamruzzaman, 2014; While, Jonas, and Gibbs, 2010; Ewing et al., 2008). The 2007 IPCC report identifies two primary anthropogenic drivers of increases in atmospheric CO2: fossil fuel combustion and land use change. Between 1970 and 2010, around 78% of the total GHG emissions increase was caused by fossil fuel combustion and industrial processes (IPCC, 2014). From 1990 to 2010, the GHGs in the U.S. has increased by 10.5% to 6,821.8 tera-grams (or million metric tons) of carbon dioxide (CO_2) equivalent (Tg CO_2 Eq.) (EPA, 2012). It is apparent that global GHG emissions will continue to grow over the next few decades under current climate change mitigation policies and related sustainable development practices (IPCC, 2007).

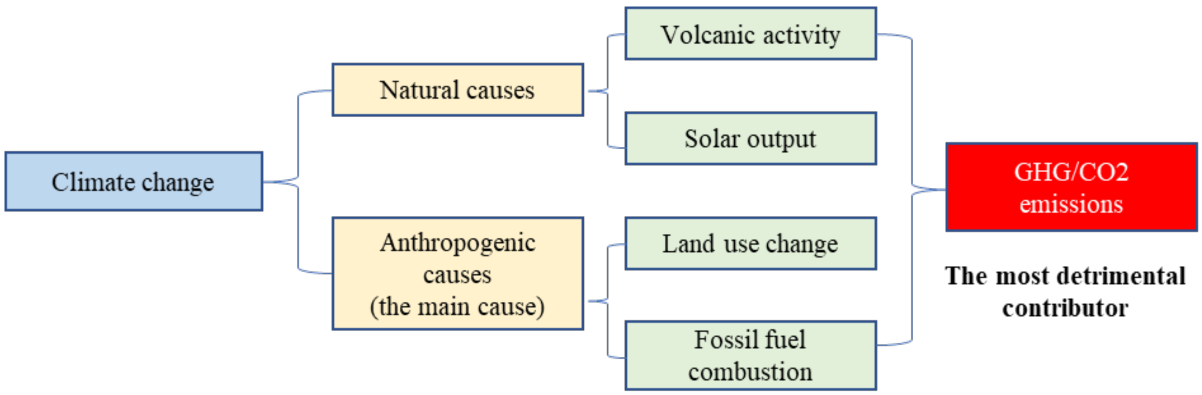


Figure 2. Diagram of the causes of climate change

5.2 The Environmental Impacts of Urban Sprawl

The environmental impacts of urban sprawl are particularly important because they are tremendous and long-lasting. These impacts have been researched quite extensively and research has produced large bodies of empirical evidences (Dupras and Alam, 2015; Hamidi et al., 2015; Carmona, 2014; Wilson and Chakraborty, 2013; Ren et al., 2012; BAPE, 2009; Holden and Norland, 2005; Burchell et al., 2002; Handy and Clifton, 2001; Johnson, 2001; Ewing, 1997; Alderman, 1997; Burton and Matson, 1996; Hillier, 1996; Hillier et al., 1993). Wilson and Chakraborty (2013) summarize the environmental impacts of urban sprawl by classifying them into four categories respectively pertaining to air, energy, land, and water. Barnes et al. (2001) stress that the environmental impacts of sprawl span local, regional, and global geographical scales. In an early and widely cited article, Johnson (2001) offers a useful summary of various environmental degradations associated with urban sprawl (p.721-722). Not all environmental impacts of sprawl are linked to climate change, but most are. This is either by contributing to that crisis directly or indirectly, or by increasing the vulnerabilities in regard to climate change felt and projected effects. Table 4 lists the types of environmental impacts of urban sprawl by following and expanding Johnson's summary. The following sections will focus on the impacts that are more specifically linked to the climate crisis.

Note: More information on the environmental impacts of urban sprawl can be found in the following papers: *Environmental impacts of urban sprawl: a survey of the literature and proposed research agenda*, by Johnson, Michael P. (2001) in Environment and Planning A, Vol. 33, pp. 717-735 and *The Environmental*

Impacts of Sprawl: Emergent Themes from the Past Decade of Planning Research, by Wilson Bev and Chakraborty Arnab (2013) in Sustainability, Vol. 5, pp. 3302-3327.

Air	**Energy**	**Land**	**Water**	**Ecosystem**
GHG/CO2	Higher energy consumption	Loss of environmentally fragile lands	Freshwater withdrawals	The loss of biomass (The Nature Conservancy, 2018, p. 43-49)
Emissions and air pollution (Stone, 2008)	Energy inefficiencies	Reduced regional open space (Ewing, 1994)	Stream hydrology and geomorphology Alteration and drying	Ecosystem fragmentation (Margules and Meyers, 1992)
Degradation of air quality	Urban heat island (Stone, Hess, and Frumkin, 2010)	Decreased aesthetic appeal of landscape (Burchell et al., 1998; Fulton, 1996)	Increased risk of flooding (Adelmann, 1998; PTCEC, 1999)	Increased vulnerability of ecosystem
Enhanced surface temperature		Loss of prime farmland (Berry and Plaut, 1978; Fischel, 1982; Nelson, 1990)	Increased vulnerability to heavy precipitation events	Reduced diversity of species
Air toxics, methane gas, NO2, SO2,		Excessive removal of native vegetation	Decrease of water quality (Tu et al., 2007)	Reduced ecosystems service (Dupras and Alam, 2015)
		Monotonous residential visual environment	Water pollution	Reduced ecosystem resilience
		Habitat loss, degradation and fragmentation		
		Presence of ecologically wasteful golf courses (Steiner et al., 1999)		
		Increased low intensity built-up area		
		Increased impervious surface		
		Extensive infrastructure		
		Soil degradations		

Table 4. Tabulating the main environmental impacts of urban sprawl

5.3 The Interplay between Urban Form and Climate Change

5.3.1 The Linkages between Urban Form/Urban Sprawl and Climate Change (GHGs)

There are growing concerns about the impacts of urbanization on climate change because "in the coming decades, urban populations are expected to double while rural populations level off or decline" (Marshall, 2008, p.3133). Moreover, cities are already responsible for approximately 80% of the overall GHG emissions (Iwata and Managi, 2016). Significant efforts have already been made in exploring the relationships between urban form, urban sprawl, energy consumption, and climate change (Baklanov, Molina, and Gauss, 2016; Ewing and Hamidi, 2015; Baur et al., 2015; Stone et al., 2010; Stone, 2008; Gonzalez, 2005; Ewing, Pendall, and Chen; 2002). As previously stated, the relationship between urban sprawl and climate change is not unilateral: "[o]ur built environment affects climate change, but it is also affected by climate change" (EPA, 2013, p.69). Climate change will influence the forms of urban development because future development patterns must cope with some of its consequences. This is like a feedback loop that makes climate change one of the most important agents in the change of land use (Deng et al., 2015). Past urban sprawl already increases our vulnerability and our ability to resist the adverse effects of climate change, which will call for resolute remediation measures. For the purpose of limiting the scope of this study, however, we focus primarily on how urban sprawl/urban development patterns have contributed to climate change.

Urban form is ranked as a driver for GHG emissions in the Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (a.k.a. the Fifth Assessment Report hereafter). The GHG emissions pertaining to urban form are imputable in particular to mobility patterns and energy use, especially for the heating and cooling in buildings (Seto et al., 2014). Bart (2010) noted that urban sprawl contributes to climate change through increased CO2 emissions by fostering car-oriented transportation, but also by consuming more land than ever before. Yigitcanlar and Kamruzzaman (2014) note that "[t]ransport and land uses are the two major sectors that contribute most in emitting CO2 in the environment" (p.2121). In 2010, agriculture, forestry, and other land use were responsible for 24%, while the transportation sector was responsible for 14% of global GHG emissions (IPCC, 2014). The following section investigates the linkage between density, land use/land cover change, transportation, and GHG/CO2 emissions, to explore the connections between urban sprawl and climate change. The diagram from Figure 3 maps the environmental, including climate change, drivers that are most frequently addressed in the literature on sprawl and the environment.

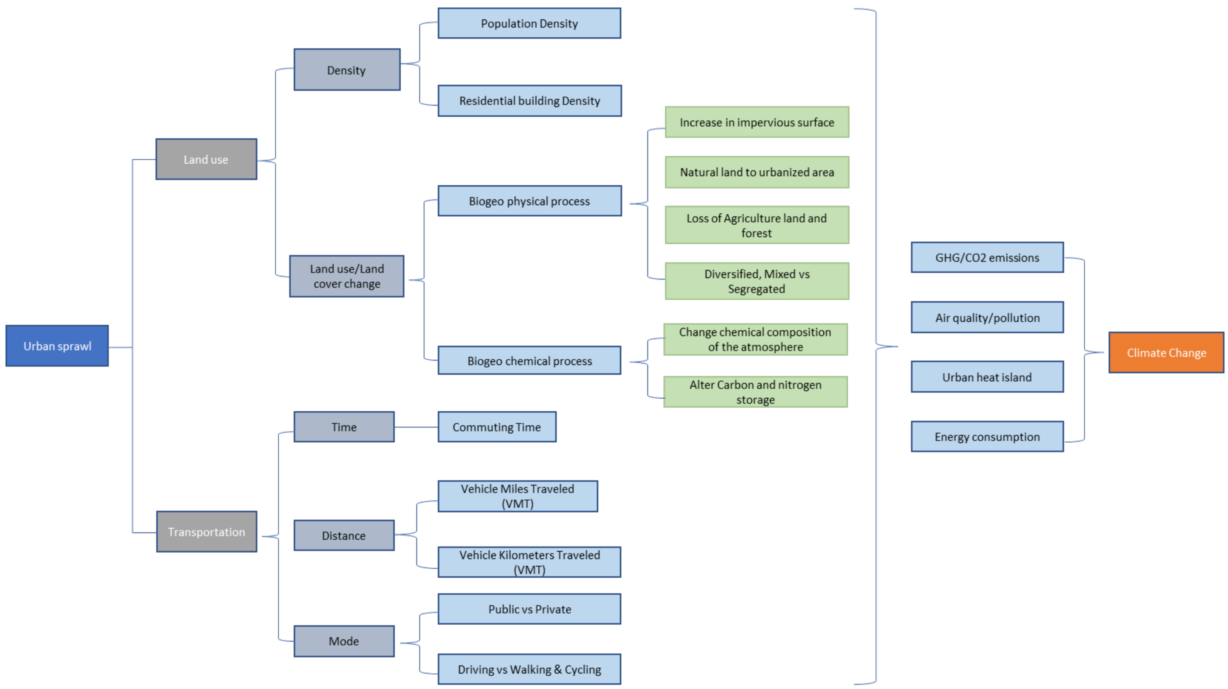


Figure 3. Diagram of urban sprawl, climate and environmental drivers

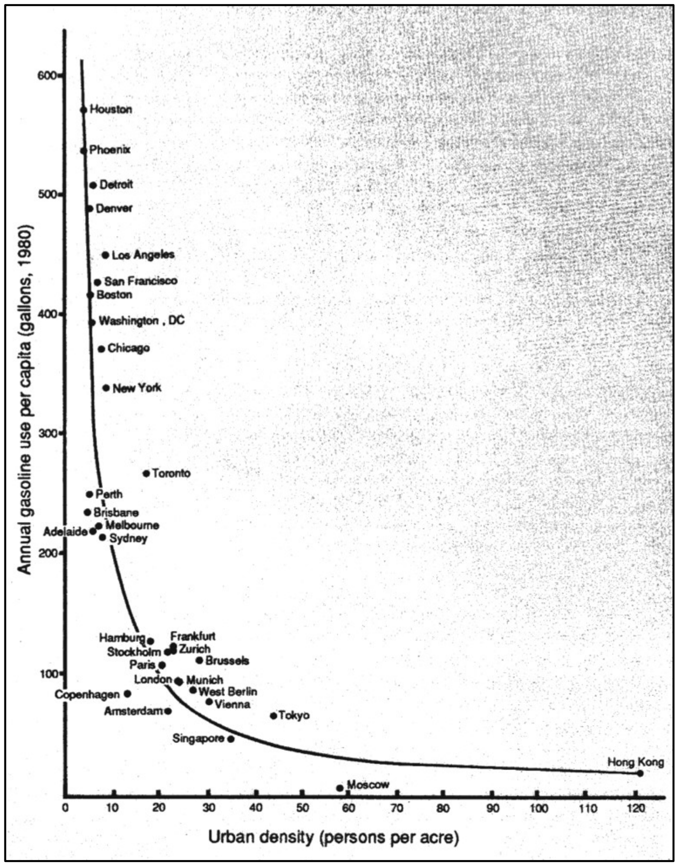
5.3.2 Urban Density, GHG/CO2 Emissions and Energy Consumption

Low density is one of the most defining characters of urban sprawl. The density of residential land-use in particular, expressed in inhabitants/land area or dwellings/land area, has been the first and most studied spatial parameter of sprawl. Not surprisingly, the first studies addressing the environmental impacts of sprawl have revolved around density. Given its importance and antecedence in the literature, we start by the effects of density on GHG/CO2 emissions. Today, density is still being widely used as a key variable for measuring urban sprawl. Such an indicator is also routinely used in planning to fix targets aimed at creating more sustainable communities (see, for instance, the PMAD in the Communauté métropolitaine de Montréal, CMM, 2011). Different density metrics have been utilized in various sprawl research to explore the complex effects of urban density on GHG/CO2 emissions and energy consumption. We focus on two such metrics used to analyze the impacts of population density (section 5.3.2.1) and residential building density (section 5.3.2.2) on GHG/CO2 emissions and energy consumption. The spatial distribution of the population, either expressed in residents or dwellings per land area, affect the

GHG/CO2 emissions in two main ways: according to their associated transportation patterns or in the form emissions associated with residential energy consumption.

5.3.2.1 Population Density and GHG/CO2 Emissions

The first wave of studies centered on the impacts of density stem from the inaugural efforts of Newman and Kenworth. Their 1989 paper was not directly addressing environmental impacts per se. Rather, they examined the relationship between population density and per capita gasoline consumption for a global sample of 32 cities around the world (Newman and Kenworthy, 1989). The results indicated a strong link between population density and transportation energy use. Per capita, gasoline consumption is negatively correlated with population density. As shown by the widely cited figure from Newman and Kenworthy (1989), U.S. cities are located on the upper left of the graph (high gasoline consumption associated with low densities), most Asian cities are located on the bottom right of the graph (low gasoline consumption and high densities), and European cities are in the middle portion of the graph (Figure 4). Toronto is situated in the middle of the pack. It is reasonable to conclude that Montréal would be situated in the same range as Toronto, since similar conditions prevail in both cities in terms of densities and public transit ridership, in particular. Many studies have since translated gasoline consumption into GHG/CO2 emissions to quantify the environmental impacts of density. Studies have shown that the spatial distribution of GHG/CO2 emissions displays different patterns in various cities or regions due to factors such as population densities, morphological characteristics, geographical location, regional climatic variation, the source of energy, etc. Other studies have tried to untangle the impacts of population density and other factors on GHG/CO2 emissions or energy consumption in major cities around the world (Lee et al., 2016; Doherty et al., 2009; Martinez-Zarzoso et al., 2007).



Newman and Kenworthy, 1989

Figure 4. The relationship between gasoline use per capita and population density in major cities

Using data from 2000, Glaeser and Kahn (2010) used 66 major cities in the United States to explore how major cities compare regarding per-household emissions. Their detailed quantitative analysis showed that gasoline usage is negatively correlated with population density but positively correlated with distance from downtown, which indicates that sprawling development induces more gasoline usage. According to their city CO2 emission ranking, New York is ranked at the bottom in terms of emissions thanks to its high employment and population concentrations, plus heavy reliance on public transportation. Greenville, South Carolina, ranks the highest. The authors stress that gasoline-related emissions in that city are almost twice the level of emissions in the New York area. These differences, within the same country, suggests that changes in urban development patterns can potentially have large impacts on total carbon emission reductions. APERC (2007) found gasoline consumption per capita of cities in Asia was negatively weakly correlated with population density compared to cities in USA and Oceania.

The above-mentioned studies offer valuable quantitative measurement of the population density on GHG/CO2 emissions, but they generally focus on exploring the relationship in a single year. As such, they do not capture the trends and patterns of change. Taniguchi, Matsunaka, and Nakamichi (2008) bridge that gap by studying the "trend in the relationship between urban layouts, specifically population density and automobile reliance over a prolonged period by using time series data" (p.415) in 38 Japanese cities. Their results reveal that high densities of population produce lower amounts of automobile CO2 emissions per capita in each year of reference compared to low-density environments, but the amount of per capita automobile CO2 emissions in high-density cities gradually increases over time in the Japanese context. That trend spread across all city types since none "shows a decrease in the amount of per-capita automobile CO2 emissions from 1987-2005". Moreover, there is a gradual tendency towards a more dispersed type of city over the period.

A recent paper by Fercovic and Gulati (2016) studied the trend of average household emissions across all Canadian cities over time. Consistent with Taniguchi, Matsunaka, and Nakamichi's findings, they confirmed that higher density is associated with lower gasoline consumption in personal vehicles, but surprisingly, and departing from the Japanese study's conclusions in that regard, they found that the average household emissions across all cities over time are falling from 11.49 tonnes/year in 1997 to 9.7 tonnes/year in 2009 (16% decrease over 12 years). Their explanation for this decline is that "population growth was higher in cities where emissions fell faster" (p.96). Their study suggested that future population growth patterns are likely to lead to greater reductions in the average household emissions for Canada if such growth remains concentrated in already denser cities and regions. Yet, their analysis does not account for intra-regional discrepancies, which is an important aspect, since most of the growth in a city like Montréal, for instance, occurs at the periphery. This aspect of their study introduces us to the next section centered on housing forms and GHG/CO2 emissions.

5.3.2.2 Residential Density and GHG/CO2 Emissions

One of the defining aspects of urban sprawl is low-density development characterized by single-family housing type, which has been associated by many scholars for its higher levels of GHG/CO2 emissions and building energy consumption. Residential building energy use is one of the major sources of GHG/CO2 in the cities. In 2013, the residential sector consumed 22% of the total energy consumption in the United States (EIA, 2013a). In comparison, in Québec, the sector comprised of residential, commercial, and institutional functions was responsible for 10.8% of the emissions in 2015, due to the prevalence of hydro-electricity (Ministère du développement durable, de l'environnement et de la lutte contre les changements climatiques, 2016). Fercovic and Gulati (2016) stress the importance of the source of energy in the ranking of GHG emissions. Their study considers both transportation and household energy consumption at home. Among all the CMAs in Canada, Montréal's residents emit the lowest GHG emissions because of the use of low carbon hydropower for household energy use, followed by Vancouver (p.96). Not surprisingly, Edmonton produces the highest emissions due to coal-based electricity supply, followed by Calgary. Many authors investigating the linkages between urban sprawl, GHG/CO2 emissions, and the associated energy consumption chose to focus on the impacts of residential density (Kim and Brownstone, 2010; Weghe and Kennedy, 2007; Norman, MacLean, and Kennedy, 2006; Newton et al., 2000).

Urban sprawl is often referred to as low-density suburban living, which is constantly compared with an urbanized lifestyle characterized by high-density apartments. Norman, MacLean, and Kennedy (2006) assess residential energy use and GHG/CO2 emissions associated with different residential density development based in Toronto. Two case studies were conducted involving a compact, multistory condominium in an inner city, versus a low-density residential development located at the suburban fringe, respectively. By using a life cycle analysis approach, their analysis shows that no matter how the data is examined, whether on a per capita basis or on a per unit living area basis, the embodied energy and GHG emissions of low-density development are higher than those found in high-density development. The authors assert that increasing residential density in urban environments may make a significant contribution to energy saving and GHG reduction. Another Toronto-based quantitative research study conducted by Weghe and Kennedy (2007) produces a more complete account of the spatial distribution of GHG emissions produced by residential buildings and transportation over the entire Toronto CMA. They found that in terms of the spatial distribution of residential buildings and their associated transportation emissions, large variations existed between census tracts, ranging from 3.1 to 13.1 tonnes of carbon dioxide equivalents per year. Among all tracts, “the top ten in terms of GHG emission were all located in the surrounding low-density tracts, and their high emissions were largely due to private auto use” (p.143). This study clearly indicates that a sprawling, auto-dependent urban form is less beneficial to sustainable development than more compact forms of development.

Similarly, Andrews (2008) distinguished the distribution of GHG emissions along the US rural-to-urban gradient. His results show that “there are clear lessons with regard to the most important factors affecting greenhouse gas emissions along the urban density gradient” (p.860). The spatial distribution of per-capita CO2 emissions displayed “an inverted “U” shape, with post-war suburbs riding the pinnacle.” The population density was negatively associated with vehicle miles traveled (VMT) per capita. The results show that, in New Jersey, detached single-family houses produce 33% more GHGs from building energy use than attached homes, and over 150% more than multi-family units.

Recently, in order to correct for residents' self-selections effects, Kim and Brownstone (2010) measured the impacts of residential density on household annual mileage traveled and fuel consumption by comparing two households that are equal in all respects except the residential density of where they live. Their analytical work demonstrates that "one household is located in a residential area that is 1000 housing units per square mile denser (roughly 50% of the sample average), the household in the denser area will drive 1500 (7.8%) less miles per year and will consume 71 (7.5%) fewer gallons of fuel than the household in the less dense area" (Kim and Brownstone, 2010, p.19). Their simulation model showed a 15% reduction of household annual mileage by relocating a household from a suburban to an urban area. They concluded that residential density has "a statistically significant and economically modest influence on vehicle usage" (p. 28).

Estiri's (2016) study concurred with such general conclusions by demonstrating that, on average, US suburban households consume more energy in residential buildings than their city dweller counterparts. Outside Northern American contexts, Ala-Mantila, Heinonen, and Junnila (2014, 2013) conducted a multivariate regression analysis to assess GHG implications of two typical dwelling types: semi-detached or detached houses and apartments in Finland. They produced concrete hard data evidence for different types of housing that supports the general conclusions reached by Estiris and others based on aggregated data. By evaluating and comparing consumption-based carbon footprints, Ala-Mantila, Heinonen, and Junnila found that if "[H]olding expenditure constant, a rural lifestyle seems to be related to the highest GHG emissions" (p.129) and that low-rise lifestyle represented by semi-detached or detached houses causes approximately 26% more emissions than high-rise ones (Ala-Mantila, Heinonen, and Junnila, 2014).

5.3.2.3 Urban Density and Energy Consumption

Urban density also has a big impact on a residential unit's energy consumption. Housing sizes and types are two important factors influencing residential energy consumption, and hence, GHG emissions in residential sectors (Lee and Lee, 2014). Newton et al. (2000) analyzed the energy consumption associated with two different housing types: detached houses and apartments in Australia. They found that the life-cycle energy consumption of apartments was 10 to 30% less than detached houses. On another scale, Ewing and Rong (2008) analyzed the U.S. Residential Energy Consumption Survey (RECS) data to explore the relationship between housing types and energy consumption. Their results show that residents of single-family homes consume 54% more energy for home heating and 26% more energy for home cooling than do the comparable residents in multifamily housing units. They also found that by doubling the home size, 16% more energy for heating and 13% more energy for cooling is needed. Overall, houses located in compact counties require roughly 20% less primary energy than houses in sprawling counties. Pitt (2013) researched the relationship between sprawl and residential energy use by simulating residential GHG emissions and energy consumption for future housing development. He found that on average, attached homes and multi-family structures are more energy efficient than single-family detached housing types. Four scenarios for potential distributions of housing showed that approximately 23% of energy savings and proportional GHG reductions can be achieved through compact, rather than dispersed, sprawling housing development. Consistent with the trends observed in other studies, Lee and Lee (2014) examined the influence of urban form on individual household's GHG emissions in 125 of the largest urbanized areas in the U.S. Their results showed that by doubling population-weighted density, a 48% and 35% reduction in CO_2 emissions from household travel and residential energy consumption can be achieved, respectively. Shammin et al. (2010) conduct a cross-section study to compare the energy consumption of sprawl versus compact living in the U.S. for 2003. By paying attention to other "sprawl-related" expenditures, their results indicated that "[r]ural households are 17% more energy intensive than urban households and households living in areas with lowest population size (less than 125, 000) are 19% more energy intensive than those living in areas with the highest population size (greater than 4 million)" (p.2372).

In conclusion, very strong evidence demonstrates that low urban densities have negative impacts on GHG/CO_2 emissions and energy consumption. For example, Lick's (2006) meta-analysis demonstrates that residential density and employment density exert a strong influence on travel behavior. Both are negatively correlated to VMT. His findings support the notion that the density is "the strongest predictor of travel behavior amongst all of the other built environment measures" (p.39). Ewing and Cervero's (2010) study, however, conducted another meta-analysis trying to identify general trends in the built environment-travel research before 2009. By computing elasticities for more than 50 refined individual studies, they found a weak relationship between density and travel: "[…] the small elasticities of VMT with respect to population and job densities" (p.275), which challenged the conventional wisdom: "population density is a primary determinant of vehicular travel […]" (p.11). Table 5 summarizes the cited research on the impact of density on energy consumption and GHG/CO_2 emissions.

Author(s) Year of Publication	**Type of Density**	**Relationship Studied with Density**	**Geographical Context**	**Main Results**
Newman and Kenworthy, (1989)	Population density	Gasoline consumption per capita	32 global cities	Per capita gasoline consumption is negatively correlated with population density.
Norman, MacLean, and Kenned, (2006)	Residential density	Energy use and GHG emissions	Toronto	CO2 equivalent emissions are 60% less for high-density than for low-density development.
Weghe and Kennedy, (2007)	Residential building density	GHG emissions	Toronto	Top ten in terms of GHG emission were all located in the low-density tracts
Andrews, (2008)	Urban density	GHG emissions distribution of along the rural-to-urban gradient	United States Canadian cities	Per-capita CO2 emissions very widely following an inverted "U" shape, with post-war suburbs at the pinnacle.
Ewing and Rong, (2008)	House size and type	Housing types and energy consumption	United States	Houses located in compact counties require roughly 20% less primary energy than those in sprawling counties.
Taniguchi, Matsunaka, and Nakamichi, (2008)	Population density	Per capita automobile CO2 emissions	38 Japanese cities	Density negatively correlated with automobile CO2 emissions Per-capita automobile CO2 emissions increased in all city types between 1987 and 2005
Glaeser and Kahn, (2010)	Population density	Household emissions	66 major US cities	Gasoline usage is negatively correlated with population density, and positively correlated with distance from downtown,
Kim and Brownstone, (2010),	Residential density	Household annual mileage traveled and fuel consumption	United States	Household residing in an area that is 1000 housing units per square mile denser drive 1500 (7.8%) less miles per year and consume 70 (7.5%) fewer gallons of fuel than households in the less dense areas

Ala-Mantila, Junnila and Heinonen, (2013)	Residential types (Semi detached and detached houses, apartment buildings)	Consumption-based carbon footprints by residential types	Finland	Low-rise lifestyle causes approximately 26 % more emissions than the high-rise one
Pitt, (2013)	Residential types (attached, multifamily, single family detached housing)	Residential GHG emissions and energy consumption for future housing development	United States	On average, attached homes and multi-family structures are more energy efficient than single family detached housing types.
Ala-Mantila, Heinonen, and Junnila, (2014)	Housing and household types	Consumption-based carbon footprints by housing and household types	Finland	Rural lifestyle related to the highest GHG emissions. Emissions decrease as density increases while moving towards city centers.
Fercovic and Gulati, (2016)	Population density	Average household emissions	Canadian cities	Denser cities produce less emissions than low density ones. Average household emissions across all cities over time are falling.
Estiri, (2016)	Households housing arrangement (city and suburban	Energy consumption by households	United States	On average, US suburban households consume more energy in residential buildings than their city-dweller counterparts

Table 5. Density impacts on energy consumption and GHG/CO2 emissions

5.3.3 Land Use, GHG/CO2 Emissions and Energy Consumption

5.3.3.1 Land Use/Land Cover Change, Land-Use Mix vs. GHG/CO2 Emissions and Energy Consumption

If density is the oldest and most often cited character of urban sprawl, another key aspect of the phenomenon pertains to the ways in which the land is affected by different anthropic functions. The terms land-use and land cover are used in urban planning and environmental studies in reference to the affectations of the land. Land-use refers more specifically to the anthropic usage of the land, while the term land cover is generally used in reference to the physical composition of the anthropic and natural landscapes. Urban sprawl entails substantial anthropogenic alterations of the natural landscape and produce built environments characterized by low-intensity usage of the land and a spatial segregation of urban functions.

Deng, Zhao, and Yan (2013, p.1) stress that the effects on the climate due to land use changes caused by human activities such as deforestation and agriculture practice have been extensively documented. According to some estimates, between one-third and one-half of Earth's land surfaces have been transformed by human development (NASA, 2005). Research has produced an important body of evidence establishing the significance of land use and land cover change on GHG/CO2 emissions, and has demonstrated that land use is playing a measurable and significant role in ongoing climate change at multiple geographic scales (Yao et al., 2015; Foley et al., 2005).

Urban sprawl itself has been associated with massive land conversion at the global scale in the past few decades. Land conversion by sprawl has exerted a significant direct and indirect influence on global climate change (Deng et al., 2013; Deng, Zhao, and Yan, 2013; Dhakal, 2010; Handy, 2005). A change in land coverage pattern (e.g., from forest, grassland, or farmland to urban land) is in itself a significant and direct contributor to climate change due to the loss of biomass, which translates into reduced carbon capture and storage capacity (Pena et al., 2007; Watson et al., 2000; Dale, 1997; Shaw, 1992). Land use patterns and dynamics also impact people's travel behavior by "affecting decisions about how much, where, when, and how to get around" (EPA, 2013, p.2), and influencing the GHG emissions accordingly (Yigitcanlar and Kamruzzaman, 2014; Stern, 2008). Given the intertwined relationship between land use and transportation, it is not surprising that many researchers studied the impacts of land use/land cover change on climate through the angle of travel behavior (Sallis et al., 2004; Boarnet and Crane, 2001; Ewing and Cervero, 2001). Section 5.3.4.3 of this report will detail that aspect.

Land use/land cover change affects the environment through various synthetic effects of biogeochemical and biogeophysical processes (Deng, Zhao, and Yan, 2013; Feddema et al., 2005). The biogeophysics effects refer to the changes of the physical features of the earth's surface (Wang, Li, and Yang, 2015, p.1). One of the ways in which land use/land cover change affects Earth natural systems is by influencing the radiation, heat, and moisture exchange process between the land surface and the atmosphere (Crutzen and Andreae, 1990). By contrast, the biogeochemical process indirectly affects the climate "by altering the rate of the biogeochemical cycle and thereby changing the chemical composition of the atmosphere" (Wang, Li, and Yang, 2015; Feddema et al., 2005).

The conversion of land contributes to climate change by influencing carbon cycles and altering the concentration of the GHG/CO2 in the atmosphere. EPA (2013) reports that about 8% of the total CO2 emissions during the decade of 2000-2010 has been caused by land use change. In urban contexts more specifically, Emadodin, Taravat, and Rajaei's study (2016) showed that urban sprawling land use patterns significantly affect local climate through changes in evaporation rate partially due to loss of valuable arable land, reduction of vegetation cover, and land degradation. Ewing et al. (2008) states that sprawl contributes to climate change not only by boosting the number of vehicle miles traveled (or VMT, a measure commonly used in transportation studies) and their associated emissions, but also by reducing the amount of available forest lands that could absorb CO2 (Ewing et al., 2008, p.21). Considering land cover and transportations, a study by Bart (2016) showed a strong correlation between the growth of artificial land areas and the increase of transport-related CO2 emissions. His statistical analysis concluded that sprawling development is strongly associated with increases of transport-related emissions and that sprawl is the main driver in the growth of transport emissions. Bart ascribed the growth of transport emissions to specific urban planning and land-use policies (or their absence) and asserted that "[S]prawl, measured in the increase of the areas covered by buildings and roads, is a stronger cause of increased road transport emissions than other possible causes, such as the growth of per capita GDP or population growth" (Bart, 2016, p.310).

Another issue associated with sprawling development is the segregation of living quarters, land serving working, and other activities. This spatial segregation of urban functions influences people's options with regards to housing and employment, while also influencing their travel behavior (EPA, 2013). An abundant amount of research has shown that mixed and diversified land uses (e.g., a mix of residential, commercial, recreational amenities); high residential and/or employment densities; well-connected street networks, and; high level of public transport accessibility, are associated with lower levels of

GHG/CO2 emissions (Cervero and Sullivan, 2011; Li, 2011; McCormack and Edwards, 2011; Leck, 2006; Cervero, 2002). Leck's (2006) research ascertained the influence of land use mix on travel, which proved to be negatively correlated to VMT. The degree of land use mix (i.e. the number of functions and their proximity from each other) not only correlates with VMT, but it also exerts an influence on the choice of the mode of transportation. In other words, people living in urban environments characterized by a diversity of functions have a propensity to commuting to work by public transit or by active modes of transportation, which are all associated with lower CO2 emissions than the automobile. Cervero (2002) reports that high density brings more transit ridership when it is accompanied by a mix of residential, commercial, and office use in proximity to the station. Brownstone and Golob (2009) conclude that people living in compact type of neighborhoods are less likely to use a car and more likely to use public transit. Hoek (2009) develop a mixed-use index (MIX) to measure the level of land use mix and testify that it can be applied as a powerful tool for New Towns planning.

Once established, the fact that mixed land use influences GHG emissions opens up a line of inquiry on how the composition and intensity of the mix could have an impact. Kim, Lee, and Choi (2014) investigated how different land-use patterns contribute differently to the reduction of CO2 emissions. They studied the impacts of mode share adjustment on CO2 reduction by comparing the Los Angeles Metropolitan Area (LAMA) and the Seoul Metropolitan Area (SMA) by simulating the potential of the transportation modal shift in favor of public transit in the two cities. The two regions have similar a population size and a comparable urbanized area size, but their land-use patterns are dissimilar. The LAMA is often seen as the epitome of the North American sprawling city, while the SMA shows dense, intensive land-use patterns. The results show that by adjusting the mode share (and increasing transit use) without weakening existing mobility levels, the potential for SMA to reduce its emissions is 20.6%, whereas LAMA can only expect to achieve a 3.5% of its current CO2 emissions (Kim, Lee, and Choi, 2014). The availability of public transportation in the SMA and the embedded automobile dependency associated with current land-use patterns in the LAMA mainly explains the difference. They suggested that, compared with dense/compact areas, sprawling automobile depended areas has limited CO2 reduction capacities when adjusting the public transit mode share. Baur, Förster, and Kleinschmit (2015) similarly analyzed the links between urban spatial properties of a city, land use, and land cover (LULC) compositions in relation to GHG emissions in 52 European cities. They found that a city's LULC compositions affect its GHG emissions. By distinguishing nine indicators of the spatial structure of a city's properties and four indicators regarding the specific distributions of various LULC class within a city, their results show that "urban density, intra-urban distances and specific LULC compositions influences GHG emissions per capita"

(Ibid., p.1202). There is a strong connection between urban sprawl and higher urban GHG emissions per capita.

Other researchers draw our attention to how various land use regulations affect vehicular CO2 emissions. Iwata and Managi (2016) examined the impacts associated with four urban planning strategies: *urbanization promoting areas, urbanization control areas, urban planning taxes, property taxes,* and vehicular CO2 emissions in Japanese cities from 1990 to 2007. The results indicate that different land use strategies impact the level of vehicular CO2 emissions differently. Some methods are more effective in low-density cities, while others work better in high-density cities: "[s]pecifically, their effects differ based on city density" (Iwata and Managi, 2016, p.369). For example, "a decrease in the *urban planning tax* rate is more effective for increasing density in low-density cities than in high-density cities. In contrast, a decrease in the *property tax* rate is found to be more effective in high-density cities" (Ibid., p.369).

5.3.3.2 Land Use, Surface Temperature and Urban Heat Island

Biomass loss, as a consequence of urban sprawl, is another way in which the latter is associated with climate change. The impacts in that regard are felt up-stream and down-stream. As it concerns up-stream impacts, biomass loss contributes to increasing the levels of GHG/CO2 emissions. When observing down-stream impacts, however, the loss of biomass increases the population's vulnerability to one major consequence of climate change: rising temperatures. The latter impacts ecological systems and agriculture, but also human health. Urbanization and sprawl, in particular, are directly contributing to increasing the land surface temperature. That phenomenon is known as the heat island effect. It is argued that urbanization influences land surface temperatures with an intensity that is comparable to that of GHG accumulation (Emadodin, Taravat, and Rajaei, 2016; Stone, 2008). The combined effect of temperature increases attributable to both factors puts the public health at risk.

Stone (2008) determined that urbanization has contributed to 50% of the increase of land surface temperature in the USA since 1950. He surveyed 45 metropolitan regions in the U.S. to observe the influence of land use on temperatures at the urban scale. A clear warming trend is noticeable in large U.S. cities. Wang, Li, and Yang (2015) used a structural equation model (SEM) to quantify the contributions of land use change to the regional climate change in Southern China. Their results indicate that "urban and surrounding areas" can influence regional micro-climates by increasing temperature, and even precipitations, to some extent. Their analysis also shows that adding vegetation, grasslands, and forested areas while restraining the sprawling of the built-up area are efficient methods that can be used to mitigate regional micro-climate change. Adeyemi et al. (2015) studied the effect of land use/land cover changes on surface temperature by focusing on the changes in vegetation and the impervious surface area across the Tshwane metropolis in South Africa between 2003 and 2013. Their results demonstrate that urban sprawl induced increases in the impervious surface area, which has been associated with enhanced surface temperatures in the urbanized area. Their findings also reveal that the impervious surface area shows a significantly higher surface temperature than vegetated areas. Cai et al. (2017) investigated spatial heterogeneities of urbanization in terms of light intensity and city size spectrum in different Chinese and US American cities. They conclude similarly that urbanization induces different changes in the thermal environment of different cities. Nilgün and Tamer (2017) have tested the effects of urban sprawl/urban growth on local temperatures between 1984 and 2014, by using Buras City as a case study. Their analysis confirmed that the spatial development pattern of Buras does exert an influence on local climate change. The results show that over the course of the study period, the monthly minimum temperatures have increased by 1.36°C.

Urban sprawl is accompanied by the creation of a large amount of impervious surface. Impervious surfaces interfere with the natural cycles of water exchange between the earth surface and the atmosphere and modify the hydrosphere (Brunsell, 2006) A large number of authors draw our attention to the relationship between urbanization, urban sprawl, urban heat island (UHI), and climate change (Bereitschaft and Debbage, 2013; Stone et al., 2010; Stone, 2008; Ewing, Pendall, and Chen, 2002). Urban heat island (UHI) refers to the phenomenon according in which the temperatures of highly mineralized urban areas are higher than the surrounding areas granted with higher vegetation coverage. The UHI effect caused by urbanization is an acute example of the influence of land use/land cover change on the regional micro-climatic conditions (Deng, Zhao, and Yan, 2013). There are many causes of UHI. Adeyemi et al. (2015) argue that the widespread impervious surface and building materials in the cities are two main causes, amongst others. Rizwan (2008) explains that the UHI effect is more specifically caused by the huge amount of solar radiation, which is absorbed by building materials such as walls, roofs, and pavements during the day and released at night. This phenomenon is called the albedo effect.

The UHI effect associated with urbanization and sprawl impacts the frequency of extreme heat events, which are responsible for a great number of heat-related fatalities associated with ongoing climate change. Stone, Hess, and Frumkin (2010) investigated the correlation between urban form and the "extreme heat events" (EHEs). They observed that the annual rate of increase of EHEs in sprawling cities is more than double the rate of increase when compared to compact metropolitan regions between 1956 and 2005, after controlling for the size and growth of the population. Since sprawled environments are globally less mineralized than more compact ones, these findings are counterintuitive. Regional Heat Island maps usually display a greater concentration of UHI in more central locations. What Stone, Hess, and Frumkin's study points to, is that by reducing the biomass, altering water systems, and pushing away forestland, grassland, and agriculture land, sprawl affects urbanized regions more importantly than compact environments.

The negative impact of sprawl on air quality is widely documented and acknowledged by research. Ewing, Pendall, and Chen (2002) demonstrate that there is a positive correlation between air pollution and sprawl. Stone (2008) found that the average number of high ozone days per year was approximately 62% higher in sprawling cities than in compact cities. His analysis shows that large metropolitan regions with a high index of sprawl exhibited a greater number of ozone exceedances than more spatially compact metropolitan regions. Bereitschaft and Debbage (2013) quantitatively evaluated the relationships between urban forms, air pollutants concentrations, and emissions among 86 U.S. metropolitan areas, while using urban sprawl metrics. Their results reveal that sprawl-like urban forms (i.e., low density, low street network connectivity, discontiguous urban development) generally exhibited a higher level of air pollution, CO_2 concentrations, and emissions from nonpoint sources after controlling for other variables.

While most empirical studies mentioned so far concentrated on metropolitan areas in developed countries, other scholars devoted their attention to developing countries. The countries which are experiencing rapid urbanization offer a fertile ground to measure the impacts of different forms of urbanization on air quality, for instance. Lu and Liu (2015) hypothesized that developing countries experiencing rapid urbanization and deep transformations may exhibit more serious effects on urban air quality. They studied the relationship between urban form and air quality in 287 Chinese cities. Their results demonstrate that urban form significantly affects air quality in China. Shanghai, the most economically developed city, possessed the highest NO_2 pollution; while Tianjin, the most heavily industrialized city, held the highest SO_2 pollution. Some key findings of this study indicate that a compact form and a polycentric shape (such as an 'H' shape) were more likely associated with lower air pollution than sprawling urban forms.

Table 6 summarizes the methods and results of the research reviewed on the links between land-use/land cover change and climate change. It also observes local micro-climatic conditions.

Author(s), Publication Year	Scope and Location	Main Method(s)	Data/Time Frame	Land Use Factors	Main Findings
Bart, (2010)	EU Member States	A simple linear multiple regression analysis	CORINE database between 1990 and 2000	Increase of artificial land area	Sprawling development is strongly associated with increases of transport-related emissions and is the most important driver of emission growth.
Stone, Hess, and Frumkin, (2010)	Metropolitan regions in the U.S.	Applying a widely used sprawl index	Urban form in 2000; EHE[1]s between 1956 and 2005	Sprawl index, frequency of EHEs	"the rate of increase in the annual number of EHEs in the most sprawling metropolitan regions is more than twice the rate of increase observed in the most compact metropolitan regions" (p.1425).
Bereitschaft and Debbage, (2013)	86 U.S. metropolitan areas	A series of linear regression models have been applied	Air pollutants data collected based on 2000 census	5 pre-existing urban sprawl indexes were selected	After controlling other variables, higher levels of urban sprawl or sprawled urban form are closely linked with higher level of air pollution and CO2 emissions.
Kim, Lee, and Choi, (2014)	Los Angeles Metropolitan Area (LAMA) vs. Seoul Metropolitan Area (SMA)	Comparative approach by employing the Cobb-Douglas functions	Data were collected based on the status quo from 2008	Distinctive land-use density: an auto-centric area vs. dense, intensive land-use area	Reduction of CO2 emissions in both areas can be achieved by the public transit mode share adjustment without weakening existing mobility levels. However, the amount of CO2 reduction of the SMA is much more significant than that of the LAMA.
Adeyemi et al., (2015)	Tshwane metropolis, Gauteng Province, South Africa	a correlation analysis to test the relationship between LST[2], NDVI[3] and NDBI[4]	Landsat 8 LCDM, 2003, and Landsat 7 ETM+, 2013	Vegetation cover and impervious surface area (ISA)	LST has a positive relationship with NDBI, while has a negative relationship with NDVI.

[1] EHEs: Extreme heat events.
[2] LST: Land surface temperature.
[3] NDVI: Normalized difference vegetation index.
[4] NDBI: Normalized difference built up index.

Wang, Li, and Yang, (2015)	Southern China	A structural equation model (SEM)	1988 and 2005	Vegetation, urban and surrounding area, and other	"Adding vegetation area is the main method to mitigate regional climate change" (p.1).
Iwata and Managi, (2016)	Japanese cities (1750)	Linear model	City-level data from 1990 to 2007	Impacts of different land use strategies	Different urban planning instruments impact the level of vehicular CO2 emissions differently. Some methods are more effective in low-density cities, while others work better in high-density cities.
Emadodin, Taravat, and Rajaei, (2016)	Tehran, Iran	MLP[5] neutral network has been used, more detailed presentation sees p.233.	Satellite images: every 5 years from 1975 to 2015; Local climatic data: 1990 to 2010.	IDM[6] has been used to measure changes in aridity between 1990-2000 and 2001-2010.	Between these two time periods, the average temperature has increased from 17.43 to 18.31. More arid area has experienced greater temperature increase.
Lu and Liu, (2016)	287 Chinese cities: four provincial level cites and 283 prefecture-level cities	A geographically weighted regression (GWR) model	NO2 data from 2008; SO2 data from 2007	Urban form indexes: the compact ration index, the fractal dimension index and the Boyce-Clark shape index	Urban form characteristics significantly affect urban air quality in China.
Cai et al., (2017)	Chinese and American cities	Compare and quantify the correlation among nighttime light intensity, surface thermal changes and city size	MODIS LST and DMSP/OLS Nighttime light data sets 2001-2012	Spatiotemporal changes of urbanization process	In general, despite the spatial heterogeneities, light intensity increases with increasing city size.

[5] MLP: MultiLayer Perceptron.
[6] IDM: an aridity–humidity index.

Moradi and Tamer, (2017)	Bursa City	Paired Samples t-Test; Holdren Model	1984 to 2014	The growth of urban settlement, the growth of urban population	During 1995 to 2003, urban growth was ascribed to 65% of urban sprawl, accompanied by a loss of forests and agricultural land, and an increase of 1.36°C monthly minimums temperature (p.26).

Table 6. The effects of Land Use/Land Cover change on climate change and local micro-climatic conditions

5.3.4 Transportation, GHG/CO2 Emissions and Energy Consumption

5.3.4.1 The Growth of Transportation Emissions

Transportation not only "forms the nexus of any urban environment" (Banerjee and Hine, 2014, p.2217), but it also accounts for the largest urban emitter of CO2, outnumbering the residential, industrial, and commercial sectors (Marshall, 2008). Global transport emissions contributed to 24% of direct CO2 emissions in 2010, while 75% of global transport emissions were due to road transport (Zhao et al., 2013; Marsden and Rye, 2010). This number is expecting to grow at a rate of 1.7 % per year until 2030. In the United States, "the largest emitter worldwide of the greenhouse gases (GHGs) that cause global warming," a full third of CO2 emissions comes from the transportation sector. The transportation share is growing, rising to 33% from 31% between 1990 and 2008 (Ewing et al., 2008, p.2). The US Environmental Protection Agency echoes these numbers and points out that transportation emissions increased 19% in the United States between 1990 and 2010. This increase was primarily due to the increase in VMT over this period (EPA, 2012). In the EU, 25 countries among all transport emissions accounted for around 20% of all GHG emissions. 93% of this comes from road transportation. That sector has emitted about 900 million tons of CO2 in the EU-27 in 2005 (Bart, 2010). In other developing areas of the world, the annual growth rates of CO2 emissions by the transport sector are expected to be even higher, namely 3.4 and 2.2% respectively (Grazi et al., 2008). As mentioned in the introduction, in Québec, road transportation contributes 33.6% of the total emissions. The sector has also seen sharp increases, rather than a reduction, in recent years (Ministère du développement durable, de l'environnement et de la lutte contre les changements climatiques, 2016).

5.3.4.2 Transportation Related GHG/CO2 Emissions

"It is hard to envision a 'solution' to the global warming crisis that does not involve slowing the growth of transportation CO2 emissions" (Ewing, 2008, p.17). The reduction of CO2 emissions from the transport sector has been identified as a major challenge for climate stabilization (Bart, 2010; Hickman et al., 2010; Chapman, 2007). Much of the literature assessing the connections between urban form/urban sprawl and transportation have primarily focused on the impacts of transportation-related energy consumption and GHG emissions (Stone et al., 2009; Marshall, 2008; Ewing et al., 2007). The energy consumption and GHG emissions in the road transport sector are evidently largely impacted by the fact that the vast majority of vehicles are powered by combustion engines using fossil energy. Fuel production and combustion for transportation is by far the most important contributor of that sector to climate change, but other sections of this report stress that urbanization predicated on automobility generates other highly negative environmental externalities.

The impacts of urbanization and transport energy use have been researched extensively. Parikh and Shukla demonstrate the positive correlation between urbanization and transport energy use by using a sample of 45 developing countries during the 1965-1987 period (Parikh and Shukla, 1995). An analysis from APERC (2007) concludes that urbanization enhanced transport energy demand by favoring motorization and increasing travel distances. Hankey and Marshall (2010) explored the specific contribution of urban sprawl to travel distances by analyzing 142 cities in the US from 1950 to 2000. Their results indicate a positive correlation between urban sprawl, VKT, transport energy use, and GHG emissions.

Leibowicz (2017) points out that the two main factors affecting transportation CO2 emissions are the transportation modes share and the total distance traveled. Both aspects are strongly linked to the urban form. Among numerous factors contributing to the growth of transportation emission, strong evidence suggests that the increase in distance traveled in vehicles using a combustion engine is the most important one. Much of the increase in vehicle travel is linked to a combination of conditions pertaining to the spatially dispersed development of cities and towns (sprawl), the separation of working and living (land-use), and the outward expansion of urban development and infrastructures (EPA, 2013). The total amount of vehicle travel is usually measured by vehicle miles traveled (VMT, or the equivalent, vehicle kilometers traveled). VMT is determined by trip lengths, trip frequencies, and trip modes (Ewing and Cervero, 2010). Ewing (2007) asserts that "Vehicle miles traveled (VMT) is a primary performance indicator for land use and transportation" (p.3079). Ewing and his colleagues consider VMT as one leg of the "three-legged stool" related to transportation CO2 reduction (the other two are vehicle fuel economy and carbon content of the fuel itself) (Ewing et al., 2008, p.2). Ewing conducted many studies attempting to explore how development patterns are affecting VMT and their associated GHG emissions. His team determined, for instance, that the VMT and average travel speeds are higher in sprawling areas (Ewing et al., 2002). In a very influential book: Growing Cooler: The Evidence on Urban Development and Climate Change, Ewing et al. (2008) summarized empirical research on the matter. The results indicate that sprawling land-use patterns and low population densities correlate with higher VMT per capita, greater gasoline consumption, underuse of public transit, and a larger amount of per-capita GHG emissions.

A growing body of literature shows that residents living in denser, compact, and transit-friendly neighborhoods drive considerably less than those residing in sprawling communities. Brownstone and Golob (2009) demonstrate, for instance, that people living in low-density residential areas are likely to use vehicles more frequently than those living in high-density residential areas. Ewing and Bartholomew's

(2008) meta-analysis suggests that compact development combined with mixed land use and easy accessibility to destinations could reduce the total VMT by 20 to 40% regionally. If applied to the national scale, the reduction could reach 10 to 14%, which would lead to a 7 to 10 % reduction in total U.S. transportation CO2 emissions. Using data from 370 US regions in 2003, Cervero and Murakami (2010) demonstrate that population density is negatively correlated with VMT per capita. Lee and Lee (2014) similarly conclude the negative correlation between urban density and transportation CO2 emissions, this time by using household surveys in the US. Hankey and Marshall's (2010) research estimated how urban form impacted total GHG emissions from passenger vehicles for 142 US cities during the 1950–2000 period, before developing 6 plausible urban expansion scenarios from 2000–2020. The results point to the fact that different types of urban development significantly impact the reductions in carbon emissions. For example, "[c]omprehensive compact growth" could reduce US 2000–2020 cumulative emissions by up to 3.2 GtCO2e…" (p.4880).

The effects of specific conditions such as accessibility, connectivity, and design on transportation and GHG emissions have also been explored. Street connectivity has received more attention. Sprawled urban forms are characterized by low street connectivity, produced in particular by the prevalence of dead-ends. Stone (2008) studied the street connectivity of 45 of the largest U.S. metropolitan regions. This was measured based on a composite factor comprised of an average block length in the urbanized portion of the metropolitan area, average block size, and the percentage of small blocks. The results indicate that "each standard deviation increase in connectivity was associated with a reduction of approximately 5.5 high-ozone days per year" (Stone 2008 quoted in EPA, 2013, p.99). Barrington-Leigh and Millard-Ball (2017) estimated the low-connectivity street-network urban sprawl's influence for GHG emissions through its effect on vehicle usage. Their study demonstrates that reducing street-network sprawl can contribute greatly to GHG emission mitigation. Specifically, their results show that by increasing street-network connectivity, the projected vehicle travel and emission reductions could nearly triple to 8.8% by 2050.

The relationship between urban form and transportation is vital for planning scholars and policymakers concerned with global sustainability and climate change (Banerjee and Hine, 2014). In addition to GHG/CO2, sprawling development patterns have also been linked with many transportation externalities, such as longer commuting times, higher rates of automobile ownership, raised auto accident rates, increased air pollution, traffic congestion, increased travel distances, highway expenditures etc. (Holcombe and Williams, 2010; Ewing, Pendall, and Chen, 2002).

The connections between urban sprawl and transportation-related GHG/CO2 emissions are undisputable. The research points to clear links between urban form and transportation associated emissions. Surprisingly though, the field of research that focuses more specifically on the relations between transportation and urban form is permeated with a few controversies and is characterized by the ambiguities that stem from discrepancies between the results of different studies. According to our interpretation, these discrepancies do not invalidate or weaken the general consensus about the link between form, transportation patterns, and emissions. Rather, they point to the difficulties in order to untangle specific relationships between urban form and transportation patterns. We contend that these difficulties have to do with methodological limitations on the one hand, and to a perfectible theoretical framework and approximative theoretical formulations with regard to the urban form on the other.

For example, Ewing and Cervero's (2010) meta-analysis reveals that travel variables were generally inelastic with respect to changes in measures of the built environment. They concluded that the connections between urban form variables and travel behavior were "statistically significant, but rather weak." Other researchers have weighed in with inconclusive and mixed results. Bento et al.'s (2005) disaggregate model analysis found that the impacts of any of the urban form measures on travel behavior are frequently insignificant and small in magnitude. In a more recent study, Gordon and Lee (2013) found that "[g]iven the population size and suburbanization, more decentralized and dispersed employment distribution was associated with shorter average commute time" (p.9). By re-examining the relationship between urban sprawl and transportation externalities, Holcombe and Williams (2010) found that sprawl "does not contribute to these transportation externalities" (p.269). While criticizing the current emphasis on quantitative methods used by many scholars, Banerjee and Hine's (2014) qualitative study showed that land-use policies have played a dominant role in shaping travel patterns at the macro-scale. By comparing 18 metrics of urban form for 542 neighborhoods in Salt Lake County, Utah, Lowry and Lowry (2014) recommend 13 out of 18 for planners and policy analysts to better capture complexity of the built environment.

The apparent difficulty for research focused specifically on urban form and transportation to reach a consensus on sprawled urban form characteristics and transportation patterns can be puzzling. As mentioned earlier, this lack of coherence shouldn't be interpreted as challenging. The clear consensus exists around the notion that sprawled cities generate more car travel, and as a consequence, GHG emissions. The science is robust to the effect that when comparing cities that are compact to cities that are sprawled, or when comparing a city's denser center to its low-density periphery, transportation patterns differ and affect the carbon emission levels. What seems to be more problematic in the research reported in this section is the effort to untangle the relations between compositional or sub-sets of attributes and properties of the form. This includes their transportation environmental impacts which points to issues with measurement methods or with the conceptualization of urban form as a spatial system.

5.3.4.3 Urbanization/Urban Sprawl and Transportation Energy Consumption

Given that the majority of transport energy comes from non-renewable sources, the transport sector is not only contributing to climate change through emitting GHG emissions, but it also exposes the world to an energy crisis in a more or less distant future (Meehl et al., 2007; Williams and Alhajji, 2003; Kerr, 1998). In 2005, the transport sector consumed more than half of the oil used globally (Poumanyvong et al., 2012). IEA (2008a) projected the world transport energy use and concluded that at current rates, emissions will rise more than 50% by 2030. Saboori et al. (2014) similarly expressed that the growth rate of transport energy use is projected to increase by 2% annually. Such projections pose great challenges, but they also mean that, if prioritized, the transport sector could play a significant role in shifting towards sustainability.

The linkages between urbanization and transport energy use have been researched extensively (Liu et al., 2017; Kaneko and Dhakal, 2012; APEC, 2007; Jones, 2004; Parmenion, Parikh, and Shukla, 1995; etc.). A positive relationship between urbanization/urban sprawl and transportation energy consumption has been established. In an early and very influential article, Parikh and Shukla (1995) conducted a multiple regression analysis to empirically study the linkages between urbanization, transport energy use, and GHG effects by using a sample of a cross-national study of the world's countries between 1965-1987. Their exploratory assessment supports the idea that GHG is positively correlated with countries' urbanization levels and urbanization as a consequence of increased transport energy use. "[I]n particular, the energy use elasticity of urbanization falls to 0.28, indicating that other influences held constant, a doubling of a country's urban population would increase its per capita fuel consumption by 28%" (p.91). Hankey and Marshall (2009) studied the impacts of urban form on passenger-vehicle GHG emission by analyzing 142 cities in the US between 1950-2000. Their Monte Carlo approach demonstrates a positive correlation between urban sprawl, VKT, transport energy use, and GHG emissions. Their results are congruent with previous findings that had established that urban sprawl contributes to transport energy use by increasing travel distance.

Poumanyvong, Kaneko, and Dhakal (2012) investigated the impacts of urbanization on transportation energy use for countries at different stages of economic development between 1975 and 2005 by using the STIRPAT[7] model. They divided the countries into three income groups: low-, middle- and high-income groups. Their results concur with research establishing a positive correlation between urbanization, national transport, and road energy use. Such a correlation has been found for all countries; though the magnitude of influence of urbanization varies considerably across different income groups. Similarly, Liu et al. (2017) also applied the STIRPAT model to investigate the impacts of urbanization on road transport energy use for 386 Norwegian municipalities from 2006 to 2009 by taking into consideration variations in urban forms. Their results confirmed that urban density is negatively correlated with road energy use per capita while unveiling a quadratic relationship between population and road energy use per capita. Liddle (2004), however, found a negative correlation between urbanization and road energy per capita by using a sample of 23 high-income countries at 10-year intervals. He suggests that urbanization decreases transportation energy use. Liddle's research does not distinguish between various forms of urbanization or control for the availability of alternative modes to the automobile, which might help to explain results seemingly at odds for the majority of studies on the matter. The latter results point, again, to the importance of developing a more robust and comprehensive theoretical framework and more precise measuring of the urban form spatial characteristics and compositions.

5.3.5 Urban Sprawl, Climate Change, and other Associated Environmental Costs

Even though GHG emissions are the most detrimental contributor to climate change, they are not its sole driver (cf. Conceptual maps in Figures 1 and 2). Urban sprawl contributes to climate change by reducing the capacity of the biomass to capture carbon while affecting ecosystems, modifying habitats, degrading water resources, causing air pollution, and consequently increasing vulnerability to climate change. Our analysis was mostly restricted to GHG emissions, energy consumption, and urban heat islands, while slightly touching air quality. This section briefly discusses the impacts of sprawl on ecosystems, natural habitats, and hydrology.

Urban sprawl entails altering natural or cultivated lands with extensive construction. The expansion of the building stock, accompanied by new roads and infrastructure networks drastically alter habitats and ecosystems: "[t]he extent of land development, the type of development, and the location of infrastructure have direct and long-lasting impacts on ecosystems" (EPA, 2013, p.2). Urbanization has

[7] STIRPAT: Stochastic Impacts by Regression on Population, Affluence and Technology

contributed to massive losses of biomass with critical impacts on biodiversity, which can be described as “the foundational underpinning of ecosystem” (EPA, 2013). Plus, emissions related to the loss of biomass, habitat loss, or carbon stored in biomass have been well documented by *The Nature Conservancy* (2018, p. 43-49). Urban development leads to the invasion of non-native species that severely alter ecosystem function and reduce biodiversity (EPA, 2013, p.118). Adverse ecosystem effects induced by urban sprawl include ecosystem fragmentation, increased vulnerability of ecosystem, reduced diversity of species, reduced ecosystem service, reduced ecosystem resilience, etc. Crossman et al. (2013) argue that land use decisions have a direct bearing on natural capital and ecosystem services supply. Another study by Dupras and Alam (2014) demonstrated how urban sprawl has negatively impacted ecosystem services value (ESV) through a 45-year period by using the Montreal Metropolitan Region as their case study. They conclude that “urban sprawl generates significant losses in ESV” (p.196).

Among the many impacts of urban sprawl, the modifying of the natural hydrological system has garnered substantial attention because of the greater severity and frequency of flooding, the number of heavy runoffs, the strong storms, and the increased exposure and vulnerability of communities to flooding hazards that are imputable to climate change. The natural hydrologic system performs invaluable ecological functions and provides many critical ecosystem services. Urban water sources are often impaired directly or indirectly by building and development practices (EPA, 2013, p.46). Impervious surfaces associated with urbanization has deep impacts on the natural hydrological cycle. Several studies have investigated the impacts of urbanization on hydrology (Kalantari et al., 2017; Konrad and Booth, 2002).

The types of impacts described in the previous paragraph are not specific to sprawl. They are the by-products of any form of urbanization. Yet, in most circumstances, because it is characterized by low density, segregated land use, and car-oriented transportation, sprawl takes a higher environmental toll than more compact forms of development. This is the case because the scale of the land conversion induced by the sprawl causes very significant loss of wetlands and forests and the degradation and fragmentation of fauna’s habitats. Similarly, low-intensity land use, low construction densities, and typical suburban street network geometrical properties entail high intensity of car transportation that translates in high levels of GHG emissions and air pollution generated by combustion engines. Besides, the phasing-out of combustion engines in favor of electrical ones, though highly desirable, wouldn’t address the other environmental issues pertaining to car-based suburban development. In relation to the number of people accommodated by sprawled development, its environmental costs are even harder to justify. Considered against most environmental metrics (GHGs, energy consumption, urban heat island, air quality, habitat loss, biodiversity, and general resource consumption) sprawl is a grossly suboptimal form of urbanization. The fundamental research indicates that if we want to fight environmental crises, and in particular climate change, curtailing future sprawl and reducing the environmental costs of existing sprawled environments should absolutely be prioritized (see Section 6).

6. Sustainable Development for Protection and Adaptation to Climate Change

6.1 Physical Planning Approaches and Initiatives for Reducing GHG Emissions

Climate stabilization requires that the global mean temperature (GMT) be kept minimally under the 2°C threshold endorsed by the 2009 Copenhagen Climate Summit. The Paris agreement reached in 2015 stipulates, based on evolving scientific knowledge, that the GMT should be kept "well below 2 degrees Celsius above pre-industrial levels" and that efforts should be pursued "to limit the temperature increase […] to 1.5 degrees Celsius" (United Nation, 2016). To give a sense of the order of magnitude of the task, early estimates situated the reduction of GHG at 40 to 70% below the 2010 levels by 2050.

The detrimental environmental impacts of urban sprawl have drawn attention from authorities, scholars, activists, and citizens. An abundant amount of applied research has explored alternative development strategies to mitigate climate change and to adapt to its consequences. These strategies can be classified into two broad categories: technological innovations and physical planning strategies. Some initiatives mainly focus on systems innovation and the development and deployment of new technologies such as alternatives to fossil energy, cleaner and more efficient modes of production, distribution, use of energy, fuel-efficient vehicles, etc. Though promising, technological transformations alone are not sufficient enough to meet the aforementioned GHG reduction goals, leaving aside adapting to the impacts of climate change.

The fundamental research reviewed in this study shows that the ways cities are built, practiced, and traveled are associated with colossal environmental costs, including significant impacts on climate change. They have further illustrated that curtailing urban sprawl could play a significant role in mitigating climate change and achieving climate stabilization. In our mind, the expression 'curtailing sprawl,' should imply stopping sprawling development as well as retrofitting existing sprawled environments. Deep cuts in GHG emissions can be achieved through an energy-efficient urban form. As Bart (2007) stresses, the ever-growing demand for automobility is rooted in the car-centric way that cities are being built, to the extent that these per-kilometer CO_2 emissions cannot be checked alone by technical solutions. Hankey and Marshall (2010) have evaluated how technological changes and urban form transformations could contribute to reducing transportation GHG emissions. They conclude that vehicle efficiency, fuel carbon content, and urban form need to be addressed conjointly if we want to achieve the desirable results (Hankey and Marshall, 2010). Marshall (2008) has singled out the potential carbon reduction benefits associated with reducing sprawl. He contends that "[r]educed sprawl, without technology innovation, [could decrease] emissions by 10 GtC during 2005–2054 (by 0.5 GtC/yr in 2055) compared with BAU" (p.3134). Studies have shown that compared with sprawl, the compact urban form can significantly reduce energy consumption and CO_2 emissions by increasing density, consuming less land, and reducing travel distances. Taniguchi, Matsunaka, and Nakamichi (2008) conclude that "[a] compact urban layout might be the most important measure to reduce CO_2 emissions and to solve problems arising from excessive reliance on the automobile" (p.416). Ewing et al. (2008) estimate that the potential reduction of annual gasoline CO_2 emissions achieved by compact development is between 5-12% and 9-16% in 45 to 50 years. Another study conducted by Lee and Lee (2014) demonstrated that doubling population-weighted density would lead to a reduction in CO_2 emissions by 48% and 35% from household travel and residential building energy use, respectively.

Various authors have asserted that transportation and land use planning strategies can greatly reduce long-term carbon emissions. Authors have also insisted on the fact that land use and transportation are interrelated, so that combined strategies are significantly more effective than those targeting those aspects individually (Bertolini, Le Clercq, and Kapoen, 2005). There is a consensus that efforts to reduce the amount of GHG/CO_2 emissions in the future must be based on integrated land use and transport planning. California's Senate Bill (SB) 375, advocated by Office of the Governor of California in 2008 as "the nation's first law to combat greenhouse gas emissions by reducing sprawl", has been strategically designed to achieve GHG reductions by incorporating transportation and land use (Barbour and Deakin, 2012). Barrington-Leigh and Millard-Ball (2017) posit that implementing land-use and transportation policies globally, in order to reduce vehicle travel, is the only feasible way to meet long-term climate targets. Ewing pleas in favor of vigorous proactive planning and advocacy to articulate a strong planning response to the challenges posed by sprawl. Ewing et al. (2008) claim that "[t]he key to making substantial GHG reductions is to get all policies and practices, funding and spending, incentives, and rules and regulations pointing in the same direction, toward smart growth and away from sprawl" (p.129). Marshall (2008) highlights, though, that better urban design represents an important, yet currently undervalued and undeveloped opportunity. Such an assertion points to some limitations of the current efforts: the articulations between urban form, transportation, and environmental causes and consequences are known and named, yet they're difficult to translate in a fully integrated physical planning approach in the absence of a synthetic portrait, and in the face of some seemingly contradictory empirical evidence.

Some authors try to specify what guiding principles should prevail for physical planning in order to turn the general policy objectives into action. Jabareen (2006) suggests that "[…] the ideal sustainable form […] is that which has a high density and adequate diversity, compact with mixed land uses, and its design is based on sustainable transportation, greening, and passive solar energy" (p.48). The objective of future development must ensure that they are not exclusively car-oriented, thus minimizing the increase of transport-related GHG emissions (Bart, 2007). The future urban form should not be built as such that owning a car is a necessity. Burchell et al. (1998) suggest further that sustainable development should seek to "limit growth to the degree that public facilities and services are in place to accommodate this growth" (p.37).

6.2 Changing Development Patterns to Adapt to the Effects of Climate Change: Urban Sprawl and Compact Development

Alternative patterns of growth and development have been proposed in the normative planning literature as a way to curb sprawl in order to help mitigate GHG emissions while improving sustainability more broadly. These approaches have been labeled: smart growth, transit-oriented development (TOD), new urbanism, compact development, pedestrian-friendly design, etc. What these approaches have in common is their intention to develop an integrated approach to physical planning. Incidentally, Johnson (2001) describes smart growth as a catch-all name for "transit-friendly and mixed-use design of transit-oriented development" (p.6). Since late 1970s, the "compact city concept" has been widely perceived as a more sustainable development pattern (Breheny, 1992; Holden and Norland, 2005). One of the main proponents of TOD is defined by Peter Calthorpe and Douglas Kelbaugh as: "a development model for a small walkable community that mixes low-rise, medium density housing for a variety of household types, with retail, civic, recreational, and employment centers along a main street - all within about a one-quarter-mile (400 m.) radius of a central transit stop for a bus or rail system." (Kelbaugh, 1997, p.111). Key principles of TOD include: organizing growth on a regional level to be compact and transit-supportive; placing commercial, housing, jobs, parks, and civic uses within walking distance of transit stops; creating pedestrian-friendly street networks, which directly connect local destinations, and; providing a mix of housing types, densities, and costs (adapted from Calthorpe, 1993). An association of architects and planning practitioners, scholars, and researchers have been created to advocate in favor of so-called New Urbanism. The organization has adopted a Charter which articulates the principles that should guide urbanization. The 10 principles of New Urbanism are walkability, connectivity, mixed-use and diversity, mixed housing, quality architecture, urban design, traditional neighborhood structure, increased density, smart transportation, sustainability, and quality of life (excerpts of the Charter of New Urbanism, retrieved at http://www.newurbanism.org, April 4, 2005).

While acknowledging the complexity of the reality with which they cope, planning approaches to sustainable development, including those concerned with fighting against climate change and adapting to its impacts, revolve around a few simple ideas. A key tenet is to curtail urban sprawl and funnel development toward urbanized areas. This should be done while prioritizing areas that are already well granted with services and amenities (roads, public transit, schools, health services, retail, etc.). There is a strong consensus on a few basic principles: 1. increasing the density of populations and activities; 2. favoring mix land-uses; 3. investing massively in the development and support of active and collective transportation modes (walking and cycling / public transit), and; 4. protecting and restoring natural systems while fostering biodiversity. In short, reducing car dependency to therefore reduce our environmental footprint, thus increasing our quality of life.

In the opening chapter of their book reporting on the best practices in sustainable architecture, landscape architecture, and urban design by Danish firms, Nielson (2017) makes a remarkable effort at achieving conceptual clarity on some key guiding principles that can frame policy and planning actions. The doughnut model by economist Kate Raworth is a key source of inspiration (Raworth, 2018). In her model, economy is conceptualized as a regenerative and distributive economic system represented as space, a.k.a. a doughnut, bounded outward by an ecological ceiling that marks the limits beyond nine of Earth's life-supporting systems (by climate change, ocean acidification, land conversion, biodiversity loss, etc., see Figure 1) are irremediably compromised, and inward by a so-called social foundation boundary within which twelve basic social needs (such as food, housing, energy, social equity) must adequately be met for all (Figure 5). Hence, the economy should be geared at meeting the needs of the population and improving its quality of life without compromising the ecological supporting systems' ability to regenerate. Circular economy (in which wastes are reintegrated in the cycle as resources) and sharing economy (in which tools and goods are pooled) are seen as promising avenues to decouple growth from resource extraction and use. Nielson (2017, p.22) suggests how the Raworth model can be combined with the *Copenhagen model for climate adaptation and city nature* in order to be reinterpreted in planning terms around issues such as food cultivation, rainwater management, microclimate regulation, CO2 reduction, noise reduction, air quality, and water quality (Copenhagen, 2016). The whole demonstration is meant to emphasize that successful transitioning must not be an exercise focused on reducing, restraining, and abandoning conveniences and amenities, but should rather lay emphasis on increasing the quality of life for the whole population without compromising the future.

This report doesn't allow for a systematic review of urban planning initiatives pertaining to the response to give to the environmental imperatives dictated by climate change. Excellent resources regarding the best planning practices on the manner are, however, available online. The European Commission, in particular, has developed the habit of systematically surveying and disseminating the best practices for all to learn and emulate.

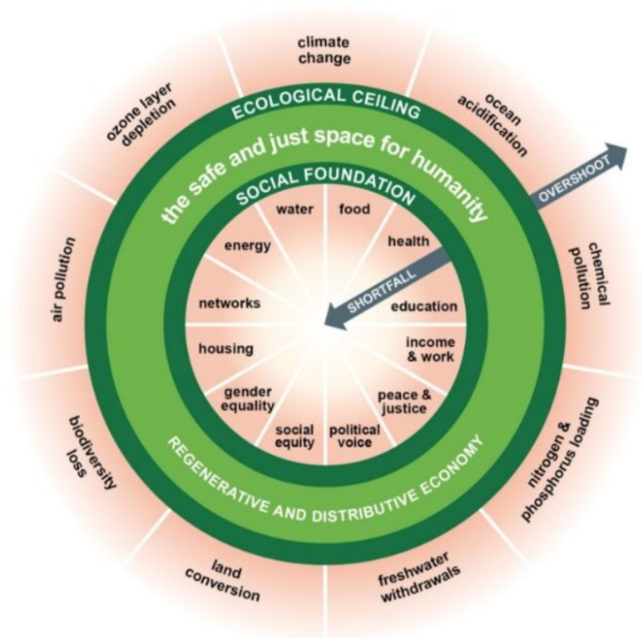


Figure 5. Raworth Doughnut Economics Model

Note: More information on the best urban planning practices and climate change can be found in: Reckien et al. (2018) *How are cities planning to respond to climate change? Assessment of local climate plans from 885 cities in the EU-28*. In J. *Clean. Prod.,* 191 (2018), pp. 207-219; European Environment Agency. (2016). *Urban adaptation to climate change in Europe 2016*. One can also consult the European Commission site under the EU regional and urban development. See for instance: https://ec.europa.eu/info/eu-regional-and-urban-development/topics/cities-and-urban-development/priority-themes/climate-adaptation-cities_en

7. Discussion and Conclusion

For any professional urban planner, many of the connections between urban sprawl and climate change appear readily understandable. In physical planning terms, low concentrations of populations and activities dispersed on a large territory implies expansive and expensive infrastructure and the use of extensive land resources, which all necessarily translate into significant environmental costs. The transportation implications of this type of development are also well known by the profession and the repercussions on GHG emissions can be easily deducted. Yet, conducting a review of the literature on the relations between sprawl and climate is not as simple as it might appear at first sight. First, there is the need to define what is meant by urban sprawl. This exercise necessitated a review of several common definitions and some exploration of sprawl causes, consequences, and characterization attempts as per Section 3. Secondly, the empirical assessment of the environmental impacts of sprawl is almost always conducted quantitatively, which presuppose that sprawl itself, or at least some of its key features, can be measured. Those aspects were addressed in Section 4. Thirdly, the pertinent literature is rarely about sprawl and climate change, per se. Most contributions, rather, address a single or a small number of aspects of this multifaceted relation. This situation requires an effort to untangle webs of causes and consequences between several natural and anthropic systems. Section 5 presents the research on salient interconnections while also shedding light on broader articulations. The fundamental research on topics relevant to our main theme is proliferating, and so is the applied research and the attempts at articulating a policy and planning response to the environmental challenges posed. Section 6 only brushes the surface on the latter topics. Excellent resources are available online regarding the best planning practices needed to cope with climate change struggles. The European Commission, in particular, has developed the habit of systematically surveying and disseminating the best practices for all to learn and emulate. The approach in this report is evidently far more modest. We instead focus our efforts on presenting a normative framework (a.k.a. the doughnut model and its reinterpretation for a planning context) that instills some conceptual clarity and helps to frame the action. We believe that, used in conjunction with our conceptual mapping of Figure 1, these tools can help planners, policy makers, and advocacy groups to weigh and interpret the pertinent science, and above all, to translate it into physical planning and policy terms.

The following paragraphs summarize the key findings of our exploration of the literature, while identifying several gaps and apparent inadequacies, before concluding.

7.1 General Consensus, Debates and Limitations in the Surveyed Research

7.1.1 General Consensus in the Research Surveyed

Some form of solid consensus exists in the literature about the relations between urban sprawl, GHG emissions, climate change, and environmental degradation more broadly. The main objective of this report was to summarize the current state of the research on these matters while clarifying the, at times, arcane relationships between contributing factors and their causes and consequences. On the aspects of eliciting consensus, summarized hereafter, studies conducted in different urban contexts and using different methods reach similar, or complementary, conclusions. Some specific relationships remain more resistant to the analysis. It is the case when researchers try to untangle the relations between specific characters or properties of the urban form and transportation. In these matters, methodological difficulties abound when confronted with overlapping and entangled factors and conditions. For example, higher urban density rarely occurs alone, as it is generally accompanied by mixed land uses and better public transit so that variables measuring those aspects tend to correlate with one another (EPA, 2013). Some of the key consensuses can be summarized as follows:

- The research on the relationship between density, GHG/CO2, and energy consumption produces a pretty straightforward portrait. The vast majority of the research shows that GHG/CO2 emissions are significantly influenced by population and residential densities. Most empirical studies show that, in general, density is not only negatively associated with the amount of GHG/CO2 emissions and energy consumption, but also with VMT. As indicated by existing research, significant differences exist among and within cities in terms of population density and the spatial distribution of GHG/CO2 emissions. The general pattern that emerges in the literature is that increased density reduces VMT. Over time, the GHG/CO2 emissions are continuing to increase in most cities, but the rate is decreasing. This tendency is especially obvious in large cities and in those that are comparatively more compact.
- Land use/land cover change contributes to climate change directly in terms of GHG emissions and more or less indirectly through various synthetic effects of bio-geochemical and bio-geophysical processes. Numerous studies report that high density, diverse land uses, well-connected street networks, complementary with a higher level of public transport accessibility are associated with low level of GHG/CO2 emissions. Though studies specifically measuring the loss of biomass due to sprawl are fairly rare, there is a

strong consensus to the effect that at a global level, land conversion from forestland and grassland to urban usages depletes the potential for the capture of carbon in measurable and significant ways. Again, in spite of the difficulty to isolate land-use patterns from other factors such as densities and public transit, it is clear that the land-use mix has an impact in conjunction with the latter aspects. An urbanized region's GHG/CO2 production and carbon storage capacities are conditioned and limited by its spatial properties and its land use/land cover compositions.

- There is a strong positive correlation between the growth of artificial land areas and impervious surfaces area, and the increase of surface temperature. Urban sprawl contributes to climate change through urban heat island effect and increases the vulnerability of populations in relation to increasing temperatures and episodes of heat waves. Sprawl does also affect the natural water cycles and the hydrographic systems (streams, wetlands, etc.). Such alterations affect the carbon cycle and increase the vulnerability to episodes of heavy rains and episodes of floods.
- The transportation sector is the largest emitter of GHG/CO2. The relationship between urban form and transportation is not straightforward. Even though there is a lack of consensus on the specific impacts of urban sprawl on commuting time and congestion as well as on other transportation externalities, the overwhelming evidence shows that urban form matters when considered globally. The composition of urban forms pertaining to the spatial distribution of populations and activities (densities and land-use) impacts travel behavior (and terms of modes and intensity). Changing characteristics in the built environment influences people's travel behavior, though more empirical work will be needed to understand more fully the specificity of the relations between the physical and spatial forms of cities and travel behavior. We suggest that such an effort should start by analyzing the material and spatial forms more rigorously and thoroughly. The indicators used to quantify the built environment attributes often appear crude and approximative.

7.1.2 The Limitations and Gaps in Research Pursued in the Field

We contend that a number of significant gaps persist in the literature on the relationships between urban physical, spatial forms and climate change. Specifically, there are limitations pertaining to the conceptualization of sprawl itself and, consequently, to the measurement of its various dimensions and overall compositional patterns. As highlighted in this report, the latter limitations affect the ability to analyze more precisely the impacts of specific attributes of urban form on transportation patterns and their associated GHG emissions. On the questions of densities, land coverage, and land-use in sprawled environments in relation to climate change, the science is more conclusive. The metrics currently utilized seem to capture the material and spatial conditions well enough to deliver results that are generally congruent. Though seemingly easy to grasp, the urban realities that the terms “compact” and “sprawled” are meant to capture are polar opposites situated at both ends of a spectrum. This raises a number of complex theoretical and methodological questions and poses important challenges for the operationalization of those concepts both for analytical and applied purposes.

Empirical research cannot determine, for instance, at what point or at what levels of density a city form can be deemed compact or sprawled. Barrington-Leigh and Millard-Ball (2015) stress that there are wide variations in the degree to which an urban area should be considered as sprawl. Further, compactness, sprawl, or any intermediary sets of conditions can be manifested in a wide variety of material and spatial forms, while presenting combinatory patterns that lead to differing environmental impacts and consequences. In addition, the notions of sprawl and compactness, and the metrics routinely used to quantify their respective attributes, say nothing about how various parts that co-exist in the same city are spatially articulated with one another or to the whole, in a specific composition. Finally, the research on sprawl does not escape a well-documented problem, which affects all types of quantitative spatial analysis: the modifiable areal unit problem, or MAUP – sometimes referred to as the “boundary problem” (Wong, 2017). The MAUP manifests itself in seemingly discordant or contradictory results depending on the spatial partitioning used, or on the spatial resolution at which the analysis is conducted (Flowerdew, 2009). The same city or region, for example, will alternatively be considered compact or sprawled depending on the spatial units of reference used for the analysis (Ewing and Hamidi, 2015; Jeager et al., 2010). Inconsistencies in results can either be due to the use of data at different spatial resolutions, or due to their use against different partitioning systems. Those cases are known as the scale and zoning effects respectively (Wong, 2009). Furthermore, the partitioning systems used to analyze sprawl are generally derived from administrative criteria. The researchers routinely use partitioning such as census tracts, municipality, or U.S. county jurisdictional limits. The problem stems from the fact that the partitioning is often at odds with the spatial trends that the research specifically aims at measuring. For example, a census tract might be comprised of residential land-use in half of its area and of industrial land-use in the other half. Assessing the residential densities against such a spatial unit will blur the picture by generating a residential average density that is at odds with the actual residential pattern manifested in the area. The MAUP is a plausible explanation for much of the discrepancies in the research results that this study has reported on.

The main limitations of the current research on the links between sprawl and climate change can be summarized as follows:

- The problems associated with the concept of density or calculation of density has been widely acknowledged and discussed in the literature (Boyko and Cooper, 2011; Berghauper and Haupt, 2010; Forsyth, 2003; Churchman, 1999; Alexander, 1993). One of the main problems associated with the calculation of density or other spatial indicators is the usage of the average. Little is conveyed about how density is distributed across a metropolitan area, let alone smaller geographical units. For instance, when data is aggregated and averaged. When quantifying urban forms, attributes within a unit of investigation (for example a census tract) might be comprised of different land uses, different residential forms, and different road network topologies. These differing factors are not taken into consideration, nor is how they combine in recognizable material and spatial compositions.
- Density (either measured in dwelling/land area, inhabitants/land area or otherwise) is a very crude indicator that does not start capturing the complexity of built environment's forms, as the same densities can be manifested in a very wide variety of compositions (Ewing and Hamidi, 2014).
- The use of data reduction techniques to collapse some of the disparate measures into a univariate index needs more validation.
- The application of static measures to dynamic areas can lead to mischaracterization. Most cities were not created dense, they acquire such a character over time by being rebuilt upon themselves. Sprawl must be conceived in a space-time context and it is not simply the increase/decrease of population, residential building, built-up areas in a given area, but over time. The concept of the time span is essential in the definition and measurement of sprawl.
- A static, or very short-term view on urban development can lead to exaggerating development effects per unit, which may, in fact, be modest on a unit basis once the development is viewed as a complete entity (Harvey and Clark, 1965, p.6).

The conceptual ambiguities pertaining to the notion of sprawl itself (the theoretical uncertainties pertaining to the characterization of its manifestations and the methodological limitations to quantify its properties and compositional make-up) compromise our ability to produce effective evidence-based physical planning. Concretely, the body of empirical research surveyed (that we deem representative on the whole) allows to conclude unambiguously that: 1. the more a city or region is affected by sprawl, the more harmful it is to the environment, and that; 2. compact and mixed-use environments, well serviced by transit systems, are less harmful to the environment than their sprawled, low-density, low-intensity automobile dependent counterparts, and finally, that; 3. the said disparities and variations can be established quantitatively. To use an image, the sets of conditions associated with compact and sprawled environments respectively induce a virtuous and vicious circle. The research, however, has yet to deliver conclusive and cohesive evidence indicating the proper mix of densities, land-uses, and transportation modes, leaving aside how to retrofit existing environments to maximize the returns on investment, environmentally speaking.

7.1.3 A Morphologist's Perspective on the Spatial and Temporal Dynamics of Sprawl

We contend that any serious attempt at measuring the impacts of urbanized habitats on the environment, or at intervening on such contexts with the aims of reducing the environmental footprint or to build-up resilience, requires a deep understanding of the urban material and spatial forms that mark the contemporary city. As well, the processes of these forms are the temporary results. Proper characterization of the urban built environments constitutes an essential facet of any such research effort. Yet, too often, environmental research satisfies itself with crude depictions of the built environment, while relying on raw measurements of their spatial characteristics. This is in spite of seemingly sophisticated geomatics analytical methods and an abundance of spatial data. One of the reasons seems to be a lack of familiarity with the theories, methods, and research outputs of the urban morphology programme. Another issue, related in part to the former, is the reliance on the partitioning of regions such as census tracts or jurisdictional boundaries that derive from administrative, rather than morphological, criteria. As a consequence, diverse material and spatial realities are conflated into regions that are internally disparate, while engendering unsound or approximative measurements of key characters and properties of the urban form (Buzzetti, Gauthier, and MacDougall, Forthcoming).

Our analysis highlights several urban sprawl dynamic aspects. It is a changing land use development process associated with some common measurable characteristics, which vary according to different perspectives (disciplines, methods, authors, or considerations). Urban morphology is a discipline concerned with material and spatial forms as well as human habitats. We believe that a novel morphological perspective is so pertinent and can overcome some limitations mentioned above. A morphological perspective anchored in Urban Morphology could trigger significant advances in re-conceptualizing the phenomenon of urban sprawl.

First and foremost, the sprawled city cannot be uncoupled from its broader urban context. Morphologically speaking, a city's spatial expansion produces a variety of urban tissues and combinatory patterns that require proper analysis. We believe that sprawl and compact city do not only represent two ends of a continuous development spectrum, but they also co-exist and co-evolve, while defining the properties and characters of the whole urban system. Urban morphology's systemic approach which allows us to identify, quantify, and characterize the various constituent parts of the built landscape as well as uncover their reciprocal spatial relations including part-to-part and part-to-whole relationships. Further, it allows assessing how the urban system is altered or retrofitted as a consequence of spatial development.

Urban morphology conceives urban form as a cultural object (Caniggia and Maffei, 2001) which is deeply rooted within a specific cultural and historical context. Sprawl must be put into specific contexts, as different cities or regions sprawl differently. Analytical morphological methods and techniques are well adapted to different cites, as they have special characters and composition rules that are case-specific. Different countries present different realities and different patterns of sprawl. Now, it is clear that if sprawl might have become a global phenomenon, it is not a universal phenomenon in its manifestations. Applications of thresholds established by different authors should be carefully examined when applying to different realities.

7.2 Conclusion

The evidences produced by the research reviewed demonstrate that urban sprawl is an unsustainable form of urban development. As such, it translates into a significant number of undesirable environmental impacts and dangerous consequences in addition to social and economic costs that this study didn't address. Effective efforts to mitigate the adverse effects of urban sprawl must be supported by a well-integrated research and planning agenda that addresses land use, including architectural and urban forms, as well as transportation. Despite significant progress in characterizing the relationship between urban form/urban sprawl and climate change, it is evident that further analysis and more robust conclusions are needed.

Sprawl has been the prominent form of urbanization experienced by most North Americans in the course of their current life. As a consequence, sprawl is sometimes seen as a fatality under our latitudes. It is perceived as the model of development that best corresponds to our contemporary lifestyle and its accompanying sets of expectations regarding material comfort, in spite of obvious negative externalities such as traffic congestion and environmental costs. For thousands of years, cities forms, functioning, and evolution have been predicated on the principle of individual locomotion, i.e., on walking. The appearance and popularization of trains and streetcars towards the end of the 19th century have been associated with a significant spatial expansion of cities (beyond their traditional limit of a 5 km radius, corresponding roughly to an hour of walking between the city limits and its center). Yet, at the local scale, the streetcar suburbs were still spatially laid out based on walking, including accessing basic necessities and services. It is obviously the appearance of the automobile that has drastically changed the conditions of production of new urban environments. Urban sprawl denotes car-oriented development patterns. In sprawled suburbs, owning a car was a necessity. Once a significant part of the urban territory could only be traveled by car, the whole urban system had to be retrofitted to accommodate that form of transport. Such conditions, accompanied by a short-sighted historical perspective, make it extremely difficult for most citizens to imagine living and moving around in their city any other way than by car. Further, this frame of reference obscures the ability to take the full measure of the wastage of natural resources associated with the sprawl spatial system. Such contextualization helps explain a certain propensity to fixate on technological expedients such as the electrification of individual transportation and residential conversion to solar energy. Though useful, focusing on such measures can obfuscate the need to call into question the whole urban development model that sprawl epitomizes, and the necessity to address the problem more comprehensively, and at what we would deem a “structural level.”

This report aimed at drawing the “big picture” in systemic terms, while highlighting some of the key articulations between land-use, including material and spatial forms, transportation, and natural systems. The portrait of fundamental research on these matters and a quick survey of the applied research points to some consensus and gaps, as well as to conceptual and methodological ambiguities and shortcomings. We suggested throughout the report that the theoretical and methodological formulations, as well as the empirical outputs of urban morphology, can be useful to achieve a greater clarity on the urban material and spatial systems, and on the status of those systems as drivers of environmental change. Such a framework, we believe, would also be helpful for translating research results in physical planning terms and to orient the actions towards the retrofitting of sprawled environments to reduce the dependence to the automobile, while reclaiming space to this mode of transportation to put it to better use.

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