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A pluralistic approach to defining and measuring urban sprawl

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The term "urban sprawl" is often used as a synonym for undesired low-density or otherwise unplanned urban spatial development. However, the precise definition and its desirability are debated. Remote sensing practitioners can contribute to our understanding of urban spatial development by measuring its spatial characteristics and dynamics and providing the data to planners and policy makers. By extension, such data can assist in defining sprawl and assessing its presence and intensity in a given metropolitan area. In this chapter, we review the extensive literature and controversial debate around the definition of urban sprawl, emphasizing common themes in definitions and those quantifiable spatial characteristics that would be of specific interest to remote sensing practitioners. The chapter shows that sprawl can be described by multiple quantitative measures, but that different sprawl measures may yield conflicting results. As a complex and multi-faceted phenomenon, we suggest that sprawl is best defined for a given case study, and quantified using a range of indicators specially selected to suit the researcher's definition of sprawl, spatial scale of analysis and specific characteristics of the study site.

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12.1 Introduction

. . . I know it when I see it

Justice Potter Stewart, 1964[1]

Justice Stewart's frequently quoted statement was not a reference to urban sprawl, but considering the widespread debate about its very definition, it is particularly appropriate and widely used in this context. Urban sprawl is indeed something that many people seem to recognize and have an opinion about, but when it comes to quantifying its dimensions, we become less certain regarding what we are measuring on the ground.

Q1 The term "urban sprawl" was first coined by Buttenhein and Cornick (1938), and its use became common throughout the latter half of the 20th century. Sprawl has been used as the descriptive, yet generic, term of choice to describe a variety of urban development forms that shared low density of buildings and population as a unifying trait. These types of urban spatial development played a predominant role in modern urban form in North America and Europe (Glaeser and Kahn, 2004) and a contentious debate regarding their desirability erupted and continues through the present (Ewing, 1997, 2008; Gordon and Richardson, 1997, 2000).

Despite broad interest that developed around the issue of urban sprawl, establishing a clear and unambiguous definition has proven to be an elusive task (Chin, 2002; Hasse and Lathrop, 2003a; Wolman *et al.*, 2005; Hasse, 2007). Commentators on sprawl refer to a broad array of defining characteristics (Hess *et al.*, 2001; Johnson, 2001; Ewing Pendall and Chen, 2002; Wolman *et al.*, 2005; Cutsinger and Galster, 2006; Hasse, 2007). Galster and colleagues (2001) write that the term "urban sprawl" became a metaphor used alternatively to describe (or imply) the patterns, processes, causes and/or consequences of particular urban spatial development patterns. A concise definition has been further muddled because the term is ultimately a cultural construct (Bruegmann, 2005). Therefore, cultural milieu, ideology, and personal experience are intimately linked to how people define sprawl. The lack of a single definition has logically led to difficulty in establishing a unified methodology for measuring the phenomenon; after all, how can we measure what we don't know we're measuring (Burchell *et al.*, 1998; Malpezzi, 1999; Torrens and Alberti, 2000; Galster *et al.*, 2001; Johnson, 2001; Ewing, Pendall and Chen, 2002)?

Most scholars and practitioners agree that a first step towards defining sprawl is to quantify various characteristics of urban spatial development and the dynamics guiding them. Once this is done, scholars, policy-makers and others can then debate the desirability of such phenomena and discuss, if needed, policies to address them. Therefore recent research efforts have focused on establishing and measuring quantifiable variables that capture various characteristics of urban spatial development.

We begin this chapter by integrating several definitions of sprawl derived from a comprehensive survey of the academic and professional literature in order to extract quantifiable spatial characteristics recurring throughout the literature. It is our belief that despite the constant refrain that there is no consensus on sprawl, there is enough agreement to move forward in quantifying relevant forms of urban spatial development. To this we add two caveats. First, sprawl researchers must be explicit in their qualitative definition of sprawl and use quantitative variables that complement their definition. Second, since different variables may yield different results, a pluralistic approach should be adopted which allows for the possibility that sprawl is a multifaceted phenomenon that appears differently on the landscape depending on how, where and when it is measured. We allow the researcher and/or end-user to determine which variables are relevant to their location-specific research and their own sprawl definitions. We conclude our overview of sprawl with a short historical narrative of urban spatial development that was/is considered sprawl.

Next, we provide an extended list of spatial variables for measuring the state of sprawl and associated processes and explore how these variables have been applied empirically. We taxonomize the variables and rank them according to criteria for what constitutes a good measure and suggest when and where the application of each variable would be recommended. We conclude by comparing results of four macro-studies of sprawl in US metropolitan regions to elucidate how the use of different measures produces similar or different results.

While we direct our narrative to remote sensing experts, we emphasize that "sprawl" is often considered as much a socio-economic phenomenon as a physical one. As such, the remote sensing literature is somewhat limited with regard to sprawl discourse, primarily measuring certain physical manifestations of urban development, like building density, time series of urban growth, and geometric parameters of urban form (Sutton, 2003; Hasse, 2007; Irwin and Bockstael, 2008; Bhatta, Saraswati and Bandyopadhyay, 2010). We note that all of these, when combined with geographically-specific socioeconomic and demographic data (e.g., Martinuzzi, Gould and Ramos Gonzalez, 2007), greatly expand our options for measuring sprawl. We assume here that professionals employing remote sensing would benefit by knowing what variables would be useful for them to quantify, and after doing so, provide the results to urban planners, the policy-making community and other stakeholders.

12.2 The diversity of definitions of sprawl

Several syntheses of sprawl definitions exist in the literature (Burchell *et al.*, 1998; Galster *et al.*, 2001; Hess *et al.*, 2001; Malpezzi and Guo, 2001; Chin, 2002; Ewing, 2008; Frenkel and Ashkenazi, 2008a, 2008b; Torrens, 2008). According to these sources, urban sprawl has been defined primarily in three ways: (1) definitions relating to describing a physical and spatial phenomenon of urban spatial development (qualitatively and quantitatively); (2) definitions that focus on the purported social, economic and/or ecological consequences of the phenomenon (described in various ways), and by extension, by normative desires to avoid perceived undesirable urban spatial development patterns, and; (3) definitions focusing on particular socio-economic trends that lead to particular urban spatial

[1] Jacobellis v. Ohio (378 US 184; 1964); available from http://caselaw.lp.findlaw.com/scripts/getcase.pl?court=USandvol=378andinvol=184 (accessed 15 November 2010).

development patterns. Examples for each of the three definitions are provided below.

12.2.1 Definitions describing an urban spatial development phenomenon

Sprawl is most often considered a particular spatial pattern of urban development characterized by low density residential and commercial development. Low density could be considered in terms of building density or population density. This development may be adjacent to existing development, as with suburbs, or scattered and discontinuous development physically separated from the central city, as with leapfrog development (Harvey and Clark, 1965; Downs, 1994; Ewing, 1997; Burchell *et al.*, 1998; Hess *et al.*, 2001; Chin, 2002; Ewing, Pendall and Chen, 2002; Glaeser and Kahn, 2004; Tsai, 2005; Torrens, 2008). As Chin points out, both forms of development are classified as sprawl, although ''the forms and resulting impact are vastly different'' (Chin, 2002). This is at least partly understood when considering that sprawl can have different definitions at different spatial scales (Tsai, 2005) – for instance at the scale of a single urban settlement or at the scale of a region of multiple settlements (see below). Sprawl is also defined as developed land highly segregated into single uses (Ewing, 1997). The presence of large blocks of exclusively residential land or commercial strip development, for example, is considered sprawl (Chin, 2002).

While there are multiple, measurable characteristics of urban sprawl (about which we expand upon in a following section), we note that there are no settled values, or quantitative thresholds, that define sprawl in absolute terms. Proposed absolute values or thresholds that separate 'good' spatial development from 'bad' are subject to debate, as is the question of what residential density constitutes sprawl (Chin, 2002). Superlatives are common throughout the sprawl literature, describing the phenomenon as ''excessive'' (Bruekner, 2000), ''wasteful'' (Torrens and Alberti, 2000) and ''inefficient'' (Fulton *et al.*, 2001; Peiser, 2001; Frenkel and Ashkenazi, 2008a; Thompson and Prokopy, 2009). Others describe the kind of urban growth considered to be sprawl as ''dysfunctional'' (Ewing, Pendall and Chen, 2002). But sprawl is clearly a relative, rather than absolute, phenomenon (Frenkel and Ashkenazi, 2008b; Bhatta, Saraswati and Bandyopadhyay, 2010). This is explicitly recognized in the work of Sutton (2003), for example, for whom sprawl is relative to an average relationship between population size and developed area across US metropolitan regions.

We suggest that one way of working towards consensus on the matter is to define sprawl as a directional process (Harvey and Clark, 1965; Hess *et al.*, 2001), rather than an absolute state of being. Accepting this, the dynamic temporal and spatial patterns of urban spatial growth become crucial to measure and monitor. Noting how these patterns change over time and space change the debate from one about sprawl (a state) into one about sprawling (a process). In other words, while we may not be able to agree that a given density constitutes sprawl, we can call a process of declining density, for example, as sprawling.

12.2.2 Definitions based on consequences of sprawl; sprawl is as sprawl does

''Ultimately,'' write Ewing and colleagues, ''sprawl must be judged by its consequences'' (Ewing, Pendall and Chen, 2002). Thus, the definition of sprawl becomes the socio-economic or ecological consequences of a particular kind of urban spatial development. Consequences might include (1) lack of accessibility between regions in the urban area (Ewing, Pendall and Chen, 2002); (2) high rates of driving and vehicle ownership (Burchell *et al.*, 1998; Ewing, Pendall and Chen, 2002); (3) increased air pollution (Ewing, Pendall and Chen, 2002); (4) undesirable ecological impacts, such as impact on ecosystem cycles or species composition (Perry and Dmi'el, 1995; Cam *et al.*, 2000; Kreuter *et al.*, 2001; McKinney, 2002; Hasse and Lathrop, 2003b; Robinson, Newell and Marzluff, 2005); (5) consumption of exurban open space and agricultural land (Burchell *et al.*, 1998; Hasse and Lathrop, 2003b; Frenkel, 2004; Czamanski *et al.*, 2008; Koomen, Dekkers and van Dijk, 2008; Thompson and Prokopy, 2009), and/or (6) catalyzing socio-economic and racial segregation (Squires and Kubrin, 2005). Some of these variables can be measured directly, particularly loss and fragmentation of open space, while others depend on proxy measures and non-remotely sensed data.

Most, if not all, of these claims are contested. For instance, Glaeser and Kahn (2004) note that while sprawl and associated increases in private automobile use may have increased air pollution, technological improvements in fuel efficiency and emissions control have led to an overall reduction in most air pollutant emissions in the United States. The claim of sprawl leading to socio-economic and racial segregation is also challenged (Glaeser and Kahn, 2004; Wheeler, 2008). Further research attests to the potential benefits of sprawl in terms of maximizing consumer preference, efficient distribution of business and residential areas, low cost relative to high-rise or high concentration settlement (Gordon and Richardson, 1997), and increasing species and ecological habitat diversity (Czamanski *et al.*, 2008).

The great interest that urban planners, policy makers, scholars and activists share regarding sprawl is, to a large degree, derived from opinions regarding how a city should develop spatially, and what the role (if any) the planner and policy maker should serve in promoting or preventing sprawl. Researchers have noted that the debate around sprawl is often the result of its ideological framing (Burchell *et al.*, 1998; Chin, 2002; Hasse, 2004, 2007). Thus, some researchers and activists define sprawl in a pejorative way in order to advocate or oppose a particular policy or plan. One's description of sprawl characteristics can thus be seen as a subjective extension of values-laden planning goals; that is, sprawl is in the eye of the beholder. Opponents of sprawl define it in terms of what it is not: highly centralized, compact cities with mixed land uses, whose transportation systems de-emphasize the role of the private automobile in lieu of public and/or non-motorized transportation (e.g., Duany, Plater-Zyberk and Speck, 2000). Advocates of more laissez faire policy approach define it in a more positive light: benign at worst and the desired expression of people's residential preferences at best (Gordon and Richardson, 1997). Simultaneously, these latter scholars provide research results that challenge the claims of the former group.

Consider two examples: the advocacy organizations Smart Growth America and The Cato Institute. Smart Growth America is an advocacy organization self-described as "a nationwide coalition promoting a better way to grow: one that protects farmland and open space, revitalizes neighborhoods, keeps housing affordable, and provides more transportation choices" (Smart Growth America, 2009). The organization also commissions research on sprawl. Their assessments of sprawl (e.g., Ewing, Pendall and Chen, 2002) are based on a positive vision of what constitutes good urban development. On the other end of the spectrum, the Cato Institute, a free market advocacy organization that seeks to "increase the understanding of public policies based on the principles of limited government, free markets, individual liberty, and peace" (Cato Institute, 2009). This institute also selects its own characteristics of what constitutes good urban development based on their ideological world view (Gordon and Richardson, 2000). As can be assumed, the reports produced by each organization, produced by reputable scholars, advocate two opposing views on sprawl, how it should be measured, its impact and its policy implications.

12.2.3 Definitions according to the social and/or economic processes that give rise to particular urban spatial development patterns

Research suggests that socioeconomic trends may lead to the aforementioned characteristics of spatial development, and thus these trends are included in the definition of sprawl. Some research defines sprawl processes as characterized by the flight of stronger income classes away from the urban center and towards the urban fringe (Ewing, Pendall and Chen, 2002), and the decline of city centers (van den Berg *et al.*, 1982, Mills and Hamilton, 1994; Golledge and Stimson, 1997). The flight of economically strong populations and retail businesses that leave for fringe areas in search of more lax building regulations and/or preferable tax remission lead to a severe decline in the municipal tax base of the region from where they came (Hadly, 2000). Squires and Kubrin (2005), consider urban sprawl to operate simultaneously with concentration of poverty and racial segregation, where sprawl is catalyzed by and catalyzes socioeconomic and racial segregation. Other researchers discuss sprawl as a result of lack of integrated land-use planning (Burchell *et al.*, 1998).

On the other hand, social and economic processes leading to sprawl are sometimes couched in positive terms, as when decentralization of employment and population is considered a desirable process (Glaeser and Kahn, 2004). Sprawl has been also described as the inevitable result of increased mobility due to an automobile-based transportation system (Glaeser and Kahn, 2004), the logical response of markets to consumer demand (Gordon and Richardson, 1997), or possibly as an expression of efficiency maximization among multiple economic players (Batty and Longley, 1994).

Again, the processes emphasized by the various researchers and/or advocates often reflect their ideological disposition. Either way, these definitions are less relevant to a volume on urban remote sensing because they depend on data other than remotely sensed data to measure them.[2]

12.2.4 Sprawl redux: focusing on the concerns of remote sensing experts

Of these definitions, we believe that the characteristics around which we can extract the most objective information, spatial characteristics of urban growth, are of particular concern to remote sensing experts. Therefore, for the remainder of this chapter, we focus on those definitions of sprawl that are physical–spatial in nature, e.g., low density building along the edges of an urban center, tracts of single land use types (e.g. separation of residential, employment and commercial centers), or development not contiguous to existing built-up areas. The distribution of such development should be measured at the neighborhood, metropolitan and regional level, as definitions of sprawl vary depending on spatial scale. These are characteristics that can be readily measured by remote sensing experts (Hasse, 2007, Martinuzzi, Gould and Ramos Gonzalez, 2007; Bhatta, Saraswati and Bandyopadhyay, 2010), and their quantification is of utmost importance in tracking sprawl over time.

The questions of whether or not these spatial characteristics are good or bad, whether they are caused by particular processes and whether they lead to particular desired or undesired environmental, economic or social processes are left aside at this point. The spatial measurements described later in the text provide a crucial foundation of data on which to build further analyses, and they are characteristics that can be derived through remotely sensed data and quantified.

12.3 Historic forms of "urban sprawl"

To understand the origins of the particular form of urban spatial development described as sprawl, we consider two major points in the history of modern urban development when profound demographic, urban and spatial changes were taking place. The first period was the industrial revolution of the 19th century. This period was marked by the massive migration from rural areas to industrial cities and their transformation into centers of activities, primarily in Europe. The period was also characterized by the massive immigration from Europe to the core cities in the United States, leading to an out-migration of the middle and upper classes out of the cities to the urban fringe (Paddison, 2001). Following the industrialization of cities and rapid rise in population densities, the quality of life in cities fell and people romanticized for life in the adjoining open spaces. The squalid conditions that developed in these major industrial cities gave rise to zoning reforms in cities and to suburban development outside of them (Gillham, 2002). From the mid-1800s in the

[2] It is possible to measure some of these socio-economic phenomena spatially through proxies (e.g. the use of "night lights" as proxies for GDP, Henderson, Storeygard and Weil, 2009), but our focus here is the measurement of physical–spatial characteristics of urban development.

United States, homes and neighborhoods began to appear in the countryside, soon to be connected with railroads and streetcars that would catalyze additional demographic movement from city to suburb (Gillham, 2002).

The process was greatly expedited in the post World War II mid 20th century, a period that was characterized by spatial diffusion of residents and activities to the outskirts of urban centers (Mills and Hamilton, 1994). In the United States, and to a lesser extent in Europe, the process of suburbanization (commonly associated with sprawl, but see below) started in earnest following World War II, with a combination of high population growth and an inability of city centers to absorb this growth.[3] A rapidly growing post-war economy, improvements in technology and a rise in standard of living all contributed to increasing demand for large-lot, single-family homes on the outskirts of cities. Concurrently, city centers were in decline (Batty, Xie and Zhanly, 1999, Golledge and Stimson, 1997). The rise of the automobile as a predominant form of transportation facilitated and expanded this process (Glaeser and Kahn, 2004) and set in motion a positive feedback mechanism: the more car-dependent society became, the more suburbs held appeal; the more suburbs proliferated, the more dependent society became on the automobile.

The actual use of the term "sprawl" began in the United States in the 1950s, and became widely used from the 1960s (Belser, 1960, Harvey and Clark, 1965, Gans, 1967, Real Estate Research Corporation, 1974).[4] From the 1970s, the term "sprawl" was often accompanied by "suburbanization," although the two are conceptually unique from one another. Suburbanization refers to the migration of urban residents to the peripheries or outside of cities in a metropolitan area in order to establish new residential neighborhoods (Angotti, 1993). Fishman (1987) differentiates between English/American suburbanization and that of continental Europe in that the former was characterized by middle and upper class residents leaving the cities for green, low-density homes in the urban periphery, while the latter was led by industry leaving the cities, followed by the working class.

Sprawl is a broader concept as defined in our introduction that includes social, demographic and economic characteristics and a broader diversity of urban spatial development characteristics of which suburbanization is just one. Other characteristic development forms include edge cities and exurban development and also included is the demographic and socioeconomic decline of urban centers.

While sprawl may be considered a global phenomenon, the history of sprawl seems largely to have been written in the United States and to a lesser degree in Europe. As early as the 1920s, planners in the United States began noting an acceleration of the rate of loss of open and agricultural land in favor of development (Burchell *et al.*, 1998). The rise of zoning regulations, which provided the legal foundation for separating land uses, is considered a major contributor to later sprawl patterns (Gillham, 2002). Later, in the United States, the strong belief in individual property rights and free markets, along with a distrust of strong, central government is posited to have had a significant impact on the shape of sprawling land development patterns. As Gordon and Richardson suggest (2000), the history of American movement from cities to suburbs might reasonably be viewed as people realizing their residential preferences.

In the United States, sprawl, as defined by loss of farms and open space, was noted by planners as early as 1929 in New York (Burchell *et al.*, 1998). Sprawl critics point to Federal zoning policies from 1922 onward, that gave rise to segregated land use, which in turn laid the foundation for an automobile-centered transportation network (Burchell *et al.*, 1998). In the 1950s and 1960s in the United States, sprawl terminology began entering the planning literature, once again emphasizing low density development and the predominance of automobiles. Leapfrog development, complemented by the rise of federal highway system, fed the critique of spatial growth patterns. By 1972, McKee and Smith (cited in Burchell *et al.*, 1998) would distill the definition of sprawl into four forms: (1) very low density development; (2) ribbon-variety development extending along access routes; (3) leapfrog development; and (4) a "haphazard intermingling of developed and vacant land."

In 1991, Garreau introduced the concept of "edge cities" (Garreau, 1991) as the evolution of non-residential urban cluster development along junctions of beltways and interstate roads. Edge cities introduced a new dimension to sprawl, in that it was not low-density residential development around a single urban core, but entirely new urban cores developing as satellites to main cities. Unlike suburbs, edge cities serve all the functions of the urban core with an emphasis on employment centers. The European analogy to edge cities have been called Functional Urban Areas (van den Berg *et al.*, 1982), and in this case, they are considered a collection of urban communities that together include residential, employment and recreational centers, developed on former agricultural land, and within functional proximity of a major urban center.

The development of edge cities added a new dimension to thinking about sprawl – the dimension of spatial scale. Now rather than envisioning only the urban core and sprawled development in connection to it, a broader scale of analysis was needed to consider regional development patterns. Whereas suburbs emphasized sprawl at a municipal level with a particular emphasis on a decline in building density, at the regional scale, terms such as satellite towns, edge cities, exurbs, and megalopolis become relevant to describe spatial broader phenomenon for which density is only one of many relevant spatial characteristics. Consequently, while density remains the most intuitive and popular spatial variable for measuring sprawl, the list of variables becomes longer when considering the multi-scalar dimensions of sprawl.

12.4 Qualitative dimensions of sprawl and quantitative variables for measuring them

In this section, we present quantifiable variables that have been suggested in the literature and employed empirically to measure sprawl. We first present several criteria – our own and drawn from the literature – that a variable measuring sprawl should

[3] Although Jackson (1985) suggests that suburbanization, which is defined as a situation when peripheral areas develop at a faster pace than central urban areas, appears as early as 1815 in the US and Britain.

[4] For a compilation of early references to sprawl from the early to mid-20th century, see Hess and colleagues (2001).

meet. Next, we present variables that have been used to measure sprawl in empirical studies. We conclude the section by ranking the variables according to the criteria we set at the outset of the section.

12.4.1 Criteria for a good sprawl measurement variable

In order to minimize discord between various studies on sprawl, spatial variables used to measure sprawl should be held up to certain criteria. These criteria include:

1. *Objectivity*. The variable must be quantifiable and reproducible (Ewing, Pendall and Chen, 2002; Lopez and Hynes, 2003; Torrens, 2008). Since sprawl is a subjective term, researchers should provide all measured values and the values at which they consider sprawl to be occurring, thereby allowing users to decide for themselves if the values suggest sprawl or not (Wilson *et al.*, 2003).
2. *Applicability to a large number of places*. The variable must be generalizable to a wide range of study sites and times and not be specific only to the study site of the current examination (Lopez and Hynes, 2003; Wilson *et al.*, 2003; Irwin and Bockstael, 2008; Torrens, 2008). If it is applicable in only particular situations, the researcher should be explicit regarding the limitations of the variable's application.
3. *Appropriateness for multiple spatial scales of investigation*. Sprawl may occur at a variety of spatial scales (e.g. housing unit, neighborhood, town. region, metropolis, state or country). A good variable is robust enough to apply to multiple scales of investigation, while others may be appropriate to only a certain scale.
4. *Meaningfulness, usefulness, and simplicity*. The variable must capture one of the descriptive elements of sprawl (Ewing, Pendall and Chen, 2002; Lopez and Hynes, 2003; Wilson *et al.*, 2003; Torrens, 2008). The data emerging from sprawl studies must be relevant to stakeholders, and therefore it is crucial that the variables are easily explained, understood and relevant to them (Lopez and Hynes, 2003; Wilson *et al.*, 2003).
5. *Ease of application*. An additional quality of a good sprawl indicator is one that is not overly dependent on complex calculations, software that requires a highly specialized skill set, or inaccessible data such that other researchers or practitioners would not be able to employ the measures in their research. Some variables are good in theory, but the data may be inaccessible or not available at the scale of resolution or historical period desired for research. On the other hand, some methodologies for data preparation demand a high level of computational or spatial analysis skills, an advanced understanding of spatial metrics, or access to computer hardware and software that may make the variables less desirable for the intended end user.

12.4.2 What shall we measure?

Prior to the calculation of sprawl measures, total built area must be measured. Urban spatial growth and its rate of change over time are not, on their own, sprawl measures. They are, however, the most important variables to measure because most sprawl measures that follow are dependent on them. Urban land cover is referred to analogously as built space or impermeable surface cover, although each has slightly different implications for how much land will ultimately be quantified as urban (Orenstein *et al.*, 2010).

Estimations of values for urban land cover and changes in land cover over time are also the most important contributions of remote sensing experts to studying sprawl processes. The sheer amount of published literature on urban remote sensing (this book included) testifies to its importance as well as to the rapidly advancing state of the art (Ward, Phin and Murray, 2000; Stefanov, Ramsey and Christensen, 2001; Zhang *et al.*, 2002; Sutton, 2003; Rogan and Chen, 2004; Xian and Crane, 2005; Martinuzzi, Gould and Ramos Gonzalez 2007; Jat, Garg and Khare, 2008; Pu *et al.*, 2008; Bhatta, Saraswati and Bandyopadhyay, 2010). Aside from estimating generic urban land cover, rapid improvements in the quality of data and interpretive methodologies make it possible to differentiate between types of urban land cover (Foresman, Pickett and Zipperer, 1997; McCauley and Goetz, 2004). Differentiating growth in residential area (as contrasted with industrial, business and commercial areas) and in low-density residential area is particularly important, as they are two sub-variables commonly used for characterizing sprawl (McCauley and Goetz, 2004; Irwin and Bockstael, 2008). Computing the amount of and change in availability of developable land, assessed in conjunction with ancillary data like statutory land use plans, also provides important data for sprawl characterization.

Sprawl measures suggested in the literature can be divided into five major groups (Table 12.1):

- density (building and population);
- relative population growth rates;
- spatial geometry of built and open space;
- accessibility between residential, commercial and business areas;
- aesthetic measures.

Due to the nature of the current volume with its emphasis on remote sensing, we focus on those variables whose values can be derived through remote sensing data and analysis. We briefly mention other variables as well, but those are generally quantified using other, non-remote sensed data, such as census and survey data. As such, aesthetic measures as a category are not included in Table 12.1, but see below).

12.4.2.1 Density

There are various types of densities, as well as many ways and scales at which to measure them (Churchman, 1999; Burton, 2000; Chin, 2002; Tsai, 2005). Density can be defined as the ratio between the amount of a certain urban activity and the area on which it exists, for instance population size (Lopez and Hynes, 2003) or housing units per unit area (Razin and Rosentraub, 2000). Population density is considered a key theme in sprawl literature (Galster *et al.*, 2001) and while some argue that it is the most important measure (Fulton *et al.*, 2001; Maret, 2002; Lopez and Hynes, 2003), they are careful to specify that, while important, it is not the only measure of sprawl. As a sprawl measure, population density fails to take into account

TABLE 12.1 Sprawl measurements assessment.

Group of sprawl measurements		Measurement	Criteria				
			Objectivity	Applicable to a large number of places	Appropriate for the spatial scale	Meaningful, useful, and simple to understand	Ease of application
Urban land cover and spatial growth[a]		Change in total amount of urban land cover	+++	+++	A	+++	+++
		Growth in residential area	+++	+++	B	++	++
		Growth in low-density residential area	++	++	B	++	++
		Amount of and change in availability of developable land	++	+	B	+++	++
Density		Gross population density	+++	+++	A	+++	+++
		Net population density	+++	+++	B	++	++
		Current and expected population divided by developed and developable land	++	+	B	++	++
		Density as a function of accessibility to the C.B.D.	++	++	A	++	++
		Density gradients	+++	++	A	++	+
		Amount of population living in low-density	++	++	B	++	++
Relative population growth rates		Sprawl Quotient	+++	+++	A	++	+++
		Suburbs versus central city	++	+	C	++	++
Spatial Geometry[b]	Composition (Degree of homogeneity/heterogeneity in land use)	Percentage contribution of each patch type	+++	++	C	+++	++
		Mean patch size	+++	++	C	++	++
	Configuration	Edge shape (e.g. circularity)	+++	++	A	++	++
		Area to circumference ratio	+++	++	B	++	++
		Continuity indices (applied primarily to open space)	++	++	C	++	++
		Leapfrog indices (applied primarily to built space). Equal to % built in urban core/% built outside urban core.	++	++	A	+++	++
		Fractal dimension	+++	++	A	+	+
Accessibility measures		Road length/area	+++	+++	A	+++	++
		Household traveling time	+++	+++	B	+++	++
		Mean Proximity Index	+++	+++	A	+++	++
		Gravity/logit models	+++	+++	A	++	++

Key: +++ Meets criteria well — A Applicable at multiple spatial scales
++ Meets criteria with some exceptions — B Applicable at some spatial scales
\+ Does not meet criteria — C Applicable at limited spatial scale

[a]Note that growth rate of urban land cover variables are not, by themselves, indicators of sprawl. Rather, these variables are crucial for calculating the values of many of the sprawl variables that follow.
[b]The user must be cautious in applying spatial indicators to measure sprawl, as such indicators may be influenced by municipal borders. For instance, in comparing a long, narrow locality with a circular locality, one may reach the conclusion that the former locality is more sprawled due to circularity.

any aspect of spatial geometry, ecological impact, or land use composition – all of which are significant elements of sprawl by all conventional definitions discussed here and elsewhere (Frenkel and Ashkenazi, 2008b).

Sprawl is generally defined as a condition in which one or more types of density is relatively low or decreases over a certain time period. But what constitutes low density? Burchell and colleagues, among others, make it clear that density a relative value:

> **Sprawl is not simply development at less-than-maximum density; rather, it refers to development that, given a national and regional framework (i.e. suburbs in various locations of the United States), is at a low relative density, and one that may be too costly to maintain**
>
> ***(Burchell et al., 1998).***

Population density can be calculated in several ways, depending on the extent of data and knowledge of the urban landscape. These include gross population density (total population/built area) (Fulton *et al.*, 2001; Sutton, 2003), net population density (total population/built residential area), and population plus expected population divided by developed plus developable land. Density gradient analyses consider density as a function of distance from urban centers or central business districts, where population per unit area declines with distance from urban centers (Batty and Longley, 1994; Alperovich, 1995, Jordan, Ross and Usowski, 1998). Researchers point out that during the past few decades density gradients have been falling (i.e. sprawl is increasing) in developed as well as developing countries (Ingram, 1998). This, they suggest, emphasizes the universality of urban sprawl.

12.4.2.2 *Relative population growth rates*

If it is possible to differentiate between built land use types and if municipal scale population data is available, a "Sprawl Index" (SI) or "Sprawl Quotient" can be estimated. These are defined as the ratio between the growth rate of built-up areas and the population growth rate in that area. A quotient higher than one implies urban sprawl (Weitz, 1999; Hadly, 2000).

Another example applying density measures is the use of the relative amount of population living in low-density as compared to high-density census tracts in US metropolitan areas (Lopez and Hynes, 2003). Similarly, sprawl has also been defined as a condition in which population growth rates in the suburbs are higher than inside the central city (Jackson, 1985).

12.4.2.3 *Spatial-geometry of built and open space*

Spatial geometry constitutes the largest group of sprawl measures. These are numerous geometric measures, many of which have been adopted from ecological research (Irwin and Bockstael, 2008) or from fractal geometry (Torrens and Alberti, 2000; Herold and Menz, 2001). They have particular relevance to remote sensing experts and others seeking to quantify spatial measures of sprawl.

As in the discipline of landscape ecology, the landscape is considered to be composed of spatially distinct "patches" with distinct ecological qualities and parameters including area, circumference, edge shape, area/circumference ratio and others. The distribution of patches across the landscape are characterized and quantified with measures including relative abundance, connectivity and degree of separation between like patches. The individual patch geometry and the aggregate distribution patterns of patches is posited to affect ecological function at the landscape scale (Turner, 1989; Gustafson, 1998). When patch theory is transferred to the domain of urban spatial analysis, patches are defined as land use types (e.g. residential, industrial, commercial, open-natural space, open-agricultural space), and the metrics transfer as well. Here, the patch geometry and distribution of urban patches are suggested to have wide ranging implications for environmental quality, economics, social relations and other social variables.

Geometric-ecological measures can be grouped into two types for urban landscape analysis: composition and configuration (Torrens and Alberti, 2000). Composition refers to how heterogeneous an area is with regard to its mix of patch types and provides information regarding the relationship between and among patches in a matrix. Configuration refers to the geometry of individual land use patches, or how regular or irregular their shape. Patch circumference, and various descriptors of shape of the patch and its edge, like circularity (Gibbs, 1961) and area/edge ratio (McGarigal *et al.*, 2002), are common measures for configuration.[5]

Fractal dimensions provide a second approach to measuring sprawl, where fractal measures replace Euclidean geometry (Batty and Longley, 1994). Fractals are defined as "objects of any kind whose spatial form is nowhere smooth, hence termed 'irregular', and whose irregularity repeats itself geometrically across many scales" (Batty and Longley, 1994). Although the measures are related to configuration, fractals arise from a conceptually different way of looking at the spatial development of cities. Research on fractal dimensions has contributed to our understanding of urban spatial development and our understanding of the forces that may shape a city's form (Benguigui *et al.*, 2000, Benguigui, Blumenfeld-Lieberthal and Czamanski, 2006, Thomas, Frankhauser and Biernacki, 2008). Torrens (2008) and Frenkel and Ashkenazi (2008b) integrate fractal variables into a list of geometric variables with which they characterize sprawl.

The degree of homogeneity/heterogeneity in built land uses (e.g. residential, commercial, industrial) is measured by composition variables (Fulton, 1996; Ewing, Pendall and Chen, 2002). Urban sprawl has been defined as a homogeneous development pattern, characterized by the absence of mixed land use (in particular, residential areas separated from trade and services) at the neighborhood and city scale (Fulton, 1996). Built-up areas with a high rate of mixed land uses are regarded as compact and sustainable (Jenks, Burton and Williams, 1996, Burton, 2000), whereas a high percentage of residential land use is considered homogenous and non-mixed, and thus, sprawling. Another way of looking at this aspect is the balance that exists between the amount of population and the number of jobs (Ewing, Pendall and Chen, 2002). A non-balanced situation where population is large relative to jobs in a single geographic unit is considered a component of sprawl.

[5] For readers interested in the mathematical equations for each of these indicators derived from landscape ecology, the easily accessible Fragstats Users Guide provides a comprehensive and detailed overview of each landscape indicator, its equation and its strengths and weaknesses (McGarigal *et al.*, 2002); see: http://www.umass.edu/landeco/research/fragstats/documents/fragstats_documents.html (accessed 15 November 2010).

Many of the variables used to measure homogeneity/heterogeneity are again drawn from the discipline of landscape ecology (McGarigal *et al*., 2002). Variables such as leapfrog and connectivity indices describe the mix of urban "patches" within a matrix of open space and measure the proximity of similar patch types from one another (Galster *et al*., 2001). These measures quantify the level of scatter and fragmentation of the urban landscape. When built areas are separated from one another by open space then the landscape is considered fragmented, which is another sprawl characteristic (Torrens and Alberti, 2000).

One of the most intuitive measures derived from landscape metrics is the number of patches of a certain land use type. The larger this number, the more heterogeneous mix of land use patches at the landscape scale. Mean patch size takes the average size of all of the patches of a given land use, and the smaller the average patch size, the more heterogeneous or fragmented the landscape and thus the more sprawled (Torrens and Alberti, 2000; Herold and Menz, 2001).

Three additional sample sprawl measures derived from landscape metrics that measure patch composition are contagion, connectance, and proximity. Contagion is the tendency of patch types to be aggregated (McGarigal *et al*., 2002); high contagion value at the municipal scale could suggest large tracts of homogeneous land use or sprawl. However, at the regional scale high contagion value might suggest a low amount of fragmentation of the landscape, with built patches clustered and not fragmenting the open space 'matrix'. Connectance and proximity both compute the functional closeness of patches of similar type, and their values are interpreted such that greater dispersal of patches (i.e. built patches in an open space matrix) represents greater sprawl.

Finally, several variables measure the degree of irregularity of the patch including circularity and edge to area ratio. In terms of sprawl, irregularity is considered sprawling, with a perfectly circular patch synonymous to compact development, as opposed to linear or irregular development (Gibbs, 1961).

12.4.2.4 Accessibility between residential, commercial and business areas

Sprawl is defined as a condition of poor accessibility, followed by the massive use of private vehicles (Ewing, 1994, 1997, Ewing, Pendall and Chen, 2002), or as Al Gore put it, "A gallon of gas can be used up just driving to get a gallon of milk."[6] Accessibility can be quantified by measuring road length, road areas, and the traveling times of households (Hadly, 2000).

Landscape ecology metrics can also be used to analyze accessibility. For example, the size and distribution of residential "patches" relative to other land uses may provide a proxy measure for accessibility between these patches and commercial and industrial "patches." Accessibility can also be assessed by calculating the fractal dimensions of road networks (Benguigui, 1998). Further, some ecological measures are useful to measure accessibility, such as "mean proximity index" (MPI) (Gustafson, 1998; Torrens and Alberti, 2000). Another group of accessibility measures is used in transportation models, including: the isochrones measurements through which one counts the number of possible trip destinations in a given area; gravity indices based on the classical gravitation model used in urban planning – the movements of goods, people and information between different spatial locations, often referred to as origins and destinations, and; utility function index gathered from discrete choice models customary to transportation planning discipline (Torrens and Alberti, 2000). Degree of dependency on private automobiles for transport is also considered to be a proxy for sprawl. Where accessibility is lower, there is a higher reliance on private automobiles to connect between the residential and other land uses (Ewing, 1997, 1994; Ewing, Pendall and Chen, 2002).

[6] Quote from a speech by Al Gore during his campaign for the US presidency, January 1999. Available from http://www.greenclips.com/00issues/139.htm (accessed 15 November 2010).

12.4.2.5 Aesthetic measures

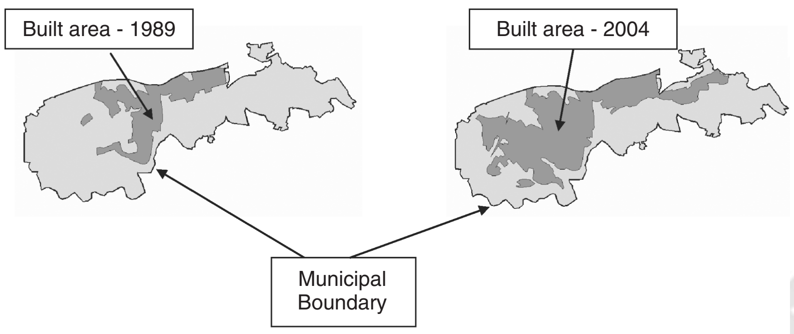
Sprawl is often considered a boring, homogeneous form of development (Fulton, 1996; Gordon and Richardson, 1997). Being subjective by definition, it is difficult to measure and quantify the aesthetics of sprawl unless by consumer preference or survey data. Several recent studies have attempted to define archetypes of urban development or sprawl, such as residential sprawl or strip-mall sprawl, and to compare various landscapes to those archetypes. It seems that much work is still needed in this area (Torrens and Alberti, 2000), and, as noted above, these measures are less relevant to remote sensing experts.

12.4.3 Choosing among the sprawl measures

The advantages and disadvantages of each of these sprawl measures can be considered on the basis of the five criteria outlined at the beginning of this section. We selected a representative sample from the span of possibilities and ranked them according to how well they comply with the five criteria. Our ranking is based on a comprehensive literature review (and thus the experiences of other researchers), as well as our own experiences measuring sprawl and conveying concepts and empirical findings to colleagues, students, professionals and stakeholders. Rankings are on a scale of one to three, with three being the highest ranking variables for the given criteria. Applicability for different spatial scales receives its own ranking system; from A to C, with A being applicable to multiple spatial scales and C to only one scale. Results are summarized in Table 12.1.

We offer three caveats to our ranking of the sprawl variables. First, a measurement that receives high marks across all categories does not necessarily make it the best measurement for all case studies or for measuring all aspects of sprawl. The sprawl quotient, for example, has disadvantages (noted below) that are only picked up in one of the five criteria and ranks highly in the other four. Further, there are measures that received low marks, but still provide important information regarding sprawl – sometimes only at particular spatial scales or for particular places, but useful nonetheless.

Second, while the user can choose from among these variables in a way that suits their specific research question, data sources may also determine the variables selected. The relevant considerations here are (1) availability of historical data and (2) the scale of resolution. With regard to the first consideration, as we have emphasized, sprawl is both a state and a process. As a process, directionality of trends is important. Therefore, it is crucial that



Sprawl Indexes	1989	2004	% change	Equation
Gross density (residents per sq)	6,487	5,286	–19%	$D_{gi} = \frac{P_i}{UA_i}$
Shape index (SH)	3.0	3.3	12%	$SH_i = \frac{L_i}{2\sqrt{\pi A_i}}$
Leap frog index (LFI)	2%	1%	–50%	$LFI_{gi} = \frac{Aout_i}{UA_i}$
Mean Patch Size (Ha) (MPS)	36.4	73.0	101%	$MPS_{ij} = \sum_{j=1}^{n} \frac{a_{ij}}{n_{ij}}$

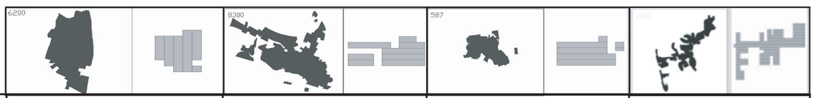
Where:
P_i = number of residents in urban settlement i
A_i = centralbuilt-up area of urban settlement i
UA_i = urban built-up area of settlement i
RA_i = Residential area of settlement i (land-use no. 1)
L_i = Perimeter of central built-up area of settlement i
$Aout_i$ = leapfrog areas in settlement i
a_{ij} = area of land-use j in urban settlement i (j = 1...n)
n_{ij} = number of polygons of land-use j in urban settlement i (j = 1...n)

FIGURE 12.1 A temporal comparison of urban spatial growth for the Israeli city of Carmiel, 1989 and 2004. The built space area estimated using maps and verified with aerial photographs and ground survey. Four sprawl measures are provided for the two dates to compare temporal trends.

spatial data be available for two or more points in time, so that temporal changes in spatial variables can be measured (see Fig. 12.1). With regard to the second consideration, the user must reconcile the tradeoff between low resolution needed to capture large areas and for comparative research between regions, and high resolution needed to capture fine-grained processes that would be lost when resolution is too low (Irwin and Bockstael, 2008). An example of this tradeoff is the utility of Landsat data: Landsat provides excellent data for large areas with high frequency of data capture, but it lacks the resolution to capture very low density development (Orenstein *et al.*, 2010). Low density development is of utmost importance when considering the extent of sprawl (Irwin and Bockstael, 2008).

Third, by ranking individual sprawl measures, we do not imply that a single measure will suffice in capturing this multifaceted phenomenon. On the contrary, since sprawl has so many dimensions, simultaneous application of multiple indicators is not only recommended, but required (Torrens and Alberti, 2000; Galster *et al.*, 2001; Ewing, Pendall and Chen, 2002; Hasse and Lathrop, 2003a; Sutton, 2003; Cutsinger and Galster, 2006). It is apparent that quantitative indicators for measuring sprawl yield ambiguous and often contrary results. Urban areas could be considered sprawled using some measures, yet compact using others (Hasse, 2004; Frenkel and Ashkenazi, 2008b; Torrens, 2008). This fact is exemplified through the use of four urban areas in Israel (Fig. 12.2). In the figure, the "Type A" urban area ranks compact using four sample sprawl measures. The "type D" urban area, on the other hand, ranks sprawled using these measures. Types B and C both rank sprawled on two of the four measures, but they are different measures in both cases. This point is further emphasized in the previous figure (Fig. 12.1), where over time at one location, population density and shape index both suggest more sprawl, while leapfrog index and mean patch size suggests less sprawl. Clearly the use of one or even two measures misses the complexity of sprawl characterization.

In response to this challenge, researchers are measuring multiple sprawl characteristics simultaneously (Ewing, Pendall and Chen, 2002; Hasse and Lathrop, 2003a; Hasse, 2004; Irwin and Bockstael, 2008; Frenkel and Ashkenazi, 2008b; Torrens, 2008), or integrating multiple measures into a single index after narrowing down the range of variables using reduction techniques (Ewing, Pendall and Chen, 2002; Frenkel and Ashkenazi, 2008b). Cutsinger and Galster (2006) argue that since metropolitan areas may be considered sprawled according to some indicators while simultaneously considered not sprawled in other dimensions, a



Sprawl Indices		Type A		Type B		Type C		Type D	
Sprawl measurement	Gross density	22,356	Compact	9,213	Compact	1,304	Sprawl	2,470	Sprawl
	Density growth rate (1985-2004)	37%	Compact	52%	Compact	1%	Sprawl	–8%	Sprawl
	Shape index	1.68	Compact	3.15	Sprawl	1.95	Compact	4.63	Sprawl
	Leap frog index	0%	Compact	2%	Sprawl	0%	Compact	9%	Sprawl
Population size 2004		138,900		211,600		2,500		13,300	

FIGURE 12.2 A comparison of four urban areas and their ranking according to four selected sprawl measures. Each urban area is illustrated with an estimate of built area derived from maps and verified with aerial photographs (left; for which the sprawl measures were calculated) and with a visually abstracted illustration (right) to simplify its geometry (right).

new typology for urban land use patterns is needed in place of a misleading 'more or less sprawled' dichotomy.

Most of the sprawl measures score high in *objectivity*; that is, they can be quantified and the methods by which they are obtained can be replicated. While the value obtained for any measure is subject to user interpretation (e.g., what density value constitutes high or low density), some measures have an added layer of subjectivity in that they require user decisions prior to calculating the value of the measure. For instance, some measures require deciding *a priori* what constitutes a low-density neighborhood, a suburb, or a central business district so that their area or distances between them can be quantified. This is straightforward in theory, but can be challenging in practice and subject to much deliberation. Other examples are those measures that depend on user-input for determining thresholds by which the measure will be calculated. Continuity index received a lower ranking for this reason because its calculation depends on the designation of threshold distances by which to calculate whether a patch is continuous (adjoining) with a similar, nearby patch. This decision is not trivial, as the choice of threshold may have significant effect on the outcome of the calculation of the measure. The other variables that depend on measuring patch types are objective as long as there is general *a priori* agreement regarding what characterizes a patch and what differentiates it from other patches.

With regard to the criteria of applicability to a large number of *diverse research sites*, we found that some of the measurements were formulated to fit uniquely to urban development patterns in the specific country being researched (primarily for the United States or Europe). Suburbs and low-density residential areas, for example, are fairly distinct to the United States context, and may have a different meaning or even irrelevance in other country case studies. Quantifying developable land is also very specific to particular countries – some countries may have statutory plans that define what is developable, while in some countries, topography and ecological conditions or indigenous land tenure rules may dictate what is developable. Thus, this variable would be difficult to use in international comparative work. Similarly, using measures that depend on a central business district (CBD) is becoming increasingly difficult. In recent years there has been great change in the evolution of big cities and metropolitan regions from the classic spatial monocentric pattern into polycentric pattern (Gar-on Yeh and Wu, 1997; Parr, 2004).

Spatial–geometric measures, on the other hand, are considered to be suitable in most places, especially when investigating landscapes partitioned into dichotomous built and open space. Their use appears most frequently in the interdisciplinary literature focusing on ecology and urban/regional planning (e.g., Leitao and Ahern, 2002; Taylor, Brown and Larsen, 2007). A caveat to this is that the relevant type of patches to measure may differ greatly from site to site. Because of this, comparative studies between sites using these measures maybe more difficult and therefore we ranked them in the middle range for this criterion.

Regarding our *multiple-scale applicability* criterion, some measures are excellent for a particular spatial scale, but difficult to apply or not applicable at another scale. Our ranking system for this criterion is based on whether the given measure is appropriate for many spatial scales (A) or only a very specific scale (C). We suggest that the researcher must carefully select an appropriate measure for the spatial scale under investigation and make no assumptions with regard to the application to other spatial scales. For example, at the scale of a single neighborhood within a city, measuring growth in residential area is a relatively straightforward task (as distinct from industrial or commercial areas).

However, scaling up to the level of an entire metropolitan area, residential area cannot always be reliably differentiated from other forms of development using standard data sources (satellite imagery, aerial photographs) unless researchers have access to detailed ancillary data sets (Vogelmann *et al.*, 1998; Yang and Lo, 2002). This is even more relevant at broader spatial scales like regions and countries. From our research in Israel, we find that using suburban development as an indicator does not work at the scale of an individual city because suburbs, defined as low density, residential neighborhoods, generally occur outside of the urban locality jurisdiction in satellite "bedroom" communities. So in our case, using suburban versus urban population growth rates is relevant mostly at the metropolitan or regional scale.

Using patch measures can be useful at multiple spatial scales, though the patch types may vary depending on the scale of analysis. Some patch types become difficult to measure or irrelevant to sprawl characteristics at certain spatial scales. Contiguity between patch types, for example, is important for regional-scale analyses where ecological open space issues are important. At the local scale, this measure has less utility.

Ranking of whether the measurement is *meaningful, useful* and *simple to understand* was conducted based on our assessment of how much professional knowledge was required for a stakeholder to understand the concept behind the measure. Many of the measures are very straightforward (how much land is built, how many people live in a certain block of land), but others require more nuanced understanding, such as density gradients, and certain geometric measurements. Fractal dimensions, as useful as they may be, are difficult to explain to a diverse audience.

The sprawl quotient is a very popular measure, but we find several instances where its application is problematic and its meaning misconstrued. For example, in compact, high density cities with aging demographic profiles, a small amount of spatial growth can result in an illogically high sprawl quotient relative to sprawling, low density (but demographically young) cities (Frenkel and Ashkenazi, 2008b). Similarly, the comparison of percentage of population living in low density versus high density urban areas can be heavily influenced by the particular demographics of each area (e.g. young families in low density versus aging individuals in high density tracts). Values may change, perhaps suggesting sprawl even in the absence of urban expansion. Negative population growth has been shown to introduce complications for the use of other per capita indices to measure sprawl, as well (Hasse and Lathrop, 2003b). On the other hand, sprawl has been shown to occur where the amount of developed land grows, even while population falls (Kasanko *et al.*, 2006), thereby producing negative values of the sprawl quotient.

Finally, we consider *ease of application*. This consideration depends on how much data is required, the need for software and associated technical ability, and/or whether quantifying the measures depends on complex calculations. At the extreme, data for some measures can be extracted and estimated with a paper map and a marking pen. Others demand access to digitized maps, remotely sensed data, GIS software and survey/census data. For instance using patch type measures may demand a high degree of *a priori* knowledge about the area and ancillary data sets to complement remotely sensed data, such that the user can define each urban patch type (e.g., residential, industrial, commercial, etc.). Still others demand proficiency at applying complex computational or mathematical calculations using professional software and programming. We give high ranking to those measurements that could be used outside of a university or well-funded government research institution, and low ranking to those measures that would be difficult to collect without large budgets and high levels of technical proficiency. Some spatial metrics received lower rankings due to the challenge of clearly defining and measuring patch types. Once patch types are defined, however, the landscape metrics can be calculated using the popular and free Fragstats software (McGarigal *et al.*, 2002), assuming GIS software proficiency.

12.4.3.1 Does choice of measures matter?

In order to assess how important the choice of sprawl measures is to the characterization of sprawl, we compared four studies that estimated sprawl across metropolitan areas in the United States (Jordan, Ross and Usowski, 1998; Razin and Rosentraub, 2000; Ewing, Pendall and Chen, 2002; Lopez and Hynes, 2003). Each of the studies employed a different sprawl measure or set of measures and in some cases, unique datasets (see Table 12.2).

The results of the comparative analysis of the studies' findings show many similarities, but also several differences (Table 12.3). In many cases the same metropolitan region appeared at the extremes (i.e., the most sprawled or the most compact) in all of the studies. These regions have characteristics of sprawl or compactness that were robust enough to manifest themselves across many measures. On the other hand, there were multiple inconsistencies in the rankings, where regions would rank highly as either sprawled or compact in one or more studies, but fall into the mid-range in other studies, being neither sprawled nor compact.

Third, there were several cases where a metropolitan region would be characterized as compact by one or more studies, but sprawled in another. In these cases, it was generally the study by Jordan and colleagues (1998) that provided a contrary result for a given region, as it did with Los Angeles, Miami, and Chicago metropolitan regions. In each of these cases, the regions were considered compact according to the measures in two or three of the other studies, while they rated sprawled in the Jordan *et al.* study. This may be due to at least three reasons. First, three studies were measuring *state* of sprawl at a given time. The fourth study measured both state and **process** between 1970 and 1990. In the case of Miami and Chicago, the areas were becoming more sprawled over time relative to their status in 1970 and 1980. Likewise, the Oklahoma City metropolitan region, rated as sprawling in one study and in the middle range in two others, was becoming more compact over time according to Jordan *et al.*[7] Second, spatial extent of metropolitan areas may have been defined differently by each author. Even though most of the researchers were working with US Census Bureau definitions, there is room for selectivity regarding which metropolitan boundaries to employ. Third, as several authors have suggested, different sprawl measures can yield disparate results regarding a single location (Frenkel and Ashkenazi, 2008b; Torrens, 2008), as also shown in Fig. 12.1. It appears that density gradients (used by Jordan, Ross and Usowski, 1998) capture elements of sprawl differently than the measures used in other studies.

This emphasizes three parallel considerations for sprawl research. First, the element of time deserves a more central role in the study of sprawl. Some scholars discuss relative values of sprawl measures, either changing in time or between places, where the difference between sprawl and compact is not an absolute, but rather, a relative change along a continuum (Pendall, 1999; Johnson, 2001). They investigate temporal changes in urban spatial development, such as increases or decreases in residential density (Hasse and Lathrop, 2003a; Frenkel and Ashkenazi, 2008b), or changes in density gradients from CBDs (Jordan, Ross and Usowski, 1998) to determine dynamic patterns of sprawl. Relative sprawl and the direction of sprawl indicators over time are thus key considerations in sprawl studies (Torrens and Alberti, 2000; Galster *et al.*, 2001; Malpezzi and

[7] A fifth study which classified level of sprawl across US metropolitan areas, and which makes use of remotely sensed data (nighttime satellite imagery) is Sutton (2003). Sutton's results support, for the most part, the classifications in Table 12.3. Little Rock, Knoxville, Greenville and Atlanta ranked as sprawled (support for the consensus), as did Oklahoma City. Lincoln, Chicago and Miami were ranked as relatively compact, although New York and Phoenix rank neither compact nor sprawled, but near the national average. Syracuse ranked as relatively compact, as did Los Angeles, adding to the ambiguity about that city.

TABLE 12.2 Five studies ranking degree of sprawl in United States metropolitan regions. Relevant results from four of the studies are summarized in Table 12.3 The fifth study, Sutton, is not included in Table 12.3, but is discussed in the text; See footnote 7).

Study	Unit of measure	Sprawl measure
Jordan, *et al*. (1998)	79 Metropolitan Statistical Areas (MSAs) and Primary Metropolitan Statistical Areas (PMSAs) as defined by the US Statistical Bureau.	Population density gradient from Central Business District (CBD) and change in density gradient over time.
Razin and Rosentraub (2000)	PMSAs and/or consolidated MSAs. Article included results for only 20 cities – the 10 most sprawled and the 10 most compact.	Index of three measures: • the percentage of dwellings in single-unit detached houses • population per square kilometer • housing units per square kilometer
Ewing, *et al*. (2002)	Every metropolitan area in the United States for which they could access all the necessary data (83 areas in total)	Index including: 7 variables representing aspects of population and residential density 6 variables representing land use heterogeneity 6 variables representing population distribution relative to city centers (which they term variables measuring ''strength of metropolitan centers.'' 3 variables representing accessibility of street networks (related to size of city blocks)
Lopez and Hynes (2003)	330 US metropolitan areas with a population of over 50 000	Sprawl index (proportion of the metropolitan area population living in high density tracks relative to that living in low density tracks)
Sutton (2003)	244 urban clusters with populations over 50 000	Relationship of each urban cluster relative to a regression of all urban clustersln urban area/urban population (area derived from remotely sensed nighttime data of light intensity)

TABLE 12.3 Similar and contrary results from the comparison of four studies (Jordan, Ross and Usowski, 1998; Razin and Rosentraub, 2000; Ewing, Pendall and Chen, 2002; Lopez and Hynes, 2003) ranking metropolitan region on scale from sprawl to compact in the United States.

Consensus – sprawled[a]	Consensus – compact[b]	General agreement – sprawled[c]	General agreement – compact[d]	Ambivalent results[e]
Little Rock, AR (4/4)	New York, NY (4/4)	Oklahoma City, OK (3/4)	Colorado Springs (2/3)	Los Angeles and Honolulu – ranked among the most compact in two studies, in the mid-range in a third study and most sprawled in a fourth study
Knoxville, TN (4/4)	San Francisco, CA (4/4)	Syracuse, NY (2/3)	Fort Lauderdale, FL (2/3)	Chicago – ranked among the most compact in three studies and among the most sprawled in the fourth study
Greenville, SC (3/3)	Jersey City, New Jersey (3/3)		Chicago, Ill (3/4)	Miami – ranked by 3 studies as among the most compact, and one as among the most sprawled.
Atlanta, GA (3/3)	Lincoln, NE (2/2)			Phoenix – one study places it among the most compact and another among most sprawled

[a] All studies that included this metropolitan region placed it near the top of their list of sprawled metropolises.
[b] All studies that included this metropolitan region placed it near the top of their lists for compact metropolises.
[c] The majority of studies (3 of 4, or 2 of 3) that included this metropolitan region placed it near the top of their list of sprawled metropolises.
[d] The majority of studies (3 of 4, or 2 of 3) that included this metropolitan region placed it near the top of their list of compact metropolises.
[e] Some studies list these metropolitan regions as sprawled while others list them as compact.

Guo, 2001). Second, in comparative studies, the precise area under investigation (Wolman *et al*., 2005) and the definition of built area (Orenstein *et al*., 2010) must be consistent. Third, sprawl should be conceptualized as a multidimensional phenomenon that requires a different measure or set of measures for each dimension (Torrens and Alberti, 2000; Galster *et al*., 2001; Ewing, Pendall and Chen, 2002; Cutsinger and Galster, 2006).

Conclusion

In this chapter, we presented multiple definitions of sprawl, the historic development of the term and associated urban development patterns, and the measures employed to quantify these patterns. We find an increasingly nuanced discussion regarding definition of and measures for quantifying sprawl. This is a productive result of a longstanding debate around all aspects of the subject.

Today, sprawl is understood to be both a pattern at a given time and a process of change over time. Sprawl is generally accepted as a relative state, warranting cross-site comparisons and multi-temporal analyses. It is defined by multiple quantitative, spatial characteristics whose values do not necessarily lead to similar conclusions; different sprawl measures may yield conflicting results. As such, the state of the art in measuring sprawl involves the application of multiple variables either in the form of an integrated index or considered in parallel and the acceptance that a defined area may display sprawl-like characteristics in some, but not all, measures.

We therefore note the importance of comparative studies such as the US metropolitan regions analyses mentioned above. These analyses each provide a comparison of multiple sites, and in the case of the study by Jordan and colleagues (1998), an analysis of change over two decades. However three of these studies (representative of much of the sprawl literature), employed only one or a few variables culled from relatively easily accessible statistical data to measure sprawl. This may be understandable considering the amount of data that would need to have been collected and processed for such a broad comparison. The result, however, is that important characteristics of sprawl, such as spatial geometry as in the cases above, were not assessed. A remotely sensed meta-analysis of US metropolitan regions would be a welcome contribution to this discussion.

The debate around the desirability of sprawl is a values-driven discussion. So, it is imperative that researchers are forthright and explicit in their chosen definition and their objectives, such that their readers, critics and end-users can assess their research in the proper context. The research community can contribute a broad range of quantitative measures that can be used to elucidate the processes and allow stakeholders to assess where we have been and where we are going. It will then be up to all of the stakeholders (researchers included) to decide whether or not they are observing sprawl, and if so, whether it is desirable process or not.

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Queries in Chapter 12

Q1. Please confirm if the spelling - "Buttenhein" or Buttenheim.