URBAN SPRAWL METRICS:
AN ANALYSIS OF GLOBAL URBAN EXPANSION USING GIS

Shlomo Angel
Robert F. Wagner School of Public Service, New York University
Woodrow Wilson School of Public and International Affairs, Princeton University
solly.angel@gmail.com

Jason Parent and **Daniel Civco**
Center for Land Use Education And Research (CLEAR)
Natural Resources Management and Engineering
University of Connecticut
Storrs, CT 06269-4087
jason.parent@uconn.edu
daniel.civco@uconn.edu

ABSTRACT

We define and present a comprehensive set of metrics for five dynamic attributes of urban spatial structure commonly associated with 'sprawl': (a) the extension of the area of cities beyond the *walkable* range and the emergence of 'endless' cities; (b) the persistent decline in urban densities and the increasing consumption of land resources by urban dwellers; (c) ongoing suburbanization and the decreasing share of the population living and working in metropolitan centers; (d) the diminished contiguity of the built-up areas of cities and the increased fragmentation of open space in and around them; and (e) the increased compactness of cities as the areas between their fingerlike extensions are filled in. We also introduce several metrics for key manifestations of sprawl. We present these metrics as well as actual calculations of these metrics for two cities: Bangkok and Minneapolis. A forthcoming paper will present similar results for a global sample of 120 cities.

INTRODUCTION: THE ATTRIBUTES AND MANIFESTATIONS OF URBAN 'SPRAWL'

A survey of this literature reveals an interesting dissonance. On the one hand, there is an almost universal consensus, with a few minor exceptions, on what are the key manifestations of sprawl: endless cities, fuzzy boundaries between city and countryside, a polycentric urban structure, ribbons and commercial strips, scattered development, and the fragmentation of open space, among others. On the other hand, there is the oft-repeated lament that sprawl—as an overarching characteristic common to all these manifestations—is ill defined and therefore difficult to measure using a single metric in a convincing way.

This paper is a contribution towards the definition and the actual measurement of key *attributes* of urban expansion or 'sprawl'[1]. The paper has one central objective: to propose summary metrics for measuring these attributes, to define them, and to describe procedures for measuring them, given classifications of satellite imagery and population data for two time periods.

The five attributes that have emerged as the key characterizations of urban sprawl in the literature and in our own investigations are:

1. The extension of the area of cities beyond the *walkable* range and the emergence of 'endless' cities;
2. The persistent decline in urban densities and the increasing consumption of land resources by urban dwellers;
3. Ongoing suburbanization and the decreasing share of the population living and working in metropolitan centers;
4. The diminished contiguity of the built-up areas of cities and the fragmentation of open space in and around them; and

[1] The terms 'urban expansion' and 'sprawl' will be used interchangeably throughout this paper without necessarily attributing positive or negative attributes to these phenomena.

5. The increased compactness of cities as the areas between their fingerlike extensions are filled in.

The literature on urban sprawl is, for the most part, highly politicized, and researchers are automatically suspect of harboring biases that prevent them from presenting an objective view of the phenomenon at hand. But that need not mean that we should abstain from trying to define and measure sprawl precisely, from making our proposed measurements transparent, or from advancing our common understanding of what specific measures mean, what they bring to light, and what they hide. This paper attempts to do just that.

Because of the public nature of the sprawl debate, we have restricted ourselves to measures of urban sprawl that correspond to common intuitive understandings of the phenomenon. As Horn and his colleagues (1993) observe, "[t]he *de facto* arbiter of what measure is best is intuition: which one most 'fully encompasses our intuitive notion' (Niemi *et. al*,. 1990), or which one best results in a 'correspondence between visual and quantitative expression' (Manninen, 1973)". This assertion necessarily means that the common understanding of what constitutes sprawl needs to be taken seriously and cannot be simply dismissed. Measures of sprawl that may be very meaningful and insightful to analysts may turn out not to be particularly useful in policy discussions or in presentations to the general public.

Following Galster and his colleagues (2001), we define and measure sprawl both as a *pattern* of urban land use—that is, a spatial configuration of a metropolitan area at a point in time—and as a *process*, namely as the change in the spatial structure of cities over time. Sprawl as a pattern or a process is to be distinguished from the *causes* that bring such a pattern about, or from the *consequences* of such patterns (Galster *et. al.,* 2001). In this paper, we examine sprawl largely as a geographic pattern or its change over time. We take sprawl to be a *relative* rather than an absolute characterization of an urban landscape. We have no interest in creating a black-and-white distinction between a sprawling city and a compact city. We are only interested in a relative measure that can be used to compare a single city at two points in time to determine whether it is more sprawling or less sprawling now than before; or to compare two cities to determine which one is more sprawling.

Land cover data derived from satellite imagery (Angel *et al.,* 2005; Civco *et al*., 2005) served as the basis for all metrics. In the next section, we introduce measures of various manifestations of sprawl. In this following five sections we introduce key attributes of urban sprawl that tend to be present—to one extent or another—in most cities regardless of any particular manifestation of sprawl in these cities. In fact, when we examine the available data for all cities in a global sample of 120 cities (the subject of a forthcoming paper) we find that only very few cities in special circumstances do not exhibit these five attributes of sprawl to one extent or another.

MANIFESTATIONS OF URBAN 'SPRAWL'

It is important to distinguish clearly between the *attributes* and *manifestations* of urban sprawl. The insistence on this distinction comes from the realization that there are different types of sprawl that are, in fact, exclusive of each other. In other words, a built-up plot in an urban landscape can be part of (a) a secondary urban center; (b) ribbon development or (c) scattered development, but not of all three. Being exclusive manifestations of sprawl, secondary centers, ribbon development, or scattered development cannot be *attributes* of the same phenomenon. Surely, there can be an urban landscape with a multiplicity of secondary centers and no ribbon developments, or with ribbon developments and no scattered development. None of these manifestations are, therefore, essential attributes of sprawl. We reserve the terms characteristics, properties, dimensions and attributes to refer to universal characterizations that are common to all manifestations of sprawl. Table 1 defines the metrics for measuring various manifestations of sprawl and Table 2 presents the metric results for Bangkok and Minneapolis.

Table 1. Metrics for measuring manifestations of sprawl.

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

Table 2. Sprawl manifestation metrics for Bangkok and Minneapolis

Metric		T_1		T_2		Annual ΔT	
		Bangkok	Minneapolis	Bangkok	Minneapolis	Bangkok	Minneapolis
Built-Up Area	km^2	683.1	886.2	1026.1	1100.0	47.6	24.3
	%	100%	100%	100%	100%	5.8%	2.5%
Main Core	km^2	208.6	402.6	459.2	545.4	34.8	16.3
	%	30.5%	54.7%	44.8%	56.4%	11.6%	3.5%
Secondary Cores	km^2	83.9	97.2	116.5	189.6	4.5	10.5
	%	12.3%	13.2%	11.4%	19.6%	4.7%	7.9%
Urban Fringe	km^2	201.4	236.1	245.6	231.8	6.1	-0.5
	%	29.5%	32.1%	23.9%	24.0%	2.8%	-0.2%
Urban Ribbon	km^2	14.2	17.1	18.6	10.2	0.6	-0.8
	%	2.1%	2.3%	1.8%	1.1%	3.8%	-5.7%
Urban Scatter	km^2	175.0	133.2	186.1	122.9	1.5	-1.2
	%	25.6%	18.1%	18.1%	12.7%	0.9%	-0.9%

THE FIRST ATTRIBUTE: THE EXTENSION OF THE AREA OF CITIES BEYOND THE WALKABLE RANGE AND THE EMERGENCE OF 'ENDLESS' CITIES

The term sprawl, in its most basic and original sense and in much of the popular literature on the subject, refers to the vast and "limitless" extent of large metropolitan areas. In this sense, it describes a major transformation of the urban landscape during the past two centuries. To quote Gottmann and Harper (1990):

> *Breaking out of the old bounds, walls, boulevards, or administrative limits which set it apart, the city has massively invaded the open country, though parts of the countryside may have kept their rural appearance. The growth in size of population has also meant a spectacular growth in area for the modern metropolis.*

Measuring sprawl, perceived in this way, is largely associated with mapping and measuring the extent of the area of cities. Table 3 defines the metrics for measuring urban extent and Table 4 presents the metric results for Bangkok and Minneapolis.

2 The neighborhood was a circle, encompassing an area of 1 km^2, that was centered on each built-up pixel.

Table 3. Metrics for measuring urban extent

Metric	Definition
Built-up area	impervious surface (IS) land cover (derived from satellite imagery)
Urbanized area	built-up area + *urbanized open space* (OS)
Urbanized OS	non-IS pixels in which more than 50% of the neighborhood is built-up
Buildable	does not contain water or excessive slope
Urban footprint	built-up area + *urbanized open space* + *peripheral open space*
Peripheral OS	non-IS pixels that are within 100 meters of the built-up area
Buildable	does not contain water or excessive slope
Open space (OS)	the sum of the urbanized and peripheral OS

Table 4. Urban extent calculations for Bangkok and Minneapolis

Metric		T_1		T_2		Annual ΔT	
		Bangkok	**Minneapolis**	**Bangkok**	**Minneapolis**	**Bangkok**	**Minneapolis**
Built-up area	km^2	683.1	886.2	1026.1	1100.0	47.6	24.3
	%	100%	**100%**	100%	**100%**	5.8%	2.5%
Urbanized area	km^2	921.3	1302.2	1351.7	1618.0	59.7	36.0
	%	134.9%	146.9%	131.7%	147.1%	5.5%	2.5%
Urbanized OS	km^2	238.2	416.0	325.6	518.0	12.1	11.6
	%	34.9%	46.9%	31.7%	47.1%	4.4%	2.5%
Buildable	km^2	233.2	391.2	318.7	475.2	11.9	9.6
	%	34.1%	44.1%	31.1%	43.2%	4.4%	2.2%
Urban Footprint	km^2	1712.5	2133.2	2213.4	2335.3	69.5	23.0
	%	250.7%	240.7%	215.7%	212.3%	3.6%	1.0%
Peripheral OS	km^2	791.2	831.0	861.8	717.4	9.8	-12.9
	%	115.8%	93.8%	84.0%	65.2%	1.2%	-1.7%
Buildable	km^2	775.7	781.3	835.1	634.8	8.2	-16.7
	%	113.6%	88.2%	81.4%	57.7%	1.0%	-2.3%
Open space	km^2	1029.4	1246.9	1187.4	1235.4	21.9	-1.6
	%	150.7%	140.7%	115.7%	112.3%	2.0%	-0.1%

THE SECOND ATTRIBUTE: THE PERSISTENT DECLINE IN URBAN DENSITIES AND THE INCREASING CONSUMPTION OF LAND RESOURCES BY URBAN DWELLERS

The first attribute of urban sprawl is principally associated with geographic extent, with the sense of the city expanding outwards. The second attribute of urban sprawl is typically characterized by the decline in average density. In fact, low density urban land use is by far the most commonly mentioned attribute of urban sprawl in the literature. It is indeed a common attribute—and most certainly a consequence—of all the manifestations of sprawl identified in the literature.

The measurement of population density typically refers to the ratio of the population inhabiting a particular place and the area of that place, measured, say, in persons per hectare or persons per km^2. Clearly, for a given population, a city occupying a smaller land area will be considered more compact and less sprawled than a city occupying a larger land area. The value of using the average density as an attribute of sprawl is that it brings out the intensity of the use of land in the city as a whole. It is intuitively clear that when very few people live on large expanses of land, land is being used less intensively and this implies more sprawl. The inherent difficulty with average density as a measure of sprawl is that it is not at all clear what exactly the *area* of the city is. In our analysis, we use the various measures of urban extent described in the previous section in combination with the population of the metropolitan area to obtain a number of density metrics. Table 5 defines the density metrics and Table 6 presents the metric results for Bangkok and Minneapolis.

Table 5. Density metrics.

Metric	Definition
Built-up area density	city population divided by built-up area
Urbanized area density	city population divided by urbanized area
Restricted to buildable area	city population divided by buildable urbanized area
Urban footprint density	city population divided by urban footprint
Restricted to buildable area	city population divided by buildable urban footprint

Table 6. Density Calculations for Bangkok and Minneapolis.

Metric	T_1		T_2		Annual ΔT	
(Densities in persons / ha)	Bangkok	Minneapolis	Bangkok	Minneapolis	Bangkok	Minneapolis
Population	8,245,332	2,166,839	9,768,215	2,483,342	2.4%	1.6%
Built-up area density	121	24	95	23	-3.2%	-0.9%
Urbanized area density	89	17	72	15	-2.9%	-0.9%
for buildable area	90	17	73	16	-2.9%	-0.8%
Urban footprint density	48	10	44	11	-1.2%	0.5%
for buildable area	49	10	45	11	-1.2%	0.7%

THE THIRD ATTRIBUTE: ONGOING SUBURBANIZATION AND THE DECREASING SHARE OF THE POPULATION LIVING AND WORKING IN METROPOLITAN CENTERS

Edwin Mills, who has written extensively on sprawl and prefers to refer to it with the non-pejorative term *suburbanization*, has shown that "the deconcentration of urban areas is a long-run phenomenon that results from basic economic and technological forces and not from social forces that are specific to a single country" (McDonald, 1989):

> *The pervasiveness and persistence of suburbanization over long time periods and among countries with very different government and private institutions indicate that suburbanization results from powerful forces and is, presumably, deeply embedded in the urban growth process. Suburbanization's critics might show some humility. (Mills, 1999)*

Colin Clark observed in 1951 that urban population densities decline as the distance from the city center increases (Clark, 1951). He postulated a decline at a negative exponential rate and that made it possible to calculate a density gradient. A steep gradient is associated with a city where the population density falls rapidly as distance from the city center increases. A shallow gradient is associated with a city where population densities are not very different in the center and everywhere else. The density gradient is obtained by (a) measuring the population density in small administrative areas (say, for example, census tracts); (b) finding the average population density in rings of increasing distance from the city center; and (c) fitting a negative exponential curve[3] to a set of points denoting average ring densities as a function of distance from the city center.

[3] The curve typically has the function $d_r = d_o e^{-\beta r}$, where d_r is the average density in a ring at a distance r from the city center, d_o is the density at the center, and β is the density gradient.

We did calculate several measures that are indirectly related to suburbanization. Figure 1 shows the relationship between the population density, of the built-up area, and the distance from the central business district (CBD)[4]. Table 7 defines the metrics for measuring suburbanization and Table 8 presents the metric results for Bangkok and Minneapolis.

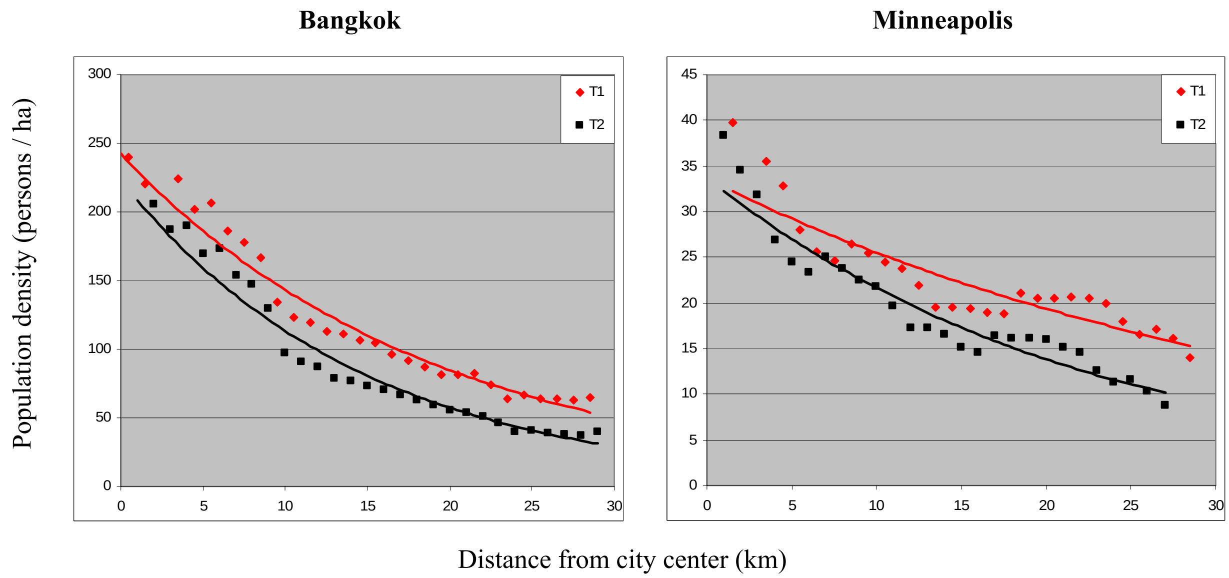

Figure 1. Population density versus distance from the city center (CBD) for Bangkok and Minneapolis.

Table 7. Suburbanization metrics

Metric	Definition
Cohesion	the ratio of the mean distance between a sample of points in the urbanized area and the mean distance among all points in a circle with an area equal to the urbanized area
Decentralization	the ratio of the mean distance to center for all points in the urbanized area and the mean distance to center for all points in a circle with an area equal to the urbanized area
City center shift	the distance between the orignial city center (CBD) and the geometric urban center (MAD center)
Minimum Avg. Distance (MAD) Center	the point with the minimum average distance to all other points in the urbanized area
Density gradient	the exponent in the equation of the exponential trendline fitting the points in the density versus distance from the CBD plot (Figure 1)

4 The CBD is the acknowledged city center determined from GPS coordinates provided by local surveyors

Table 8. Suburbanization calculations for Bangkok and Minneapolis

Metric	T_1		T_2		Annual ΔT	
	Bangkok	**Minneapolis**	**Bangkok**	**Minneapolis**	**Bangkok**	**Minneapolis**
Cohesion	1.6	1.2	1.5	1.2	-1.2%	-0.2%
Decentralization	1.5	1.2	1.4	1.2	-1.0%	-0.2%
City center shift (km)	3.3	1.5	3.8	1.8	1.9%	1.5%
Density gradient	-0.05	-0.03	-0.07	-0.05	NA	NA

THE FOURTH ATTRIBUTE: THE REDUCED CONTIGUITY OF THE BUILT-UP AREAS OF CITIES AND THE FRAGMENTATION OF OPEN SPACE IN AND AROUND THEM

The fourth general attribute of sprawl is the decreasing contiguity of the built-up area of cities, typically exemplified by development that *leapfrogs* over open space, by the increase in the amount of leftover vacant spaces in the interstices of built-up areas and around them, and by the increasingly fuzzy boundary between town and country. In an important sense, if we look at the great wave of urbanization and the formation of cities as the mutual attraction and the coming together of people, sprawl is a manifestation of their drawing apart, of their repulsion from each other, and of their desire to limit their social and economic contacts while increasing their privacy, the size of their homes and businesses, and their enjoyment of open space.

The characterization of sprawl as the reduced contiguity of the city views it as a pattern of non-compact or non-contiguous built-up patches, or—as a process—as a tendency of new urban developments to *leapfrog*, that is to skip over open space and leave it vacant and undeveloped—either temporarily or permanently. The perception of sprawl as the reduction of the contiguity of the built-up areas of cities focuses attention on the relationship between the built-up area and the remaining open spaces in a given urban landscape.

The equation of sprawl with the amount of left-over open space in the urban development process is the one adopted by Burchfield and her colleagues (Burchfield *et. al,* 2005), for example, who define a sprawl index for an urban area as "the amount of undeveloped land surrounding an average urban dwelling". They find that in the United States, "on average, 42 percent of the land in a square kilometer surrounding residential development was open space circa 1976. Remarkably, this figure remained almost unchanged at 43 percent in 1992". Table 9 defines the metrics for measuring contiguity and openness and Table 10 presents the metric results for Bangkok and Minneapolis.

Table 9. Contiguity and openness metrics

Metric	Definition
New development	built-up pixels existing in the land cover for T_2 but not T_1
Infill	new deveopment occurring within the T_1 urbanized open space
Extension	non-infill new deveopment intersecting the T_1 urban footprint
Leapfrog	new development not intersecting the T_1 urban footprint
Openness index	the average percentage of open space within a 1 km^2 neighborhood for all built-up pixels
Open space contiguity	the probability that a built-up pixel will be adjacent to an open space pixel
Open space fragmentation	the ratio of the combined urbanized and peripheral open space area to the built-up area

Table 10. Contiguity and openness calculations for Bangkok and Minneapolis.

Metric		T1 Bangkok	T1 Minneapolis	T2 Bangkok	T2 Minneapolis	Annual ΔT Bangkok	Annual ΔT Minneapolis
New development	km^2	-	-	-	-	342.89	214.00
Infill	km^2	-	-	-	-	261.81	187.90
	%	-	-	-	-	76.4%	87.8%
Extension	km^2	-	-	-	-	40.29	20.70
	%	-	-	-	-	11.8%	9.6%
Leapfrog	km^2	-	-	-	-	40.78	5.40
	%	-	-	-	-	11.9%	2.5%
Openness index		0.54	0.46	0.46	0.41	-0.02	-0.01
Open space contiguity		0.77	0.66	0.61	0.57	-0.03	-0.02
Open space fragmentation		2.08	1.69	1.45	1.28	-4.95	-3.16

THE FIFTH ATTRIBUTE: THE INCREASED COMPACTNESS OF CITIES AS THE AREAS BETWEEN THEIR FINGERLIKE EXTENSIONS ARE FILLED IN

The fifth attribute of global urban expansion or "sprawl" is the gradual increase in the compactness and cohesion of cities—their becoming less fingerlike, if you will— despite the reduction of the contiguity of built-up areas and the preponderance of vacant spaces in and around them. Table 11 defines the metrics for measuring the overall compactness of the urbanized areas of cities, and Table 12 presents the metric results for Bangkok and Minneapolis.

Table 11. Compactness metrics

Metrics	Definitions
Single Point Compactness (SPC)	the ratio of the area of the urbanized area and the area of the circle with the same average distance to the MAD center of all pixels in the urbanized area
Constrained SPC	the ratio of the area of the urbanzied area and the buildable area in the circle with the same average distance to the MAD center of all pixels in the urbanized area

Table 12. Compactness Calculations for Bangkok and Minneapolis.

Metric	T1 Bangkok	T1 Minneapolis	T2 Bangkok	T2 Minneapolis	Annual ΔT Bangkok	Annual ΔT Minneapolis
SPC	0.44	0.73	0.50	0.75	1.99%	0.37%
Constrained SPC	0.44	0.77	0.51	0.81	2.05%	0.61%

CONCLUDING REMARKS

The limited scope of this paper did not allow us to provide a broader and more rigorous exposition of the rationale behind the approach to the generation of the class of sprawl metrics described here, nor to give well-defined procedures for calculating them. The former will be the subject of a forthcoming paper that will also include the calculation of metrics for a global sample of 120 cities, as well as a discussion of how to use these metrics to define a single over-arching measure of sprawl. The latter is presently being developed as a GIS-based computer program that will be made available to researchers who want to derive sprawl metrics for additional cities and to conduct various analyses of the data. It is our belief that the more rigorous and transparent approach to measuring the manifestations and attributes of sprawl described in this paper will make it possible to ground policy discussions in better empirical data.

ACKNOWLEDGMENTS

The work reported in this paper was supported, in part, by the World Bank's Urban Development Division under the project *The Urban Growth Management Initiative: Confronting the Expected Doubling of the Size of Cities in the Developing Countries in the Next Thirty Years*, and, in part, by the NSF Division of Social and Economic Sciences-funded project *Causes and Consequences of Urban Expansion.* [CLEAR Publication Number 050323.2]

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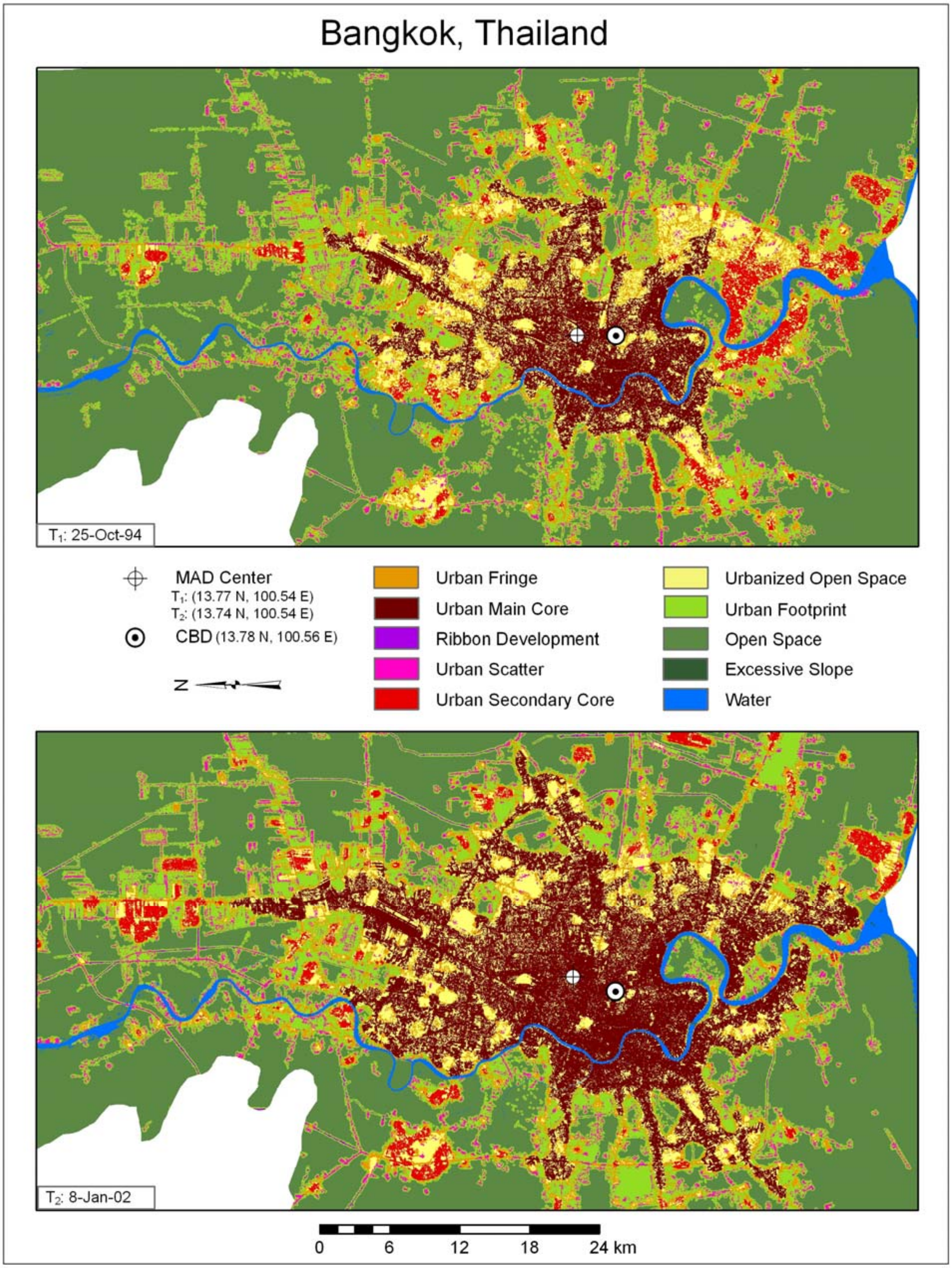

Figure 2. The urban landscape of Bangkok.

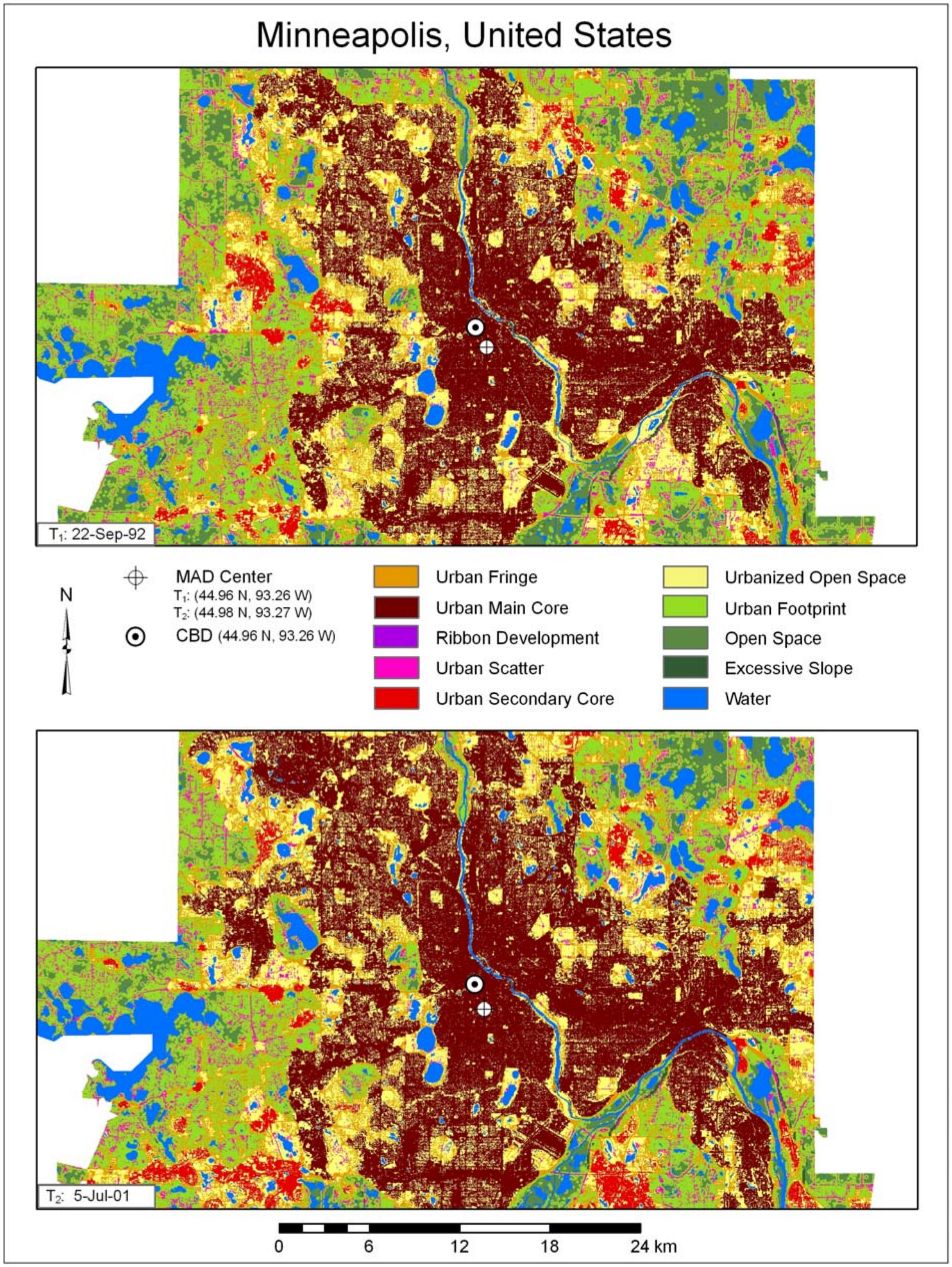

Figure 3. The urban landscape of Minneapolis.

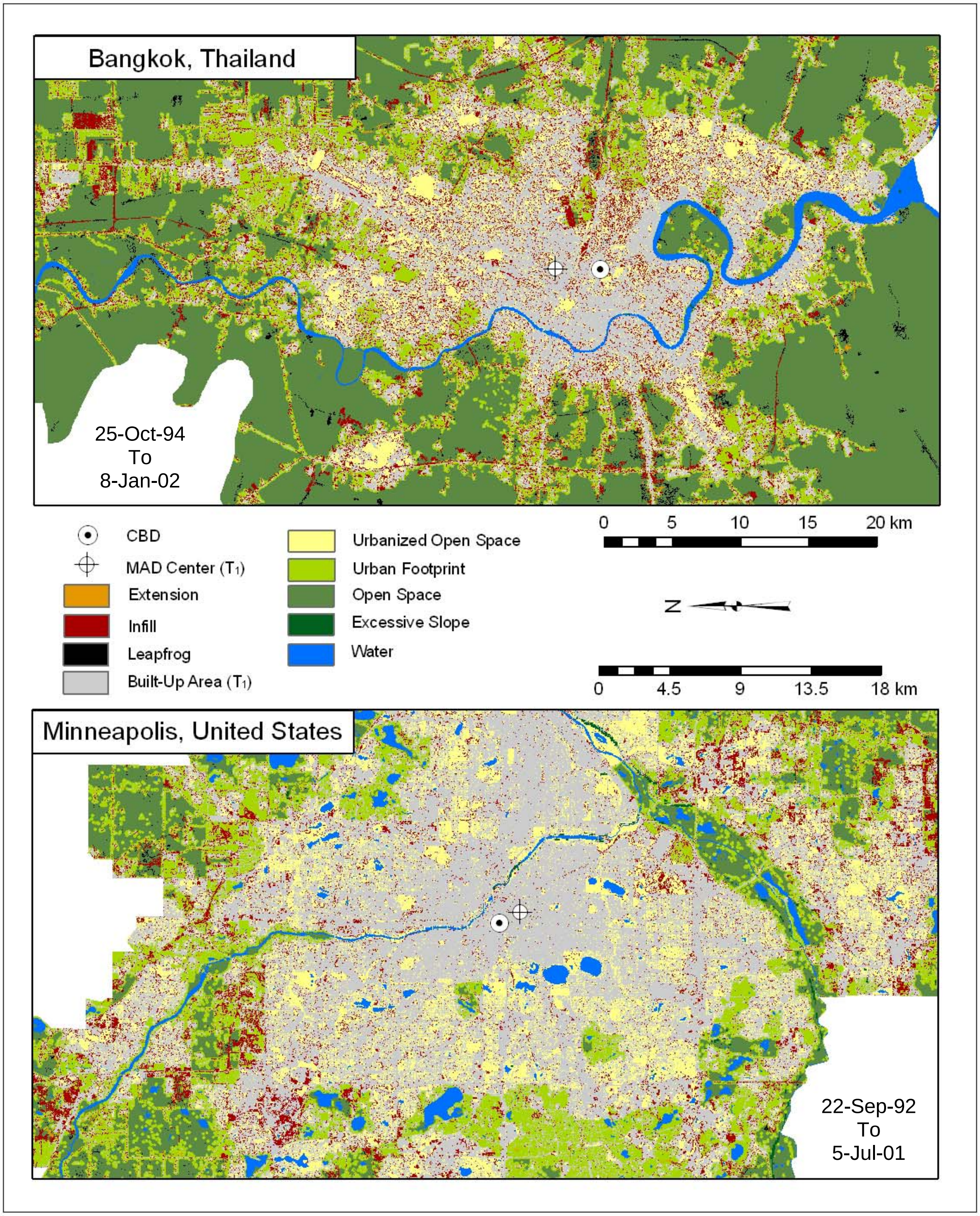

Figure 4. Classification of new development for Bangkok and Minneapolis.