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Compact, Dispersed, Fragmented, Extensive? A Comparison of Urban Growth in Twenty-five Global Cities using Remotely Sensed Data, Pattern Metrics and Census Information

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Abstract

Despite growing recognition of the important role of cities in economic, political and environmental systems across the world, comparative, global-scale research on cities is severely limited. This paper examines the similarities and differences in urban form and growth that have occurred across 25 mid-sized cities from different geographical settings and levels of economic development. The results reveal four city types: low-growth cities with modest rates of infilling; high-growth cities with rapid, fragmented development; expansive-growth cities with extensive dispersion at low population densities; and frantic-growth cities with extraordinary land conversion rates at high population densities. Although all 25 cities are expanding, the results suggest that cities outside the US do not exhibit the dispersed spatial forms characteristic of American urban sprawl.

1. Introduction

Technological, demographic, political and economic changes during the past century have had substantial impacts on the landscape and this complex set of factors will continue to drive land use and land cover change in decades to come. Urbanisation of the world's population and human modification of the environment are among the most visible,

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irreversible and rapid of these transformations. Over half of the 6 billion people on Earth currently live in cities and metropolitan areas, up from just 5 per cent in 1900 (UN, 2005). This dramatic demographic shift has parallelled the expansion of built-up/urbanised land. While population trends are often well-documented, virtually no data exist on how much land is used for industrial, residential and transport purposes, how this figure has changed over the past decades or century, or how cities compare internationally in terms of amounts, rates and patterns of expansion. It is clear that cities in nearly every region have witnessed conversion of vegetated or agricultural land for urban uses. Understanding of the amounts and patterns of urban spatial expansion, as well as the specific drivers responsible for these modifications, is sorely lacking.

Remotely sensed data have begun to play a substantive role in investigating alterations of the Earth's surface within and near urbanised areas, and in monitoring and modelling these changes (Howarth and Boasson, 1983; Ehlers *et al.*, 1990; Green *et al.*, 1994; Seto *et al.*, 2000; Schneider *et al.*, 2003; Herold *et al.*, 2003). Satellite remote sensing offers a tremendous advantage over historical maps or air photos, as it provides recurrent and consistent observations over a large geographical area, reveals explicit patterns of land cover and land use, and presents a synoptic view of the landscape (Jensen and Cowen, 1999). A proliferation of new methods (Paola and Schowengerdt, 1995; Chan *et al.*, 2001; Langevin and Stow, 2004) and readily available data sources (Tucker, 2004) have made monitoring urban changes easier and more rapid than in the past. Despite these advances, investigations are consistently completed on a city-by-city basis, with little or no comparison performed among studies.

From a theoretical standpoint, the forms and patterns of urban land development have garnered attention for nearly a century (Burgess, 1925/1967; Hoyt, 1939; Christaller, 1933; Harris and Ullman, 1945; Blumenfeld, 1954; Alonso, 1964; Muth, 1969; Batty and Longley, 1988; Fujita *et al.*, 1999). Evidence to support the range of theories is rare, however, due to past difficulties of collecting land use data. One particularly hot topic in recent decades has been the less-than-rigorously-defined idea of sprawl, a term referring to anything from low-density urban development to dispersed or even decentralised forms of urban expansion (Ewing, 1997; El-Nasser and Overberg, 2001). Studies of sprawl have focused primarily on the US, where land use data have proliferated in the past few years to corroborate that new growth is often discontinuous and extensive (Stefanov *et al.*, 2001; Yang and Lo, 2002; Hasse and Lathrop, 2003; Dietzel *et al.*, 2005; Burchfield *et al.*, 2006). Research outside the US has begun to emerge, often relying on North American concepts of sprawl to describe trends in Europe (Antrop, 2004; Kasanko *et al.*, 2006), China (Deng and Huang, 2004) and even such diverse locations as Ghana (Yeboah, 2003), Israel (Frenkel, 2004), India (Lata *et al.*, 2003), and Saudi Arabia (Mubarak, 2004). However, direct comparisons have not been made between American metropolitan areas and those around the world, so it is not apparent whether the extensive or so-called sprawling types of land conversion witnessed in the US are indeed an appropriate model for other regions/cultures of the world.

The primary goal of this research is to improve understanding of urban growth during the 1990–2000 decade in cities around the globe. A secondary objective is to compare a diverse set of cities to the sprawling urban landscapes present in the US to determine not only similarities and differences in land development, but the best ways of quantifying urban sprawl. To characterise the nature of changes and compare/contrast trends across cities and nations, we use a set of indicators that describe: (a) the spatial extent of urban areas;

(b) the rates of land conversion; (c) the location and pattern of new urban land; (d) the amount of discontinuous growth; and, (e) the efficiency of land development, as suggested by population density. We apply these indicators to 25 metropolitan areas distributed primarily among three more developed countries/regions (MDCs), including Canada, the US and the EU, and seven less developed countries (LDCs), including Mexico, Brazil, Turkey, Egypt, Kenya, India, China and Vietnam. Land use change information is derived for each city from change detection analysis of remotely sensed data, application of landscape metrics and use of demographic data.

2. Study Areas

2.1 Selection of Metropolitan Areas

Because cities from different regions are characterised by different land cover types (concrete, roofing tiles, trees, grass), have an array of shapes and sizes, and are surrounded by a variety of landscapes (agriculture, desert, forest), a key requirement for this study was to create a sample that was geographically comprehensive and included city types within each region. Three characteristics were used to define the sample: the world region in which the city was located; the city population size; and, data availability. First, we weighted each of nine world regions (based on the UN stratification, 2003; see Table 1) by its percentage of the global urban population (UN, 2003) to determine the distribution of an initial sample of 30 cities across the world (see Schneider, 2005, for details). South-east Asia, for instance, had 21 per cent of the world's urban population in 2000, so 6 of the 30 cities were drawn from this region.

Secondly, we defined our target population by selecting metropolitan areas of regional importance in terms of size and economic status. Population size was used as a proxy variable to identify large cities with substantial regional and global influence (Moomaw and Shatter, 1996). We targeted cities with over 1 million inhabitants, but limited the sample to cities with populations of less than 5 million in order to focus on areas not identified as 'megacities'. Finally, the main aim of this research required comparison of characteristics of urban growth such as population density (as part of a larger objective to connect urban expansion to socioeconomic drivers of change; see Schneider, 2005), making it imperative to limit the study to locations with accessible, reliable and disaggregated census data. Further, census data *circa* 1990 and 2000 were necessary to coincide with the dates of NASA's freely available satellite dataset. In this fashion, purposive sampling was used (countries highlighted in grey, Figure 1), a technique that assumes selected elements are representative of the larger population (Rea and Parker, 1992). A sample of 30 cities was then drawn at random from the targeted group in each region. This study represents results from 25 cities in this 30-city sample.

Although the target population satisfies the need for a geographically diverse dataset, the sample is biased towards post-industrialised, industrialised and emerging market cities, where demographic and socioeconomic data are more readily available. Conclusions on urbanisation drawn from this research must be weighed in light of this bias.

3. Methods

3.1 Defining Urban Land

Two difficulties arise when comparing any set of metropolitan areas: defining what types of land are in fact 'urban'; and, determining what geographical area should be considered. To handle each of these issues, it is possible to divide descriptions of urban areas into both physical and functional definitions. On the one hand, urban land in physical terms refers

Table 1. Population and urban land data for the 25 cities in the study, stratified by regional division

				Population[b]		*Amount of urban land (sq km)*	
Region[a]	*Number*	*Country*	*City*	*1990*	*2000*	*1990*	*2000*
North America	1	Canada	Calgary	658 810	874 360	280.2	380.9
	2		Montreal	847 728	1 025 705	893.5	944.9
	3	USA	Sacramento	1 355 107	1 640 558	647.3	769.6
	4		Phoenix	2 122 101	3 072 149	1 170.3	1,412.5
	5		Baltimore	2 366 061	2 531 628	832.5	993.2
	6		Washington, DC	3 539 938	3 967 634	1 261.6	1,511.1
Latin America	7	Mexico	Monterrey	2 694 550	3 414 282	339.5	404.0
	8		Guadalajara	3 139 364	3 864 823	317.4	421.6
	9	Brazil	Brasilia	1 808 768	2 401 841	306.3	462.6
	10		Belo Horizonte	3 529 159	4 390 064	449.0	559.8
	11		Curitiba	1 993 290	2 648 677	352.1	439.3
Europe	12	Spain	Madrid	4 947 555	5 423 384	442.8	554.5
	13	Czech Republic	Prague	2 327 056	2 284 049	367.8	381.9
	14	Poland	Warsaw	2 415 900	3 005 471	320.1	356.5
Africa	15	Egypt	Alexandria	3 070 915	3 607 540	245.8	297.0
	16	Kenya	Nairobi	3 097 045	4 269 250	134.5	175.1
Western Asia	17	Turkey	Ankara	3 236 626	4 007 860	211.2	334.9
South-Central Asia	18	India	Ahmedabad	5 210 804	7 143 109	181.4	216.5
	19		Bangalore	6 512 356	8 400 526	183.6	272.0
	20		Lakhnau	2 762 801	3 681 416	108.4	139.0
South-Eastern Asia	21	China	Chengdu	5 870 387	7 574 034	338.7	549.7
	22		Dongguan	1 741 731	6 445 777	311.4	1180.3
	23		Guangzhou	8 296 422	15 203 181	477.6	1441.9
	24		Wuhan	5 002 024	8 966 422	267.5	367.1
	25	Vietnam	Hanoi	2 311 500	3 007 829	257.0	348.1

[a]Seven of the nine UN world regions (UN, 2003) are shown, since two regions were not sampled in the first results of this study.

[b]The population of each metropolitan area was determined using census data compiled for disaggregated political units corresponding to the urban land area of each city, which were then summed to determine the value for the city as a whole.

Note: Both population and urban land data were adjusted to reflect the 1990 and 2000 time-points using simple interpolation.

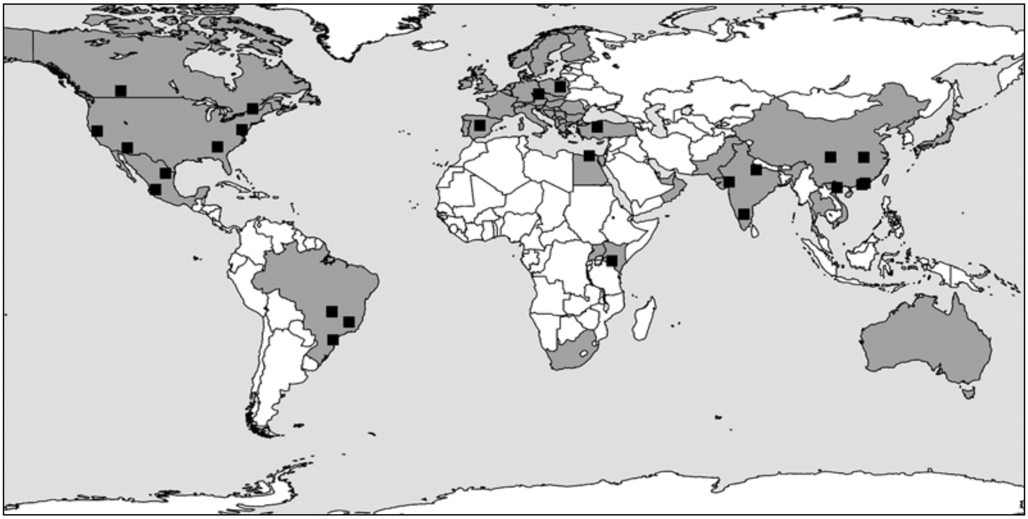


Figure 1. The final sample of 25 metropolitan areas (black squares), selected on the basis of population size (1–5 million inhabitants), world region, and availability of reliable socioeconomic data (countries shown in dark grey)

to the land cover types present, including any number of surfaces and vegetation types. With remotely sensed data, urban is often best defined as the percentage of impervious surface (Arnold and Gibbons, 1996). This research follows this convention, where urban and built-up land must dominate greater than 50 per cent of an image pixel for that pixel to be labelled urban. When vegetation (such as a golf course or park) dominated a pixel, these areas were not considered urban, even though in terms of land use, they may function as urban space.

To determine the spatial extent of the city, a more functional definition of 'urban' is appropriate. Political boundaries, while often used to delineate urban space, are not a reliable means of doing so since they change frequently over time, overestimate or underestimate urban land use and are not comparable across or within nations (Cohen, 2004). Instead, we sought to find a standardised way of defining the geographical extent of each city, as well as the extent of the central city core. To do this, it is useful to understand the city within a socioeconomic framework, where the urban area is defined: by the movement of people and goods within and across the city (Castells, 1996); by multiple nuclei, as clusters develop at varying distances from the urban core (Harris and Ullman, 1945); and, as an economic unit including small towns dependent upon or symbiotic with the larger city (Fujita *et al.*, 1999; Duranton and Puga, 2005). Considering the metropolitan area in this way ensures that all areas that function as part of the city (whether socially, politically or economically) are included in the analysis. Once maps of urban areas (*circa* 2000) were completed, a series of GIS operations (including buffering and areal estimation) was used to select a boundary that would be large enough to incorporate all functional areas of spatially extensive cities (as in the US and Canada), while at the same time be constrained enough to exclude small cities far from the urban core that do not perform as part of the greater metropolitan area (as in India and China). Similar to the buffering procedure used by Wolman *et al.* (2005) for population data, we buffered each city's centre in an increasing, step-wise manner, calculating the percentage of the total urbanised area within the circular area at each interval. We found that a radius of 40 km from the city centre (defined here as the location of the original central business district determined using ancillary information and very high resolution imagery) was consistently the most appropriate value for balancing the trade-off between 'too big' and 'too small'.[1]

In addition to the standardised spatial extent boundary, a core urban area was delineated for each city based on the density of urban land in 1990. Since the majority of urban expansion occurs along the urban-to-rural transition zone, it was critical to have a means to compare this transition area across cities that may vary considerably in core city size. Each city was partitioned into a series of 1-km rings extending outward from the original central business district. Urban land densities (i.e. the amount of urban or built-up land divided by the total land area) were then examined in a step-wise manner for successively larger areas. A final core area was established at the point where urban land densities fell below 50 per cent. Due to the varying spatial extents of the sample cities, the radius of each core ranged from 3 km (Dongguan, China), to 27 km (Phoenix, US). Outside the central core area, a series of three 8-km buffers were then used to divide the remaining landscape into fringe (i.e. the first 8-km buffer), periphery (i.e. the second 8-km buffer) and hinterland (i.e. the third 8-km buffer) areas. This ring-based analysis is firmly rooted in classic urban theories that describe cities as a series of concentric zones with differentiated functions (Burgess, 1925/1967). The use of rings as the spatial unit of analysis depends on the assumption that expansion is monocentric in form, or that growth moves outward from the central core (Blumenfeld, 1954). The bias introduced by this assumption is limited since many of the mid-sized cities of the sample are not yet large enough to exhibit multiple nuclei that are equal in dominance to the central core. Moreover, the ring-based analysis is able to capture the development of nuclei or expansion around a secondary centre because of the narrow spacing of the rings. Nevertheless, the results may be affected by this assumption of monocentricity.

3.2 Indicators for Measuring Sprawl

Large volumes of literature have been devoted to the study of urban form and growth, and especially to the concept of urban sprawl (Johnson, 2001; Squires, 2002; Nechyba and Walsh, 2004). The costs and impacts of dispersed land development have been well-documented (Ewing *et al.*, 2002; Alberti, 2005), with particular concern focused on the land-consumptive and inefficient nature of sprawling urban expansion, the increasing loss of critical land resources such as agriculture and the growing lack of accessibility to jobs, schools, hospitals, etc. However, analysis, debate and policy-making have been hampered by a lack of rigorous, quantitative comparisons of metropolitan regions using spatially explicit, empirical data (Wolman *et al.*, 2005). The most common difficulties in quantifying urban sprawl consist of pinning down what is meant by the term sprawl and determining how it should be measured.

Before tackling ways to measure urban form, it is thus important to review the most widely accepted and commonly used definitions of sprawling urban land as a means for providing a descriptive framework for comparison of different urban areas. The most simple (and possibly most vague) definition refers to sprawl as the excessive spatial growth of cities (Brueckner, 2001). The key here is 'excessive'; while cities must grow to accommodate expanding populations, the claim is that, in some cities, too much land conversion occurs. Secondly, sprawl is often defined as a 'low-density' phenomenon, either in terms of low population density or low density of development (El-Nasser and Overberg, 2001; Lopez and Hynes, 2003). Expanding on this idea in more detail, sprawl is characterised by forms of growth including scattered or leapfrog development, strip development, large expanses of low-density or single-use development, as well as a lack of accessibility (Galster *et al.*, 2001; Ewing *et al.*, 2002). Finally, any functional definition of sprawl must clarify that sprawl is not a categorical, wholesale transformation of the landscape but, rather, a matter of degree. For our purposes, we have adopted the definition developed by Ewing *et al.* (2002) which includes three key dimensions: a dispersed population in low density development; the presence of widely separated buildings and structures; and, new development on the outskirts of the city that lacks a well-defined activity centre. This definition includes both a micro-level approach (i.e. sprawl as indicated by the development of land in small patches widely spaced from one another) and a macro-level description (i.e. sprawl as defined by the change of city structure from monocentric to polycentric in form).

Quantifying sprawl has appeared as a topic of research in just the past few years and different approaches have emerged to evaluate a variety of spatial, demographic or social characteristics associated with different urban patterns. The most popular of these measures are routinely based on population information (often the most readily available data), used either alone as population density per county, census block, etc. (El-Nasser and Overberg, 2001; Lopez and Hynes, 2003; Hammer *et al.*, 2004) or in conjunction with land cover information, such as the ratio of population to urban area or the amount of land developed per person (Webster, 2002; Hasse and Lathrop, 2003; Wolman *et al.*, 2005). A few studies have included measures of accessibility and proximity, such as auto dependence, road network accessibility or even distance to jobs or commercial areas (Filion *et al.*, 1999; Galster *et al.*, 2001). While these studies are useful for understanding the human/social ramifications of dispersed land, the primary shortcoming is that all rely on demographic data (such as population, households) rather than explicit land use information. In this analysis, we show that sprawl can be better characterised using land cover patterns derived from remotely sensed imagery in conjunction with census information.

The simpler land-based measures of sprawl include documenting the extent of built-up areas, growth rates and percentage change in area (Kasanko *et al.*, 2006; Tsai, 2005). Detailed analysis of the amounts of new industrial, residential and commercial land has also been attempted, including estimation of the land cover types these areas replaced (Hasse and Lathrop, 2003). More sophisticated spatial measures offer a means to quantify complex dimensions of sprawl such as patchiness, clustering, scatter, dispersion, interspersion, etc. and are estimated using landscape pattern metrics (Luck and Wu, 2002; Dietzel *et al.*, 2005) or spatial statistics such as Moran's I (Tsai, 2005). Pattern metrics are a useful way to measure urban land configuration, especially considering that urban land conversion often occurs at the scale of plots or patches (whether within the city or outside it) and not at the level of individual pixels. The drawback to these studies is that a large number of landscape metrics are usually reported, many of which supply redundant information and/or confusing results in an urban context. Researchers often use different subsets of metrics that they deem appropriate, further making comparison across studies extremely difficult.

With these issues in mind, a group of four indicators was selected (see Table 2). Spatial extent- and population-based indicators (groups 1 and 4) were estimated for each metropolitan area as a whole, using the standardised spatial extent within a 40-km radius of the city centre. To match this boundary, population data were collected from local statistical agencies at the district level (or equivalent) for the time-points 1990 and 2000, and then aggregated to form metropolitan-wide values for 1990 and 2000 (see Table 3 for data sources). Population density is often conveyed using one of two metrics, both of which are used here: the number of persons per square kilometre at a given time-point; and, the ratio of change in population to the change in amount of urban land. The first measure provides an indicator of how densely the population is packed into a given area of the city, while the second offers a measure of the number of persons added per square kilometre developed. If the ratio is low, a substantial amount of land has been converted for a modest population increase. This type of growth is often considered inefficient and excessive, exemplified by sprawling bedroom communities, strip development, etc. that have a considerable impact on resources and the environment. On the

Table 2. Urban growth indicators used for the analysis of each metropolitan area

Group	*Indicator*	*Significance*
1. Size of built-up area and rate of change	1a. Spatial extent of urban area in 1990, 2000 (sq km)	Size of urban extent provides starting and ending points of a city's trajectory
	1b. Amount of new urban land, 1990–2000 (sq km)	Reveals differences in initial sizes of each city, which can vary dramatically due to differences in history, policy, economics and culture of city
	1c. Percentage increase, 1990–2000, annual percentage increase	Rates of expansion reveal amounts of available land converted to urban uses, while percentage increase normalises urban expansion rates by initial city size
2. Density of built-up land	2a. Ratio of amount of urban land to all land, 1990 and 2000 (percentage)	Offers information on whether new land development is low or high density, as well as spatial location of changing densities
	2b. Change in density of urban land: difference in ratio of urban expansion to all land, 1990–2000	For a given area of new land development, a large increase in built-up land density indicates infilling, while a smaller increase indicates more dispersed growth
3. Fragmentation, scatter	3a. Patch density, 1990–2000	Measures the number of patches per unit area of land
	3b. Percentage change in patch density	Reveals pattern or form of development, quantifies whether newly urbanised land is contiguous or patchy
4. Population density	4a. Population per sq km of urban land	Measure of efficiency of land use, how much land is needed per person added
	4b. Ratio of change in population to change in amount of built-up land	High population to land ratios imply more efficient land use change, while low values imply more land is needed per person, a less efficient type of urban expansion

Table 3. Sources of census data and digital boundary data for each city, grouped by country

Country	*Source of data*	*Link (if applicable)*	*Census dates*
Canada	Census of Canada, Statistics Canada Institut de la Statistique Quebec Calgary Academic Data Center Profile of Census Tracts in Montreal and Calgary, Statistics Canada, Ottawa, Canada	http://www.statcan.ca http://www.stat.gouv.qc.ca http://www.ucalgary.ca	1991, 1996, 2001
USA	US Bureau of the Census	http://www.census.gov	1990, 2000
Mexico	Instituto Nacional de Estadistica, Geografica e Informatica (INEGI)	http://www.inegi.gob.mx	1990, 2000
	Gobierno de Estado Nuevo Leon Gobierno de Estado Jalisco Center for Interational Earth Science Information Network (CIESIN) Georeferenced data sets of Mexico, 1990	http://gobierno.nl.gob.mx http://www.jalisco.gob.mx http://sedac.ciesin.org	1990, 2000
Brazil	Instituto Brasiliero de Geografia e Estadistica (IBGE) Instituto Nacional de Pesquisas Espaciais (INPE)	http://www.ibge.gov.br http://www.inpe.br	1991, 1996, 2001
Spain	Instituto Nacional de Estadistica (INE)	http://www.ine.es	1991, 2001
Czech Republic	Cesky Statisticky Urad Czech Republic, Praha and Stredocesky Statistical Yearbooks	http://www.czso.cz	1991, 2000
Poland	Polska Statystyka Publiczna Macewieckie Statistical Yearbooks	http://www.stat.gov.pl	1990, 2001
Egypt	Central Agency for Public Mobilization and Statistics (CAPMAS) State Information Service, Egypt Alexandria Statistical Yearbooks	http://www.capmas.gov.eg http://www.sis.gov.eg	1986, 1996, 2000
Kenya	International Livestock Research Institute Kenya Population Census, 1989, 1999, Kenya Central Bureau of Statistics, Ministry of Finance and Planning, Nairobi, Kenya	http://www.ilri.cgiar.org	1989, 1999
Turkey	State Institute of Statistics, Turkey Ankara Statistical Yearbooks	http://www.die.gov.tr	1991, 2001
India	Registrar General and Census Commissioner of India	http://www.censusindia.net	1991, 2001
	Indiastat Census of India, 1991, 2001, Office of Registrar General, Delhi	http://www.indiastat.com	
China	National Bureau of Statistics China Data Center, University of Michigan China Population and Information Research Center China, Hubei, Sichuan, Guangdong Statistical Yearbooks	http://www.stats.gov.cn http://www.chinadatacenter.org http://www.cpirc.org.cn	1990, 2000
Vietnam	Vietnam General Statistical Office Statistical Yearbooks	http://www.gso.gov.vn	1995, 2000

If no weblink is listed, hard copy statistical yearbooks were utilised.

other hand, a high ratio indicates that very little land has been converted despite a large population increase, which may indicate either efficient growth (residential communities in apartment buildings or mixed use areas) or a possible population boom resulting from high birth rates or rising migration. While these measures are used extensively by urban planners and land managers to compare cities, previous studies rely on the amount of urban extent derived from the area within political boundaries. This study quantifies these values using explicit values of urban land, which we believe presents a more accurate picture of population density than urban boundaries that may underestimate or overestimate the actual built-up area of the city.

Urban land density and patch-based indicators (groups 2 and 3) present two different measures of urban form/pattern. First, the density of urban land reveals important information about the location of development and the level of dispersion. Patch-based indicators, alternatively, describe the degree of fragmentation within a city. Since both are used to define characteristics of urban sprawl, the concepts of dispersion and fragmentation are often confused or used interchangeably. It is important to recognise that these terms describe very different processes, however. Dispersion describes the movement of the city outward from the central core, as evidenced by increasing levels of land development at large distances from the city centre. Fragmentation depicts the character of land development as either patchy or leap-frog in style, in which urban patches are often mixed with non-urban uses. The scale of each, in fact, also varies. Fragmentation often describes localised land effects (i.e. the micro scale), whereas dispersion occurs at a scale above this, explaining processes at the level of the city or region (i.e. the macro scale).

Since urban land density and patch-based indicators are less meaningful when considered for the city as a whole, these two sets of indicators were estimated using the ring and core–periphery frameworks. These indicators were derived using landscape metrics, applied within each core/ring using the public domain software Fragstats (McGarigal and Marks, 1995). After exploring a number of metrics, it was determined that patch density, or the number of patches per unit area, offers simple, straightforward results without having to determine *a priori* at what patch size urban development becomes scattered and potentially detrimental to the environment, resource use, transport costs, etc. Patch density provides an intuitive, easy-to-understand metric for city comparison: a decrease in the number of patches over time is a direct indication of infilling, while an increase in patch number for the same area offers evidence of scatter or fragmentation. This metric has also proved to be robust when spatial extent or resolution vary (Li and Wu, 2004; Wu 2004).

3.3 Remote Sensing of Urban Areas

To quantify rates of urban expansion and changes in form, this research required detailed maps of land cover change for each city. Satellite remote sensing has been used to map urban areas for nearly three decades (Jensen and Toll, 1982; Forster, 1985; Treitz *et al.*, 1992; Gao and Skillcorn, 1998; Longley and Mesev, 2000; Stewart *et al.*, 2004). The vast majority of these studies investigate the magnitude of growth in one city at a time for purposes of city planning or environmental assessment, however, with little comparison performed among studies and little assessment of growth trends of cities from different nations or from a larger sample of global cities.

In the sections that follow, a brief review of the steps for creating maps of land cover change is described. These steps include data acquisition, automated processing of maps of land cover change for each metropolitan area, and assessment of accuracy (for a more extensive description of methods, see Schneider, 2005).

Image acquisition. Mapping urban change in a large group of cities would not have been a feasible task even a few years ago. The cost of imagery and the time required for processing have been prohibitive until very recently. Newly available data sources, combined with advances in data storage, processing speed and classification algorithms/change detection methods, have made a study of this magnitude possible for the first time.

For each of the cities, two co-registered Landsat images coincident with years 1990 and 2000 were required to characterise urban change (Table 4). The large amount of data required for such an undertaking has only been possible because of the University of Maryland's Global Land Cover Facility database (GLCF, 2005) and NASA's 2004 release of the GeoCover dataset (Tucker, 2004). Since ideal months and years of image acquisition were not always available, some images deviated from the decadal time-points (1990 and 2000), or months of acquisition were offset by several months or seasons (Figure 2). To compare land cover change across cities, the results were adjusted to correct disparities in the number of years between dates. Variability from the use of non-anniversary data image pairs (comparing leaf-on vs leaf-off images from two dates, for instance) is more difficult to remedy, however, and may affect accuracy and reliability of the change maps (Song and Woodcock, 2003; Lunetta *et al.*, 2004).

In addition to the metropolitan areas processed for this investigation, maps of land cover change for 4 of the 25 cities were acquired from two independent research projects. The methods used and results achieved by these studies closely matched those followed in this research, thus maps of Guangzhou and Dongguan, China (Seto *et al.*, 2002) and Washington, DC, and Baltimore, USA (Dougherty *et al.*, 2004) could be incorporated directly. Once acquired, these maps were checked for quality, accuracy and consistency, and updated as needed.

Rapid analysis of urban expansion. Identification of land cover changes in each metropolitan area was accomplished in three phases: image preprocessing; change detection using unsupervised methods; and, post-processing filtering and hand-editing. For scenes not already orthorectified, the first phase of work included geometric correction to ensure that pixels of each image date aligned in a common map co-ordinate system.

The second phase of work included estimating the quantity and type of land use/land cover changes apparent in the images. After consideration of the numerous change detection methods available (Singh, 1989; Mas, 1999; Rogan and Chen, 2004), a simple unsupervised clustering (the k-means algorithm) of the stacked, multidate images was employed to discern both stable and changed land cover classes. The basic premise of this technique is that change classes have distinct combinations of spectral signatures from non-change classes, and hence are separable. To apply this method successfully, a large number of spectral clusters must be used to handle the added variability from using two dates of imagery.

The following classes were labelled for each city: stable urban areas; urban expansion (conversion of land from other cover types to urban uses); and, stable non-urban land cover types, such as forest, agriculture, desert or natural vegetation. The third and final phase, post-processing, relied on application of a majority filter using a 3 × 3-pixel moving window. Hand-editing, common to remote sensing studies, was also employed as needed to correct errors.

Accuracy assessment. To validate the maps of land use change, the final step involved cross-validation methods and ground-based accuracy assessment, when possible. Because of the large number of metropolitan areas in this study as well as time and cost limitations, only 10 of 21 cities were considered for accuracy assessment (the 4 maps of change

Table 4. Metropolitan areas considered in the study and dates of Landsat imagery used to generate maps of urban expansion

	Country	*City*	*Dates of Landsat images* *1990*	*2000*	*Landsat scene path, row*
1	Canada	Calgary	07.26.1985; 08.14.1992	07.09.1999; 08.28.2000; 08.28.2000	042024, 024025[†]
2		Montreal	08.26.1989	06.08.2001	014028, 014029[†]
3	USA	Sacramento	07.03.1989	07.09.2000	044033
4		Phoenix	03.18.1991	04.19.2000	037037
5-6		Baltimore–Washington, DC[a]	05.16.1987	10.05.2001	015033
7	Mexico	Monterrey	04.06.1992	11.28.1999	028042
8		Guadalajara	03.07.1990	11.03.1999	029046
9	Brazil	Brasilia	04.06.1989	07.31.1999; 08.02.2000	221071
10		Belo Horizonte	06.04.1989	06.26.2000	218074
11		Curitiba	07.18.1994	09.02.2002	220078
12	Spain	Madrid	03.25.1989	04.22.2002	201032
13	Czech Republic	Prague	07.06.1991	06.20.2000	191025, 192025[†]
14	Poland	Warsaw	05.25.1992; 08.29.1992	05.07.2000; 05.07.2000	188023, 188024[†]
15	Egypt	Alexandria	09.11.1984; 05.15.1990; 04.29.1993	12.23.2001; 06.17.2002	177038, 177039[†]
16	Kenya	Nairobi	02.25.1987	02.21.2000; 02.10.2002	168061
17	Turkey	Ankara	07.02.1987	05.10.2000	177032
18	India	Ahmedabad	10.19.1990; 10.15.1992	10.27.1999; 10.22.2000	148044, 149044[†]
19		Bangalore	01.14.1992	11.27.2000	144051
20		Lakhnau	11.21.1989	11.11.2000	144041
21	China	Guangzhou[b]	10.13.1990	09.14.2000	122044
22		Dongguan[b]	10.13.1990	09.14.2000	122044
23		Chengdu	05.01.1988; 04.24.1991, 08.16.1992	11.02.2000; 10.07.2002	129039
24		Wuhan	07.19.1991	07.09.2002	123039
25	Vietnam	Hanoi	10.21.1992; 12.27.1993	11.04.2000; 01.13.2003	127045

[a] Map of land cover change produced by Dougherty *et al.* (2004).
[b] Map of land cover change produced by Seto *et al.* (2002).
[†] Indicates that the metropolitan area covered two scenes.

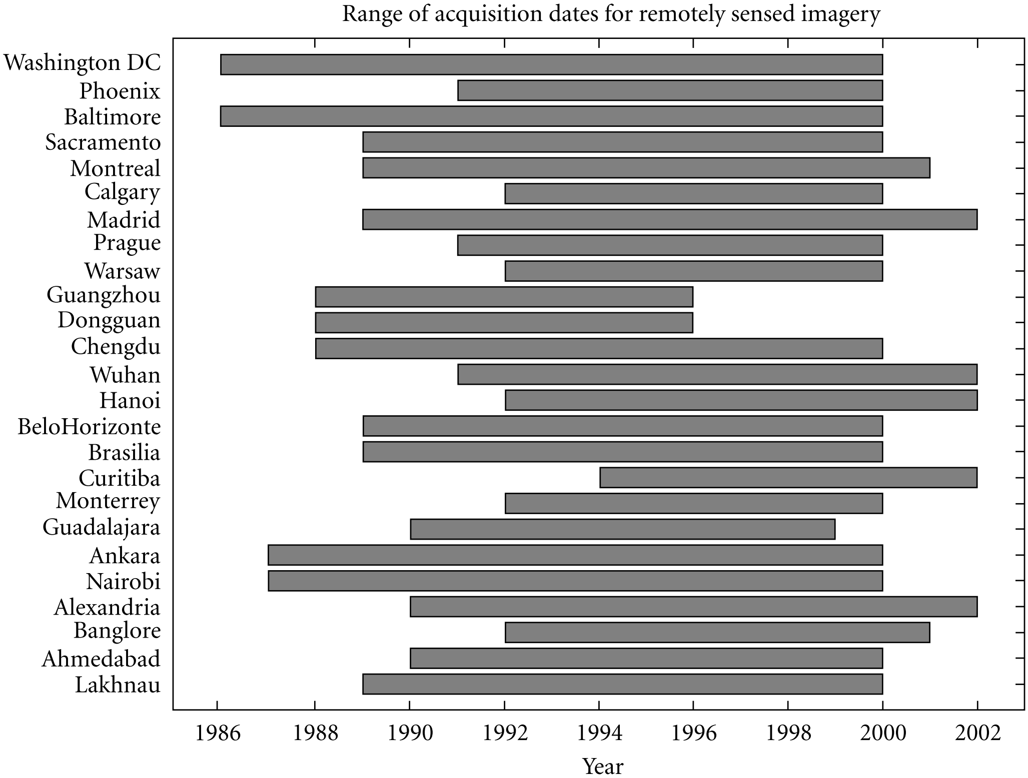


Figure 2. Years of data acquisition (end-points) for each metropolitan area, illustrating the offset from the 1990 and 2000 time-points of interest

produced by independent research were not included since they were assessed independently). For each of these 10 cities, a stratified random sampling design was employed to select 200 one-pixel sites. Each site was labelled by an independent analyst using aerial photos, ancillary data sources and visual interpretation of the satellite imagery. Sites that were difficult to label were visited on the ground in 6 of the 10 cities (Table 5). For the remaining 4 cities, local experts were consulted to determine the correct labels for hard-to-identify sites. Overall accuracy ranged from 84 to 97 per cent for these 10 cities, rates which show that the maps are sufficiently accurate for interpreting amounts and patterns of urban expansion.

4. Results and Discussion

4.1 Maps of Urban Expansion

Upon examining the 25 cities visually (Figure 3), a number of trends are immediately clear. In terms of spatial extent, the US cities are noticeably larger at the beginning of the study period (1990, shown in white), as compared with the rest of the sample cities. Montreal, Canada, exhibits a similar trend of expansive/extensive land use, followed closely by cities in Mexico and Brazil. Cities in Europe, India and China, meanwhile, are much smaller to begin with and, despite some considerable development, remain comparatively small by the year 2000. The cities with the largest amounts of land conversion (change from 1990 to 2000, shown in black) are those in

Table 5. Rates of overall accuracy for the classified maps of urban expansion for 10 cities in the sample

City	*Overall accuracy (percentage)*	*Ground assessment*
Phoenix, USA	94.5	April, 2004
Calgary, Canada	92.1	local contact
Madrid, Spain	92.4	July, 2003
Guadalajara, Mexico	93.8	June, 2001
Brasilia, Brazil	93.0	local contact
Prague, Czech Republic	96.3	July, 2004
Ankara, Turkey	89.0	January, 2003
Nairobi, Kenya	85.2	local contact
Bangalore, India	84.1	local contact
Chengdu, China	97.4	November, 2002

Note: Six of the 10 cities were visited for assessment purposes (dates of field campaigns are shown in the final column), while the remaining 4 cities were assessed with assistance from local contacts.

China, especially Dongguan and Guangzhou, both of which appear as outliers in the results of all four types of urban growth indicators. Other notable increases in urban land include large areas of new development visible in Calgary, Sacramento, Brasilia, Madrid, Ankara, Vietnam, Chengdu and Wuhan. Harder to discern in the figures are extensive small changes, such as those in Washington, DC, and Baltimore, as well as in Belo Horizonte.

The patterns of expansion can be divided into three major trends: small plots developed at the edge of the urban core; large tract development adjacent to existing urban land (but not necessarily in/near the core); and, small, patchy areas of newly converted land located farther from the established urban core area than the first two types. Although spatial expansion in US cities clearly follows the third trend—scattered and far from the central urban core—the majority of the cities in the sample follow the first two trends, with all new growth concentrated close to established urban land. Cities in India, for example, display newly urbanised land in a tight band around the extent of the 1990 city. On the other side of the globe, cities in Canada and Mexico follow suit.

4.2 Spatial Extent and Rates of Land Conversion

Before considering more complex measures of density and patchiness, it is important to understand the larger trends in spatial extent and rates of expansion (Figure 4). The initial sizes of each city (the amount of urban land in 1990) vary dramatically, from just 100 sq km to over 1300 sq km, reflecting the history, policies, economics and culture of each city prior to the 1990–2000 period of study. The majority of the cities (18 of 25) fall near the median size of 330 sq km, although cities in developing countries such as India fall far below this value. The dispersion about the median value helped to establish the cut-off values for three trends apparent in the sample at the beginning of the period (the grey bar): small cities ranging from 100 to 245 sq km, including cities in LDCs (such as India, Turkey and Egypt and Kenya); mid-range cities with 270 to 480 sq km of urban land (those clustered around the median), including a range of cities from across the globe (Canada, Brazil, Mexico, China, the EU), with the notable exception of the US and India; and, large cities with 800 to 1300 sq km, located in the US and Canada.

With respect to the amounts of new land developed (Figure 4, black bar), these values range from only 14 sq km (Prague) to nearly 1000 sq km (Guangzhou) over the 10-year period, with a median value near 100 sq km (equivalent to ~30 per cent increase from 1990 to 2000). The amount of new land added is positively correlated to the initial spatial extent of the city; with few exceptions, small cities add small amounts of land and large cities add larger amounts of land. By the year

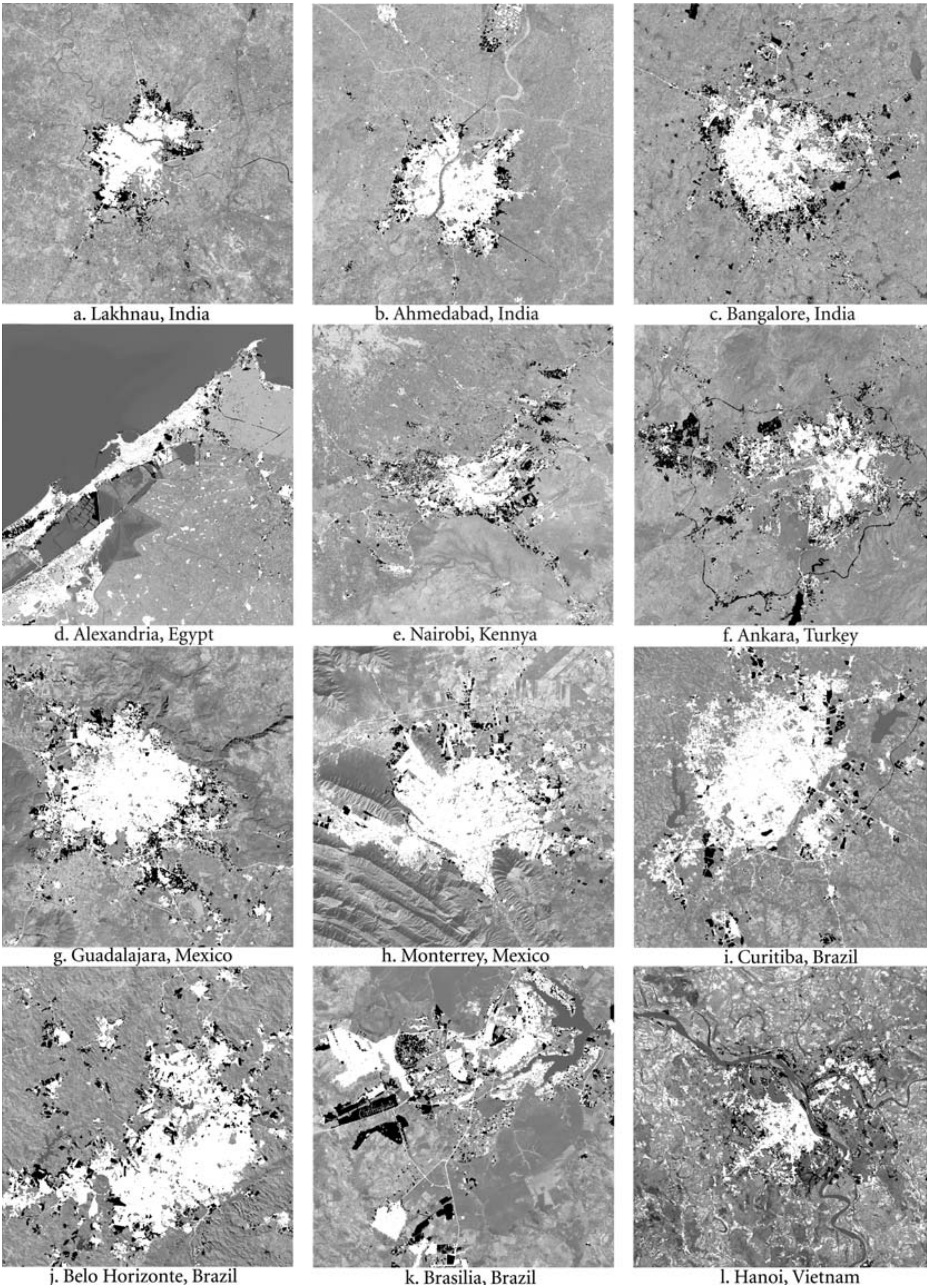


Figure 3. Maps of urban expansion for the 25 cities *(continued)*

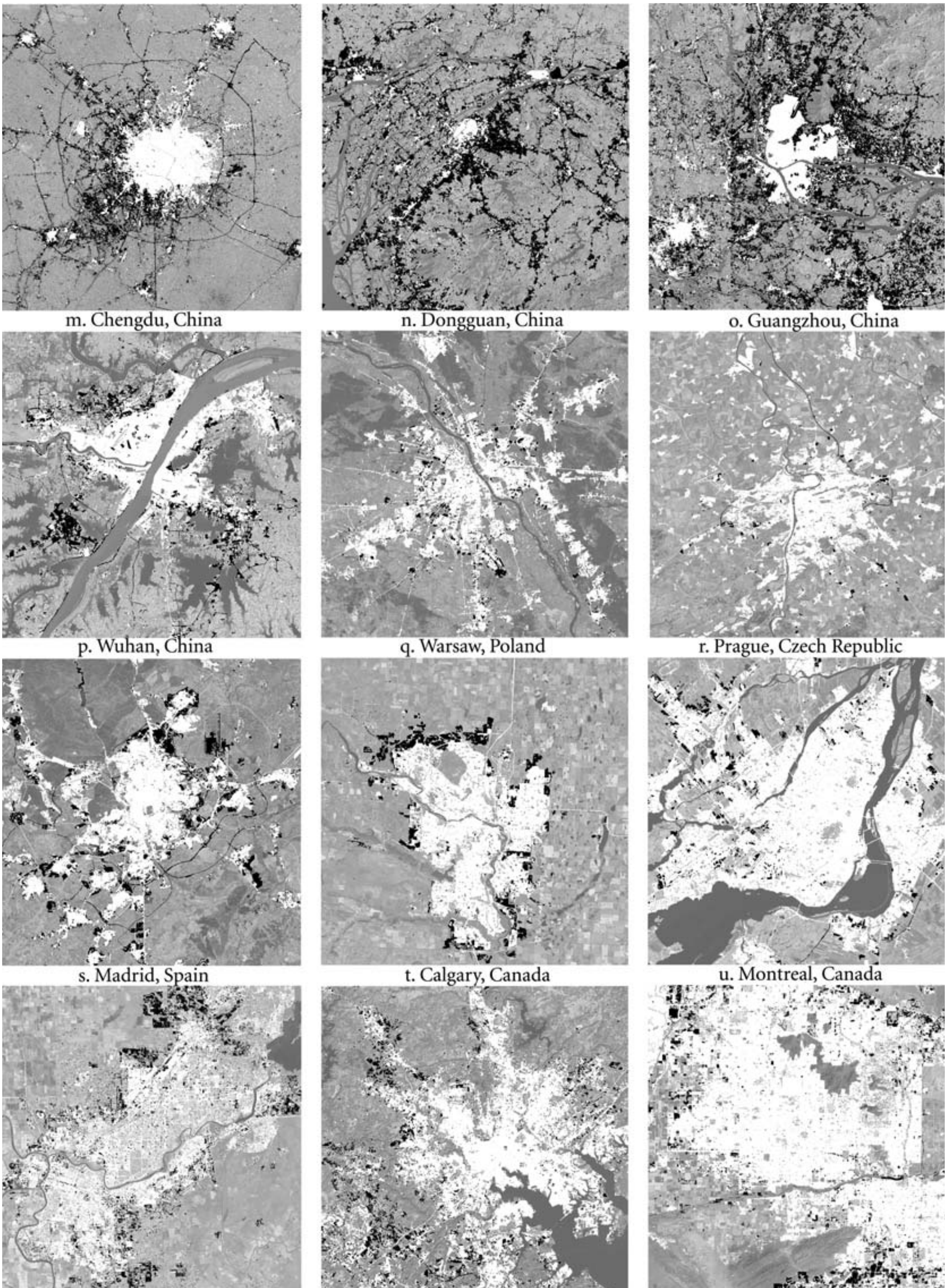
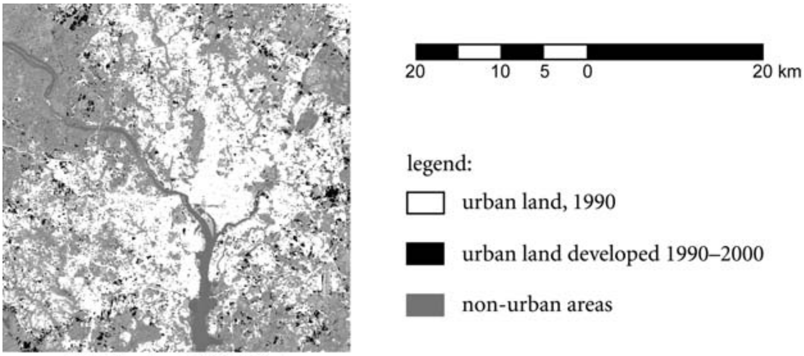


Figure 3. Maps of urban expansion for the 25 cities *(continued)*



y. Washington, D.C., U.S.A.

Figure 3. Maps of urban expansion for the 25 cities

Notes: Built-up land in 1990 is shown in white and newly urbanised land is shown in black. Each city is shown with the Landsat *circa* 2000 image in the background.

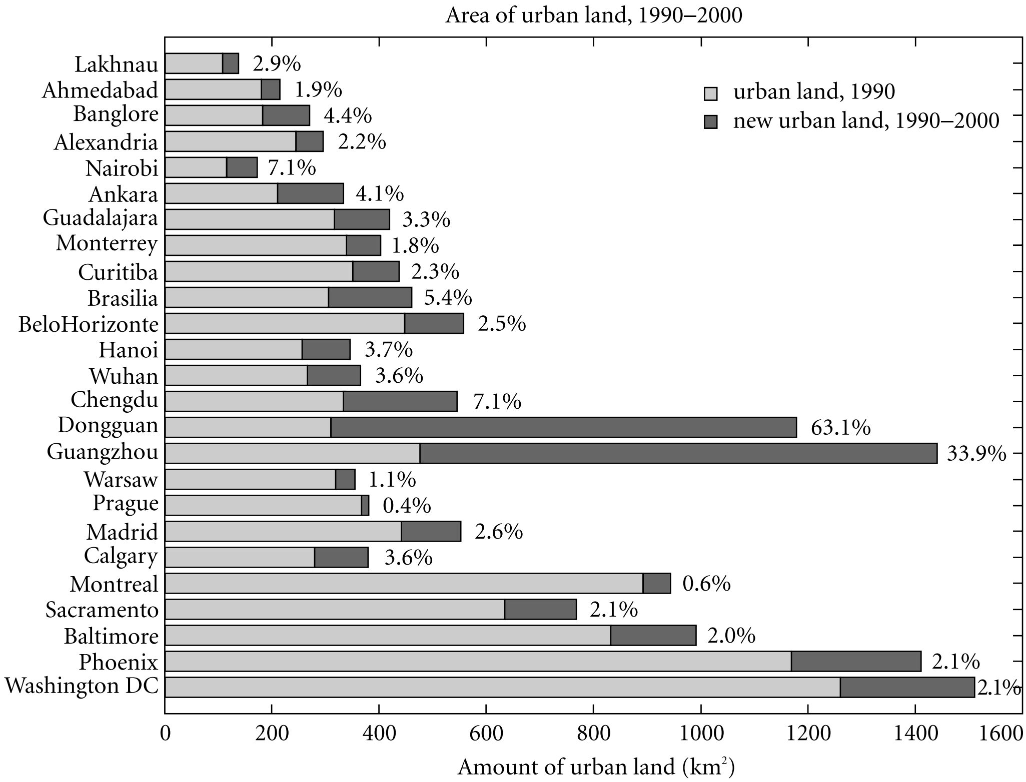


Figure 4. Amounts of urban land for each city in 1990 and 2000

Note: The average annual percentage increase is shown at the end of each bar.

2000, the original groupings based on the 1990 spatial extent have been altered only slightly. Three cities originally in the mid-range group have grown considerably, now topping 550 sq km or more: Chengdu, Madrid and Belo Horizonte. Although significantly larger, they have not expanded into the group of cities dominated by those in the US (cities greater than 950 sq km). The unprecedented growth in Dongguan and Guangzhou, however, has propelled these cities into this top group.

The annual percentage increase (shown at the end of each bar, Figure 4) offers a view of urban expansion that normalises for the spatial extent of the city. The annual percentage increase ranges from less than 1 per cent to just over 7 per cent, with the two Chinese outliers at 30 and 56 per cent increase/year. Again discounting for outliers, the cities cluster around the median growth rate of 2.5 per cent, ranging from 1.8 to 3.4 per cent increase/year. The exception to this is a set of cities with sizeable rates of land conversion, from 4.4 to 7.1 per cent increase/year. This group with rapid changes includes Bangalore, Brasilia, Ankara and Chengdu, a diverse set of cities all located in LDCs. Each of these cities has instituted plans and policies designed to industrialise and expand economically, which may account for their high rates of land conversion as compared with the other cities that did not have such proactive policies. Calgary, Hanoi and Wuhan, with rates of expansion ranging from 3.3 to 3.7 per cent, might also be included in this category. All US cities, meanwhile, fall close to or below the median rate of spatial expansion, ranging between 2.0 and 2.2 per cent. This result is somewhat surprising considering the expansive nature of these cities, their sustained levels of development over the past decades and anecdotal reports of continued land conversion. The vast city of Montreal, as well, has experienced an average rate of expansion of only 1.1 per cent per year. This result suggests that rates of land development may slow as a city grows larger, in effect, indicating that rapid rates of growth are no longer feasible due to the large quantities of land that would need to be converted to sustain them. A size threshold may also be possible, in which the city does not expand further due to the increased time and energy costs for commuting and transport of goods.

4.3 Density of Urban Land

Increases in core and ring density are estimated as the percentage change normalised by the amount of land in the core/ring that is available for development. Turning first to changes in core area densities (Figure 5), three major trends are apparent. First, the core area values for the majority of the cities (15 of 25) are dispersed around the sample median, 13.6 per cent, falling either below (7.5 to 11.5 per cent) or above (15.7 to 19.2 per cent) the median value. Secondly, only two cities, Prague and Montreal, show very slight increases in core densities, at ~3.6 per cent. Neither of these cities exhibits much urban expansion overall, so it is not unexpected that their core rates of change are equally low. Finally, large increases in core density are seen in five cities, ranging from 30.6 to 42.9 per cent. These five cities—Madrid, Ankara, Dongguan, Chengdu and Guangzhou—are part of the 'high-growth' group of cities that have witnessed large relative and absolute amounts of urban spatial expansion in general (Figure 4). It is not surprising that demands for new urban space in these areas would occur within and adjacent to the core city at very high levels. The remaining four cities in this 'high-growth' group (Bangalore, Brasilia, Calgary and Wuhan) have rates of core density increase that are much lower, within a few percentage points of the sample median (13.6 per cent). These results reflect the fact that each of these four areas has limitations that prevent land development within the

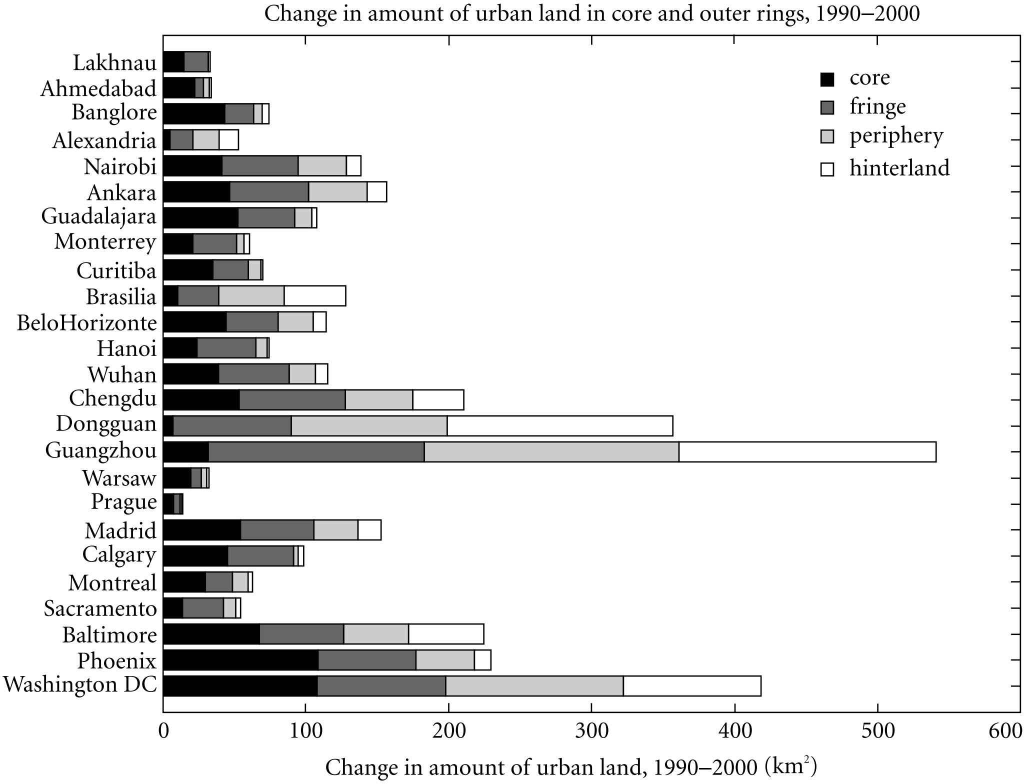


Figure 5. Change in the amount of urbanised land (sq km) from 1990 to 2000 for the core area and successive 8-km rings (fringe, periphery and hinterland)

core: Calgary and Brasilia have large areas devoted to green space, while both Wuhan and Bangalore have physical restrictions such as waterways and hilly terrain that impede land conversion.

What is most interesting, however, is the distribution of newly developed urban land among the three rings outside the core (fringe, periphery and hinterland). Following theories on urban growth cycles or phases (Blumenfeld, 1954; Boyce, 1966; Korcelli, 1976), levels of growth should decrease outward from the city core with a given periodicity. In other words, amounts of land conversion to urban uses should be highest in the core (dark grey) and fringe (grey), followed by successively smaller amounts of new land development in the periphery and hinterland (light grey and white, Figure 5). The majority of cities (18 of 25) exhibit this trend, shown clearly in the results for Monterrey, Belo Horizonte, Wuhan and Madrid. Eight of these 18 cities have appreciable amounts of new urban land in the core and fringe only, and little to no land development in the outer rings (for example, Lakhnau, Prague and Calgary). In this way, land conversion in the core takes the form of infilling, while expansion into the fringe zone can be considered evidence of a new wave of diffusive growth.

Six cities illustrate the reverse trend, however. Rather than decreasing, the amount of land conversion is constant or increases in all three rings outside the core. The large amounts of new urban land in the fringe, periphery and hinterland in Dongguan and Guangzhou are easily explained by the relatively small spatial extent of their cores at the outset (3 and 7 sq km respectively). Considering the vast amount of land development that occurred in these cities as a result of land and market reforms, developers had no choice but to expand farther and farther from the core. In Alexandria and Brasilia, the dispersed pattern of growth across all rings is more indicative of the city shape than actual sprawling or excessive diffusion of the city. Both of these cities have developed in a more elongated pattern by necessity (due to biophysical constraints such as water) and/or design (policies that promote residential sub-divisions outside the city). In Baltimore and Washington, DC, the reasons for dispersion are less apparent. These results—large amounts of new development evenly distributed over an extended area outside the core—clearly show that the expansion of American cities follows patterns characteristic of urban sprawl. At the very least, this trend illustrates that Baltimore and Washington, DC, are located within a large, polycentric conurbation, where land conversion is occurring in each town or nucleus in the network rather than proximate to the central city.

One final way to visualise changing patterns of urban land density is shown in Figure 6, where values of core density are plotted against those for urban land density outside the core (here, the area within the fringe, periphery and hinterland rings combined) for the years 1990 and 2000. The slope of each trend line corroborates the result that

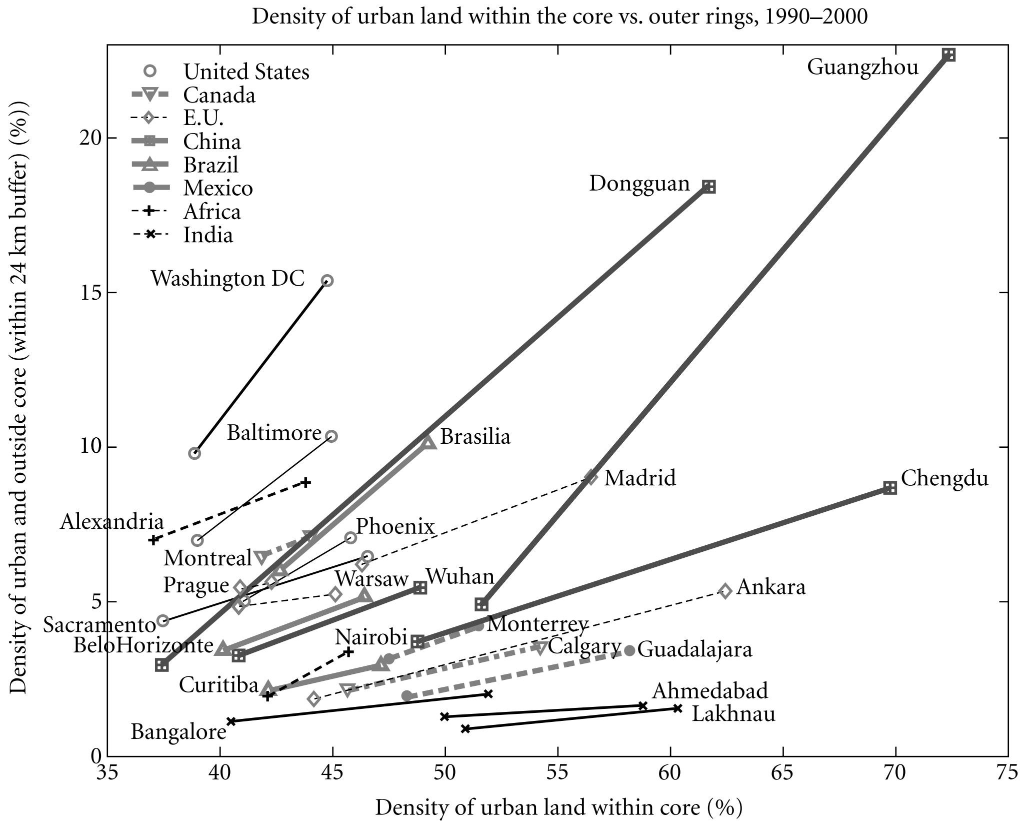


Figure 6. Changes in urban land density within the core (*x* axis) and outside the core (within a 24-km ring outside the core, shown on the *y* axis) of each city, from 1990 (lower point) to 2000 (top point)

the cities fall into either the dispersed growth category or the 'fringe-only' growth category. Cities with considerable increases in density across all three outer rings have slopes close to 1, while those with only slight increases outside the central core have much flatter slopes ranging from 0.2 to 0.3. In addition, the graph elucidates another interesting result. As compared with cities in the US, China and the EU, (where fringe density levels range from 4 to 10 per cent or greater), cities in Mexico and India, as well as Curitiba and Calgary, have relatively lower density levels outside the core, below 4 per cent in 1990 and 2000. This result reveals that, despite moderate to high levels of new land development, these cities have retained tight core areas rather than expanding outward in a dispersed manner.

4.4 Fragmented vs Contiguous Patterns of Urban Land

Patch density was assessed for each city both across space and through time using a series of 1-km rings extending outward from the city centre (Figure 7). In general, results show that the number of patches is initially small at the city centre (distance = 0 on the *x* axis), but increases rapidly moving outward from the core. Patch density peaks in each city near the core edge, approximately 10 to 20 km from the city centre (the core extent is shown by the vertical dashed line in each graph). This result is expected, since metropolitan areas often have more patchy or scattered development in this transitional area, where residential land use is mixed with cropland, green space areas and other vegetation types.

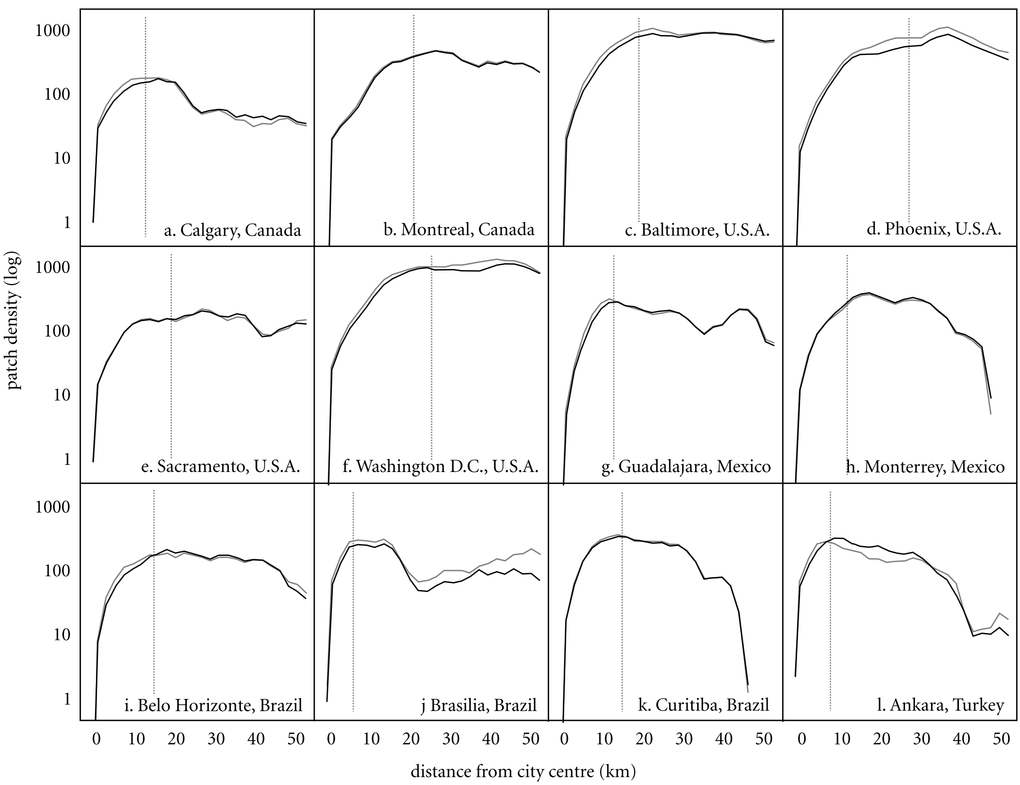


Figure 7. Patch density measured across space (distance from the centre of the city outwards, as indicated on the *x* axis) and time *(continued)*

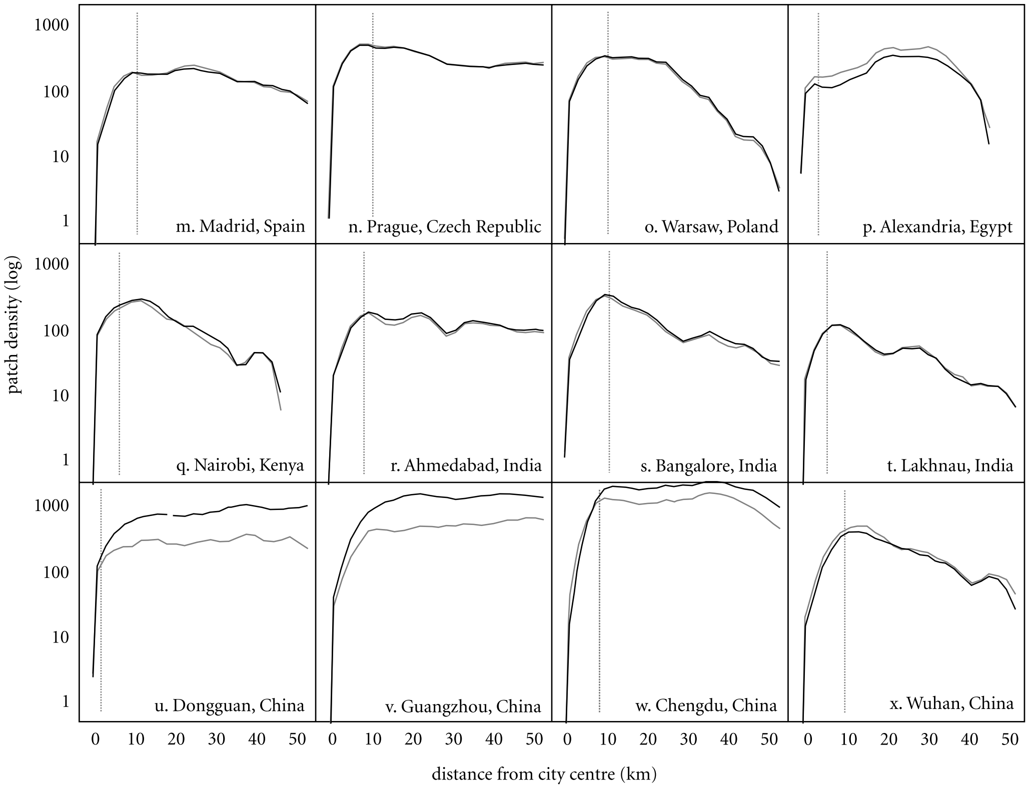


Figure 7. Patch density measured across space (distance from the centre of the city outwards, as indicated on the *x* axis) and time

Notes: Trends *circa* 1990 are shown by the grey line, while trends *circa* 2000 are shown in black. Cities are grouped according to nation/region. Hanoi, Vietnam is not shown.

After this peak at the core edge, the number of patches per ring declines (~20–50 km from the city centre). Because this drop occurs in rings without a large amount of urban land, this result is more an indication of a decline in urban land density than a decline in the relative scatter or fragmentation of that land. In a few cities, secondary peaks are apparent, which correspond to satellite cities and clusters of urban land conversion outside the city core (for example, Guadalajara, Brasilia, Nairobi). These peaks suggest a trend towards a more macro-scale type of dispersion rather than fragmentation *per se*.

The patch density results for seven cities diverge from these trends slightly. Cities in China and the US (graphs u–x and c–f, Figure 7) exhibit a far greater number of patches as compared with the rest of the cities in the sample: trend lines are nearly an order of magnitude higher than those in the rest of the sample, despite normalisation of the patch number by land area. Patch density does not decline with distance from the core as in the majority of the cities, but remains elevated through the periphery and hinterland areas, as far as 50 km from the city centre. This result may be due to the fact that more land is dedicated to green space (parks, forests, open areas), usually for amenity or aesthetic purposes (Wolman *et al.*, 2005). However, this trend may also suggest that these cities are expanding in a more extensive, dispersed form compared with the others in the sample.

For trends in fragmentation through time, the most noticeable trend in all cities is the decrease in patchiness from 1990 (grey trend line) to 2000 (black trend line). This drop points to areas of urban expansion that have filled in previous gaps between plots of established urban land. Nearly every city exhibits this type of infilling, whether within the city centre or core (for example, Ankara, Chengdu) or over a more extensive area between the core and fringe zones (for example, Madrid, Brasilia). For most cities, this drop provides additional information on how far new land development extends from the core. For cities in India and Turkey, for example, this drop in patch density stretches roughly from 4 to 12 km from the city centre. In Brazil, Mexico and the EU, however, this region extends from 5 to 30 km, a distance more than double that in India and Turkey. Interestingly, US cities also show decreased fragmentation over time. Considering the already scattered, dispersed nature of these cities in 1990 (Figure 5), it is likely that any new land development would automatically appear as infilling in form.

In just under half of the cities, the number of patches per unit area has increased from 1990 to 2000 at some point along the continuum from core (distance = 0) to periphery. This result is a direct indication of new, fragmented development, a trend most pronounced in Chengdu, Dongguan and Guangzhou. To a lesser extent, new patchy growth occurs in Ankara (at 18-24 km), Calgary (at 18–50 km), Belo Horizonte (at 26–46 km) and in all three cities in India (at ~18–24 km).

4.5 Population Density

The most striking result in Figure 8 is the vast range of population densities across the set of cities, from extremely low population density in Montreal (~1000 persons/sq km) to very high values in Ahmedabad (greater than 35 000 persons/sq km). Cities with very low population densities, between 900 and 3000 persons/sq km, include all US cities and Montreal. In Mexico, Brazil and the EU, cities generally have slightly higher population densities, from 5500 to 10 000 persons/sq km. The majority of the cities in the sample fall in this mid-range group. Finally, cities with greater than 10 000 persons/sq km include all cities in China and India, as well as Ankara, Turkey and Alexandria, Egypt.

When changes in population density over the 10-year period are considered (the grey bar vs the black bar), two distinct trends are apparent. First, the rapid rates of expansion in Dongguan and Guangzhou have resulted in substantial drops in population density from 1990 to 2000. Development of land is occurring far more rapidly than population increase in these cities. Unfortunately, these figures might be deceptive, since official Chinese census data do not report all persons living within city boundaries, due to a registration system that does not permit many migrants from rural areas to register as urban inhabitants (Liang and Ma, 2004). If this 'floating population' is taken into account (estimated by various sources as hundreds of thousands to millions), it is probable that these cities are actually witnessing stable or even increasing population densities.

The results show a second trend in terms of changes to population density. The set of 'rapid-growth' cities identified by the expansion rates and population density indicators have also undergone changes in urban land area at a relatively faster rate than population growth. Each of these cities (for example, Bangalore, Ankara) has a population density level that is falling over time, as well as a population to urban land ratio (at the end of each bar, Figure 8) that is far lower relative to existing population densities.

Beyond these two trends, the remaining cities show no distinct patterns of increasing or decreasing population density. In the remaining cities, nearly half of the cities have increasing population densities (for example, Monterrey, Curitiba, Warsaw, Alexandria),

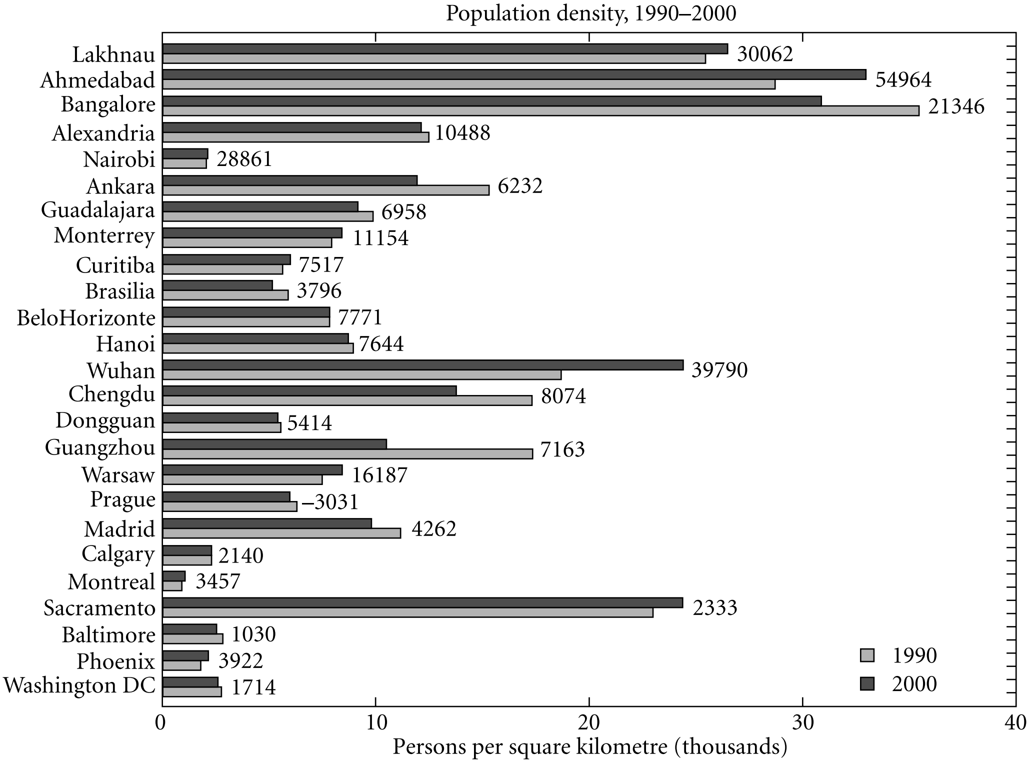


Figure 8. Number of persons per square kilometre of urban land for each city in 1990 (grey) and 2000 (black)

Note: The ratio of change in population to change in amount of urban land, 1990–2000, is shown at the end of each bar.

while the rest have witnessed declining population densities over the same period (for example, Guadalajara, Madrid, Alexandria). Even results in US cities are split: population densities in Washington, DC, and Baltimore have decreased, while Sacramento and Phoenix in the west have increased, most probably due to migration from Mexico and Latin America. These results suggest that the link between population change and urban spatial expansion is not as clear as previously thought. Urban land conversion may not be directly correlated to population changes, but may instead be caused by a number of proximate and indirect drivers unrelated to population changes.

4.6 Summary and Discussion

The 25 cities were assessed across four broad areas: amounts and rates of urban expansion, location and density of urban land, fragmentation of urban land, and density of population. Although each metric is informative in its own right, it is clear that one indicator alone is not sufficient for understanding the various dimensions of urban sprawl. Rather, results from the suite of metrics must be considered concurrently to provide a more comprehensive and cohesive picture of urban growth and expansion.

When all measures are considered together, four possible 'city types' emerge based on the way the data cluster for each indicator (shown in Tables 6 and 7). US cities are characterised foremost by their impressive sizes (in terms of amount of land), but also by their dispersed form of expansion and significantly lower population densities as compared with the rest of the cities in the sample. Other than Montreal, Canada, no other city exhibits this same set of qualities and thus the group can be characterised as *expansive-growth cities*. Note that these expansive cities are nearly three times larger in spatial extent (1040 and 1216 sq km in 1990 and 2000 respectively) than the sample median for all cities (330 and 430 sq km), although their yearly percentage increase is lower, at 1.7 per cent (Table 6). The extensive area of these cities results in population densities far lower (2103 and 2109 persons/sq km in 1990 and 2000) than the sample densities (7899 and 8440 persons/sq km) or the densities of other groups (between 9900 and 16 000 persons/sq km). Most significantly, *expansive-growth cities* show sustained increases in urban land in both the periphery and hinterland rings (the two outermost rings), a trend which is not apparent in the majority of the sample cities. The overall sample median rate of increase for the periphery and hinterland is 1.8 and 0.5 per cent respectively, while US cities have witnessed increases in urban land density of 3.4 and 2.0 per cent. Although this difference does not appear significant, it is important to remember that the outer rings in *expansive-growth cities* are quite large in area. Thus, a relatively small percentage increase translates to a large amount of land in absolute terms. By comparison, no other city in the sample approaches the magnitude of these figures, or exhibits land conversion rates that could create similar spatially extensive urban development in the next 10 years. Should Brasilia (with one of the most rapid absolute growth rates), for example, continue to add ~150 sq km every 10 years for the next several decades, it would take 60 years for the city to reach a size close to that of an *expansive-growth city*.

Chinese cities also set themselves apart due to their extremely rapid land conversion rates and tendency towards both dispersion and fragmentation in their development patterns. While these cities begin small in size (376 sq km), they have developed at a rate six to seven times the median of the group (682 sq km from 1990 to 2000). This type of development can be termed frantic-growth, which has occurred at such a rapid pace that it has been largely unregulated. Dongguan and Guangzhou are witnessing amounts and rates of land conversion that are unprecedented in history and unparallelled anywhere else in the world, primarily as the result of dramatic policy decisions that have led to considerable increases in GDP, increased foreign investment and trade, and a rise in rural–urban migration. Although Dongguan and Guangzhou are fast approaching the expansive extent of US cities, these two cities are considered anomalous both internationally and within China. Wuhan and Chengdu, by comparison, have received more modest levels of investment and trade in China's recent 'Go West' programme and, as a result, are expanding at rates relative to those in Mexico, Brazil, India and the EU. It is important to note that, while these four cities represent some of the diversity of Chinese urban areas, Chinese cities that have not been targeted for development may exhibit lower rates of spatial expansion. Our sample, in this regard, may not show a balanced view of ongoing urban processes in China.

The remaining cities considered in this research fall into one of two categories, a division which is, in fact, unrelated to their geographical location or their economic status as 'more developed' or 'less developed' (MDCs vs LDCs). *High-growth cities*, including Calgary, Bangalore, Brasilia, Ankara, Hanoi and Wuhan, exhibit rapid urban development relative to the rest of the group, with land conversion rates ranging from 3 to 7 per cent annually (compared with the median of 2.6 per cent) and decreasing population

Table 6. Summary statistics for the four city types established in this research

			City types			
Group	*Category*	*All cities*	*Expansive growth-cities*[a]	*Frantic-growth cities*[b]	*High-growth cities*[c]	*Low-growth cities*[d]
Spatial extent and rates	City size, 1990 (sq km)	329.4	1,039.5	375.9	249.8	312.4
	City size, 2000 (sq km)	430.4	1,215.5	1,057.3	363.5	377.0
	Increase in urban land, 1990–2000 (sq km)	102.5	176.0	681.4	113.8	64.6
	Annual rate of spatial expansion (percentage)	2.6	1.7	34.7	4.8	2.1
Density of built-up land	Radius of core area (km)	11.0	23.0	6.0	10.0	11.0
	Increase in urban density, 1990–2000 (percentage)[e]					
	Core	13.6	7.6	40.9	19.6	13.8
	Fringe	4.9	4.8	22.0	6.1	3.3
	Periphery	1.8	3.4	13.2	2.3	1.0
	Hinterland	0.5	2.0	10.1	1.1	0.4
Fragmentation	*Change in number of patches, 1990–2000 (percentage)*[f]:					
	Core	–30.3	–26.2	–36.2	–41.8	–30.4
	Fringe	–12.4	–21.5	48.0	–14.5	–16.0
	Periphery	–4.2	–16.6	119.8	9.9	–7.1
	Hinterland	–7.2	–11.4	134.8	–18.0	–6.1
Population density	Persons per sq km of built-up land, 1990	7 899	2 103	13 431	15 551	12 310
	Persons per sq km of built-up land, 2000	8 440	2 109	9 928	14 952	12 730
	Persons added per sq km of built-up land, 1990–2000	7 060	2 531	6 884	14 661	14 633

[a]*Expansive-growth cities* are Montreal, Sacramento, Baltimore, Phoenix and Washington, DC (five cities).
[b]*Frantic-growth cities* are Chengdu, Dongguan and Guangzhou (three cities).
[c]*High-growth cities* are Calgary, Brasilia, Ankara, Bangalore, Lakhnau, Wuhan and Hanoi (seven cities).
[d]*Low-growth cities* are Guadalajara, Monterrey, Belo Horizonte, Curitiba, Madrid, Prague, Warsaw, Alexandria, Ahmedabad, and Nairobi (ten cities).
[e]The increase was calculated as the ratio of the change in amount of land to the area available for development.
[f]The change in patch number was normalised by land area.
Note: To discount the effect of outliers, all figures above represent the median for the sample or subsample.

densities. Although land conversion is constrained to areas near the core or urban fringe, new growth has been sufficiently rapid so as to take a more scattered or fragmented form outside the core. *Low-growth cities*, however, exhibit some change in the 10-year period, but nearly all land conversion has been more infilling than scattered in form. Moreover, population densities in *low-growth cities* are increasing: the median ratio of change in population to change in urban land is 14 633 persons/sq km, significantly higher than existing population densities of 12 310 and 12 730 in 1990 and 2000. This result provides evidence that any land development that has occurred has parallelled population growth, a trend which is not apparent in any of the other city typologies. Ten of the 25 cities—more than one-third of the sample—fall within the low-growth category, including cities in Mexico, Brazil, the EU, Egypt, Kenya and India. Despite vastly different economies, policies and cultures, results show that these *low-growth cities* are developing in a very similar, compact fashion.

Although *high-growth cities* are not expanding in a dispersed fashion similar to *expansive-growth cities*, it is possible that *high-growth cities* are at an early stage in development similar to US cities during their transition to a car-based economy. Critics argue that, given sufficient time, cities around the world—especially those on a path towards industrialisation—will follow the same path as *expansive-growth cities*, producing development far from the urban core. If this were indeed the case, results of this analysis should indicate a set of cities in the middle of this transition, such as Calgary and cities in the EU, as well as Guadalajara, Monterrey, Curitiba and Brasilia, which are all experiencing economic growth and industrialisation (the latter group, despite location in the developing economies of Mexico and Brazil, are far more developed than national figures imply). However, results show that these cities have spatial extents and rates of expansion at more modest levels, closer to the sample median than the median of *expansive-growth cities*. Indeed, the results illustrate that the 25-city sample is divided into two sets on nearly opposite ends of the spectrum: *expansive*- and *frantic-growth cities* on one end, with absolute rates of land conversion near 200 sq km or higher over the 10-year period and substantial amounts of new urban land far from the core and fringe areas, and the remaining cities with expansion rates below 100 sq km and constrained development near the core on the other (Figure 4 and Table 6).

The patch dynamics for two of the groups, *frantic*- and *high-growth cities*, show evidence of increased fragmentation, while both *expansive*- and *low-growth cities* follow a trend towards infilling (or decreased fragmentation), indicated by the rates of change in patch number for the fringe, periphery and hinterland areas (Table 6). Not surprisingly, the core areas of all groups show a decrease in patch number, within a few percentage points of the overall sample median of -30.3. By definition, there is only a small amount of land remaining in the core that is available for development, thus any new land conversion naturally fills in the leftover, undeveloped gaps. Similar to the results for changes in land density, *expansive-growth cities* exhibit a consistently larger drop in patch number across the fringe, periphery and hinterland areas compared with the sample median.

The patch number values for the fringe, periphery and hinterland areas in *frantic-growth cities*, on the other hand, have been influenced heavily by the rapid rates of land conversion and fragmentation in Dongguan and Guangzhou. The patch density measure for the group shows a consistent increase in patchiness outside the core, from a median of 48 per cent in the fringe, to 135 per cent in the hinterland. Chinese cities had virtually no urban land in these outer rings prior to 1990, so rapid land development in these areas is automatically expressed as an increase in patch number. However, this increase is substantial enough to suggest that newly developed areas are scattered and irregular in form. In *high-growth cities*, increased fragmentation is less pronounced in the group values than if observed for each city individually (Figure 7). Although patch number declines in the fringe and hinterland rings of *high-growth cities*, a noticeable increase (9.9 per cent) is present in the peripheral ring. The reasons why land conversion in these particular cities has occurred in an irregular, scattered manner are not immediately clear. Fragmentation may be the result of complex socioeconomic and demographic interactions that drive and influence the spatial structure of cities. In Chengdu, Calgary, Bangalore and Brasilia, the locational decisions of multinational firms and joint-venture industries towards suburban amenities, high-tech and industrial parks have led to patchy development far from the city core (Schneider *et al.*, 2005). Policies and land pricing have also influenced the spatial configuration of cities (Webster, 2002; Audirac, 2003), such that new land development is actually pushed out of the city by high inner-city land prices or by tax incentives given to developers who build outside metropolitan boundaries.

Conversely, increased patchiness may simply be the result of a lack of land availability near the core and fringe areas, since these areas may simply be too dense to permit infilling. Theories of urban dynamics hypothesise a 'zone of maximum growth' that moves outward from the city core with a particular periodicity, a concept also referred to as urban cycles or phases (Blumenfeld, 1954; Korcelli, 1976). Following these ideas, urban growth is essentially a two-step process of diffusion and coalescence. First, new land development occurs in a scattered, patchy form outside the city. As the process continues, infilling among the patches begins to occur, or the city 'coalesces' into a more contiguous urban fabric. This two-step cycle then repeats. For instance, cities that exhibit patchy new land development in this study, such as those in *high-growth cities*, may be in the diffusion stage of growth, while *expansive-growth cities* are in the coalescence stage after a period of extended patchy growth. Whether a city experiences diffusive or coalescent-type expansion is, of course, highly dependent on the past history of the city and on the shape of the city (monocentric vs polycentric), and is particularly influenced by land use policies that permit or prohibit land conversion.

Finally, the location of areas converted to urban land may be influenced by the availability of land for development. Geophysical constraints such as mountains and waterways play a significant role in local land use decisions, as do zoning regulations that dictate the future use of open/vacant space. The land conversion rates reported earlier are adjusted to exclude unavailable regions such as high slopes and waterways. Unfortunately, this adjustment is incomplete, since consistent data on the suitability of land for development, zoning ordinances in place and enforcement of these laws are not available for all cities. If these issues are taken into account, some rates of development may actually be higher than those reported here. Similarly, fragmentation of the urban fabric may also be directly affected by land availability, rather than the result of social or economic driving-forces.

5. Conclusions

This study has demonstrated that the spatial extent, rates of expansion and patterns of urbanisation can be quantified using the combination of remotely sensed data, spatial pattern metrics and statistical census data. The results from this research have provided a starting-point for comparing amounts, rates and patterns of growth in cities across the globe. In addition, we have made initial progress towards understanding whether cities around the world are developing in patterns similar to the sprawling urban forms seen in many US cities. The results show that, other than partial similarities apparent in two rapidly developing cities in China, none of the cities exhibits the large, dispersed spatial forms characteristic of the US cities in this study.

Cities in the sample show tremendous variability in city extent, amount of land development, dispersion, fragmentation and population density. Despite this, four clear patterns, or templates for urban growth, are apparent, which we have designated *expansive-growth*, *frantic-growth*, *high-growth* and *low-growth cities* (Table 7). The majority of the cities (17 of 25) fall into either the high- or low-growth categories, distinguished by relatively rapid, fragmented types of development (high-growth) or modest rates of land conversion that have occurred as 'infill' within partially developed areas (low-growth) keeping these cities compact by comparison. The dispersed pattern, large spatial footprint and low population density of US cities are unique among the sample, thus the term expansive-growth is suitable for this group. Finally, Chinese cities also exhibit a distinctive trend: these *frantic-growth cities* have experienced extraordinary rates and fragmented patterns of land conversion to urban uses, as well as consistently high population densities. Given the histories of the *expansive-* and *frantic-growth cities*, their land use patterns can be understood as outcomes of a range of economic, social and political determinants. US and Canadian cities, for instance, have developed around a car-oriented society with entrenched preferences for large homes and large lots, while selected Chinese cities have undergone an astonishing economic and demographic transformation following significant reforms on the coast and, later, in the interior.

'Urban sprawl' is a tremendously descriptive, although somewhat hackneyed term for an extensive, low-density form of urban land conversion associated with reduced agricultural productivity, environmental degradation, reduced efficiency in public services, increased commuting times and fuel consumption, etc. (Johnson, 2001). Researchers, land managers, urban planners and the like have been quick to label any low-density urban expansion or fringe development around the world as sprawl. This study has shown, however, that the term should be used with caution when applied to cities outside the US and Canada. The amounts and patterns of land development in non-American cities are, in reality, quite different phenomena. Any land conversion in these cities has occurred within the core and fringe areas of the city and, while at times fragmented, none of the cities in the sample shows any trend towards the dispersion or low population densities common to nearly all US cities. Patchy land development in non-US cities may not be a form of urban sprawl at all, but could be seen as part of a larger process of diffusion and coalescence (a two-step cycle of leap-frog growth followed by infilling) that occurs in all cities experiencing conversion of land to urban uses.

In addition to providing information on how cities compare in terms of land use, this study has introduced an alternative method for delineating metropolitan areas. One of the biggest challenges still facing urban researchers is the measure of 'urban' itself. Comparison of urban land conversion both within and across nations is hindered by differences in how cities are measured and lack of a standardised definition of 'urban', both of which affect how data are collected and assessed. When considering such a controversial topic as urban sprawl, differences in measurement can have considerable impacts. Underestimating the urban area tends

Table 7. Summary of characteristics for the four city types derived from this study

Group	*Number*	*Spatial extent of city*	*Percentage increase in spatial extent*	*Dispersed or constrained*	*Scattered or contiguous*	*Population density*	*Change in population density*	*Examples*
Expansive-growth cities	5	Large	Small	Dispersed	Contiguous	Low	Decline	Baltimore Washington Montreal
Frantic-growth cities	3	Small	Large	Dispersed	Scattered	High	Decline	Guangzhou Dongguan Chengdu
High-growth cities	7	Small	Large	Constrained	Scattered	High	Decline	Calgary Brasilia Ankara Bangalore Wuhan
Low-growth cities	10	Small	Small	Constrained	Contiguous	High	Decline	Guadalajara Curitiba Ahmedabad Nairobi

to decrease the degree of sprawl, for instance, while measurements that overestimate urban expansion can heighten the apparent degree of sprawl, thereby lending support for more stringent policies and regulations. Using remotely sensed data, we provide a new framework for determining core, fringe and periphery areas of the city based on explicit amounts of urban land, land cover densities and standardised ring-buffer sizes. Measures such as these help to reduce bias introduced by political boundaries or constructs, and facilitate comparison of cities within and across nations.

This study forms part of an emerging research trend to quantify urban growth, and more specifically, shapes and patterns of urban expansion. All comparative studies of urban sprawl up to this point have focused on US cities, however. To understand the social, economic and environmental impacts caused by rapid urban expansion at local, regional and global scales, it is imperative that we begin to determine the rates, forms and patterns of urban change in cities around the world. Effective land management and policy decisions require understanding, modelling and predicting land conversion in cities across a range of ecosystems, cultures and political/governmental systems. This study has focused on measures perceptible in medium-resolution remotely sensed data—in other words, those related specifically to land development. This information, when combined with additional economic, demographic and accessibility-based measures, will make a significant contribution towards this process.

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Note

1. Five of the 25 cities have some amount of urbanised land outside the 40-km boundary, including Washington DC, Baltimore, Brasilia, Guangzhou and Dongguan. With the exception of Brasilia, this effect is a result of the proximity of each city to a nearby city (the Washington–Baltimore corridor in the US and Guangzhou–Dongguan in the Pearl River Delta region) and the spatial expansion that has occurred between the two. The remainder of the sample cities all exhibit less than 3 per cent of the total urbanised land area outside the 40-km boundary.

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