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Using remote sensing and GIS integration to identify spatial characteristics of sprawl at the building-unit level

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6.1 Introduction

One of the most remarkable human activities in terms of transforming and impacting the natural environment is the development of land for settlement. Patterns and configurations of urbanization have implications for a wide gamut of issues and policies, from environmental quality to health, to transportation and energy, to social and economic welfare. Global trends of rural to urban population migrations, coupled with the unprecedented technological capability of modern societies to construct urban environments, have led to magnitudes of urbanization unparalleled at any former period in history. In the USA alone, 2.08 million acres of open land was urbanized annually between 1992 and 2002 (3.95 acres/minute), an increase from 1.37 million acres/year of urbanization between 1982 and 1992 (Natural Resources Conservation Service, 2004). Not only are the rates of urban growth accelerating, but the patterns of urban growth are becoming more dispersed. The importance of urban sprawl to many public-interest, government and academic agencies has led to multiple initiatives of research and analysis. Many researchers,

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policy makers and stakeholders have an interest in monitoring, evaluating and influencing patterns of urban growth, increasing the need for a more comprehensive understanding of the phenomenon of sprawl than currently exists. Considering the land-based and spatial nature of urbanization, geospatial scientists have a significant role to play in the discourse on sprawl. Furthermore, the geospatial technologies of *remote sensing* and *GIS* are logical tools to be widely utilized for the analysis of sprawl, or problematic spatial patterns of urban growth. While geospatial research to date has only just begun to be utilized within the urban planning and policy discourse regarding sprawl, great promise exists for advancing the study and management of sprawl through the integration of remote sensing and GIS.

Since the onset of flight in the early twentieth century, remote sensing has been utilized for the delineation, analysis and evaluation of urbanization. Techniques and platforms vary widely, from film-based low-altitude monochromatic aerial photography to digital space-based hyperspectral sensors, each with particular benefits and abilities that can aid in the analysis of sprawl. Likewise, GIS has been widely utilized for urban analysis for the past several decades, greatly advanced by the creation of GIS-based demographic data by government agencies such as the US Census Bureau. Many academic sprawl-related studies utilize the US Census TIGER GIS database for various geographic extents, such as metropolitan areas (MAs) and urbanized areas (UAs), as well as census tracts and census blocks. Because remote sensing and GIS techniques and technologies have become so closely interrelated, it is now possible to seamlessly utilize both within the same computing environment. However, this ease of integration has only recently become available. In the past, urban research has tended to develop along two largely separate tracks, one following a more demographic approach (primarily GIS-based) and the other following a more physical/environmental approach (primarily remote sensing-based). As these two tracks continue to merge and become integrated, both technologically and methodologically, new methods become available for researchers to more effectively delineate, analyse and understand the patterns and processes of sprawl.

6.2 Sprawl in the remote sensing and GIS literature

Past studies of sprawl can be divided into two general camps, *physical landscape-based analysis* and *demographic-based analysis*. Remote sensing has been most often employed in physical approaches to analysing sprawl, due to its ability to provide temporal/spatial information on the physical covering of the Earth at a given time period. The usefulness and potential application of remote sensing for urban analysis has steadily grown with the increasing numbers of remote sensing platforms, decreasing costs and ever-increasing sophistication of computer techniques. This point was recently highlighted by several prominent remote sensing journals that dedicated entire issues to focus solely on urban themes, e.g. *Remote*

Sensing of the Environment 2003; **83**(3), and *Photogrammetric Engineering and Remote Sensing* 2003; **69**(9).

Remote sensing literature has tended to use the term 'sprawl' as related to urbanization somewhat loosely, often to indicate rapid urbanization, or urbanization along the urban/rural fringe, or low-density urbanization (Hurd *et al*., 2001; Weng, 2001; Epstein *et al*., 2002). Classic change-detection techniques utilizing multi-date imagery have been one common approach for identifying newly developing areas of low-density urbanization (e.g. Civco *et al*., 2002). Other remote sensing approaches have utilized night-time lights as a proxy for urban extent to identify low-density sprawl (Sutton, 2003; Cova *et al*., 2004). However, these remote sensing approaches thus far arguably lack meaningful application to the processes and patterns responsible for sprawl.

GIS-based studies of sprawl have tended to use the term more precisely than has the remote sensing literature. A number of seminal sprawl-measurement studies have occurred in recent years that utilized a primarily GIS demographic approach. Several papers have utilized population density-based metrics to provide cross-comparisons and rankings for multiple metropolitan areas within the USA (Fulton *et al*., 2001; Nasser and Overberg, 2001; Lopez and Hynes, 2003). Many of these approaches utilize US Census Bureau data for MAs, which consists of the counties with population and commuting ties to a major city. Other studies have used the US Census Bureau's UAs, which are incorporated areas and census designated places of 2500 or more persons. For example, Galster *et al*. (2001) utilized US Census metropolitan data variables for calculating their eight measures of sprawl. Theobald (2001) developed metrics for *rural* sprawl based on population densities in census tracts specifically outside of urban areas. Sprawl analytical methods employed thus far have tended to utilize either a primarily vector GIS-based or primarily remote sensing-based approach. We will come back to this point later in the chapter and unite GIS and remote sensing as we explore the most recent progress in sprawl research. However, we first must tackle one of the confounding issues in the sprawl discussion, namely, what exactly is being discussed? How do people view the idea of sprawl?

6.2.1 Definitions of sprawl

Many books have been written and studies conducted on various aspects of urbanization. However, the term 'sprawl' is often incorrectly used as a synonym for *urban growth* in general. The identification of sprawl as a specific type and potentially problematic pattern of urbanization first arose in public discourse in the middle of the twentieth century, when suburban subdivisions began to arise in areas peripheral to existing urban locations (Hess *et al*., 2001). To the lay person the term 'urban sprawl' is generally used to refer to spreading suburban development patterns associated with repetitive housing tracts, strip shopping malls and increased traffic congestion.

In recent decades the term has tended to be more indiscriminately used. Any development unwanted by a particular interest is often labelled as 'sprawl', regardless of the fact that it may actually embody characteristics of *smart growth* (the catch phrase for urbanization that is well-designed and non-sprawling), such as high-density, in-fill and mixed use. This inconsistent and sometimes contradictory use of the term 'sprawl' creates a risk that the word will become hackneyed or outright meaningless. In order for the phenomenon of sprawl to be adequately delineated, analysed and managed, a more precise and universally agreed-upon meaning needs to be established.

In the past several decades the interest in sprawl, and consequently the number of research articles focusing on sprawl, has risen across multiple disciplines, from public policy to environment to land management. The academic literature of urban sprawl has itself sprawled into what is characterized by Galster *et al*. (2001) as an ambiguous 'semantic wilderness'. Galster *et al*. categorize the literature into six groups of definitions that look at sprawl in the following ways: (a) sprawl defined by example; (b) sprawl defined by aesthetic definition; (c) sprawl as the cause of an unwanted externality; (d) sprawl as a consequence; (e) sprawl as selected patterns of land development; and (f) sprawl as a process of development of land use. Any use of geospatial technologies to assist in sprawl research will be more effective if it can be based on a clear definition. While sprawl may have many non-spatial socio-economic characteristics, remote sensing and GIS are spatial technologies and therefore are most useful with a definition based on the spatial pattern, extent and configurations that urbanization takes upon a landscape.

By most definitions, sprawl is a pattern of urbanization that carries with it inherent problems, dysfunctions and inefficiencies (Burchell *et al*., 1998; Ewing, 1997; Johnson, 2001). The urban planning and policy literature provides a number of references to sprawl that help to define it in terms of a specific spatial form of urban growth. Reid Ewing (1997) offers a summary of 17 references to sprawl in the literature as being characterized by 'low-density development, strip development and/or scattered or leapfrog development'. Ewing also uses a transportation component to help define sprawl. He suggests that the lack of non-automobile access is also a major indicator of sprawl. Burchell and Shad (1999) present a working definition of sprawl as 'low-density residential and nonresidential intrusions into rural and undeveloped areas, and with less certainty as leapfrog, segregated, and land consuming in its typical form'. Consensus is emerging that sprawl is complex and cannot be characterized as a singular homogeneous phenomenon, but instead has multiple possible characteristics. Furthermore, sprawl is different from place to place (Burchell *et al*., 1998) and can be grouped into at least three different families relating to *urban sprawl*, *suburban sprawl* and *rural/exurban sprawl* (Hasse, 2004; Theobald, 2004). Many other papers refer to sprawl as urbanization with specific spatial characteristics (Table 6.1).

The discourse on *smart growth* also helps to inform the development of sprawl measures, because the spatial characteristics of smart growth are in some respects the

Table 6.1 Spatial characteristics of sprawl found in the literature

Characteristic	Description	Selected references
High/inefficient land consumption; low population density	Low population density; high levels of urbanized land per person; rate of land urbanization greater than rate of population growth, especially in fringe areas	Black, 1996; Downs, 1998; Freeman, 2001; Galster *et al*., 2001; Harvey and Clark, 1965; STPP, 2000; Montaigne, 2000; Hasse, 2003
Fringe development	Development away from city centre; rapid development of open spaces on city boundary	Besl, 2000; Downs, 1998; Galster *et al*., 2001; Katz and Bradley, 1999
Lack of connectivity	Arterial street systems; lack of grid; lots of dead ends	Duany and Plater-Zyberk, 1998; NRDC, 1996; Hasse, 2003
Leapfrogging; scattered development	Development that skips over empty parcels	Clawson, 1962; Mills, 1981; Downs, 1998; Gordon and Richardson, 1997b; Yeh and Li, 2001; Hasse, 2003
Separation of uses	Different land uses (employment, retail, residential) are far apart; residential development beyond edge of employment and retail services; lack of residential development in city centre	Brown *et al*., 1998; Downs, 1998; Duany and Plater-Zyberk, 1998; Ewing, 1994, 1997; Galster *et al*., 2001; Hasse, 2003
Lack of functional open space	Lack of open space that performs a useful public function; ill-defined residual space	Anonymous, 1999; Ewing, 1997, 1994; Hasse, 2003
Lack of non-auto transportation accessibility	Dispersed spatial patterns and long distances to destinations preclude use of public transit, bicycle and pedestrian modes of travel.	Downs, 1998; Ewing, 1997, 1994; Hasse, 2003
Aesthetics and architecture	You know it when you see it. Big-box retail; strip malls; no sidewalks; excessively wide roads. Large, disjointed buildings set back from street, highly articulated, rotated on lots	Duany and Plater-Zyberk, 1998; Gore, 1998; Koffman, 1999; Kunstler, 1996; NRDC, 1996; Hasse, 2003

Adapted and modified from Hess *et al*. (2001).

mirror opposites of the characteristics of sprawl. According to the US Department of Environmental Protection, smart growth principles promote development which:

> . . . has mixed land uses; takes advantage of compact building design; creates a range of housing opportunities and choices; creates walkable neighborhoods; fosters distinctive, attractive communities with a strong sense of place; preserves open space, farmland, natural beauty, and critical environmental areas; strengthens and directs development towards existing communities; provides a variety of transportation choices; makes development decisions predictable, fair, and cost effective; and encourages community and stakeholder collaboration in development decisions. (US EPA, 2005)

The spatial patterns of smart growth and sprawl are inherently different and able to be distinguished at various scales through appropriate geospatial methods.

6.2.2 Spatial characteristics of sprawl at a metropolitan level

A number of spatial-based measurements designed to capture various sprawl signatures have evolved out of the characteristics of sprawl listed in Table 6.1. Torrens and Alberti (2000) explored developing an empirical landscape framework to sprawl measurement that focuses on the characteristics of *density*, *scatter*, the *built environment* and *accessibility*. They outlined a set of metrics for quantifying these characteristics that employ *density gradients*, *surface-based approaches*, *geometrical techniques*, *fractal dimensions*, *architectural and photogrammetric techniques*, *measurements of landscape composition and spatial configuration*, and *accessibility calculations*. One of the seminal works of spatial measurements of sprawl at the metropolitan level was developed by Galster *et al*. (2000), who define sprawl as 'a pattern of land use in an urbanized area that exhibits low levels of some combination of eight distinct dimensions: density, continuity, concentration, compactness, centrality, nuclearity, diversity, and proximity' (Galster *et al*., 2001). They operationalized six of these indicators to compare the characteristics of sprawl for 13 metropolitan areas in the USA. Figure 6.1 portrays the schematic diagrams from Galster *et al*. (2001), demonstrating the spatial patterns captured by each metric for sprawling and non-sprawling metropolitan areas.

A number of other studies have also taken a GIS-based approach to develop sprawl measures for comparing metropolitan areas. Malpezzi (1999) analysed the spatial distribution of population within census tracts of US Metropolitan Statistical Areas (MSAs), calculating various indices of *density* as well as *commuting patterns*. Ewing, Pendall and Chen (2002) developed an index for sprawl which combined individual measures for: *residential density*; *neighbourhood mix of homes, jobs and services*; *strength of activity centres and downtowns*; and *accessibility of the street network*. Hess *et al*. (2001) developed a suite of seven spatial metrics for sprawl that focused on *land consumption*, *population concentration*, *separation of land*

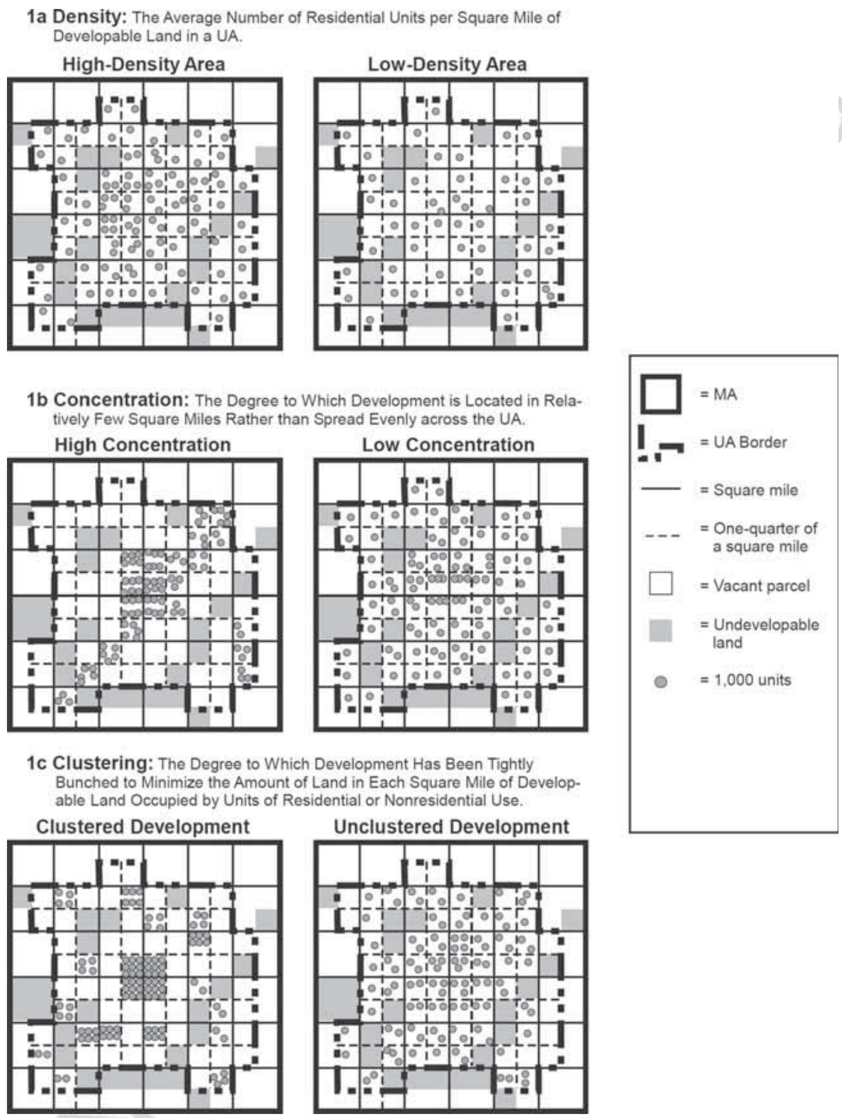
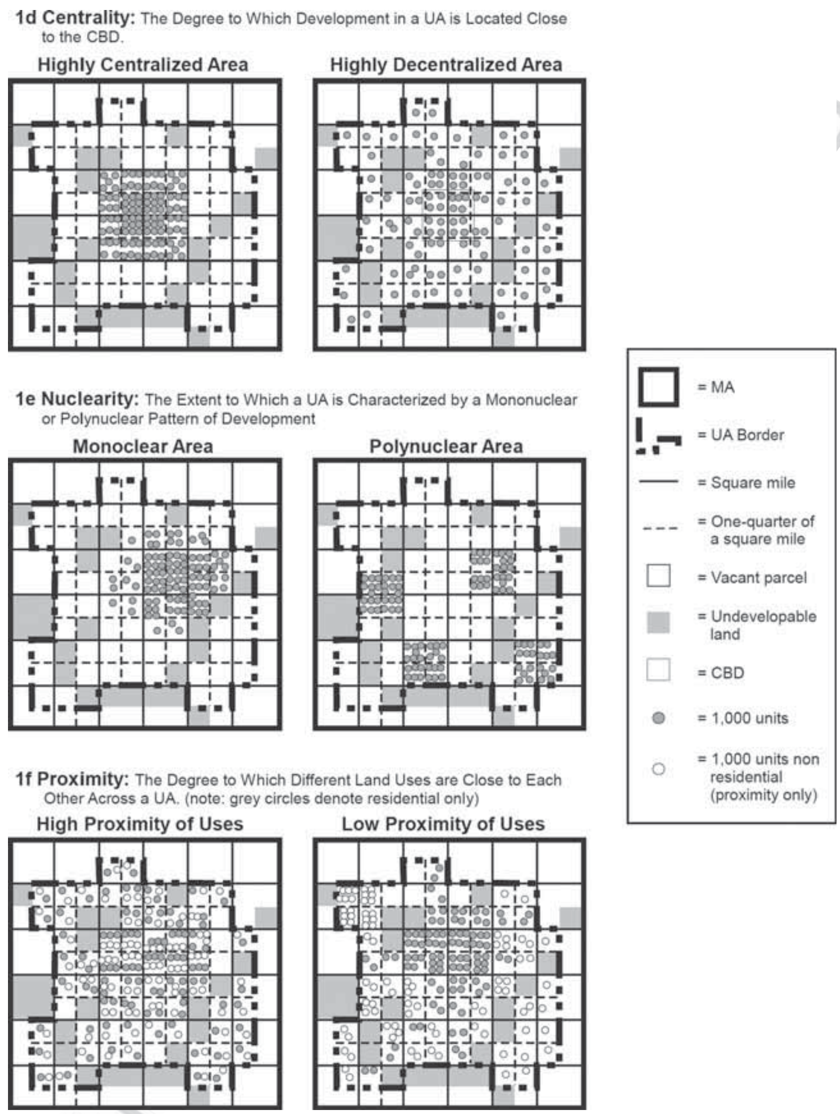


Figure 6.1 Metropolitan-level spatial measure of sprawl. Galster *et al*. (2001) utilized US Census metropolitan areas (MAs) and urbanized areas (UAs) data to operationalize six measures of sprawl at the metropolitan level, including: (a) density; (b) concentration; (c) clustering; (d) centrality; (e) nuclearity; and (f) proximity. Reproduced by courtesy of the Fannie Mae Foundation from Galster *et al*. (2001)



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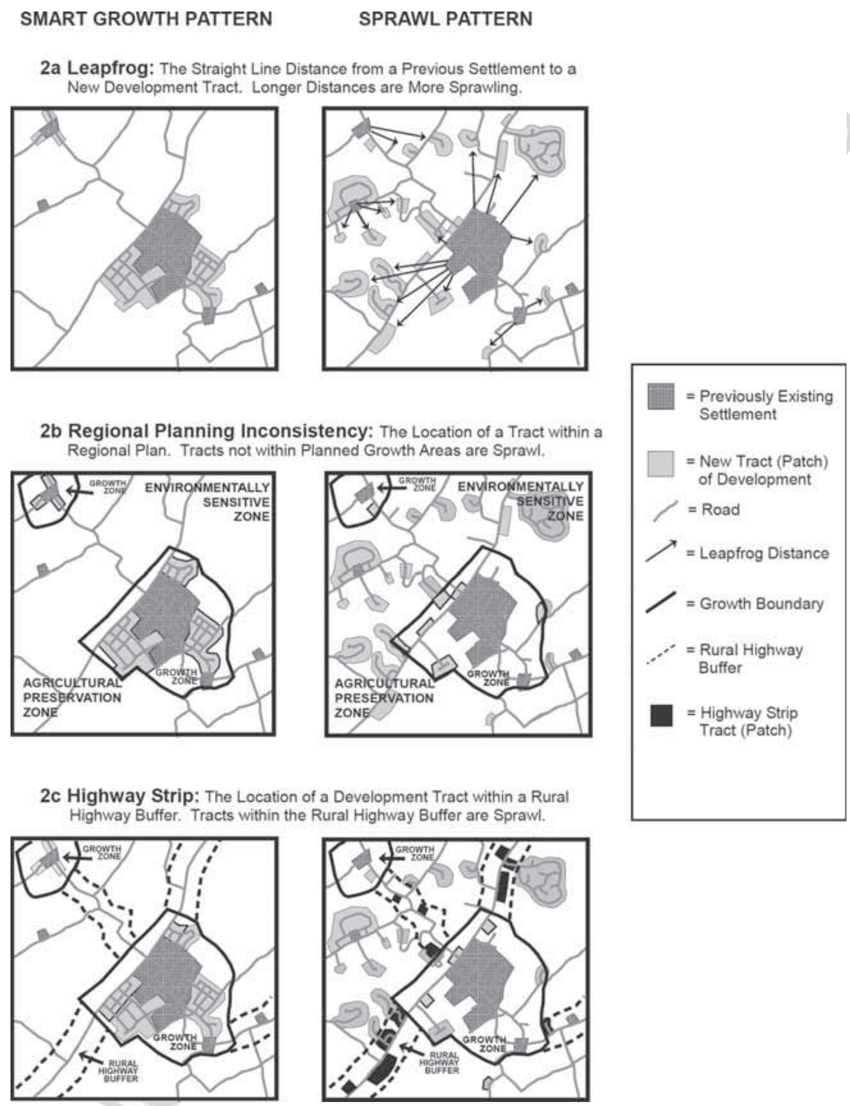

Figure 6.2 Development tract-level spatial measures of sprawl. Hasse (2004) developed 12 geospatial measures of urban sprawl (GIUS) at the development tract level. These conceptual schematic diagrams illustrate selected GIUS measurement for a fictitious town that grows with a smart growth pattern (left) and sprawl pattern (right). The measurements selected include: (a) leapfrog; (b) regional planning inconsistency; (c) highway strip; (d) community node inaccessibility; (e) land resource impacts; and (f) impervious surface coverage. From Hasse (2002) AQ1

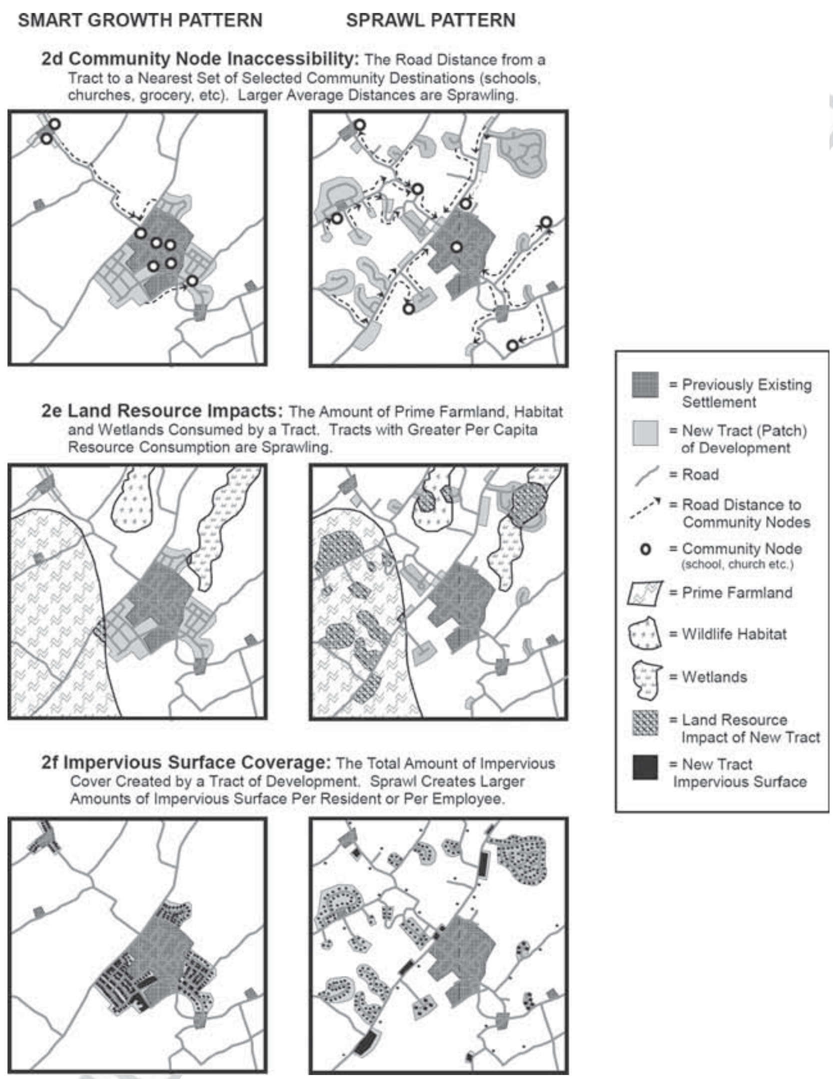

Figure 6.2 (Continued)

uses/accessibility, and *temporal patterns of sprawl*. They calculated their metrics for 49 urbanized areas within the USA, finding little correlation between the measures, suggesting that sprawl has a heterogeneous spatial nature on an interurban scale.

6.2.3 Spatial characteristics of sprawl at a submetropolitan level

The studies covered thus far have been conducted on a metropolitan scale, providing a single value index to characterize certain aspects of sprawl for an entire urban region. A comparison of the results for various cities is interesting and sometimes surprising (alas, Los Angeles is not even close to being the most sprawling city in the USA). However, some researchers question how much meaning to place on these measures, as well as how valuable such measures are to inform policy decisions (Hess *et al*., 2001; Hasse and Lathrop, 2003b; Song and Knaap, 2004). As argued by Hasse and Lathrop (2003b), there is likely much more variation in sprawling urbanization within any particular metropolitan area than exists between different metropolitan areas. Some of the most recent sprawl analysis work has focused on submetropolitan measures of sprawl. Song and Knaap (2004) derived a set of neighbourhood-scale sprawl measures adapted from a planning support software system called INDEX, developed by Allen *et al*. Song and Knaap operationalized five measures of urban form, including: *street design and circulation systems*; *density*; *land use mix*; *accessibility*; and *pedestrian access* for 186 neighbourhoods in metro-Portland, Oregon. Utilizing census blocks as a proxy for neighbourhoods, Song and Knaap focused on two neighbourhoods, one that embodied the characteristics of new urbanism (the so-called 'smart growth') and the other that represented Portland's average suburban tract. Song and Knaap also conducted a correlation analysis of their measures, by the median age of neighbourhood housing stock, to establish the change in sprawling characteristics of Portland over time.

At the submetropolitan level, the problematic characteristics of sprawl can be more systematically identified and measured than at the metropolitan level. Hasse (2004) created a set of 12 geospatial indices of urban sprawl (GIUS), designed specifically to provide information about what characteristics are considered problematic or dysfunctional for an individual development (Table 6.2). The GIUS measurements were utilized to evaluate and compare three recently constructed housing tracts within a county on the rural/urban fringe of New Jersey. The GIUS metrics are micro-measures of sprawl that provide quantitative information for individual development tracts for three categories of characteristics: (a) *land-use patterns*; (b) *transportation patterns*; and (c) *environmental impact patterns*. The GIUS metrics employ various GIS-based spatial measurements of landscape parameters identifiable in land use, road networks and various environmental mapping sources. Six of the GIUS measures are provided in schematic form for two scenarios of a fictitious town; one scenario with sprawl and the second scenario with smart growth (Table 6.2).

Table 6.2 Twelve tract-level GIUS measure of sprawl

Measure	Description	Calculation
1. Density	Measures the intensity of land utilization for a given tract	Areal size of tract divided by number of housing units within tract
2. Leap-frog (Figure 6.2a)	Measures the degree to which new tracts skip over vacant parcels adjacent to previous settlement	Straight line distance from new tract to previous settlement
3. Segregated land use	Measures the degree to which new tracts are mixed with other categories of urban land use	Count the number of different categories of urban land use within a 1500 ft buffer (i.e. 10 minute walk) to new tract
4. Regional planning inconsistency (Figure 6.2b)	Indicates whether a new tract is inconsistent with regional and state plans	Tract is assigned a weighted value dependent on its location within a regional plan
5. Highway strip (Figure 6.2c)	Indicates whether a new tract is situated in strips fronting along rural highways	Tract is overlaid with a 500 ft buffer of rural highways
6. Road infrastructure inefficiency	Measures the inefficiency of road infrastructure by measuring road length, number of intersections and cul-de-sacs of new development tracts	Length of road, number of intersections and number of cul-de-sacs are summed by tract and divided by the number of units within the tract
7. Transit inaccessibility	Measures the degree to which non-auto modes of travel are accessible to new tracts	Calculates road distance from tract to pedestrian/bicycle routes and public transportation stops
8. Community node inaccessibility (Figure 6.2d)	Measures how scattered a new tract is from important community centres such as schools, libraries, fire/rescue, police, recreational facilities, etc.	Calculates road distance from tract to a set of nearest community nodes
9. Consumption of important land resources (Figure 6.2e)	Measures the degree to which new tracts consume important agricultural and natural land resources	Calculates the area of prime farmland, core forest habitat and wetlands displaced by tract and divides by the number of units

10. Sensitive open space encroachment	Measures the proximity of new tract to sensitive open space, including documented threatened/endangered wildlife habitat and preserved farmland	Calculates the distance of tract to nearest wildlife habitat and preserved farm parcels
11. Impervious surface coverage (Figure 6.2f)	Measures the amount of impervious surface imposed from a given tract	Calculates the total area of impervious coverage of a tract and divides by the number of units within the tract
12. Growth trajectory	Measures the pace of growth in terms of new development and locality size and remaining available land	Calculates the percentage of urban spatial increase in terms of: (a) previous urban extent; (b) municipal size; (c) remaining available land

Adapted from Hasse (2002).

The GIUS measures were operationalized for Hunterdon County, New Jersey, for all housing tracts constructed county-wide between 1986 and 1995 (Hasse, 2004). To demonstrate the functionality of the GIUS measures, three development tracts were selected that epitomized the most sprawling, average and smartest-growing development that occurred, as measured by the GIUS metric (Figures 6.3a–c). The study established that many of the spatial characteristics of sprawl can be

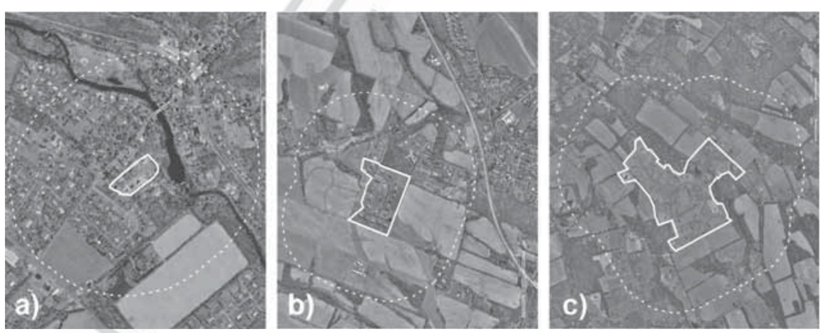

Figure 6.3 Selected development tracts for demonstrating GIUS. These three tracts of suburban development were selected from a countywide GIUS analysis of new development. The tracts have been named for the municipality in which they were located: (a) Califon; (b) Readington; and (c) Alexandria. Each tract is delineated by a solid white line and a dashed 1500 ft pedestrian accessibility buffer. Reproduced with permission of the University of Wisconsin Press from Hasse (2004)

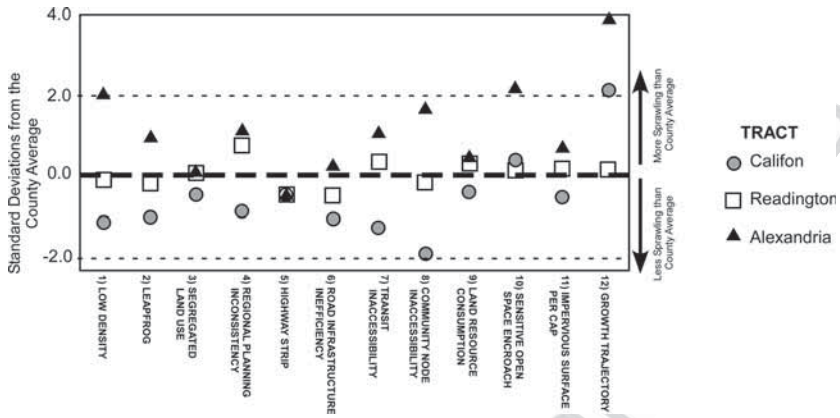

Figure 6.4 Normalized GIUS measures for three selected tracts. This graph depicts the value of each GIUS metric in standard deviations from the county average. While the three selected tracts effectively demonstrate lower than average, average and higher than average sprawl values in the county for most of the variables, the measure are not highly redundant. Many other development tracts within the county had a broad mixture of values. From Hasse (2002)

meaningfully quantified and compared at the micro-level of individual housing tracts (Figure 6.4).

6.3 Integrating remote sensing and GIS for sprawl research

While Hasse's GIUS sprawl indices (2004) are primarily spatial-based measurements and therefore might be placed within the GIS- based camp of sprawl analysis, many of the data utilized by Hasse were originally derived from remote sensing-based data sources, such as digital orthophotography, making this work a substantial integration of remote sensing and GIS. Many of the GIUS measures could be adapted to other platforms of remote sensing- and raster-based analysis.

A number of other recent works in sprawl research rely more substantially on combining both GIS and remote sensing technologies and techniques. Analytical approaches that integrate remote sensing and GIS technologies are able to provide a more robust and sophisticated line of attack than either technology can provide in isolation. Software advances are facilitating the ease with which researchers are able to integrate vector-based GIS, raster-based GIS and remote sensing techniques. There are substantial benefits to integrating the physical land use/land cover information provided by remotely sensed data and the growing body of socio-economic and infrastructure information available for GIS.

The most basic category of GIS integration with remote sensing is land use mapping derived from remotely sensed sources. For example, a number of sprawl-related studies conducted in New Jersey (Hasse and Lathrop, 2001, 2003a; MacDonald and Rudel, 2004) utilize the state's highly detailed digital land use/land cover database, which was delineated statewide from on-screen digitizing of digital orthophotography (Thornton *et al*., 2001). While the analysis relied heavily on vector-based GIS techniques to measure temporal landscape changes, the data layers required for the calculations included *land use/land cover*, *impervious surface*, *fresh water wetlands*, and *prime farm soils*. Each of these data layers used remotely sensed imagery as its primary source.

Some approaches to sprawl research have utilized a primarily remote sensing approach augmented by various ancillary GIS data or GIS spatial methodology. For example, Yeh and Li (1998, 2001) used remotely sensed data to measure and monitor the degree of urban sprawl for cities and towns in China, using an entropy measure of dispersal along roads. Sudhira *et al*. (2004) integrated IRS 1C and LISS multispectral imagery with Survey of India (SOI) topo-sheets to develop temporal metrics of sprawl in Karnataka, India. While these studies are somewhat ambiguous in making a clear distinction between specific characteristics of sprawl and urban growth in general, they demonstrate the utility of augmenting large-scale remote sensing platforms with ancillary GIS data, such as overlaying vector-based roads with digital imagery to better evaluate urban processes related to sprawl.

A more sophisticated analysis of sprawl, utilizing the European CORINE land cover dataset, which was compiled from multiple satellite imagery and ancillary GIS sources, was conducted for 15 cities within Europe (Kasanko *et al*., 2005). Five indicator sets were developed to shed light on whether European cities were experiencing a dispersion of population density, by examining *residential land use*, *land taken by urban expansion*, *population density* and *urban density*. The team found that European cities were becoming more dispersed in general but that there were also significant differences in the densities of growth between southern, eastern and north-western cities.

One of the problematic characteristics of sprawl is the wasteful consumption of important natural resources. Sprawling development patterns impose a large ecological footprint by moving a relatively small number of residences into large-lot housing. The integration of remote sensing and GIS can facilitate the study of natural resource impacts attributable to sprawl. Hasse and Lathrop (2003a) developed a set of 'land resource impact' (LRI) indicators that measured the per capita population impact of sprawling urbanization on five specific critical land resources, including: (a) *urban density* (i.e. efficiency of land utilization); (b) *prime farmland loss*; (c) *core forest habitat loss*; (d) *natural wetlands loss*; and (e) *impervious surface cover gain*. By integrating demographic census data with landscape change data, the authors were able to demonstrate impacts on a per-capita basis, in order to illustrate that sprawling development patterns consume more resources for each person provided with housing than do smart growth patterns. The five measures were calculated

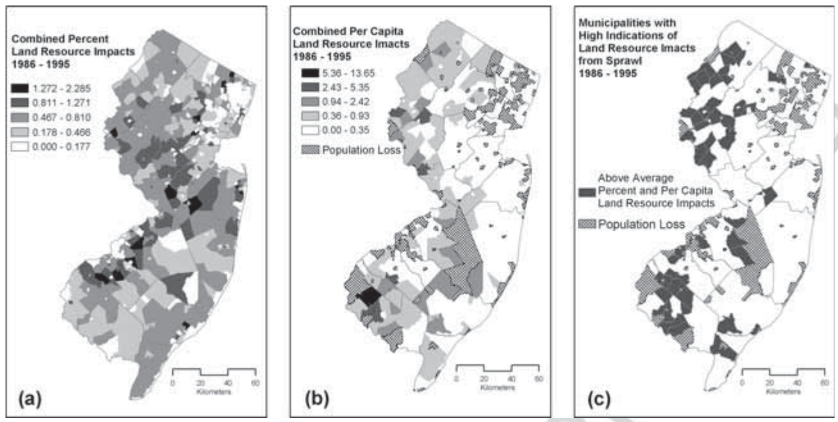

Figure 6.5 Land resource impact indicators of sprawl in New Jersey. Sprawl consumes significant quantities of important land resources including: prime farmland, forest core habitat, and freshwater wetlands. These maps depict the municipalities that: (a) lost the greatest percentage of these resources; (b) lost the greatest amounts of the resource per person added to the population; and (c) have both high percentage and per capita loss. Reproduced with permission from Hasse and Lathrop (2003b). ©Elsevier (2003)

on an individual municipal basis and then combined into an index that provides an overall indication of the municipalities in which sprawl is having the greatest impact on critical land resources (Figure 6.5). The data utilized for this analysis were derived from remotely-sensed sources, such as orthophotography for the land use/land cover and wetlands delineation (Thorton *et al*., 2001). The prime farm-soils soil maps were generated by the US Natural Resources Conservation Service on a county basis, and originally derived from aerial photography, geological maps and in-field samples. Lathrop (2004) updated the statewide analysis by incorporating new development polygons screen-digitized from SPOT imagery.

The approach to sprawl that focuses on the physical environment also includes a substantial literature of ecology-based studies that often employ remote sensing techniques to characterize the degree of urban intensity within a landscape ecology context (Jensen *et al*., 2004; Forys and Allen, 2005; MacDonald and Rudel, 2005; Theobald, 2004). The FRAGSTATS software package (McGarigal and Marks, 1995), widely used to generate landscape-based metrics for landscape ecology (Gustafson, 1998), is now being applied to urban analysis. Herold *et al*. (2005) explored a framework for combining remote sensing with these landscape ecology metrics in order to improve the analysis and modelling of urban growth and land use change. The authors demonstrated through a pilot study of the Santa Barbara, California, coastal area that the combination of remote sensing GIS-based spatial metrics can contribute an important new level of information to urban modelling and urban dynamic analysis. This line of landscape-scale (i.e. tract-level or patchlevel) GIS-remote sensing integration for urban analysis holds great potential for moving beyond some of the past limitations of modelling urban dynamic process and specifically urban sprawl.

Meaningful integration of remote sensing data with spatial metrics for measuring sprawl is also beginning to occur in some of the urban planning and geography literature. The previously discussed work of Galster *et al*. (2001; Figure 6.1) broke new ground in developing sprawl spatial measurements by converting census-based GIS data into a grid. The Galster study developed a number of spatial metrics with some similarities to landscape ecology metrics by creating half-mile and 1-mile grids of the census data polygons. Wolman *et al*. (2005) argued that the methodology of Galster *et al*. (2001) was limited in several respects, including its inability to compensate for land that was impossible to develop when calculating various density measurements. Wolman improved on Galster *et al*.'s methods by integrating land use data from the US Geological Survey's (USGS) National Land Cover Database (NLCDB). The NLCDB is a nationwide land-use map derived from remotely sensed satellite imagery at 30 m resolution. Wolman's integration of land cover data demonstrably changed Galster *et al*.'s density measures from as little as 2.6 to as much as 27.1 for selected metropolitan areas, although very little change in rank occurred from Galster *et al*.'s original study. The integration of remote sensing for updating land use/land cover information in sprawl analysis will continue to mature as sprawl metrics are refined and the ease with which timely ground data can be added to the analysis improves.

One of the problems interfering with a more substantial use of geospatial technologies (especially remote sensing) within urban research is that many of the metrics and analyses thus far developed have had a poor relationship to urban spatial theory and/or application in policy making. The development of sprawl measurements that can take advantage of the benefits of integrating remote sensing and GIS needs to be applicable to planners in the trenches. One of the places in which there is great potential for geospatial science, landscape metrics and planning and policy to mutually enhance one another is the topic of sprawl. Developing better digital representations of the urban process requires exploration of the urban process at its most fundamental scale.

6.4 Spatial characteristics of sprawl at a building-unit level

One area of research that holds promise for advancing urban analysis and urban sprawl also opens new avenues for integrating remote sensing with GIS. By breaking down urban processes to the most fundamental units, the basic building blocks of urban organization can be reproduced within a digital environment. 'Urban atomization' entails rethinking how to represent and model the urban phenomenon within a GIS at the most fundamental urban unit. Typically, urban social analysis has tended to occur within a vector GIS digital environment, while environmental/landscape analysis has tended to utilize raster-based approaches. While each method has its advantages and disadvantages for modelling landscape structure, there are nevertheless still many limitations with both raster and vector analytical approaches related to issues of scale, temporal change, data conversion and ecological fallacy/modifiable areal unit problem (MAUP) Openshaw 1984a, 1984b) among many others. It can be awkward at best to represent many aspects of urban processes in either a solely-raster or solely-vector data platform. In order to move beyond these limitations, it may be advantageous to represent urban phenomena by reducing urban structure down to the smallest basic elements.

Instead of trying to fit the urban process into raster cells or polygons, researchers are asking how to best model the fundamental components of the urban process within state-of-the-art geospatial digital environments. Considering that the urbanization process consists of the nexus between the physical built environment and social processes, a robust GIS urban modelling environment should be built upon the most basic fundamental unit or smallest elements by which the urbanization process functions. Demographic data are often available to researchers at the metropolitan, neighbourhood, census block and zip code level, making these spatial units logical choices for analysis of sprawl thus far highlighted throughout this chapter. In contrast, the social units by which demographic data are collected through surveys and censuses are often the individual person living within the city, the family and the household, but these data are protected from public disclosure due to issues of privacy. The urban process is complex and dynamic and consists of a combination of the physical urban structure and the social structure of the people living in and using the city. Since individuals, families and households are highly transitory, it can be argued that *building units* emerge as the logical fundamental or smallest solid 'atom' of urban spatial structure.

By modelling urban spatial structure as elemental building units that exist at a particular time and location in space, building units become the 'urban atoms' of a data structure that can then be organized and combined into a nested hierarchy of functional entities at the appropriate scale for the phenomenon of interest. To use a biological analogy, building units can be viewed as the most basic *cells* of urban structure. Neighbourhoods can be conceptualized as logical groupings of building unit cells into discrete functional areas or the 'organs' of the urban organism. Neighbourhoods linked together through transportation and infrastructure networks become the functional urban systems. The city itself combines the various neighbourhoods and systems into the complete functioning (or sometimes dysfunctioning) urban organism.

New GIS data structures, such as the ESRI Geodatabase, hold potential for innovative nested hierarchal approaches to urban geospatial data modelling. Individual components of the atomic urban data model can be modular and object-orientated, so that each building unit can 'know' its own location, statistical summaries of the people living/employed in the building, the land area occupied and the building floor area, available social and health-related data, etc. Object-orientated building units could also contain information about their own date of creation and thus be incorporated into temporal modelling of urbanization. Urban data structure could become hierarchical, meaning that, depending on the scale of interests, building units could be represented as points, polygons or triangular irregular networks (TINs), and multiple units could be grouped into regions to represent a neighbourhood or interpolated into a surface to visualize particular variables, etc. Atomic urban data structure will also facilitate new approaches to integrating remote sensing data with object-orientated GIS data, substantially advancing all branches of urban analysis, including sprawl.

Work is just beginning on an urban atomization approach that integrates remote sensing with building unit locations. Mesev (2005) is exploring the use of postal points, which are GPS building location points generated by the Ordnance Survey of Great Britain that map the building centroid of commercial or residential buildings with postal delivery. This dataset is updated four times a year and provides a highly accurate spatial inventory of building units. Mesev integrates these postal points with IKONOS imagery to examine spatial patterns of residential neighbourhoods and commercial areas. Groups of these points were used to characterize the spacing and arrangement of residential and commercial buildings, using nearest-neighbour and linear nearest-neighbour indices. Although the pilot analysis explored only two UK cities for two relatively non-complex variables, including *density* (compactness vs. sparseness) and *linearity*, Mesev argues that multiple avenues of research can emerge, such as automated pattern recognition through building unit integration with remote sensing imagery.

6.5 A practical building-unit level model for analysing sprawl

Hasse and Lathrop (2003b) utilized an urban atomization approach to evaluate several characteristics of sprawl by measuring sprawl characteristics for individual housing units. Hasse and Lathrop contended that a housing-unit approach to measuring sprawl is the most meaningful because each house can have a different performance of sprawl and smart growth. By generating measures at the atomic (housing-unit) level, Hasse and Lathrop were able to rescale the data up to any geography of interest, such as a housing tract, census block or municipality. This effectively solved a number of rescaling and overlay issues and limitations. Hasse and Lathrop's method for locating each housing unit was accomplished by intersecting remote sensing-derived urban land use/land cover classified regions with digital parcel maps and generating centroids for the resulting polygons (Figure 6.6). This technique is particularly necessary in rural areas, where housing

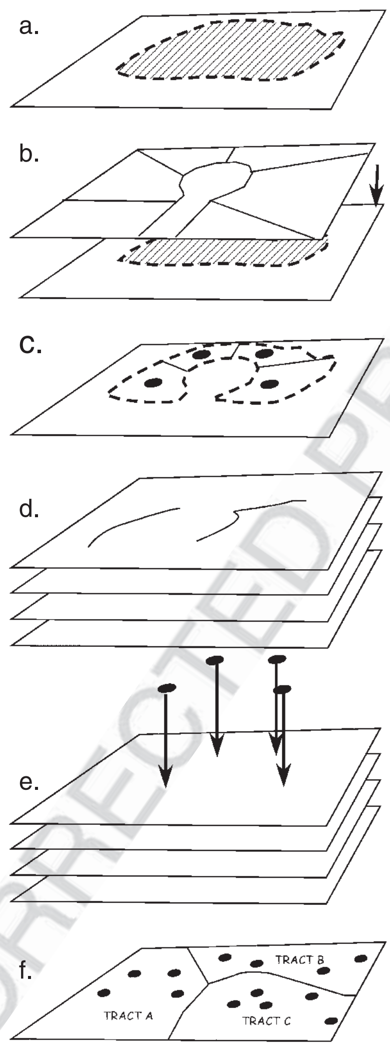

Figure 6.6 Delineation of housing unit locations through the integration of GIS and remote sensing. Household locations are delineated as vector point locations through a multi-step process: (a) delineation of new urbanization (image classification or heads-up digitizing); (b) intersection of new development patches with digital parcel map; (c) polygon centroids estimate location of new housing unit; (d) generation of various sprawl parameters, e.g. density, leapfrog, segregated land use, highway strip, and community node inaccessibility; (e) assignment of various sprawl parameters to housing unit point theme; (f) summary of individual housing unit metric values by regions of interest, such as census tracts or municipalities

unit locations are unlikely to be aligned with the tax parcel's physical centroid. The resulting point dataset is an accurate estimate of each housing unit location (Figure 6.7).

Although most of the 12 GIUS measures developed on a tract-level can be applied to the housing-unit scale, five measures are described here in detail,

Figure 6.7 Housing unit location automation. This image depicts an orthophoto of one newly developed housing tract. The thick lines delineate the 'patches' of new urban growth as classified by the land use/land cover dataset. The thin lies delineate the property parcel lines. The target symbol denotes the automated centroid location estimated for each new housing unit. Sprawl measurements are calculated for each housing unit centroid

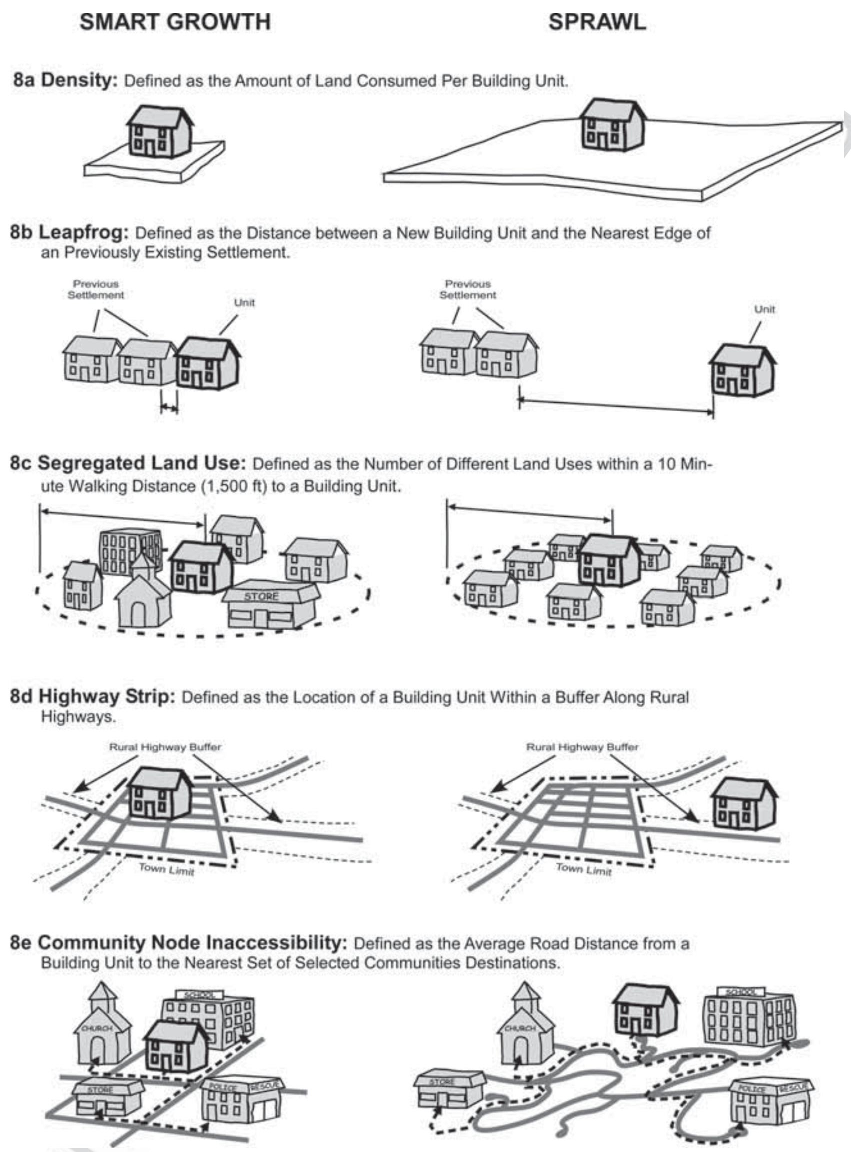

Figure 6.8 Conceptual diagrams for housing unit sprawl measures. Sprawl measurements are conducted for individual housing units for selected characteristics, including: (a) density; (b) leapfrog; (c) segregated land use; (d) highway strip; and (e) community node inaccessibility. Other sprawl characteristics are also measurable at the housing-unit level, which facilitates scaling to any geography of interest

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including: *density*, *leapfrog*, *segregated land use*, *community node inaccessibility* and *highway strip*, The calculations are made using various GIS techniques and the corresponding values are assigned to each new housing unit for the set of five selected metrics. The data are then scaled-up to municipality by summarizing the housing points within each municipal boundary, in order to provide a 'sprawl report card' for recent growth for each locality. The following section details the Hasse and Lathrop housing unit level methodology (from Hasse and Lathrop, 2003b).

6.5.1 Urban density

The urban density indicator provides a measure of the amount of land area occupied by each housing unit (Figure 6.7a). The municipal urban density (UD_{mun}) was calculated by summing the land areas for each new housing unit and dividing that sum by the total number of units within each municipality, as depicted in equation 6.1. Lower density indicates a sprawling signature for the density measure.

$$UD_{mun} = \frac{\sum DA_{unit}}{\sum N_{unit}} \tag{6.1}$$

where:
UD_{mun} = urban density index for new urban growth within a municipality,
DA_{unit} = developed area of each unit, and N_{unit} = number of new residential units.

6.5.2 Leapfrog

Tracts of urban growth that occur at a significant distance from previously existing settlements are considered 'leapfrog' (Figure 6.7b). The leapfrog indicator was calculated by measuring the distance from the location of each new housing unit (at time 2) to previously settled areas (at time 1). The previous settlements were delineated as tracts of urban land use existing in time 1 that corresponded to designated place names on USGS quadrangle maps or existing tracts larger than 50 acres (20.23 hectares). This process filtered out smaller non-named tracts of time 1 urban areas that had already leapfrogged from settled areas. A straight-line distance grid was generated from these 'previously settled' tracts and the grid value was assigned to each new housing unit. The housing-unit leapfrog value was then scaled to the municipal leapfrog index (LF_{mun}) by summarizing the leapfrog field value of the housing-unit point layer by municipality, as depicted in equation 6.2. New growth that occurs at large leapfrog distances is considered sprawling.

$$LF_{mun} = \frac{\sum Dlf_{unit}}{\sum N_{unit}} \tag{6.2}$$

where LF_{mun} = leapfrog index for new urban tracts within a municipality, Dlf_{unit} = leapfrog distance for each new unit, and N_{unit} = number of new residential units.

6.5.3 Segregated land use

Segregated land use consists of large tracts of similar land use that requires use of the automobile for basic daily destinations (Figure 6.7c). Since mixed land use areas may look segregated at a micro-level, the definition of segregated land use employed here is building units that are located beyond reasonable walking distance to multiple other types of urban land uses. In order to accomplish this, the mix of land use is examined within a 1500 ft (457.2 m) pedestrian distance (the typical distance a pedestrian will walk in 10 minutes; Nelessen, 1995). Housing units within walking distance to multiple other types of urban land uses are considered *mixed*, while housing units with only other housing within the pedestrian distance are considered *segregated*.

The segregated land use metric was calculated by converting the vector-based 'urban' land use/land cover data layer to a grid. The dataset included 18 different classes of *urban* land use, some of which were recoded to better reflect the segregated land use analysis. A *neighbourhood variety* calculation was performed on the gridded urban land use, utilizing a radius of 1500 ft (457.2 m) to represent the pedestrian distance. This produced a grid surface where every cell was enumerated according to the variety or mixture of different urban land use categories within the search radius.

Since the other sprawl indicator measures produce output in which higher values indicate higher sprawl, the *mixed land use* surface grid was inverted to a *segregated land use* value, where higher numerical values represent a greater indication of the non-mixed (i.e. segregated) characteristic associated with sprawl. This was accomplished by subtracting the mixed-use grid from a constant grid with a value equal to 1 plus the most mixed grid cell occurrence (in the pilot study the maximum mixed land use occurrence was 7). The value of the segregated land use grid for a 1500 ft radius was then assigned to each housing unit point. The municipal-level segregated land use index (SL_{mun}) was calculated by averaging the segregated land use value of each new housing unit by municipality, as depicted in equation 6.3. New building units that have a higher segregated land use value are considered sprawling for this measure.

$$SL_{mun} = \frac{\sum Seg_{unit}}{\sum N_{unit}} \tag{6.3}$$

where SL_{mun} = segregated land use indicator by municipality, $Seg_{unit} = \mathbf{X}$ – number of different developed land uses with 1500 feet (457.2 m), $\mathbf{X} = 1$ plus the maximum land use mix in a given dataset (note: the baseline land use mix will vary by dataset), and $N_{\text{unit}} =$ number of new residential units.

6.5.4 Highway strip

The highway strip development component of sprawl is usually typified by fast food restaurants and retail strip malls, but can also include single-family housing units lining rural highways (Figure 6.7d). However, this analysis focuses only on residential growth. As developed, the highway strip index is a binary measure. Residential units are designated highway strip if they occur along rural highways outside of town centres and the associated urban growth boundaries. New housing units within the delineated rural highway buffer are considered sprawling for this measure.

For this study, the highways were delineated from the dataset as all non-local roads (i.e. county-level highway or greater) outside of designated centres of the New Jersey State Plan. The buffer was set at 300 ft (100 m), a common depth for a 1 acre (0.405 ha) housing lot. Housing units that fell within the buffer were coded to 1 and units outside the buffer were coded to 0. The municipal level highway strip index (HS_{mun}) was calculated by summing the number of new residential units that occurred within the highway buffer and Normalizing by the total number of new units that were developed within the entire municipality, as depicted in equation 6.4. This provided, in essence, a probability measure of highway strip occurrence for each municipality. Municipalities that experienced a higher ratio of highway strip development were considered more sprawling for this measure than municipalities with lower ratios.

$$HS_{\text{mun}} = \frac{\sum HB_{\text{unit}}}{\sum N_{\text{unit}}} \tag{6.4}$$

where $HS_{\text{mun}} =$ highway strip indicator by municipality, $HB_{\text{unit}} =$ residential unit within the 300 ft highway buffer, and $N_{\text{unit}} =$ number of new residential units.

6.5.5 Community node inaccessibility

The community node inaccessibility index measures the average distance of new housing units to a set of nearest community nodes (Figure 6.7e). The centres chosen in this analysis included schools, libraries, post offices, municipal halls, fire and ambulance buildings and grocery stores. The centres were chosen to reflect likely destinations for any residents within a community, as well as the availability of data for centre locations. The set of community nodes is intended to be an index, not an exhaustive set of destinations. It is argued that these selected destinations are reasonable proxy for destinations overall and thus provide valuable insight into the accessibility, as measured by road distance from each housing unit. Each selected community destination (i.e. node) was identified in the county-wide digital parcel map, utilizing the owner information as well as interpretation of digital orthophotos and hard-copy county maps.

New housing units were analysed for their road network distance to the community nodes, utilizing a cost/distance calculation over a gridded roads and urban mask. Road network distances were generated for each individual selected community node type to all housing units. The individual community node distance values were averaged into a single community node distance value. The municipal-level community node inaccessibility index (CNI_{mun}) was calculated by summarizing the new housing unit community node distance values by municipality as depicted in equation 6.5. Sprawling land use patterns have significantly higher average road distance between new units and the set of selected community nodes.

$$CNI_{\text{mun}} = \frac{\sum \overline{Dcn}_{\text{unit}}}{\sum N_{\text{unit}}} \tag{6.5}$$

where CNI_{mun} = community node inaccessibility index by municipality, $\overline{Dcn}_{\text{unit}}$ = average distance of new residential unit to the set of community nodes, and N_{unit} = number of new residential units.

6.5.6 Normalizing municipal sprawl indicator measures

Each of the five individual sprawl metrics highlighted here reflects a particular geospatial characteristic of urban growth and provides useful analytical information. However, the measures are not standardized, but reflect an appropriate measurement unit for each particular trait. For example, some measurements such as *leapfrog* are linear distances, some such as *density* are areal measures and yet others such as *segregated land use* are in numbers of land uses. The diversity and range between these measurement units precludes direct comparison between metrics. Normalization of the measures through percentile rank, however, results in index values that can be cross-compared. Once the individual sprawl measures were normalized to percentage ranks, they were summed together to produce a single cumulative summary measure of sprawl, or what Hasse and Lathrop characterize as a *meta-sprawl indicator* for each municipality. Housing unit-level calculations facilitate a new approach for rescaling data. While the authors demonstrate rescaling to the municipal level (an appropriate scale due to local zoning control in New Jersey), summary sprawl measures could be calculated for any geographical extent of interest by summarizing the individual housing units by any desired geographical unit, such as census tract, county or metropolitan area.

This case study demonstrates that the development of a housing unit-level urban database promises to provide a more robust means of analysing urban form for characteristics of sprawl and smart growth than previous urban data models. However, the development of such building unit-level databases for extensive spatial areas is challenging. Most of the socio-economic data that is available for analysis is aggregated to larger geographic areas, such as a census block, commuter zone or zip code. Digital parcel maps still do not exist for many areas. Furthermore, identifying the location of individual housing units on a metropolitan scale is a formidable task, resulting in large databases of potentially hundreds of thousands of records. Techniques of data compression, indexing and random sampling of housing-unit data may need to be developed in order to make the data more manageable for larger spatial scales.

Nonetheless, the potential advantages of analysing urban form at its atomic level warrant the effort of developing building-unit based urban geospatial databases. An urban atomic database model also has the potential for innovative integration of remote sensing. Integration can be potentially facilitated in data development, data enhancement and data updating. For example, in data development, building-unit point location may be accomplished through integrating remote sensing imagery with automated address matching of a regional telephone directory. Points could be generated by the GIS address-matching geo-location algorithm and then adjusted for increased spatial accuracy by an automated remote sensing image recognition system. Traditionally, GIS data have been utilized as ancillary data within a remote sensing environment, such as overlaying roads and census tracts to enhance classification accuracies. The urban atomization model turns this relationship around, where the point location is enhanced by remotely sensed data as ancillary information. The possibilities for integrating remote sensing with GIS through an urban atomization approach extend well beyond the analysis of sprawl. Nonetheless, urban atomization for sprawl analysis, in particular, holds significant potential for advancing the delineation, characterization and analysis of the phenomenon of sprawl at the elemental scale at which it occurs, one house at a time.

6.6 Future benefits of integrating remote sensing and GIS in sprawl research

The interest in sprawl from many stakeholders and agencies will continue to grow, due to the broad implications that continued patterns of sprawl will have for ecology, society, economics and politics. While there has been substantial advancement in the identification, characterization and analysis of sprawl over the past several decades, the research is still arguably in an early stage. This chapter has highlighted some of the ways in which the geospatial technologies of remote sensing and GIS are being utilized to study the phenomenon of sprawl on multiple levels, from the metropolitan level down to the building-unit level. The integration of remote sensing and GIS is both advancing and being advanced through this sprawl research.

The building unit-level analysis as highlighted in the second half of this chapter holds particular promise for benefiting from the joining of GIS and remote sensing, because it allows for new avenues of integration between the physical land cover information that remote sensing imagery can provide and the socio-economic information that is more readily available for GIS. A building unit-level integration of GIS and remote sensing is not only of interest from an academic perspective but also from a policy perspective, because it performs at a level that can provide meaningful information to the stakeholders of the urbanization process.

Ultimately, this is where geospatial research can make its greatest contribution to the understanding and management of sprawl. The integration of remote sensing and GIS can assist in developing sprawl analytical methods that are employable to academics, policy makers and multiple other stakeholders. By integrating the two platforms, the combined strengths of each can overcome a number of limitations of utilizing remote sensing or GIS separately. Integration will lead to progress in urban research in areas such as image recognition, object-orientated urban feature modelling and near-real-time land data updating. Furthermore, this research can lead to development of a better urban typological system that objectively and justifiably characterizes urbanization patterns into appropriate categories, based on specific goals of public interest, such as land use efficiency, transportation, water quality and environmental health.

Considering growing population pressures, the continuing pace of urbanization and the impacts associated with modern patterns of sprawl, the need to study sprawl will continue for the foreseeable future. The integration of remote sensing technologies and GIS will play a significant role in advancing the understanding of the phenomenon of sprawl, while hopefully providing the tools for steering urbanization towards less problematic forms.

References

Allen, E. (2001) INDEX: Software for community indicators. In *Planning Support Systems: Integrating Geographic Information Systems, Models, and Visualization Tools*. ESRI Press: Redlands, CA, USA.

Burchell, R. and Naveed, S. (1999) The evolution of the sprawl debate in the United States. *West. Northwest* **5**, 137–160.

Burchell R. W., Shad, N. A., Listokin, D., Phillips, H., Seskin, S., Davis, J. S., Moore, T., Helton, D. and Gall, M. (1998) *The Costs of Sprawl – Revisited*. Transportation Research Board Report No. 39. National Academy Press: Washington, DC, USA.

Civco, D. L., Hurd, J. D., Wilson, E. H., Song, M. and Zhang, Z. (2002) A Comparison of land use and land cover change detection methods. ASPRS–ACSM Annual Conference and FIG XX11 Congress, Washington, DC, USA; 22–26.

Cova, T. J., Sutton, P. and Theobald, D. M. (2004) Exurban change detection in fire-prone areas with nighttime satellite imagery. *Photogrammetric Engineering and Remote Sensing* **70**, 1249–1257.

El Nassar, H. and Overberg, P. (2001) What you don't know about sprawl. *USA Today* 22 February, 1A, 6A-9A.

Epstein, J., Payne, K. and Kramer, E. (2002) Techniques for mapping suburban sprawl. *Photogrammetric Engineering and Remote Sensing* **68**, 913–918.

Ewing, R. (1997) Is Los Angeles-style sprawl desirable? *Journal of the American Planning Association* **63**, 107–126.

Ewing, R., Pendall, R. and Chen, D. (2002) *Measuring Sprawl and Its Impact.* Smart Growth America: Washington, DC, USA.

Forys, E. and Allen, C. R. (2005) The impacts of sprawl on biodiversity: the ant fauna of the lower Florida Keys. *Ecology and Society* **10**(1): 25 [online]: http://www. ecologyand-society.org/vol10/iss1/art25/

Fulton, W., Nguyen, M. and Harrison, A. (2001) *Who Sprawls Most: How Growth Patterns Differ Across the United States*. Centre on Urban and Metropolitan Policy, The Brookings Institute: Washington, DC, USA.

Galster, G., Hanlon, R., Wolman, H., Colman, S. and Freihage, J. (2001) Wrestling sprawl to the ground: defining and measuring an elusive concept. *Housing Policy Debate* **12**, 681–717.

Gustafson, E. J. (1998) Quantifying landscape spatial patterns: what is the state of the art? *Ecosystems* **1**, 143–156.

Hasse, J. E. (2002) Geospatial Indices of Urban Sprawl in New Jersey. Doctoral Dissertation, Rutgers University, New Brunswick, NJ, USA; 224 pp.

Hasse, J. E. (2004) A geospatial approach to measuring new development tracts for characteristics of sprawl. *Landscape Journal: Design, Planning and Management of the Land* **23**, 1–4.

Hasse, J. E. and Lathrop, R. G. (2003a) A housing unit-level approach to characterizing residential sprawl. *Photogrammetric Engineering and Remote Sensing* **69**, 1021–1029.

Hasse, J. E. and Lathrop, R. G. (2003b) Land resource impact indicators of urban sprawl. *Applied Geography* **23**, 159–175.

Hasse, J. E. and Lathrop, R. G. (2001) *Measuring Urban Growth in New Jersey*. Centre for Remote Sensing and Spatial Analysis, Rutgers University, New Brunswick, NJ [online]: http://www.crssa.rutgers.edu/projects/lc/urbangrowth/nj_urban_growth.pdf

Herold, M., Couclelis, H. and Clarke, K. C. (2005) The role of spatial metrics in the analysis and modelling of urban land use change. *Computers, Environment and Urban Systems* **29**, 369–399.

Hess, George R., Daley, Salinda S., Dennison, Becky K., Lubkin, Sharon R., McGuinn, Robert P., Morin, V. Z., Potter, K. M., Savage, R. E., Shelton, W. G., Snow C. M. and Wrege, B. M. (2001) Just what is sprawl, anyway? *Carolina Planning:a Journal of the University of North Carolina Department of City and Regional Planning* **26**, 11–26.

Hurd, J. D., Wilson E. H., Lammery S. G., and Civco, D. L. (2001) Characterization of forest fragmentation and urban sprawl using time sequential Landsat imagery. Proceedings of the ASPRS Annual Convention, St. Louis, MO, USA.

Jensen, R., Gatrell, J., Boulton, J., Harper, B. (2004) Using remote sensing and geographic information systems to study urban quality of life and urban forest amenities. *Ecology and Society* **9**(5): 5 [online]: http://www.ecologyandsociety.org/vol9/iss5/art5/

Johnson, M. P. (2001) Environmental impacts of urban sprawl: a survey of the literature and proposed research agenda. *Environment and Planning A* **33**, 717–735.

Kasanko, M., Barredo, J. I., Lavalle, C., McCormick, N., Demicheli, L., Sagris, V. and Brezger, A. (2006) Are European cities becoming dispersed? A comparative analysis of 15 European urban areas. *Landscape and Urban Planning* **77**(1–2), 111–130.

Lathrop, R. G. (2004) Measuring land use change in New Jersey: land use update to Year 2000. CRSSA Technical Report No. 17–2004–1, Rutgers University, New Brunswick, NJ, USA [online]: http://crssa.rutgers.edu/projects/lc/reports/landuse_upd.pdf

Lopez, R. and Hynes, H. P. (2003) Sprawl in the 1990s: measurement, distribution and trends. *Urban Affairs Review* **38**, 325–355.

MacDonald, K. and Rudel, T. K. (2005) Sprawl and forest cover: what is the relationship? *Applied Geography* **25**, 67–79.

McGarigal, K. and Marks, B. J. (1995) *FRAGSTATS: Spatial Pattern Analysis Program for Quantifying Landscape Structure.* USDA Forest Service General Technical Report No. PNW-GTR-351. US Department of Agriculture: Pacific Northwest Research Station, Portland, OR, USA; 122 pp.

Malpezzi, S. (1999) Estimates of the measurement and determinants of urban sprawl in US metropolitan areas. Unpublished paper, Centre for Urban Land Economics, University of Wisconsin, Madison, WI, USA.

Mesev, V. (2005) Identification and characterization of urban building patterns using IKONOS imagery and point-based postal data. *Computers, Environment and Urban Systems* **29**, 541–557.

Natural Resources Conservation Service (NRCS) (2004) *National Resources Inventory 2002 Annual NRI Land Use*: http://www.nrcs.usda.gov/technical/land/nri02/landuse.pdf

Nelessen, A. C. (1993) *Visions for a New American Dream: Process, Principles, and an Ordinance to Plan and Design Small Communities*. Edwards Brothers: Ann Arbor, MI, USA.

Openshaw, S. (1984a) The modifiable areal unit problem. In *Concepts and Techniques in Modern Geography* 38. GeoBooks: Norwich, UK.

Openshaw, S. (1984b) Ecological fallacies and the analysis of areal census data. *Environment and Planning A* **16**, 17–31.

Song, Y. and Knaap, G-J. (2004a) Measuring urban form: is Portland winning the battle against urban sprawl? *Journal of the American Planning Association* **70**, 210–225.

Sutton, P. C. (2003) A scale-adjusted measure of 'urban sprawl' using nighttime satellite imagery. *Remote Sensing of Environment* **86**, 353–369.

Sudhira, H. S., Ramachandra, T. V. and Jagadish, K. S. (2004) Urban sprawl: metrics, dynamics and modelling using GIS. *International Journal of Applied Earth Observation and Geoinformation* **5**, 29–39.

Theobald, D. (2001) Land use dynamics beyond the American urban fringe. *Geographical Review* **91**, 544–564.

Theobald, D. M. (2004) Placing exurban land use change in a human modification framework. *Frontiers in Ecology and Environment* **2**, 139–144.

Thornton, L., Tyrawski, J., Kaplan, M., Tash, J., Hahn, E. and Cotterman, L. (2001) NJDEP land use land cover update 1986 to 1995, patterns of change. Proceedings of the Twenty-First Annual ESRI International User Conference, San Diego, CA, USA.

Torrens, P. and Alberti, M. (2000) Measuring sprawl. Unpublished paper No 27, Centre for Advanced Spatial Analysis, University College London, London, UK.

US EPA (2005) *Smart Growth: Environmental Protection Agency*: http://www.epa.gov/smartgrowth/index.htm

Weng, Q. (2001) A remote sensing–GIS evaluation of urban expansion and its impact on surface temperature in the Zhujiang Delta, China. *International Journal of Remote Sensing* **22**, 1999–2014.

Wolman, H., Galster, G., Hanson, R., Ratcliffe, M., Furdell, K. and Sarzynski, A. (2005) The fundamental challenge in measuring sprawl: which land should be considered? *The Professional Geographer* **57**, 94–105.

Yeh, A. G. O. and Li, X. (1998) Sustainable land development model for growth areas using GIS. *International Journal of Geographical Information Science* **12**, 169–189.

Yeh, A. G. O. and Li, X. (2001) Measurement and monitoring of urban sprawling: a rapidly growing region using entropy. *Photogrammetric Engineering and Remote Sensing* **67**, 83–90.

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Chapter 06

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