Environment and Planning A 2002, volume 34, pages 1443 – 1458

DOI:10.1068/a3496

The use of remote sensing and landscape metrics to describe structures and changes in urban land uses

Martin Herold, Joseph Scepan, Keith C Clarke
Department of Geography, University of California, Santa Barbara, CA 93106-4060, USA;
e-mail: martin@geog.ucsb.edu, kclarke@geog.ucsb.edu
Received 30 April 2001; in revised form 22 April 2002

Abstract. Remote sensing technology has great potential for acquisition of detailed and accurate land-use information for management and planning of urban regions. However, the determination of land-use data with high geometric and thematic accuracy is generally limited by the availability of adequate remote sensing data, in terms of spatial and temporal resolution, and digital image analysis techniques. This study introduces a methodology using information on image spatial form—landscape metrics—to describe urban land-use structures and land-cover changes that result from urban growth. The analysis is based on spatial analysis of land-cover structures mapped from digitally classified aerial photographs of the urban region Santa Barbara, CA. Landscape metrics were calculated for segmented areas of homogeneous urban land use to allow a further characterization of the land use of these areas. The results show a useful separation and characterization of three urban land-use types: commercial development, high-density residential, and low-density residential. Several important structural land-cover features were identified for this study. These were: the dominant general land cover (built up or vegetation), the housing density, the mean structure and plot size, and the spatial aggregation of built-up areas. For two test areas in the Santa Barbara region, changes (urban growth) in the urban spatial land-use structure can be described and quantified with landscape metrics. In order to discriminate more accurately between the three land-cover types of interest, the landscape metrics were further refined into what are termed 'landscape metric signatures' for the land-use categories. The analysis shows the importance of the spatial measurements as second-order image information that can contribute to more detailed mapping of urban areas and towards a more accurate characterization of spatial urban growth pattern.

1 Introduction

Over 70% of the population in developed countries lives in urbanized areas (Henderson and Xia, 1997). Population growth, regional in-migration, and increasing ecological problems require advanced methods for city planners, economists, ecologists, and resource managers to support sustainable development in these rapidly changing regions. In order to make intelligent decisions, and to take timely and effective action, planners need extensive, comprehensive knowledge about the causes, chronology, and effects of these processes. Recent research has identified a number of different approaches for data acquisition and for land-use characterization and analysis which utilize remote sensing imagery as source data in the derivation of spatial data sets with high temporal and spatial resolution (Hall et al, 1995).

A major problem in urban area remote sensing from space is the heterogeneity of the urban environment. This environment typically consists of built-up structures (for example, buildings, transportation nets), several different vegetation cover types (parks, gardens, agricultural areas), bare soil zones, and water bodies (Barnsley et al, 1993). In order to record accurately this complex spatial assemblage, high spatial sensor resolutions (Welch, 1982) are required. Until the development of the IKONOS satellite (with 1 m panchromatic and 4 m multispectral resolution) such data were not continuously available from civilian space-borne systems. Several studies have demonstrated the high potential of digital remote sensing data as source information specifically useful for analysis of the urban and suburban environment: urban land-use and infrastructure mapping and monitoring (Barnsley et al, 1993; Henderson and Xia, 1997; Jensen and Cowen, 1999; Meaille and Wald, 1990); urban climatic investigations (Kim, 1992; Quattrochi and Ridd, 1994); estimation of socioeconomic information (Henderson and Xia, 1997; Imhoff et al, 1997; Jensen and Cowen, 1999; Sutton et al, 1997).

Traditional visual interpretations of high-resolution air photographs can provide comprehensive information about urban areas. The basis of such analysis is the interpreter's knowledge of spatial arrangements of urban land-cover features (for example, pattern shapes, frequencies) that are used to characterize urban land use (Bowden et al, 1975; Haack et al, 1997). In recent years, most urban land-use studies have employed data from optical remote sensing satellites [including Landsat Thematic Mapper (TM), Systeme Probatoire d'Observation de la Terre (SPOT), Indian Remote Sensing (IRS 1C)] where an effective separation of vegetation, water, and built-up land-cover categories is possible on a purely spectral basis (Ridd, 1995; Sadler et al, 1991). The separation of built-up and bare soil or rock areas as well as the discrimination of urban cover types and land uses (residential, commercial, industrial, and cultural) remains problematic with these data, principally because of the similar spectral response of these portions of the urban land-cover mix (Barnsley et al, 1993; Sadler et al, 1991). The hierarchical US Geological Survey land-use/land-cover classification scheme (Anderson et al, 1976), separates urban and built-up land as one individual class at the first level (level I class) and identifies seven discrete urban land-use classes at the more detailed level II. In general, the level II classes represent a further thematic discrimination of level I classes. Examples for urban Anderson level II classes are residential, commercial, industrial, or transportation. It is not possible to derive urban land use accurately with this type of high thematic resolution using only the spectral response and widely used 'per-pixel' classifiers (Barnsley et al, 1993; Mesev, 1998).

Several different approaches have been developed to improve the thematic accuracy of urban land-use analyses by utilizing additional analysis or data. Baraldi and Parmiggiani (1990), Forster (1993), Gong and Howarth (1990), Gong et al (1992), and Steinnocher (1996) have used structural and textural information from remote sensing data to improve land-use classification accuracies. Ancillary digital information such as census data (Mesev, 1998; Sadler et al, 1991) or residential density data have been integrated in the classification process, but showed only a slight improvement of the classification (Sadler et al, 1991).

Some recent research has been directed toward quantitatively describing the spatial structure of urban environments and characterizing patterns of urban structure through the use of remotely sensed data. A recent approach employing fractal methods to describe urban land-use structures was developed by Batty and Longley (1988). Urban environments are characterized by high structural complexity and fragmentation in contrast to areas of natural vegetation (De Cola, 1989; Lam, 1990). Mesev et al (1995) derived fractal indices of an urban area from remote sensing data utilizing a maximum-likelihood classifier and demonstrated an increased capability to describe the structure and changes in urban morphology. Webster (1995) described "urban morphological fingerprints" from remotely sensed images. These authors also indicated that further research is required in order to apply remote sensing data and fractal or spatial methods better to urban land-use analysis (Batty and Xie, 1996).

In this study we describe a technique to quantify spatial urban patterns from high-resolution optical remote sensing data to describe structures and changes in urban land use. We base this approach on three concepts:

1. Multispectral optical remote sensing allows an accurate separation of diverse urban land-cover types (including built-up areas, vegetation, and water) to derive accurate

thematic land-cover maps. However, residential and commercial urban land-use categories typically cannot be accurately discriminated by applying per-pixel analysis methods.
2. Spatial and textural context is important information for urban area characterization. We utilize landscape metrics as quantitative measures of spatial structures and pattern to describe urban land-use features.
3. The discrimination of inner-city structures requires remote sensing data exhibiting very high spatial resolutions. Such data are quite recently available from new satellite sensor systems. As this study was implemented before such data were publicly available, we undertook development and evaluation of this approach employing digitized aerial color infrared photographs. These images have a spatial resolution on the order of 3 m, similar to currently available data from new space-borne systems.

In this paper, methodological issues and problems are described and discussed in section 2. The image processing used is presented in section 3. This section also includes a description of the Santa Barbara/Goleta, California sites where these techniques were implemented and tested. Results of this study are summarized in section 4.

2 Methodology

2.1 Landscape metrics

Landscape metrics or indices can be defined as quantitative indices to describe structures and pattern of a landscape (McGarigal and Marks, 1994; O'Neill et al, 1988). The development of landscape metrics is based on information-theory measures and fractal geometry. Their use for describing natural and geographic phenomena is described in De Cola and Lam (1993), Mandelbrot (1983), and Xia and Clarke (1997). Important applications of landscape metrics include the detection of landscape pattern, biodiversity, and habitat fragmentation (Gardner et al, 1993; Keitt et al, 1997), the description of changes in landscapes (Dunn et al, 1991; Frohn et al, 1996), and the investigation of scale effects in describing landscape structures (O'Neill et al, 1996; Turner et al, 1989). Related investigations usually focus on the structural analysis of patches, defined as spatially consistent areas with similar thematic features as basic homogeneous entities, in describing or representing a landscape (McGarigal and Marks, 1994).

Based on the work of O'Neill et al (1988), a number of different metrics were developed, modified, and investigated (for example, Li and Reynolds, 1993; McGarigal and Marks, 1994). The most commonly used metrics are the *contagion index* and the *fractal dimension*.

The contagion index describes the fragmentation of a landscape by the random and conditional probabilities that a pixel of patch class i is adjacent to another patch class k:

$$\mathsf{CONTAG} = \left\{1 + \frac{1}{2\ln m}\left[\left(\sum_{i=1}^{m}\sum_{k=1}^{m} p_i \frac{g_i}{\sum_{k=1}^{m} g_{ik}}\right) - \ln p_i \frac{g_{ik}}{\sum_{k=1}^{m} g_{ik}}\right]\right\}100, \qquad (1)$$

where
m is the number of patch types (classes),
p_i is the proportion of the landscape occupied by patch type (class) i,
g_{ik} is the number of adjacencies (joins) between pixels of classes i and k.
The contagion index measures to what extent landscapes are aggregated or clumped (O'Neill et al, 1988). Landscapes consisting of patches of relatively large, less fragmented cover are described by a low contagion index. If a landscape is dominated by a relatively greater number of small or highly fragmented patches, the contagion index is high.

Table 1. Features of the used landscape metrics in Fragstats, after McGarigal and Marks (1994), Li and Reynolds (1993).

Code	Name	Calculation scheme	Type	Units	Range
FRACT	fractal dimension (FD)	2 ln (patch perimeter)/ ln (patch area)	patch	none	$1 \leqslant X \leqslant 2$
%LAND	percent of landscape	class area/total landscape area	class	percent	0–100%
PD	patch density	number of patches/total landscape area	class	numbers per 100 ha	$\geqslant 1$, no limit
PSSD	patch size standard deviation	RMS error (deviation from mean) in patch size	class	ha	$\geqslant 0$, no limit
ED	edge density	sum all edge lengths/total landscape area	class	meters per ha	$\geqslant 0$, no limit
AWMPFD	area weighted mean patch FD	sum of (FRACT of all patches × patch area/total landscape area)—see Eqn. 2	class	none	$1 \leqslant X \leqslant 2$
CONTAG	contagion index	Sum, over patches of all classes (i, j), of two probabilities (randomly, conditional) of patch (class i) being adjacent to patch (class j)—see Eqn. 1	land-scape	percent	0–100%

The fractal dimension usually describes the complexity and the fragmentation of a patch by a perimeter-area proportion. Fractal dimension values range between 1 and 2. Low values are derived when a patch has a compact rectangular form with a relatively small perimeter relative to the area. If the patches are more complex and fragmented, the perimeter increases and yields a higher fractal dimension.

In this study, landscape metrics were calculated using the Fragstats program (McGarigal and Marks, 1994). This public domain software allows the user to calculate a variety of landscape metrics. In addition to contagion index and the fractal dimension metrics, other, less complex, landscape metrics were derived. These were: percent cover (the percentage of the area covered by a class relative to the total landscape area), patch density, patch size standard deviation, and edge density. Table 1 shows the name, calculation method, metric type, units of measure, and the possible range for each landscape metric used here. The metric type refers to the thematic zones of the landscape for which a metric is calculated. For example, the fractal dimension metric is computed for every patch; other metrics are related to a certain class (describes all patches of that class) or to the total landscape.

All metrics were selected for use in this study because of their information content and their potential utility in analyzing different domains of different test sites. For example, patch-density and edge-density metrics are calculated relative to the total landscape area. This was required because the analyses used different test sites with similar, but not equal, landscape areas. The fractal dimension as a measure of the fragmentation for every patch was applied as a derived metric called area weighted mean patch fractal dimension (AWMPFD):

$$\mathrm{AWMPFD} = \sum_{i=1}^{m} \sum_{j=1}^{n} \left(\frac{2 \ln(0.25 p_{ij})}{\ln a_{ij}} \; \frac{a_{ij}}{A} \right), \tag{2}$$

where
m is the number of patch types (classes),
n is the number of patches of a class,
p_{ij} is the perimeter of patch ij,
a_{ij} is the area of patch ij,
A is total landscape area.
This AWMPFD averages the fractal dimensions of all patches by weighting larger land-cover patches higher. This improves the measure of class-patch fragmentation because the structure of smaller patches is often determined more by image pixel size than by characteristics of natural or manmade features found in the landscape (Krummel et al, 1987; Milne, 1991).

2.2 Homogeneous urban patches

A basic approach of this study was to define and spatially discriminate areas of similar urban structure for the application of the landscape metrics, which would then characterize the spatial structure and pattern existing in a given region. This concept is based upon the 'photomorphic region' approach developed for aerial photographic interpretation (Peplies, 1974) and the assumptions presented by Barr and Barnsley (1997). Photomorphic regions are defined as image segments with similar properties according to their size, shape, tone or color, texture, and pattern. Within the context of landscape metric derivation, such regions are termed in this study 'homogeneous urban patches' (HUPs) and spatially defined in this study as *areas of homogeneous urban land-use structure*. The following general rules for HUPs are defined:
(a) HUPs should characterize one type of urban land use (for example, commercial, residential) with similar size, density, and spatial pattern of built-up structures.
(b) HUP size should be sufficient for an adequate landscape metric analysis. HUPs should be large with respect to the image resolution, but at least one or two urban blocks in extent. Very small homogeneous areas (those with just one or two structures) are too small for urban land-use characterization.
(c) Where possible, HUP boundaries should be selected along streets and other relevant natural and anthropogenic features such that large built-up patches remain contiguous.
(d) Areas of other land cover such as bare soil, agriculture, or large water bodies should be excluded.
(e) For multitemporal analysis the most recent available remote sensing data should be utilized for HUP segmentation.

The HUP concept provides a major advantage to other spatial structure investigations of urban areas using remotely sensed data. It allows the characterization of thematic-defined, irregularly shaped areas (Barr and Barnsley, 1997), whereas other approaches merely use a quadratic filtering window (kernel) and per-pixel information (Forster, 1993; Gong et al, 1992; Sadler et al, 1991) as basis for thematic data analysis.

3 Data processing and test sites

Test areas for this study were selected in different districts of the Santa Barbara, California region (color plate 1, see page 1455). Imagery covering the study site was acquired from the University of California Santa Barbara Map and Image Library (MIL). The MIL archives an extensive collection of historic aerial photography, satellite imagery, and other analog and digital data sets. Three sets of color-infrared aerial photographs were identified for use in this study. These photographs were originally acquired by the National Aeronautics and Space Administration as well as the United States National Aerial Photography Program (NAPP; Light, 1993).

Three dates of aerial photograph sets with a scale of 1 : 130 000 were chosen: February 1978, November 1988, and May 1998. This data set allowed for a multitemporal analysis covering a ten-year period which has been found to be a sufficient time frame for urban land-use change mapping (Jensen and Cowen, 1999).

In general, air photographs are fairly inexpensive data sources that provide the spatial and temporal resolution requirements (especially comprehensive historical time series studies) for local scale urban growth investigations (Jensen and Cowen, 1999; Welch, 1982). These analog image datasets are limited in their spectral information and contain radiometric distortions that usually results in a lower digitized image data quality compared with digital imaging systems (Light, 1996). Improved digital remote sensing data with high spatial resolution are now available from the IKONOS multispectral space-borne sensor and are considered to be the start of a new era of remote sensing application to urban areas (Ridley et al, 1997; Tanaka and Sugimura, 2001), especially concerning data quality and data availability (Meinel et al, 2001; Toutin and Chen, 2000). IKONOS data have limitations including costs of data and temporal resolution considering the time scale of urban growth processes. Accordingly, this study uses historical air photographs to investigate urban land-use structures and urban growth processes. The scale of the air photographs (1 : 130 000) provides more equal spatial configurations (spatial resolution and spatial extent) than multispectral IKONOS data and shows the potential of the proposed approach that can be further investigated and improved in future studies employing IKONOS data. Hence, the data-quality limitations of the air photographs have to be considered in image analysis. A number of image-processing steps were required. The positive transparency aerial photographs were digitized by using an IKONIX, Inc. linear array digitizing system scanner. The photography was scanned at 600 dots per inch, which resulted in a spatial resolution of approximately 3 m. The data were geometrically corrected, georeferenced, and then merged into image mosaics as two or three individual air photographs were necessary to cover the whole Santa Barbara study area. To transform image spectral response into thematic information, the images were individually classified using an unsupervized approach for class delineation with a manual visual reclassification into 'vegetation' and 'built-up' thematic classes. Some inconsistencies were identified in the multitemporal image classification. These resulted from seasonal differences in the sun illumination conditions and in the vegetation cover between the various dates of air photograph acquisition and from radiometric distortions caused by vignetting effects in the air photographs. Accordingly, only some parts of the entire study area were available and selected as test sites for comparative multitemporal analysis. The classification problems resulting from the spectral limitations of the air photographs and from the different sun illumination effects were reduced by assigning just two land-cover classes: built up and vegetation. These two classes are spatially and spectrally clearly separable in the air photographs and represent the dominant land-cover categories found in urbanized or residential areas (Sadler et al, 1991; Ridd, 1995). Errors caused by seasonal changes in vegetation cover were minimized by including only the 1978 and 1988 images in the analyses as they are from a similar season. The 1998 image was not utilized for multitemporal analysis. Resultant errors in the image classification could not be quantified because of a lack of ground-truth information, a general problem in historical remote sensing data analysis. The generally clear spectral and spatial separation of the land-cover classes allows for the derivation of multitemporal binary land-cover maps of sufficient accuracy to introduce and evaluate the proposed approach. Resultant classification errors do not significantly change the general pattern of spatial land-cover structure and urban growth. This study demonstrates some of the limitations of air photographs when utilized as base data in a digital processing environment. Aerial photography is an important data source for historical urban growth studies; however, problems of data quality and analysis may be encountered compared with investigations based on digitally acquired space-borne remote sensing data.

The eight test sites were chosen for this study as HUPs, and landscape metrics were computed for each of these test sites. Six of the sites were selected principally for the analysis of urban land use/land cover (table 2). The remaining two sites were chosen in order to study changes in land-cover features resulting from urban growth (section 4.2).

Table 2. Santa Barbara/Goleta area test sites.

Urban land-use structure type	Test site location
Commercial and industrial areas (CMI)	Two test sites near Goleta airport
High-density built-up residential areas (HDR)	Two test sites in Goleta (North and East)
Low-density built-up residential area (LDR)	Two test sites in the Hope Ranch area (North and South)

4 Results

4.1 Landscape metrics and urban land-use structures

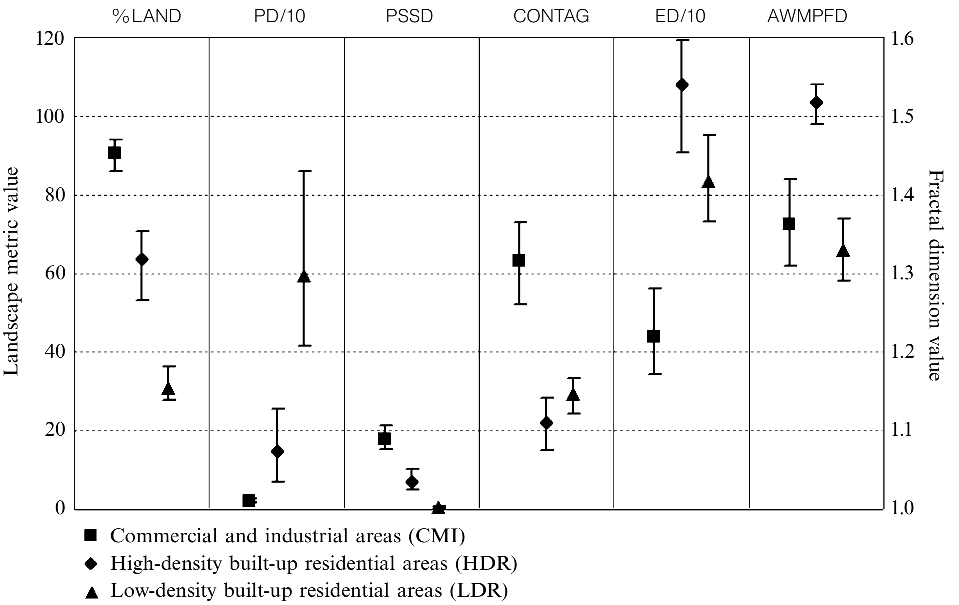
The first objective of the study was the separation of different urban land-use classes on the basis of spatial structure. Color plate 2 shows an example of test sites for the three land-use categories: commercial and industrial areas (CMI), high-density built-up residential areas (HDR), and low-density built-up residential areas (LDR).

CMI are dominated by large building structures and extensive impervious cover (paved areas). Property parcels are spatially aggregated into large tracts of built-up cover, interspersed with areas of sparse vegetation cover. The high-density HDR test sites represent a common land-use pattern in which single-family residences are sited along a regular street pattern. The vegetated zones composed of landscaped lawns, shrubs, and trees surrounding each residence and parks or other recreational areas are associated with each neighborhood. Similar to the CMI test sites, no single parcel shapes are identifiable in the HDR cover type, but mean structure and parcel sizes are distinctly smaller. Vegetation is dominant in the LDR test sites. The residential structures are larger, with enclosed large single-family dwellings (including ranches) surrounded by extensive vegetated tracts common in this cover type. In contrast to the patterns found in the CMI and HDR sites, single parcels within the LDR sites are not spatially aggregated and they form independent patches.

The metrics calculated from the 1988 and 1998 aerial photography covering the three sets of test sites (CMI, HDR, LDR) were compared by mean, minimum, and maximum values for each landscape index (figure 1, over).

Figure 1 shows that the landscape metrics provide an accurate representation of the spatial arrangement of vegetation and built-up areas for the three types of land-use structure and distinct differences are seen among the three HUPs. The percentage of the landscape area (%LAND) areas quantifies the different ratio of vegetation and built-up area for each cover type. Built-up area values are approximately 0.90 for CMI; 0.65 for HDR; and 0.30 for LDR.

Patch density (PD) and the patch size standard deviation (PSSD) values yield information about the density and the size of built-up areas as well as their spatial aggregation for each cover type. CMI test sites have the lowest PD ($\sim$20 per 100 ha) and the highest PSSD ($\sim$19 ha). The HDR sites show intermediate values for these metrics (PD $\sim$150 per 100 ha; PSSD $\sim$8 ha) resulting from smaller built-up structures



Note: All metrics, except the contagion index (CONTAG), describe structures of the 'built-up' class. PSSD is patch size standard deviation. The patch density (PD) and the edge density (ED) values were rescaled by dividing them by a factor of 10 to adjust them to the first *y*-scale landscape metric value. The secondary *y*-axis (fractal dimension value) is related only to the 'area weighted mean patch fractal dimension' (AWMPFD). For landscape units see table 1.

Figure 1. Mean, maximum, and minimum values for three urban land-use structures derived from the classified air photographs 1988 and 1998 (four values for every land use).

and more vegetated areas, causing a lower spatial coherence. The highest PD ($\sim$600 per 100 ha) and the lowest PSSD (0.5 ha) is found in the LDR areas, principally because of the nearly complete spatial separation between built-up parcels. The wide range of the PD values resulted from the variance present among the test sites.

The contagion index (CONTAG) describes the fragmentation of the HUP, which is dependent on the dominance of a class, mean parcel, and built-up-structure size, and the spatial configuration of the land cover. Accordingly, the large building structures and the sparse vegetation typical of the commercial regions are reflected by a higher CONTAG ($\sim$63) than in both residential test sites ($\sim$22 and $\sim$29). HDR areas show higher landscape fragmentation. A similar disparity exists in the edge density (ED) values between the CMI test sites and both residential areas: the more heterogeneous residential areas have a higher ED ($\sim$107 and $\sim$84 m per ha).

The area weighted mean patch fractal dimension (AWMPFD) measures a different dimension of urban land-use structure. This metric is a measure of the fragmentation of each built-up patch, and not for the whole HUP, as is measured by the contagion metric. The highest values ($\sim$1.52) is found in the HDR areas. HDR patches consist of spatially aggregated parcels and buildings of small size along a regular street pattern, resulting in a highly fragmented patch structure. The patches of the LDR regions are not coherent and show a more compact shape, which leads to a lower fractal dimension ($\sim$1.33). Approximately the same AWMPFD values can be found for the CMI regions, whose small patch fragmentation result from their large size and compact structure as well as the domination of one land-cover type which prevents a detection of single houses.

An analysis of the metric values shown in figure 1 also indicate that the different metrics are individually sensitive to different characteristics of the urban landscape.

The combination of different spatial information (such as the percentage of landscape, the spatial aggregation of built-up areas, or the mean parcel and building size) suggests that a functional separation among the three regions is possible by utilizing selected landscape metric measures. The different landscape metrics may thus be considered as 'landscape metric signatures' (LMSs) for the various urban land-use categories in the study area. These signatures can be used to develop and define indices as aggregated information for land-use structures.

4.2 Landscape metrics and changes in urban land use

The La Cumbre and Isla Vista test sites were investigated because of a well-documented change in urban land use between 1978 and 1988. To describe the influence of this change on the spatial landscape structure of the areas, landscape metrics were comparatively interpreted for the two dates.

4.2.1 *La Cumbre test site*

The changes in the urban structure in this test site detected in the 1978 and 1988 air photographs are presented in figure 2. The growth of built-up areas in different parts of the imagery clearly shows the displacement of vegetation areas by built-up structures. The housing and parcel structures in 1988 are comparable with the HDR areas. The spread of HDR areas between the two dates resulted in a finer textured and more fragmented urban landscape.

Figure 3 (see over) presents the variation of the landscape metrics regarding the changes in land-use structure between 1978 and 1988 (figure 4) and the LMSs described in figure 1. The percentage of built-up zones of the total landscape area (%LAND) increases from approximately 25% in 1978 to more than 50% in 1988. This describes the transition of this area from a low-density built-up condition with a landscape dominated by natural cover to an urban condition. The PD shows a decrease from ~ 590 to ~ 320 per 100 ha in combination with a slight rise of the PSSD, from ~ 1 to ~ 3 ha.

1978 1988

Air photograph

Classification

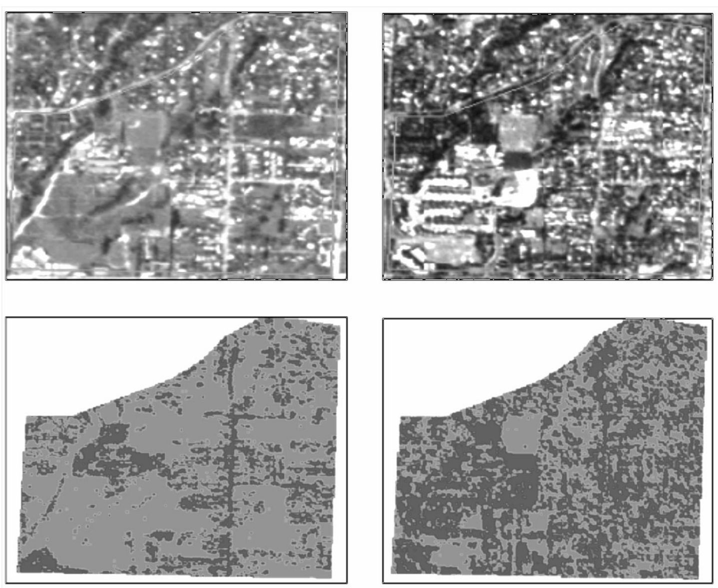


Figure 2. Changes in urban land-use structure of the La Cumbre region between 1978 and 1988 represented in the air photographs and the classified distribution of vegetation (gray) and built-up areas (black).

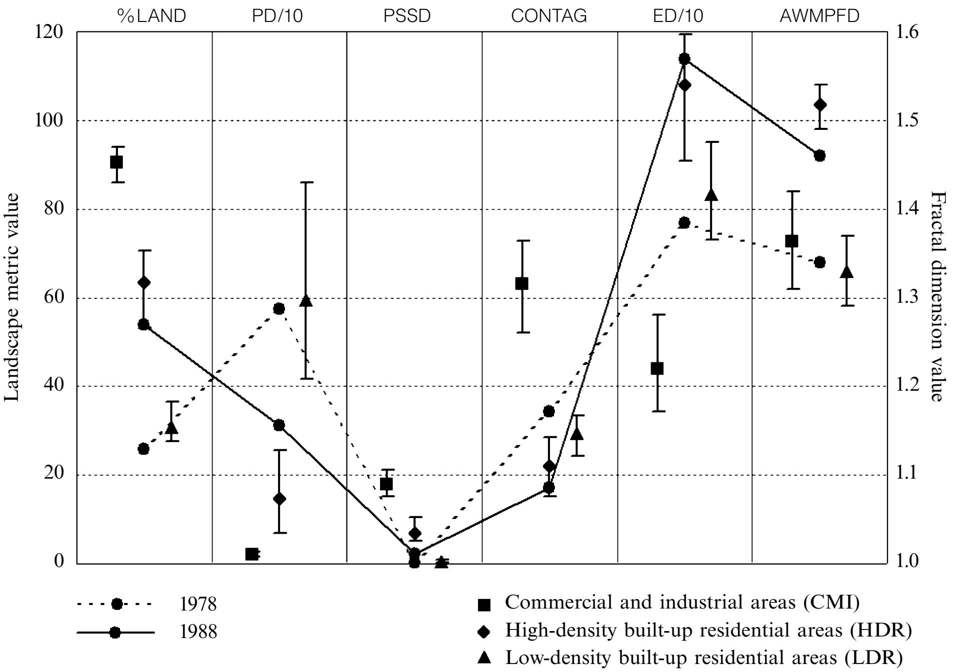


Figure 3. Changes of six landscape metrics in the La Cumbre area between 1978 and 1988 in comparison with the 'landscape metric signatures' (see figure 1).

The proportion of built-up areas increases, but individual structures border more on one another and form fewer patches with a higher size variance.

The decreasing CONTAG and increasing ED values indicate a higher fragmentation of the area in 1988. This fact was already apparent at the interpretation of the changes in the air photograph (figure 2), where the vegetation-dominated urban landscape of 1978 became spatially more heterogeneous and fragmented during the spread of anthropogenic structures by 1988. The fragmentation of the built-up patches, expressed by the AWMPFD, increases by 0.12. This can be predominantly ascribed to a higher %LAND and the higher spatial aggregation of single built-up structures in the aerial photographs. This is reflected in the PD and PSSD metrics derived for this test site.

The change of the landscape metrics in comparison to the LMS which were developed indicates a transition of an LDR area to a HDR landscape structure between 1978 and 1988. This variation is evident in all metrics, whereas some values lie outside the range of the LMS derived from other test sites.

4.2.2 *Isla Vista test site*

The Isla Vista test site was selected as an example of changes within an existing urban environment between 1978 and 1988. This district predominantly consists of multiple-family dwellings and student housing units with a very high population density. The continuous demand for housing leads to an increasing density of the built-up areas and this condition shows clearly in the 1978 and 1988 aerial photographs.

Figure 4 shows portions of the 1978 and 1988 air photographs and the corresponding classified images. In the 1978 air photograph, some vegetated areas appear as open spaces inside the otherwise high-density built-up area. The vegetation zones are mostly open lots, identifiable by their rectangular shape. By 1988 most of these open spaces were developed, causing a change in spatial landscape structure with the increased density of the urban space.

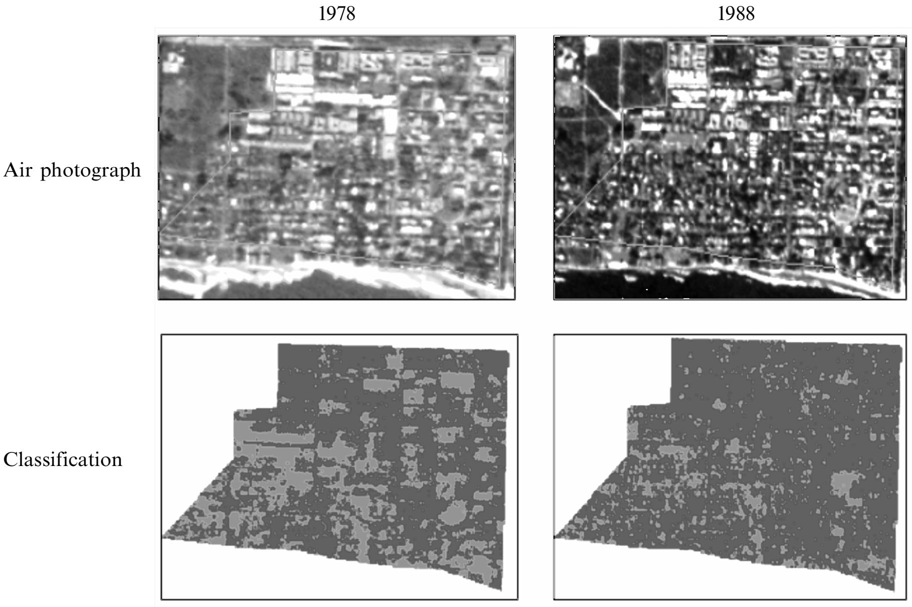


Figure 4. Changes in urban environment in the Isla Vista region between 1978 and 1988 represented in the air photographs and the classified distribution of vegetation (grey) and built-up areas (white).

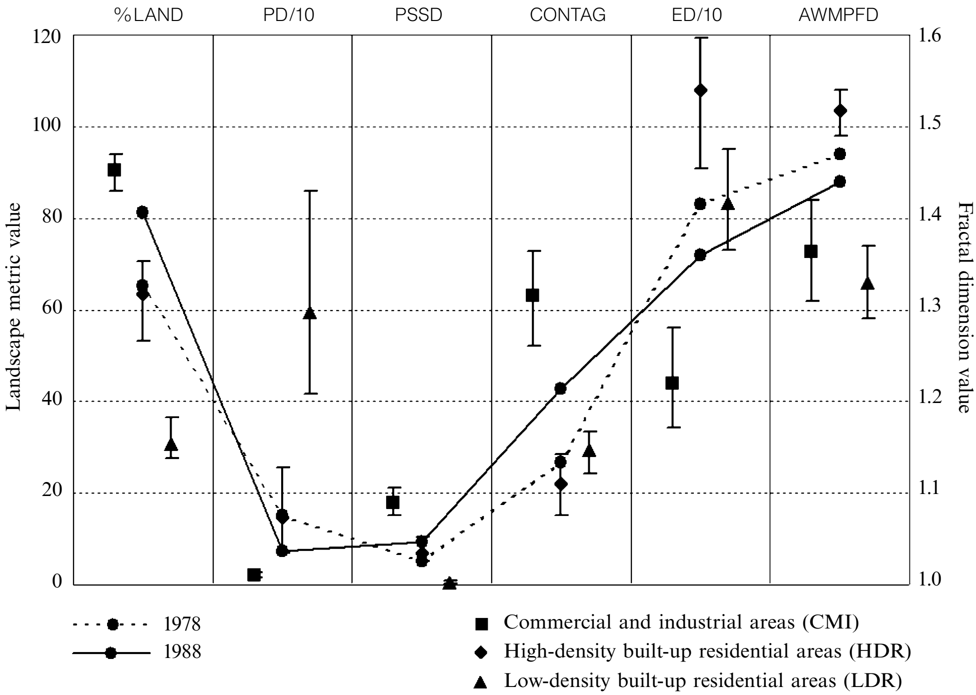


Figure 5. Changes of six landscape metrics in the Isla Vista area between 1978 and 1988 in comparison with the 'landscape metric signatures' (see figure 1).

The differences in the values of the various landscape metrics between 1978 and 1988 compared with the LMS are shown in figure 5. The %LAND metric increases from 0.65 in 1978 to more than 0.80 in 1988, clearly documenting the increasing urban density. The patch density decreases from $\sim$150 to $\sim$80 per 100 ha and the patch size standard deviation increases from $\sim$7 to $\sim$10 ha. These values are similar to the changes in the La Cumbre test site (figure 3) and indicate an increasing spatial aggregation of the built-up areas, resulting in fewer patches with a higher variance in size.

The changes of the CONTAG, ED, and AWMPFD fragmentation metrics indicate a lower spatial heterogeneity of the landscape thanks to an increasing dominance of the built-up class as well as the disappearance of open urban space resulting in a less fragmented landscape. This process is markedly different in the Isla Vista test site. In the La Cumbre test site the urban growth process produced a more highly fragmented landscape.

The LMS of the Isla Vista test site shows a compaction of the urban space, from a signature typical of HDR in 1978 trending toward a CMI signature in 1988 (figure 5). The %LAND, CONTAG, and the AWMPFD all clearly indicate this trend. The PD and the PSSD values show, however, that the urban land use in Isla Vista can still be clearly characterized as residential. This fact again shows the importance of different metrics for a robust land-use differentiation.

5 Conclusion and future research

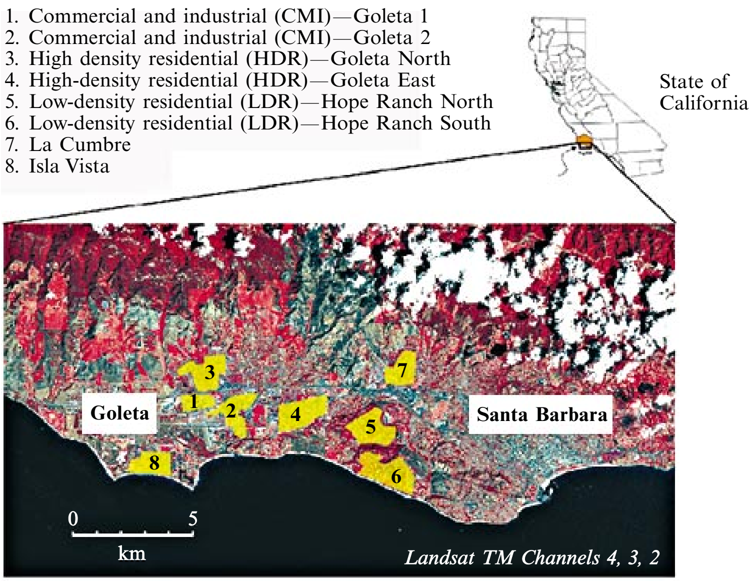
There are two fundamental problems in identifying specific urban land uses with digital remote sensing techniques; urban areas typically exhibit a spatially heterogeneous land cover and there is a great deal of similarity in spectral response from the different land cover and land uses in this environment. Therefore, in order to derive accurate urban classifications it is necessary to utilize data acquired by high spatial resolution sensors in conjunction with classifiers that are more sophisticated than routine per-pixel algorithms. In this study we examined the use of spatial structure information—landscape metrics—derived from classified remote sensing data to describe structures and changes in urban land use. The methodology uses 'homogeneous urban patches' and digitally classified color infrared air photographs for the calculation of the landscape metrics derived using the Fragstats program. Six landscape metrics were selected for the analysis.

Three urban land-use categories were investigated in accordant test sites: commercial and industrial, residential with high-density built-up structure, and residential with low-density built-up structure. The comparative evaluation of the landscape metrics shows distinctive differences between the land-use categories. Four principal variables were determined to be critical in describing land-cover features in the urban environment of a 'homogeneous urban patch':

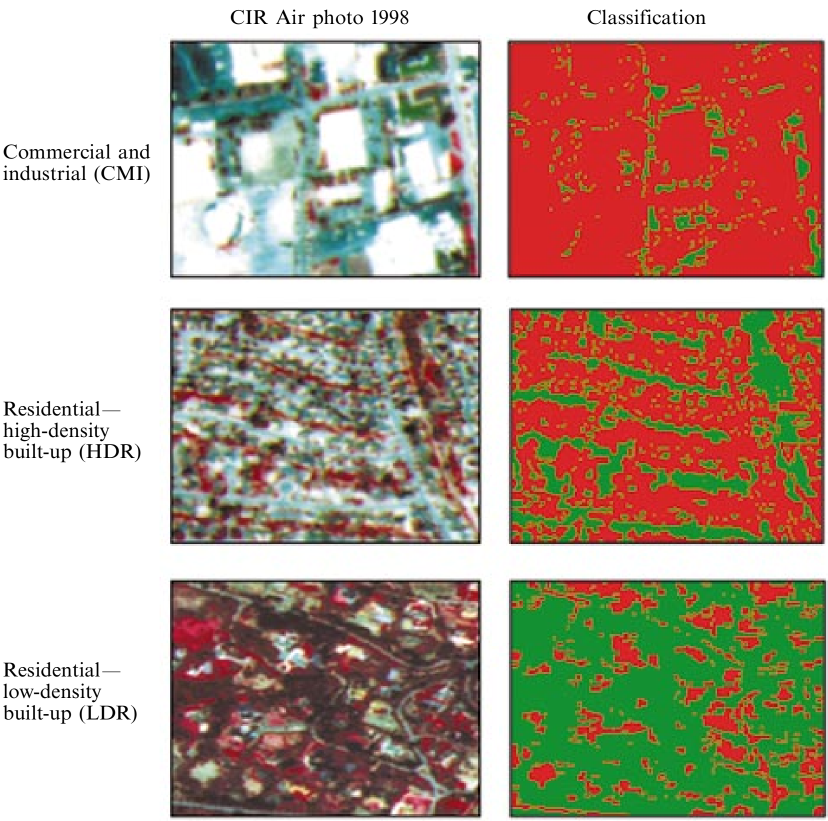
1. domination of a land-cover class, either built-up or vegetation,
2. the housing density and spatial arrangement,
3. the mean housing and plot size,
4. spatial aggregation of the built-up areas.

The results show the importance of different landscape metrics for a robust land-use characterization. The metrics may be considered as 'landscape metric signatures' (LMSs) as they serve as accurate and predictive discriminators of urban land uses within the study area.

Two urban test sites were examined in order to document the utility of landscape metrics to identify the displacement of vegetated ground cover by built-up structures. In the first test site, a landscape structure change was caused by a spread of three types



Color plate 1. Location of test areas in the Santa Barbara region shown with Landsat TM scene.



Color plate 2. Examples of air photographs and classification results (built-up = black; vegetation = gray) for three test sites of different urban land uses.

of urban structures into zones of open land cover. The spatial structure of the second area was modified by the increased density of the built-up urban area through disappearance of vegetated lots as open urban space.

In both test sites, the variation of the landscape metrics have shown an increasing ratio of built-up zones within the total landscape area as well as increasing spatial aggregation of the built-up patches. A different trend was observed, however, for measures of fragmentation. Urban growth in zones of open or natural land cover produced higher structural density. This increased density, as well as increased density within already built-up areas, produced a decrease in the fragmentation of the landscape.

This analysis of LMS values for both test sites demonstrates that they provide useful and accurate measures of different processes of urban growth. In addition, the effects of these processes on the spatial arrangement of vegetated land cover (both natural and man-made) as well as built-up areas can also be accurately identified and described.

This study clearly demonstrates the utility of landscape metrics for analysis of the urban environment. A long-term objective of this research, however, is to implement such analytic techniques operationally for various applications. If this goal is to be reached, significant research is still required as the process of extracting the LMS measures from the raw remotely sensed data is complex and requires specialized knowledge in order to implement both the necessary image processing as well as the geostatistical analysis that is required in order to derive the landscape metric information data.

An important future research objective will be the further evaluation of different spatial metrics as well as the aggregation of metric information (spatial urban indices) to develop robust measurements of urban morphological structures. Spatial measurements allow a very robust characterization of urban form (Banister et al, 1997; Longley and Mesev, 2000) and are useful for representing urban processes and functionality and contributing to urban models. The issue of the input remote sensing datasets is also of importance. Digitized aerial images were utilized in this study and such imagery is available to almost every local or regional planning agency. New, high-spatial resolution satellite data are also now commercially available. These datasets can undoubtedly serve as input data for the types of analysis described here. Our future research will seek to test such applications. We are encouraged by the results of this study and are confident that high-resolution satellite data will also prove useful in such analysis.

Acknowledgements. The authors gratefully acknowledge the support provided for this research as part of National Aeronautics and Space Administration Research Grant NAG5-3620. We would also like to recognize the contribution made to this research by the late Dr John E Estes, Director of the Remote Sensing Research Unit and Professor of Geography at the University of California Santa Barbara.

References

Anderson J R, Hardy E E, Roach J T, Witmer R E, 1976, "A land use and land cover classification scheme for use with remote sensor data", professional paper 964, US Geological Survey, Reston, VA

Banister D, Watson S, Wood C, 1997, "Sustainable cities: transport, energy, and urban form" *Environment and Planning B: Planning and Design* **24** 125 – 143

Baraldi A, Parmiggiani F, 1990, "Urban area classification by multispectral SPOT images" *IEEE Transactions in Geosciences Remote Sensing* **28** 674 – 680

Barnsley M J, Barr S L, Hamid A, Muller P A L, Sadler G J, Shepherd J W, 1993, "Analytical tools to monitor urban areas", in *Geographical Information Handling: Research and Applications* Ed. P M Mather (John Wiley, Chichester, Sussex) pp 147 – 184

Barr S, Barnsley M, 1997, "A region-based, graph-oriented data model for the inference of second order information from remotely-sensed images" *International Journal of Geographical Information Science* **11** 555 – 576

Batty M, Longley P A, 1988, "The morphology of urban land use" *Environment and Planning B: Planning and Design* **15** 461 – 488

Batty M, Xie Y, 1996, "Preliminary evidence for a theory of the fractal city" *Environment and Planning A* **28** 1745 – 1762

Bowden L W, 1975, "Urban environments: inventory and analysis", in *Manual of Remote Sensing Volume 12* Ed. L W Bowden (American Society of Photogrammetry, Falls Church, VA) pp 1815 – 1880

De Cola L, 1989, "Fractal analysis of a classified Landsat-scene" *Photogrammetric Engineering and Remote Sensing* **55** 601 – 610

De Cola L, Lam N N S, 1993, Introduction to fractals in geography", in *Fractals in Geography* (Prentice-Hall, Englewood Cliffs, NJ) pp 3 – 22

Dunn C P, Sharpe D M, Guntensbergen G R, Stearns F, Yang Z, 1991, "Methods for analyzing temporal changes in landscape pattern", in *Quantitative Methods in Landscape Ecology: The Analysis and Interpretation of Landscape Heterogeneity* Eds M G Turner, R H Gardner (Springer, New York) pp 173 – 198

Forster B C, 1993, "Coefficient of variation as a measure of urban spatial attributes using Spot HRV and landsat TM" *International Journal of Remote Sensing* **14** 2403 – 2409

Frohn R C, Mcgwire K C, Dale V H, Estes J E, 1996, "Using satellite remote sensing analysis to evaluate a socio-economic and ecological model of deforestation in Rondonia, Brazil" *International Journal of Remote Sensing* **17** 3233 – 3255

Gardner R H, O'Neill R V, Turner M G, 1993, "Ecological implications of landscape fragmentation", in *Humans as Components of Ecosystems; Subtle Human Effects and the Ecology of Populated Areas* Eds S T A Pickett, M J McDonnell (Springer, New York) pp 208 – 226

Gong P, Howarth P J, 1990, "The use of structural information for improving land-cover classification accuracies at the rural – urban fringe" *Photogrammetric Engineering and Remote Sensing* **56** 67 – 73

Gong P, Marceau D J, Howarth P J, 1992, "A comparison of spatial feature extraction algorithms for land-use classification with SPOT HRV data" *Remote Sensing of Environment* **40** 137 – 151

Haack B N, Guptill S C, Holz R K, Jampoler S M, Jensen J R, Welch R A, 1997, "Urban analysis and planning", in *Manual of Photographic Interpretation, Volume 2* Ed. W R Philipson (American Society of Photogrammetry and Remote Sensing, Falls Church, VA) pp 517 – 554

Hall F, Townshend J, Engman T, 1995, "Status of remote sensing algorithms for estimation of land surface state parameters" *Remote Sensing of Environment* **51** 138 – 156

Henderson F M, Xia Z-G, 1997, "SAR applications in human settlement detection, population estimation and urban land use pattern analysis: a status report" *IEEE Transactions in Geosciences Remote Sensing* **35** 79 – 85

Imhoff M L, Lawrence W T, Stutzer D C, Elvidge C D, 1997, "A technique for using composite DMSO/OLS 'city lights' satellite data to map urban area" *Remote Sensing of Environment* **61** 361 – 370

Jensen J R, Cowen D C, 1999, "Remote sensing of urban/suburban infrastructure and socio-economic attributes" *Photogrammetric Engineering and Remote Sensing* **65** 611 – 622

Keitt T H, Urban D L, Milne B T, 1997, "Detecting critical scales in fragmented landscapes" *Conservation Ecology (online)* **1**(1) 4, http://www.consecol.org/vol1/iss1/art4

Kim H H, 1992, "Urban heat island" *International Journal of Remote Sensing* **13** 2319 – 2336

Krummel J R, Gardner R H, Sugihara G, O'Neill R V, Coleman P R, 1987, "Landscape patterns in a disturbed environment" *Oikos* **48** 321 – 324

Lam N S N, 1990, "Description and measurements of Landsat TM images using fractals" *Photogrammetric Engineering and Remote Sensing* **56** 187 – 195

Lam N, Quattrochi D A, 1992, "On the issues of scale, resolution and fractal analysis in the mapping sciences" *The Professional Geographer* **44** 88 – 98

Li H, Reynolds J F, 1993, "A new contagion index to quantify spatial patterns of landscapes" *Landscape Ecology* **8** 155 – 162

Light D L, 1993, "The national aerial photography program as a geographic information system resource" *Photogrammetric Engineering and Remote Sensing* **59** 61 – 65

Light D L, 1996, "Film cameras or digital sensors? The challenge ahead for aerial imaging" *Photogrammetric Engineering and Remote Sensing* **62** 285 – 291

Longley P A, Mesev V, 2000, "On the measurement and generalisation of urban form" *Environment and Planning A* **32** 473 – 488

McGarigal L, Marks B J, 1994, "FRAGSTATS manual: spatial pattern analysis program for quantifying landscape structure", http://ftp.fsl.orst.edu/pub/fragstats.2.0

Mandelbrot B B, 1983 *The Fractal Geometry of Nature* (W H Freeman, New York)
Meaille R, Wald L, 1990, "Using geographical information system and satellite imagery within a numerical simulation of regional urban growth", in *Remote Sensing and Geographic Information Systems* Ed. A L MacLean (ASPRS, Bethesda, MA) pp 210 – 221
Meinel G, Neubert M, Reder J, 2001, "The potential use of very high resolution satellite data for urban areas—first experience with Ikonos data, their classification and application in urban planning and environmental monitoring", in *Proceedings of the Symposium on Remote Sensing of Urban Areas, Regensburg, Germany, June 2001* Ed. C Juergens, Regensburger Geographische Schriften Heft 35 (on supplement CD Rom), University of Regensburg, Germany
Mesev V, 1998, "The use of census data in urban image classification" *Photogrammetric Engineering and Remote Sensing* **64** 431 – 438
Mesev T V, Batty M, Longley P A, Xie Y, 1995, "Morphology from imagery: detecting and measuring the density of urban land use" *Environment and Planning A* **27** 759 – 780
Milne B T, 1991, "Lessons from applying fractal models to landscape patterns", in *Quantitative Methods in Landscape Ecology: The Analysis and Interpretation of Landscape Heterogeneity* Eds M G Turner, R H Gardner (Springer, New York) pp 199 – 235
O'Neill R V, Krummel J R, Gardner R H, Sugihara G, Jackson B, Deangelis D L, Milne B T, Turner M G, Zygmunt B, Christensen S W, Dale V H, Graham R H, 1988, "Indices of landscape pattern" *Landscape Ecology* **1** 153 – 162
O'Neill R V, Hunsaker C T, Timmins S P, Jackson K B, Ritters K H, Wickham J D, 1996, "Scale problems in reporting landscape pattern at regional scale" *Landscape Ecology* **11** 169 – 180
Peplies R W, 1974, "Regional analysis and remote sensing: a methodological approach", in *Remote Sensing: Techniques for Environmental Analysis* Ed. J E Estes (Hamilton Publishing Company, Santa Barbara, CA) pp 277 – 291
Quattrochi D A, Ridd M K, 1994, "Measurement and analysis of thermal energy responses from discrete urban surfaces using remote sensing data" *International Journal of Remote Sensing* **15** 1991 – 2022
Ridd M K, 1995, "Exploring a VIS (vegetation-impervious-surface-soil) model for urban ecosystem analysis through remote sensing: comparative anatomy for cities" *International Journal of Remote Sensing* **16** 2165 – 2185
Ridley H M, Atkinson P M, Aplin P, Muller J P, Dowman I, 1997, "Evaluating the potential of the forthcoming commercial U.S. high-resolution satellite sensor imagery at the Ordnance Survey" *Photogrammetric Engineering and Remote Sensing* **63** 997 – 1005
Sadler G J, Barnsley M J, Barr S L, 1991, "Information extraction from remotely sensed images for urban land analysis", in *Proceeding of the 2nd European Conference on Geographical Information Systems (EGIS'91), Brussels, Belgium, April* (EGIS Foundation, Utrecht) pp 955 – 964
Steinnocher K, 1996, "Integration of spectral and spatial classification methods for building a land use model of Austria" *International Archives of Photogrammetry and Remote Sensing Part B4* **31** 841 – 846
Sutton P, Robert D, Elvidge C, Meij H, 1997, "A comparison of nighttime acquired satellite imagery and population density for the continental United States" *Photogrammetric Engineering and Remote Sensing* **63** 1303 – 1313
Tanaka S, Sugimura T, 2001, "A new frontier of remote sensing from IKONOS images" *International Journal of Remote Sensing* **22** 1 – 5
Toutin T, Chen P, 2000, "Demystification of Ikonos" *Earth Observation Magazine* number 7, 17 – 22
Turner M G, O'Neill R V, Gardner R H, Milne B T, 1989, "Effects of changing spatial scale on the analysis of landscape pattern" *Landscape Ecology* **3** 153 – 162
Webster C J, 1995, "Urban morphological fingerprints" *Environment and Planning B: Planning and Design* **23** 279 – 297
Welch R, 1982, "Spatial resolution requirements for urban studies" *International Journal of Remote Sensing* **3** 139 – 146
Xia Z G, Clarke K C, 1997, "Approaches of scaling geo-spatial data", in *Scale in Remote Sensing and GIS* Eds D A Quattrochi, M F Goodchild (CRC Lewis, Boca Raton, FL) pp 309 – 360