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A multi-scale framework for mapping and analysis of the spatial and temporal pattern of urban growth

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ABSTRACT: In the past, remote sensing has shown an ability to detect and describe urban growth patterns at different spatial scales. With new remote sensing devices (e.g. IKONOS, MODIS), with innovative image processing techniques and with further development of decision support tools (e.g. GIS and urban land use change models), remote sensing has new opportunities to provide useful information in support of sustainable development and "smart growth" for urban areas. Given that urban dynamics impact many spatial scales, we present a framework for the mapping and analysis of predictable patterns of urban at different spatial scales in order to analyze the urbanization process. We discuss problems of urban area mapping at the super-regional/global scale, and more directly address issues of spatial and spectral sensor requirements for urban mapping on the local and regional scale. We conduct urban growth analysis using spatial measurements of changes in the urban environment on the regional scale, and urban land cover structure on the local scale, in the Santa Barbara, CA area. Results show how the new era of remote sensing data and superior methods allow for a better mapping, understanding, modeling, and prediction of the spatial and temporal dynamics of urban growth at each of the different scales.

1 INTRODUCTION

The dynamic processes at work in urban areas (expansion in area, increase in population, changes in economic and social structures) affect both natural and human systems, and operate across geographic scales. There is an emerging desire to manage the dynamics or urban systems, reflected in sustainable development and smart growth initiatives and policies (Kaiser et al. 1995). However, urban planning and management rarely consider the scale-dependent nature of urban processes, a nature only marginally reflected in the usual hierarchical organization of city and regional planning institutions. Figure 1 shows a conceptual representation of the spatial evolution of a city in the United States. The patterns are the result of socioeconomic, natural, technological and social factors that both drive and are profoundly affected by the evolving spatial structure of cities in the landscape. Urban area expansion starts with a historical core that grows and disperses to new individual development centers or cores usually located near a main transportation axis (commonly, surfaced roads) and directly dependent upon the urban core. Given this general locational pattern, those areas follow a trajectory of organic growth or outward expansion, and finally coalesce and urbanize the open space in interstices between the central urban core and satellite centers. A last "saturated" spatial configuration of urban development forms the core for further urbanization at a less detailed spatial scale following the same stages of spatial evolution as shown in Figure 1. This "pulsating" conceptual representation emphasizes the scale variations given one example of urban expansion, since obviously different cities in a region are at different stages in the cycle at any given time. Urbanization can also be seen as a complex interaction between distinct processes that relate to specific scales themselves: e.g. the evolution of city transportation and communications networks; competition between commercial centers; industrial agglomeration; differential regional urban growth and land use change; and the housing market (Alberti & Waddell 2000, Weber 2001). The study of these processes involves the investigation of specific spatial and temporal growth patterns. The resulting information gained can improve the representation and modeling of the dynamics only if we also consider and clearly define the scale of urban change specific processes.

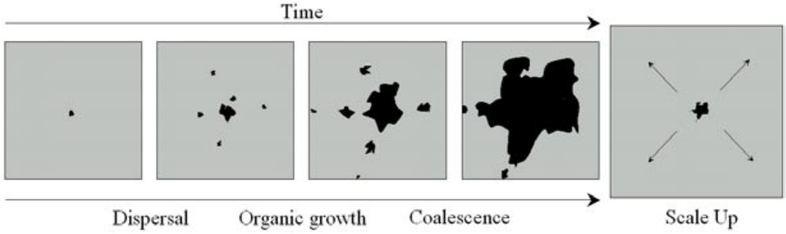
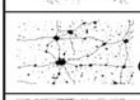


Figure 1: Hypothetical sequence of the spatial evolution of an urban area.

Table 1. A multi-scale framework for the mapping and analysis of urban land use change with remote sensing.

Scale	Growth/Change Processes	Remote Sensing Mapping Entity	Spatial/Temporal Resolution
 Global/ Super-Regional	Global urbanization trends Uneven development Regional polarization	Spatial extent of urban area	1 km / 10-50 ys
 Regional/ City-region	Counter-urbanization Urban de-concentration Formation of exurbs/edge cities		30 m / 5-10 ys
 City	Socioeconomic segregation Intra-urban land use transition	Urban land cover objects (e.g. built up structures, vegetation patches)	5 m / 2-5 ys
 District/ Block	Housing/land development Neighborhood changes		1 m / 1-2 ys

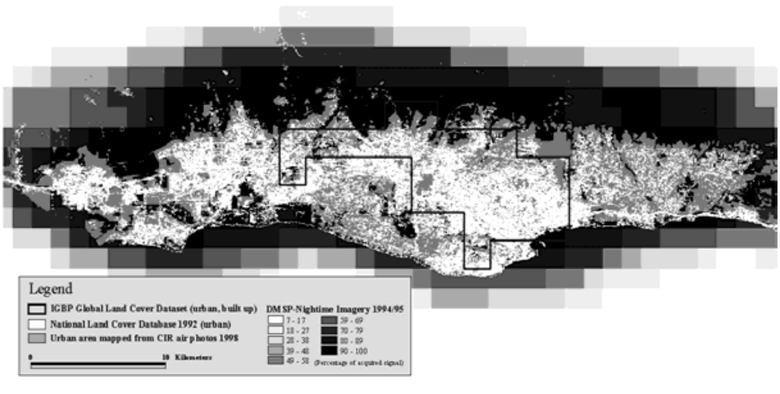


Figure 2. Urban extent of the Santa Barbara/Goleta urban region represented in different datasets compared to the map made by visual air photo interpretation used in this study.

Remote sensing methods have been widely applied in the mapping of land surface features in urban areas (e.g. Haack et al. 1997, Jensen and Cowen 1999), emphasizing the fact that remote sensing represents a key source of data, that is spatially consistent and covers large areas with both high geometric detail and high temporal frequency. Where revisit is possible, and satellite programs are either long-lived or durable, the historical time series critical for detecting and mapping urban change are pos sible. Recent developments in civilian remote sensing have radically improved the mapping of urban areas from remote sensing, and include the IKONOS satellite (Tanaka and Sugimura 2001), hyperspectral sensors (Ben Dor et al. 2001, Herold et al. 2002b) and MODIS (Schneider et al. 2001), and now can provide a more detailed and accurate urban area mapping at different spatio-temporal scales. Improvements in data availability and data analysis methods offer the chance to provide accurate maps at nearly all the spatial scales relevant to urban dynamics. Accordingly this paper develops these ideas towards a multi-scale view of remote sensing data analysis for urban growth and land use change. The general concept underlying our ideas, illustrated in Table 1, is a multi-scale framework for the mapping and analysis urban land use dynamics with remote sensing. We highlight four levels of geographical scale. Each scale is associated with specific urban dynamics, determines their spatial characteristics, is influenced by different drivers and factors of growth, and shows scale-specific effects and patterns as result of the process separation. Based on the framework, we discuss scale issues related to both remote sensing data analysis and the investigation and modeling of urban change dynamics.

2 SCALE IN REMOTE SENSING

2.1 *Spatial scale*

Scale--the spatial and temporal dimension of an object or process--is crucial to geographic analysis (Meentemayer 1989, Lam and Quattrochi 1992). Four meanings of scale are often used: cartographic scale, geographic scale, operational scale and measurement scale. For remote sensing based urban area mapping, the spatial extent of the study area defines the geographic scale. Measurement scale is determined by image pixel size or, more typically, the image spatial (or geometric) resolution or "Instantaneous Field of View" (IFOV, Jensen 1996). In general, the level of geometric detail in land cover representation by remotely sensed data is determined by the spatial heterogeneity of the target land cover structures and the sensor spatial resolution. Different studies have emphasized the investigation of resolution-dependent variables and critical spatial resolutions for the detection and analysis of real world phenomena at different scales (Woodcock and Strahler 1987).

Remotely sensed data have been applied to the analysis of urban land cover and land use at several spatial scales. Given the regional to global scale (Table 1) the main measurement objective has been the spatial extent of the urban area. Every related study requires a clear definition of what is considered an urban area versus a rural area. In general, the demarcation between urban and rural areas on the edges of cities may not be distinct. The US Bureau of the Census quantitatively defines urban areas based on population, land area and population density, and by spatial arrangement. A second common approach in delineating urban areas from their rural surroundings is by using image-processing techniques based on spectral response. Similar to the urban definitions from administrative data, discrimination of the urban extent from imagery is problematic and requires consideration of cross methodological issues. Weber (2001) stated: "it is necessary to develop a precise and clear definition of urban land use and land cover categories so as to be able to define the limit of urban areas" and "the morphology of urban areas might to be the most objective and easily obtained criterion for defining contiguous built up areas." For the accurate use of remote sensing data in urban extent delineation Barnsley et al. (1995) and Weber (2001) proposed a combination of remote sensing classification with population data and spatial distance analysis.

The problem of defining and discriminating urban and rural land in remote sensing based analysis is highlighted in Figure 2, which presents the various delineations of Santa Barbara's urban extent using different remote sensing sources compared to the urban extent derived from visual air photo interpretation (considered the "true" urban extent). The exaggeration of urban areas in nighttime acquired DMSP is obvious due to atmospheric influences, the coarse spatial resolution (2.7 km pixel size) and uncertainties in georectification. The IGBP-DISCover data set was the first complete global land cover data set developed from remote sensing data and is at a one-kilometer spatial resolution. Urban areas are represented in DISCover in the "Urban and Built Up" category. However, they were not mapped from NOAA/AVHRR data, as was the rest of the dataset. This reflects the difficulty of mapping urban areas at a coarse global scale. Even at the relatively high 1 km DISCover resolution urban areas are characterized by small extents and fragmented shapes and with an indistinct spectral pattern compared to other land cover classes. The urban areas in the IGBP dataset show a significant under-representation as they were obtained from the Defense Mapping Agency's Operational Navigation Charts generated in the 1950's and 1970's. Considering the problems with the mapping of urban areas at the super-regional and global scale, precise classification remains complicated. However, with new sensor systems like MODIS the super-regional scale mapping of urban areas should be significantly improved in the near future (Schneider et al. 2001).

The urban areas in the National Land Cover Database (NLCD) were derived from Landsat TM data and include the areas that are built up at a 30 m pixel resolution. The NLCD dataset is a typical remote sensing data product based on pixel-by-pixel digital classification, and represents the physically build up structures rather the actual extent of the urban land use area. Most regional scale analyses focused on a specific urban area have applied data from the Landsat TM and SPOT sensors. The multi-spectral spatial sensor resolution ranges from 20-30 meters. These resolutions are still too coarse for a clear geometric identification of urban land cover objects (Welch 1982, Woodcock and Strahler 1987, Jensen and Cowen 1999). Accordingly, different approaches were used to improve the mapping accuracy or acquire additional thematic information using data from these sensors:

- Spatial, textural, contextual or filter processing of the image data for more detailed mapping (Gong and Howarth 1992, Foster 1993),
- Inclusion of ancillary information in the image classification process (Mesev 1998, Sadler et al. 1991),
- Utilization of spectral mixture analysis for more detailed characterization of urban/near urban environment (Ridd 1995),
- Improving spatial resolution using sensor fusion algorithms (Ranchin et al. 2001),
- Visual interpretations of urban land use structures in satellite images (Ehlers et al. 1990).

In contrast to the regional and global scales, the primary remote sensing mapping objectives on the local scale are specific land cover objects or map features such as building structures, roads or individual vegetation patches (Table 1). The accurate mapping of these targets requires higher spatial sensor resolutions. Figure 3 highlights this issue by representing the resolution-dependent representation of high residential built up areas. The blue (dark) graph represents the change in local variance (3x3 neighborhood) as it was derived from Woodcock and Strahler (1987). The peak at 10-15 m spatial resolution shows the areas where the pixelsize is about the spatial dimensions of land cover objects in a high-density residential area. The graph in red (light) shows the change in fractal dimension, hence the level of generalization in how built up areas are represented in land cover classification results derived from air photos (3 m resolution, degraded in increments to 15 m), Daedalus scanner data (15 m) and Landsat TM data (30 m). The general decrease shows the increasingly generalized representation of the built up structures as the spatial resolution declines and the shape of the objects are more determined by the quadrangular form of the grid cells and not by real world characteristics. Accordingly, different studies have suggested a spatial sensor resolution of higher than 5 m for an accurate spatial representation of urban land cover objects such as building structures or urban vegetation patches based on qualitative considerations and experience (Welch 1982, Woodcock & Strahler 1987, Jenson and Cowen 1999). However, open systematic quantitative investigations of spatial sensor resolution requirements for urban area mapping are still insufficient to date.

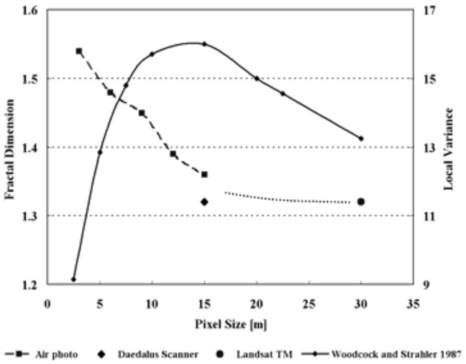


Figure 3. Representation of built up structures in high-density residential areas dependent on spatial resolution shown for analysis using local variance (blue, dark) and for fractal dimension (red, light).

2.2 *Spectral Scale*

The spectral capabilities or spectral resolution of a remote sensing device are usually characterized by the number of spectral bands and the wavelengths and bandwidth covered by these bands (Jensen 1996). In terms of urban area remote sensing, the spectral response is fairly complex and indistinct due to the heterogeneity of the urban environment, typically consisting of built up structures (e.g. buildings, transportation nets), multiple different vegetation covers (e.g. parks, gardens, agricultural areas), bare soil zones and water bodies (Barnsley et al., 1993, Ridd 1995). Consequently, there is no explicit "spectral urban signal" (Figures 4 and 5).

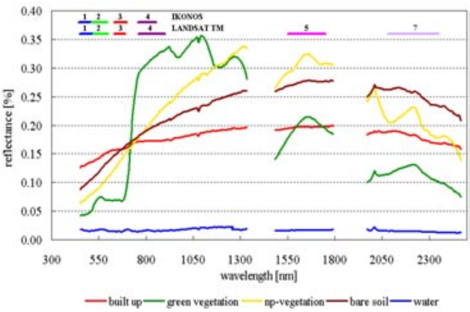


Figure 4. Mean spectral signatures derived from AVIRIS of five major land cover classes in the Santa Barbara, CA area shown with spectral coverage of IKONOS and LANDSAT.

Common multi-spectral data allow for an effective pixel-based separation of vegetation, water and built-up land cover categories on a purely spectral basis. The separation of built-up and bare soil/rock areas as well as areas of non-photosynthetic vegetation are often problematic using these data due to their similar spectral response from the most common satellite sensor systems (Figure 4, Sadler et al., 1991). The further separation of urban land cover types, such as different impervious surfaces (roads, roof types) or different vegetation types require data with higher spectral resolution (spectral upscaling). In this context, hyper-spectral remote sensing does allow for more detailed urban land cover mapping (Ben Dor et al. 2001, Herold et al. 2002b).

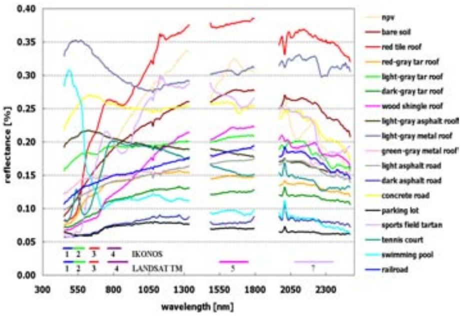


Figure 5. Spectral signatures of different urban land cover types from AVIRIS data acquired in the Santa Barbara, CA region (Note: The major water vapor absorption bands are interpolated).

Spectral scaling in mapping urban areas has to consider the spectral properties of urban materials (see Figure 5), the capabilities of recent sensor systems and the most suitable wavelengths for effective spectral separation of urban areas in general. On one hand, the comprehensive spectral information provide by hyperspectral sensors is considered "too much", due to the high correlation between the bands and the fact that a selected number of bands can provide most of the information required to map urban areas (Herold et al. 2002b). On the other hand, recent space-borne systems, like IKONOS, QUICKBIRD and LANDSAT ETM, are limited in their spectral resolution. This fact is shown in spectral coverage of IKONOS and LANDSAT compared to urban spectra (Figure 4 and 5) and in the diagram presented in Figure 6. The graph in Figure 6 highlights the spectral separability of different urban land cover types for three different sensor configurations. The IKONOS and LANDSAT TM data were simulated from AVIRIS using the spectral response functions available from the satellite data provider in 10 nm intervals. The AVIRIS sensor is represented by the most suitable 10 channels for separating these urban land cover types. The lowest Bhattacharyya distance for all urban targets with some significant low peaks is found with the IKONOS data. The low separability peaks disappear for LANDSAT TM, and the highest Bhattacharyya distance, or largest separability, values are found for AVIRIS data. This is a clear indication of the limitations of the IKONOS sensor in separating urban land cover categories due to its limited spectral information.

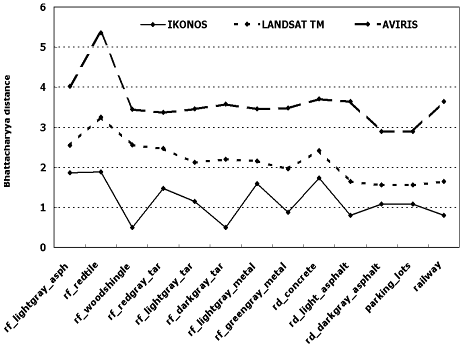


Figure 6:.Minimum class separability (Bhattacharyya distance) of urban land cover classes for three sensors (rf=roof, rd=road).

These results show that there are specific scale-related issues related to the spectral dimension in mapping of urban land cover, especially the limitations of current satellite sensor systems. Further analysis should consider and address these questions to provide a more detailed evaluation of spectral properties of urban materials and their spectral separability, including the investigation of the most suitable wavelengths to clearly assess and refine spectral scaling issues in remote sensing for urban zones.

3 SCALE IN ANALYSIS AND MODELING

In the previous section we discussed scale-related issues in mapping of urban areas from remote sensing. Considering the general framework shown in Table 1, the following section discusses and investigates the scale-dependent analysis and modeling of urban dynamics.

3.1 *Urban modeling*

Different land use change models have recently been described and compared in two reports. (Agarwal et al. 2000, EPA 2000). Considering models with a focus on simulating the spatial patterns of urban growth and land use change, the modeling approaches show strong scale-dependency in terms of the model framework, in the spatial discrimination of components of the urban environment, and in the thematic representation of urban land use and socio-economic parameters. The models operating on the regional scale (e.g. LTM, LUCAS) usually focus on simulating the impact of urban change on the surrounding environment by modeling the growth of an urban area. These models are raster-based and consider the urban area in one land use class (urban extent) with a very basic intra-urban discrimination based on the population density. More small-scale models like CUF-2 and UPLAN are focused on modeling urban land use change and discriminate the urban environment based on mainly raster-based concepts. They require a detailed urban land use categorization following the Level II and III of the USGS land use/cover classification scheme such as different densities and building structures of residential areas, commercial or industrial districts. The UrbanSim model operates on an even more detailed scale, resulting in a more local scale modeling of housing construction and land development. It requires no land use categorization, as these characteristics are represented by socioeconomic attributes attached to each land parcel. In general, the parcel is the preferred spatial model spatial granularity if economic processes and the behavior of key human agents like land owners are considered in the model. The UrbanSim model uses a raster-based approach in which the urban land development module is linked to the ecological modeling system in order to represent the different scale and characteristics of accordant processes and variables. The spatial resolution demands of the raster-based models vary according to the purpose and the characteristics of the studies for which they are applied. The grid cell resolutions used range from 30m x 30m to 100m x 100m. Some models use coarser spatial accuracy for special land use classes (UPLAN model) or for scale dependent description of processes like the LTM- and UrbanSim models.

3.2 *Analysis of change processes*

One major advantage of remote sensing datasets is their availability and consistency over large areas and across historical time series. We seek to provide a unique source of information on how the spatial characteristics of cities change over time. Given those observations and the resulting information about spatial and temporal dynamics, this approach contributes to an improved understanding and representation of how urban areas grow and change as function of scale and differently influenced processes. Examples of analyzing spatial and temporal urban growth dynamics in the Santa Barbara, CA region at different scales are shown in Figure 7. Changes in the urban environment were mapped from historical air photos. Further investigations applied the FRAGSTATS program (McGarical et al. 2002) to calculate spatial metrics for the description and analysis of the growth processes. The example shown at the top of Figure 7 represents the regional urban growth of Santa Barbara from its downtown core area with the largest growth rate in the 1960s and 1970s. The growth started with the allocation of small individual development units in the 1940s and 1950s around the downtown area causing a peak in the urban patch density, an increased number of urban patches and a decreased percentage of the total area covered by the largest patch (the downtown area). Until 1967 more individual urban development patches were allocated, causing a peak in the number of individual pixels and a significant growth in total area (urban sprawl). The decreasing patch density of the total area in the largest urban patches and the mean nearest-neighbour distance indicate a much larger area affected by urbanization than in the years before. By 1976, many individual urban patches had coalesced and formed larger urban areas with higher fragmentation, as shown by the fractal dimension. This trend continues to date, with decreasing fragmentation and a fairly low mean nearest-neighbour distance indicating the loss of open space between the urban areas. The continuous growth in total area equally happens by allocating new development units and the expansion of existing urban area shown by the fairly stable number of individual patches and the percentage of urban land in the urban core area.

The example at the bottom of Figure 3 shows the change in six different spatial metrics, and indicates the impact of the urban expansion on the landscape structure. The La Cumbre area shows an allocation of new residential development at all parts of the neighborhood between 1978 and 1988. This process of urbanization caused a decrease in individual built up patch density, hence a higher level of spatial aggregation of the built up areas, with a higher variance in size. The complexity of the landscape increased significantly, as shown in the decreased contagion and the higher edge density. The fractal dimension indicates the greater degree of fragmentation of the built up areas as a function of the growth and spatial aggregation. The Isla Vista area showed a change in landscape structure caused by the further development of individual units in residential areas. The result is a more dense residential land use. The growth pattern shows a similar trend in the first three metrics than that indicated for the La Cumbre area. However, the contagion, the edge density and the fractal dimension all show significant differences in the impact of the urban development on the spatial landscape structure. The complexity of the landscape and the fragmentation of built up patches decreased due to the disappearance of vegetated areas and the higher dominance of the built up class, including the spatial aggregation of the built up areas.

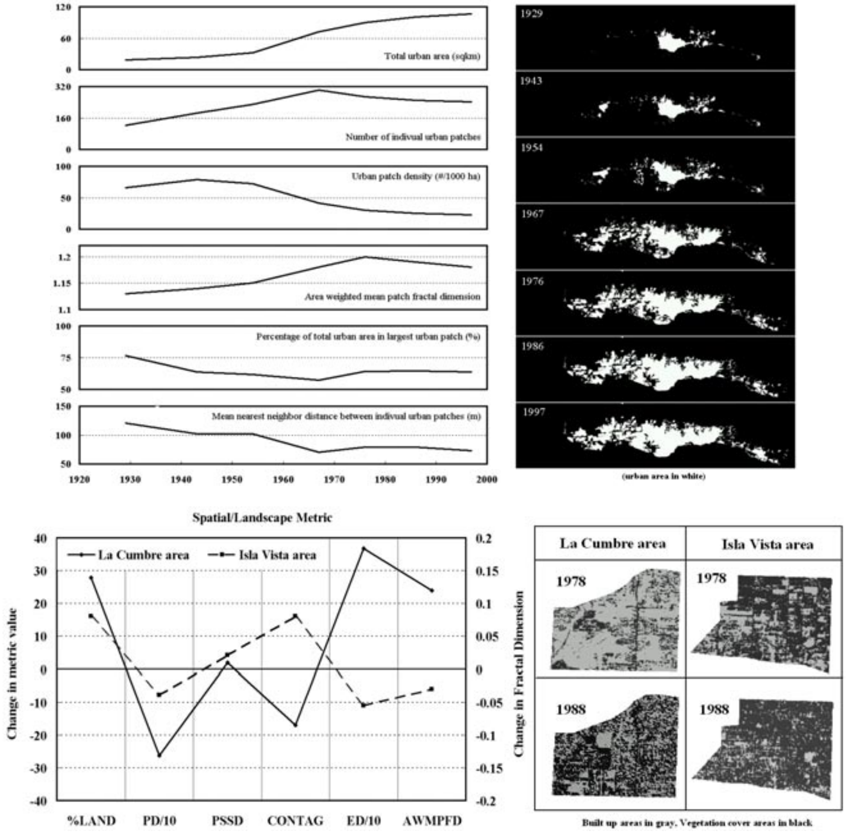


Figure 7. Spatial metrics describing the spatial and temporal growth dynamics mapped from multi-temporal air photos in the Santa Barbara, CA region on the regional scale (top) and the local scale (bottom) (Note: %LAND = Percent of landscape (built up), PSSD = Patch size standard deviation, CONTAG = Contagion index, PD = Patch density, ED = Edge density, AWMPFD = Area weighted mean patch Fractal Dimension).

Both examples show the contribution of utilizing remote sensing and spatial metrics for detailed analysis of urban growth and land use change patterns (Barnsley and Barr 1997, Herold et al. 2002a). According to the multi-scale framework shown in Table 1, the examples clearly indicate the specific patterns of growth that are observed on different scales. Individual metrics represent specific spatial and temporal dynamics, e.g. the significant impact of urban sprawl on the landscape structure. Considering further investigations and evidence, the changes in metrics over time could be analyzed as more general temporal growth or change signatures representing processes of urban development and land use change and their impact on urban spatial structure. Most studies have followed the deductive view in investigating urban growth processes and have related them to specific consequent structures (from process to structure). The remote sensing based approach investigates the problem by measuring spatial structures and analyzing their temporal changes as the result of specific processes (from structure to process). This perspective incorporates "real world" remote sensing-based measurements of urban dynamics rather than generalized consideration as is commonly used in theories and models of urban spatial structure and change.

4 CONCLUSION

The study of urban growth and land use change dynamics based on remote sensing requires the consideration of spatial scale. Given recent developments in remote sensing technology, we presented and discussed a general framework that structures the use of remote sensing to observe and analyze specific urban change dynamics from local to global scales. The multi-scale perspective and the land cover heterogeneity of urban environments require that suitable attention by given to selection of the most suitable spatial and spectral sensor settings for mapping urban areas. We also emphasize this multi-scale character in the analysis and modeling of spatial and temporal urban growth patterns. Use of the approach can significantly benefit from the utilization of remote sensing data products. We have presented examples from remote sensing based urban growth analyses using the spatial metrics of change on the regional and the local scale in the Santa Barbara, CA area. The results show how the new era of remote sensing data and methods allow for a better mapping, understanding and modeling of the spatial and temporal dynamics of urban growth at different scales.

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