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Urban Patterns and Processes: a Remote Sensing Perspective

MARTIN HEROLD, Jena

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Abstract: Remote sensing is a significant, yet under-used, data source for the study of urban phenomena; the key being a freeze-frame view on the spatio-temporal urban patterns, albeit in unprecedented detail. Quantitative descriptors of the characteristics and geometry of urban land cover features (spatial metrics) can describe the structure of urban environments and so allow the detailed exploration of urban patterns and dynamics of change. Several examples are discussed for using remote sensing in the analysis of rapidly urbanizing areas in California. The studies focus on urban land cover and land use, urban morphology and socio-economic characteristics, spatial pattern and growth process characteristics, and empirical observations and urban theory. Future emphasis is needed in the field of urban remote sensing to integrate the different levels of observations that, so far, has widely remain blind to pattern and processes.

Zusammenfassung: *Fernerkundung städtischer Muster und Prozesse*. Das Potential der Fernerkundung zur detaillierten Erfassung städtischer Raumstrukturen und -muster wird nur unzureichend zur Erarbeitung eines besseren theoretischen Verständnisses urbaner Systeme und Wachstumsprozesse angewandt. Diese Studie erarbeitet eine Synthese verschiedener Beispiele aus dem kalifornischen Raum. Auf der Basis von Satellitendaten und Raumstrukturmaßen werden Zusammenhänge zwischen städtischer Landbedeckung und Landnutzung, urbaner Morphologie und sozioökonomischer Eigenschaften, räumlicher Muster und Wachstumsprozessen bzw. empirischer Ergebnisse und urbanen Modellen vorgestellt.

1 Introduction

Understanding urban patterns, dynamic processes, and their relationships is a primary objective in the urban research agenda with a wide consensus among scientists, resource managers, and planners that future development and management of urban areas requires detailed information about ongoing processes. Central questions to be addressed are on how cities are spatially organized, where and when developments happen, and ultimately why and how did urban processes result in specific spatial pattern. Remote sensing, although challenged by the spatial and spectral heterogeneity of urban environments (JENSEN & COWEN 1999, HEROLD et al. 2004) seems to be an appropriate source of urban data to support such studies (DONNAY et al. 2001, HEROLD et al. 2005). Detailed spatial and temporal information of urban morphology, infrastructure, land cover and use patterns, population distributions, and drivers behind urban dynamics are essential to be observed and understood. Urban remote sensing has attempted to provide such information. But, despite proven advantages, remote sensing based urban mapping and monitoring has largely focused on technical aspects of data assembly and physical image classification and thus has widely remained "blind to pattern and processes" (LONGLEY 2002, LO 2004). In fact, the comprehensive spatial and temporal detail provided by remote sensing observations and quantitative measure-

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ments of urban structures have only rarely been explored in the context of understanding, representation and modeling spatial process characteristics (LONGLEY & MESEV 2000, HEROLD et al. 2005).

The aim of this paper is to evolve a better understanding on what is possible to observe using urban remote sensing and how such information can be integrated to improve our theoretical knowledge about urban areas and their dynamics. Different approaches will be presented from California case studies. Their description will be brief and with a minimum of technical detail. But they emphasize different avenues taken to study urban patterns and link them with urban processes.

Concluding discussions will attempt to structure the different indicators and approaches. The discussions will follow a main line of argumentation: urban remote sensing is missing key contributions and potentials to both scientific progress and applications if it remains widely focused on simply observing patterns or detecting changes without asking questions of "How?" and "Why?" related to urban processes.

2 Linking land cover to land use

Analysis on a per-pixel (spectral) basis provides urban land cover or material characterization rather than urban land use information. As in visual air photo interpretation, the most important information for a more detailed mapping of urban land use characteristics is derived from image context, pattern, and texture (BARNSLEY & BARR 1997). One successful approach for describing spatial land cover heterogeneities in urban areas are spatial metrics (HEROLD et al. 2002). They can be defined as measurements derived from the digital analysis of thematic-categorical maps exhibiting spatial heterogeneity at a specific scale and resolution. They have been developed for categorical, patch-based representations of landscapes. Patches are defined as homogenous regions for a specific landscape property of interest such as land cover categories "building" or "vegetation" or "urban". In contrast to natural environments, man made structures have been identified as one of the few examples of objects within a landscape that have distinct and crisp bound-

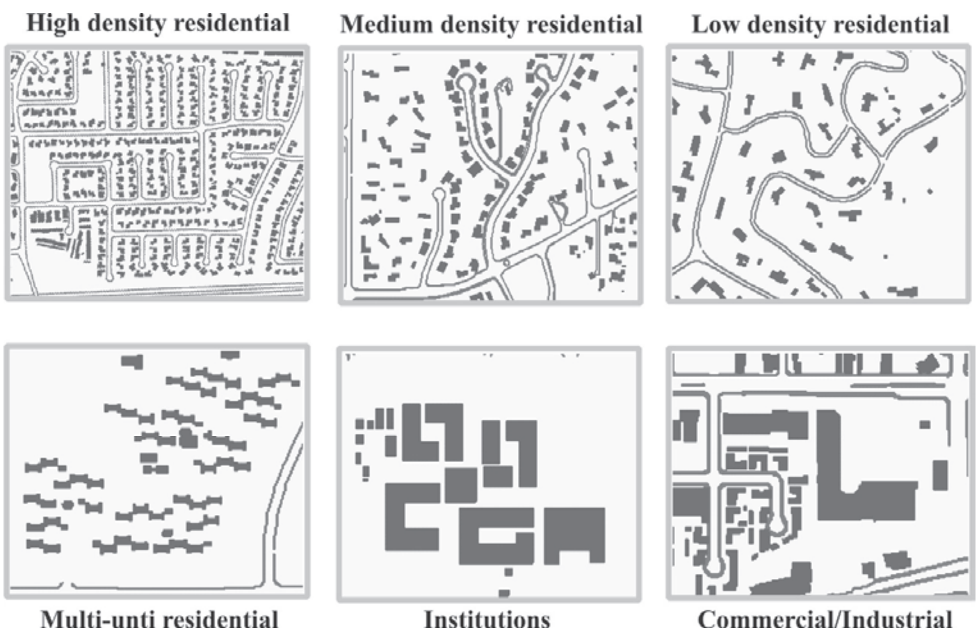

Fig. 1: Examples of spatial configuration for major urban land use categories.

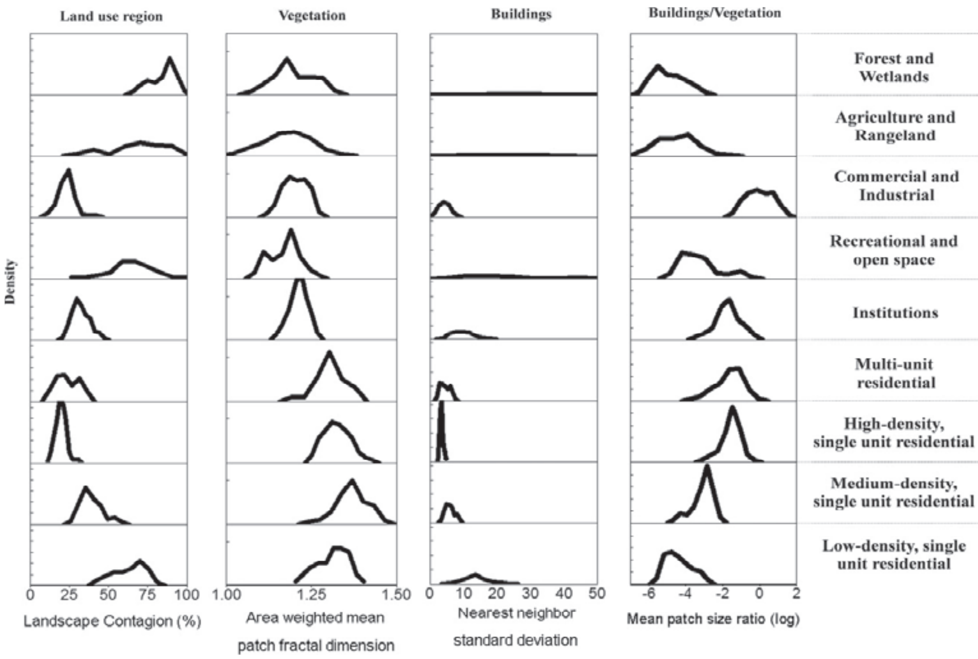

Fig. 2: Density graphs of four spatial metrics for nine types of land uses found within urban areas from IKONOS data. The metrics represent different spatial features noted on top of each graph. The last metric the log ratio of the mean building size and the mean vegetation patch size.

aries. Metrics represent spatial heterogeneity at a specific spatial scale, determined by the spatial resolution, the spatial domain, and the thematic definition of the map categories at a given point in time (Herold et al. 2005). When applied to multi-scale or multi-temporal datasets, spatial metrics can be used to analyze and describe change in the degree of spatial heterogeneity (O'Neill et al. 1988, Herold et al. 2003a).

For studying urban land use patterns the question for spatial metric analysis becomes: What characterizes the spatial land cover heterogeneity of urban areas and how can they describe urban characteristics? For example, the heterogeneity of the class "buildings" can be related to the size of structures (small versus large buildings), their shape (compact versus complex and fragmented), and the spatial configuration (regular versus irregular).

Size is measured by the "mean patch size"; the variation in size by the "patch size standard deviation" metric. Shape can be quantified by the "fractal dimension" metric, an area/peri-meter ratio that increases as spatial forms get more complex, and by the number of edges or edge length of a patch. Spatial building patterns are described by the "mean nearest neighbor distance" and the "nearest neighbor distance standard deviation" metrics, with the latter metric increasing as the spatial pattern of buildings gets more irregular. Similar measures can be applied to explore the heterogeneity of the vegetation areas. For more detail on the spatial metrics, please refer to McGarigal et al. (2002).

The spatial metrics for typical Santa Barbara, CA land use region (derived from remote sensing data interpretations, Fig. 1 and 2) are based on a land cover discrimination of the urban environment in the three main classes: buildings, vegetation, and the rest. The contagion is lowest for single unit high density residential, multi-unit residential and commercial/industrial areas (Fig. 2). These land uses represent a most heterogeneous, fragmented type of urban landscape. High contagion is found for forest, wetlands, agriculture, rangelands and a distinct residential gradient with lower contagion for higher residential density. The fractal dimension of the vegetation areas reflects high fragmentation for all residential land uses, e. g. residential development pattern results in disperse vegetation structures. Although having less area vegetation coverage, urban land uses like commercial or public institutions show more compact vegetated areas. The nearest neighbor standard deviation describes the regularity of the building pattern. The values for forest, wetlands, agriculture, recreational and open spaces are indistinct as they have no inherent or characteristic built up pattern. High density single unit residential areas have the most distinct regular building configuration reflecting the typical American block pattern. Commercial and industrial, multi-unit residential and medium density single unit residential also indicate a high degree of regularity. The building configurations in low density residential area are significantly more detached resulting in more irregularity in the spatial pattern.

This thematic exploration of commonly applied spatial metrics emphasizes that the

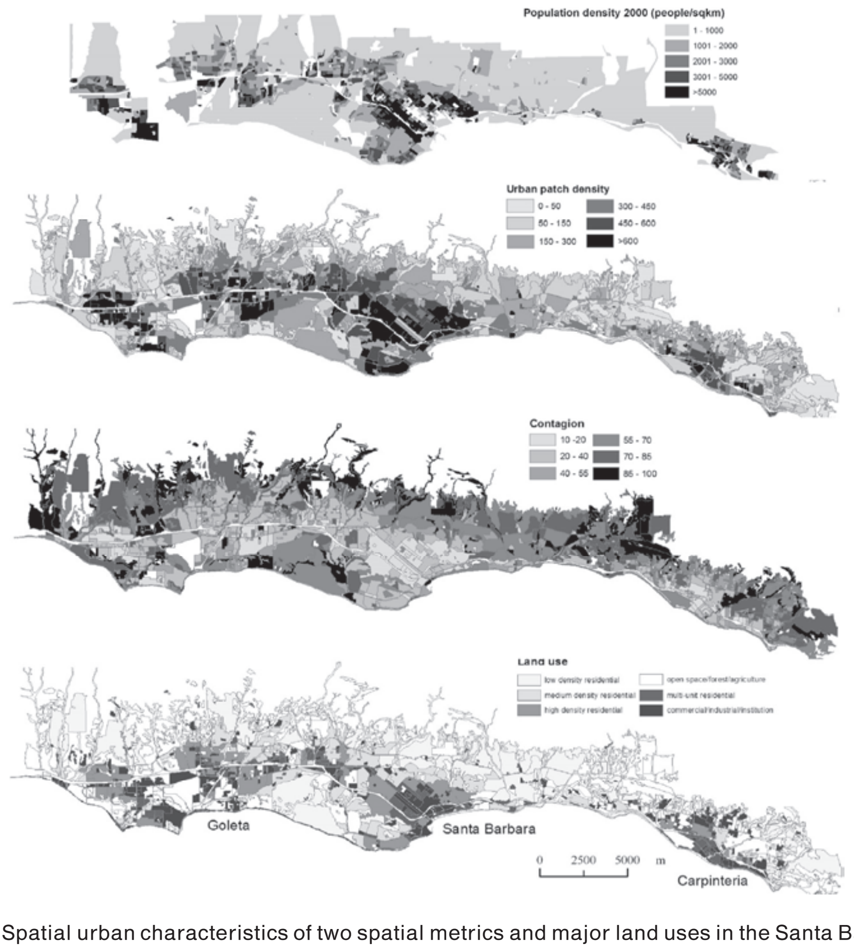

Fig. 3: Spatial urban characteristics of two spatial metrics and major land uses in the Santa Barbara South Coast urban area derived from IKONOS data and CENSUS population density. The metrics describe the spatial heterogeneity for each land use region (see HEROLD et al. 2003a). The population density and land use map highlights the three urban core areas in the region of Santa Barbara, Goleta, and Carpinteria.

metrics itself are fairly simple statistical measurements. They require comprehensive interpretation to be used in describing intra-urban environments based on their land cover characteristics. Ultimately it would be useful to identify or develop a set of "urban metrics" transferable and comparable among different urban areas and to adjust the skew and range of the values to apply further analysis method, e. g. urban land use classification based on the metrics. An example of an aggregated metric is the mean patch size ratio in Fig. 2. This metric describes the ratio of mean building size versus the mean size of the vegetation patches. Except for commercial and industrial uses, the vegetation patches are larger than the buildings and represent the spatial characteristics of the individual land uses.

In correspondence to Fig. 2, intra-urban patterns of spatial metric distributions are presented in Fig. 3. The building patch density shows an obvious correspondence with the population density. High values of this metric reflect high and medium density residential land uses with high numbers of individual buildings per area unit. The contagion is lowest for single unit high-density residential, multi-unit residential and commercial/industrial areas. In fact, the contagion metric follows a concentric pattern with heterogeneous urban environments near the central urban (low contagion) and a gradient of increasing contagion towards the peripheral rural areas. This goes along with a distinct residential gradient of lower contagion for higher residential density (see Fig. 1 and 2). In a related study, Herold et al. (2003a) show that metric and texture measurements can be used to accurately classify different land use types from this IKONOS dataset.

3 Linking urban form to population density

The previous section highlighted the relationship between urban land cover pattern and land use. Describing discrete land use categories, however, does not take full advantage of the spatial metrics that quantify urban form on a continuous scale. Residential land use types are intrinsically related to demographic characteristics. Spatial patterns shown in Fig. 3 suggest an obvious relationship between spatial metrics (describing urban form) and population density. Based on US 2000 Census block level data and IKONOS spatial metric measurements, Fig. 4 highlights the relationship between the metrics and population densities.

A positive correlation exists between population density and the amount area covered by buildings patches. This seems intuitive since a larger area covered building usually coincides with higher population density for each census block. A negative relationship is shown for the Contagion. The more homogenous the urban environ-

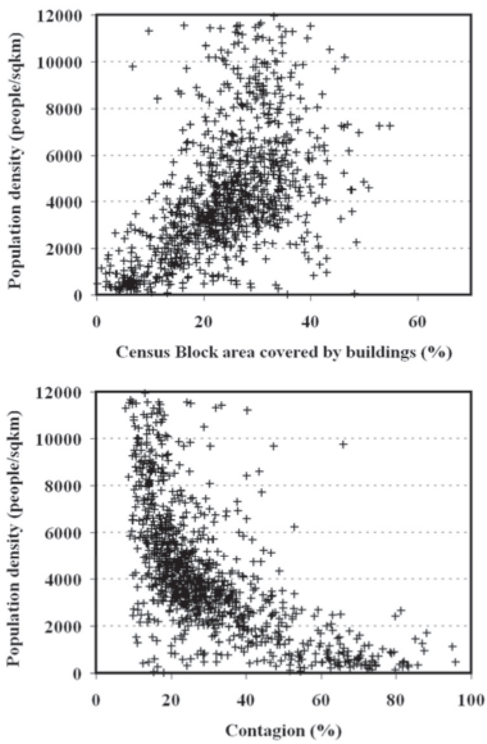

Fig. 4: Relationship between two spatial metrics and population density for n = 1092 Census 2000 block with residential land use in the Santa Barbara South Coast. The spatial metrics describe the land cover class buildings and have been derived from classified IKONOS data for each Census block.

ment is, the lower the population density. High-density residential areas represent fragmented urban landscapes with the heterogeneity decreasing for lower-density residential areas (Fig. 2).

Thus, building area proportions and the spatial heterogeneity are linked to the population density. The graphs in Fig. 4, however, show a fair amount of scattering indicating problems for direct estimation of population densities from remote sensing derived spatial metrics. The variance in the relationship increases for higher population densities, thus the metrics would better predict low population densities are less sensitive to changes in areas for high population densities. This is further emphasized by the non-linear correlation between Contagion and population density. Low Contagion values ($\sim$ 20%) do not allow for a clear distinction between areas with 6000–12000 people/sqkm. High-resolution remote sensing and spatial metrics can indeed help to estimate population density, but a quantitative derivation may not be able without considering additional data or specific spatial methods (Liu et al. 2006). A determinant relationship was not expected since the spatial urban patterns are diverse and not only driven by the number of people living there. However, a distinct link exists and a changing physical structure of an urban residential landscape would be clear indicator of ongoing demographic processes.

4 Linking spatial patterns and processes

From an urban process perspective it is important to study spatial urban land cover and land use characteristics as outcome of specific development characteristics. Existing and measurable urban pattern result from growth processes that, controlled and constrained by spatial growth factors, created the urban landscape in the first place. It should be possible to link the current urban landscape configurations to spatial distribution of the underlying growth factors. Such an investigation can be attempted through a combination of high-resolution remote sensing land cover mapping products and spatial metrics as quantitative descriptors of urban form. The method to link the remote sensing/spatial metric measurements and the spatial growth factors is provided by Geographically Weighted Regression (GWR) analysis. The method of Geographically Weighted Regression (GWR) has been developed in response to the need for locally specific spatial regression models (Fortheringham et al. 2002). GWR addresses the issue of spatial non-stationarity directly and allows regression relationships to vary over space, e. g. the predictors and regression parameters might vary for urban versus rural areas. In a case study, GWR was applied to explore the relationship between growth factors (independent predictor variables) and the spatial metrics (dependent variables). The study was conducted for residential areas in the Santa Barbara urban area (see Fig. 3). The three urban growth factors identified to have a major influence in the urban evolution of the area are topographic slope, distance to highways, and distance to the central urban core. Basically, the GWR analysis emphasizes how well the spatial urban structure as cumulative outcome of urban development processes (described by the metrics) is explained by spatial distribution of urban growth factors. The application of GWR is essential to assess the relationship of growth factors versus metrics on a more local, intra-urban level (e. g. different city districts) rather than as a global model for the whole urban area.

Tab. 1 shows the GWR regression parameters for the multivariate prediction of five spatial metrics from the spatial growth factors. The local sample sizes (bandwidth) are in the order of 38 to 88 points, which corresponds to 8–20% of the total number 484 observations. The value *Global R-sq* or global coefficient of determination represents the R-squared of the global regression model including all observations; the *GWR R-s* describes the overall strengths of spatially weighted regression. The significance of each predictor in the global regression analysis is reflected in the t-values (*T-slope,*

Tab. 1: Results of the GWR analysis for multivariate regression models considering three growth factors (distance to urban core, distance to highways, and slope) versus five spatial metrics. One metric represent the heterogeneity whole landscape (land use region, Contagion), two metrics describe characteristics of the land cover class buildings (PL = area percentage of buildings, PD = patch density), two the class vegetation (PD = patch density, AR_S = Standard deviation of vegetation patch sizes).

	Land-scape	*Buildings*		*Vegetation*	
	CONTAG	PL	PD	PD	AR_S
Local sample	70	94	88	88	38
Global R-sq	0.55	0.30	0.34	0.30	0.34
T-slope	7.12	−6.39	−6.62	−5.94	0.13
T-core	7.91	−2.06	−3.8	−4.44	7.89
T-highway	8.05	−4.27	−4.02	−3.21	7.33
GWR R-sq	0.73	0.47	0.51	0.47	0.68

T-core, T-highway). If the absolute t-value is above 1.96 the predictor can be considered significant and useful for the regression model. T-values below 0 indicate a negative linear relationship between the growth factor and the spatial metric. Except for one regression model were one growth factor is not significant (the factor slope in predicting the patch area standard deviation – AREA_SD).

Comparing the Global CoD and GWR CoD indicate the improvements in the regression models using geographically weighted regression. This result is not surprising since the local regression models better adjust to specific local characteristics and relationships than the global approach. The overall GWR CoD for these metrics are pretty high and range from 46 to 72% of described variance (Tab. 1); hence the growth factors are able to predict most of the spatial urban patterns of the area as emerging characteristics of historical urban growth processes. The study has further shown that areas with highly predictable urban patterns represent historically grown or planned urban characteristics that are representative for the major urban development processes in this region. The internal urban system is in balance or in some stage of desired development. The areas with lower predictability reflect an internal gradient in spatial urban structure to more unplanned urban or rural development patterns. They are under particular development pressure and it can be expected that the urban structures will gradually become a part of the balanced existing system if urban expansion continues. In this context, these areas are also of major importance for urban planning. Important regional planning actions in this region like protection of agricultural land, the establishment of an urban growth boundary, or fostering of highly desired land use types (affordable housing), can be expected to have a main impact in these regions where internal urban evolution seems not completed. These conclusions show that the combined use of remote sensing, spatial metrics and GWR improves our understanding of the internal structure of cities and provide further empirical evidence on the relationship between urban form and growth processes (Geoghegan et al. 1997).

5 Linking empirical observations and urban theory

Of particular potential is the combined application of multitemporal remote sensing with spatial metrics. Monitoring and analysis using this technique can provide a unique source of information on how various spatial characteristics of cities change over time. Temporal change 'signatures' of metrics can reflect specific dynamic change processes effecting spatial urban structure. Several studies have shown that the empirical observation of temporal urban growth signatures with spatial metrics contributes to a better understanding and representation of urban dynamics. It offers a new perspective into urban change theory and has the potential to contribute to urban growth and land use change modeling (Herold et al. 2003b, 2005).

However, one important step in such empirical analysis is to synthesize the observations into a more general theoretical under-

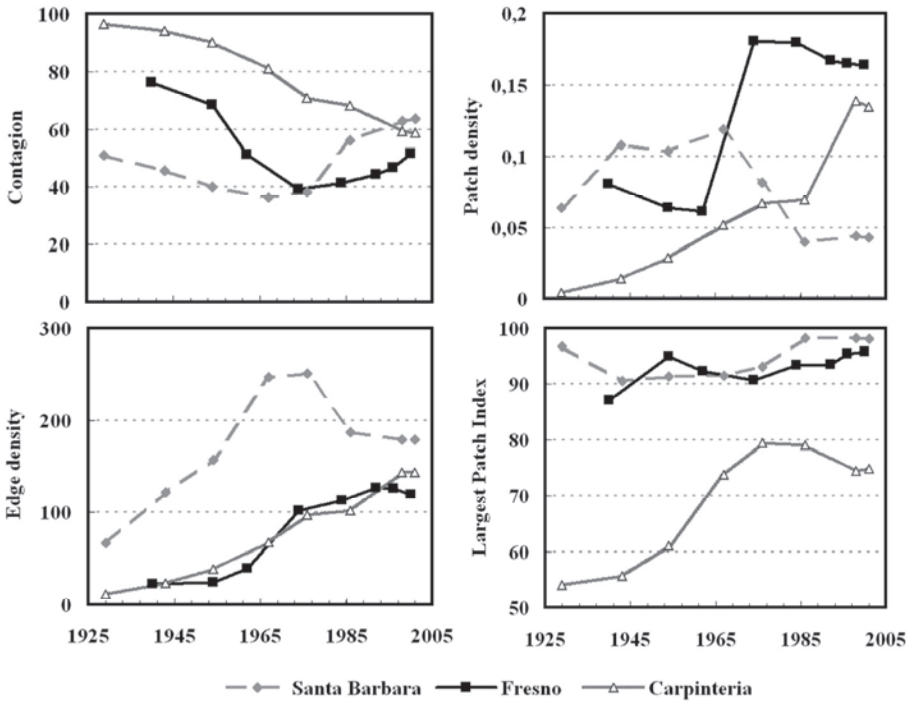

Fig. 5: Temporal growth signatures of three different cities of California: Santa Barbara, Fresno, Carpinteria, derived from remote sensing observations using spatial metrics.

standing of urban dynamics (Dietzel et al. 2005). Remote sensing observations usually follow an inductive, bottom up perspective: to provide empirical observations of actual spatial structures in great spatial and temporal detail and linking their changes over time to specific processes at work (from structure to process). The rather traditional perspective followed by the urban modeling and spatial urban theory community is deductive or top-down. Their focus is on deriving urban structures as the spatial outcomes of pre-specified processes of urban change (from process to structure). Linking both perspectives is a central task both deductive and inductive approaches could benefit by being used in combination. This avenue has only recently been explored with a combination of remote sensing, spatial analysis and spatial metrics to establish the link between empirical observations and urban theory (Dietzel et al. 2005, Herold et al. 2005).

Fig. 5 compares temporal signatures of metrics mapped for different cities in California. These cities vary in size (50.000–1.000.000 inhabitants) and the regional growth characteristics have been quite different (Central Valley versus South Coast). Santa Barbara showed major growth during the 50ies and 60ies of the last century, Fresno in the 1970–90ies, and Carpinteria is just currently developing as subsidiary center near Santa Barbara. The temporal signatures (Fig. 5) emphasize that similar growth pattern exists for all of this three different areas considering that the timing and the absolute values are shifted due to specific local growth characteristics. Dietzel et al. (2005) have attributed these observations into phases of Coalescence and Diffusion that is characteristics for several investigated cities (Fig. 6). Urbanization, as it is reflected by the contagion metric, results in a transformation from homogenous non-urban to a heterogeneous mix of urban and

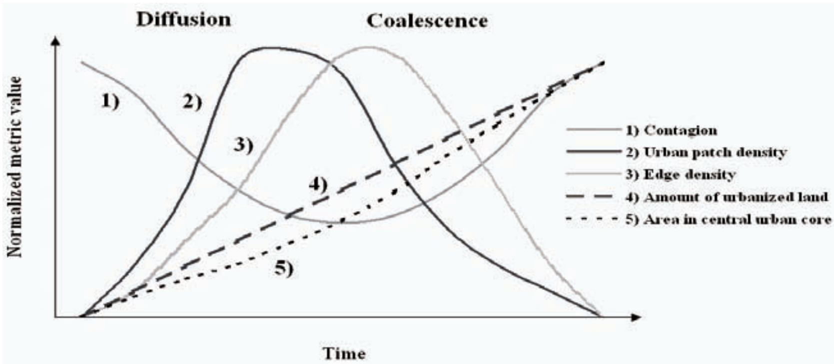

Fig. 6: Theoretical spatial metric signatures for a full cycle of urbanization for uniform isotropic growth at a specific scale (after DIETZEL et al. 2005).

non-urban. At some time in the progression of development there is a transition to a homogenous urban landscape. The other spatial metrics capture spatio-temporal phases. The diffusion phase is characterized by a large number of new urban areas in the nascent urban system comprised by the original core and peripheral development centers. The patch density peaks and amount of urban land in the largest patch is the lowest at this point. The low point in the contagion metric marks the transition from diffusion to coalescence. Coalescence starts as urban areas spatially aggregate. This is reflected by a decrease in the patch density and an increase in the edge density metrics. The terminal point of coalescence is complete urban build out when all, or nearly all, of the available land has been urbanized. This "final" stage can be seen as an initial urban core for further urbanization at a less detailed scale. Similar growth pattern, hence with different temporal dimension, can be observed on these different scales (DIETZEL et al. 2005).

In Fig. 5, the phase of diffusion corresponds to 1940–1960ies for Santa Barbara and 1960–70ies for Fresno. While Santa Barbara and Fresno are currently in the process of coalescence, Carpinteria is at the end of the urban diffusion process. However, the link between empirical measurements (Fig. 5) and the theoretical concept (Fig. 6) is, for now, only of a qualitative nature. A quantitative comparison reveals differences among metric signatures, in amplitude, duration, location and extent. These differences were anticipated since urban growth is not constant over time and the different regions. Furthermore, the spatial configuration of these areas are not uniform nor are the initial conditions for each developing city system identical with regard to the starting point for empirical observations. Local urban growth factors such as topography, transportation infrastructure, growth barriers or planning efforts affect the spatial growth pattern. However, the local variations yield important information about the ongoing processes. They can be interpreted as "distortions" i. e. amplifications, lagging, or damping the metric signatures. As in other urban models, the distortions can be thought of as the residual between the growth pattern under uniform, isotropic spatial and temporal conditions and the observed existing urbanization dynamics. Considering that understanding of patterns and processes through urban modeling is largely limited by the available data (LONGLEY & MESEV 2000), these examples show that time-series analysis of remotely sensed imagery using spatial metrics can provide an addition to urban theory. In fact, spatial metrics are one key to build a bridge between remote sensing analysis, understandings of the spatial evolution of urban areas, and the analytical modeling of urban systems.

6 Discussions and Conclusion

The examples have emphasized the variety of indicators describing urban characteristics and changes available from earth observations. They include the mapping and monitoring of spatial, spectral, and temporal urban patterns in both the physical built up environment and vegetation. In general, remote sensing adds an inductive, bottom up perspective to understanding urban patterns and processes. It incorporates "real world" remote sensing-based measurements of urban form and dynamics rather than generalized consideration, as are commonly used in traditional spatial theories and models of urban spatial structure and change. Certainly, the patterns obtained from remote sensing data may represent an aggregate outcome of many different processes at work. Often it is difficult to disentangle the effects of the different variables and trends of interest. Thus, the remote pattern measurements have to be clearly structured to the operational scale of urban change processes. A conceptual attempt summarizing the case studies presented in this paper is shown in Fig. 7. The most elementary *pixel scale* reflects changes in urban material characteristics, e. g. aging processes reflected in spectral characteristics. The *land cover* level reflects dynamics in common urban land cover objects such us building constructions, expansion of roads, decreasing urban vegetation patches or similar changes. If land cover changes are aggregated to larger areas, they can reflect or lead to changes in urban *land use*. Examples are infill development and redevelopment, or evolving brownfields.

Urban land use dynamics are intrinsically linked with socio-economic, political, or demographic drivers (Knox 1994) and thus provide a useful platform for studying urban dynamic processes. On a coarser level, *urban areas* reflect an agglomeration of urban land uses usually arranged in distinct intra-urban patterns. Growing urban areas reflect spatio-temporal patterns of expanding urban land uses into rural areas. Urban growth of one particular city is usually directly link with changes in other urban agglomeration, e. g. gravity relationships or regional polarization within a system of cities. Linking remote sensing pattern measurements across scales strongly depends on the process of interest and remains a critical research question. But, earth observation may have the potential to establish such relationships. For example, a new urban development driven by population growth will basically be observed on all relevant scales. To conclude, the main argument of this paper is that urban remote sensing can add a significant new perspective to understand urban patterns and processes. Such potential has been widely neglected in the past. The remote sensing technology has proven oper-

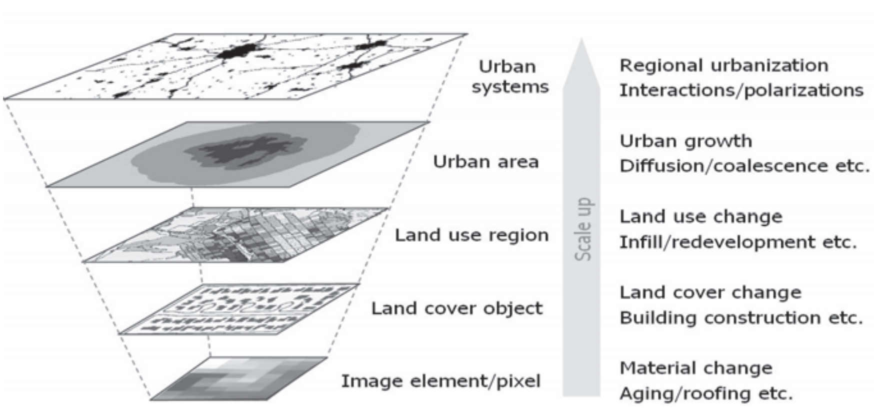

Fig. 7: Observing multi-scale dynamics for mapping and modeling of urban growth processes with remote sensing.

ational capabilities and many studies have provided mapping and monitoring products but rarely have asked the question of land change process behind observed patterns and dynamics. Remote sensing may provide the answers to questions asked in the early days of urban geography. Better theoretical understanding on the internal structures of cities, the link between urban form and socio-economic and demographic characteristics, and the spatio-temporal behavior of cities and urban systems are of particular importance for progress in the field urban geography. Remote sensing is not expected to address all questions but both traditional urban geographic research could benefit by being used in combination, with the traditional perspective helping to narrow down the possibilities suggested by the detailed analysis of urban form and their changes. Better process understanding and improved concepts will ultimately help in solving contemporary urban problems through providing information needed for sustained urban planning and management.

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Anschrift des Verfassers:

Dr. MARTIN HEROLD
Friedrich-Schiller-Universität Jena
Institut für Geographie
Löbdergraben 32, D-07743 Jena
e-mail: m.h@uni-jena.de

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