REMOTE SENSING DERIVED MAPPING TO SUPPORT URBAN GROWTH THEORY

M. Herold[a], J. Hemphill[b], C. Dietzel[b], and K.C. Clarke[b]

[a] ESA GOFC-GOLD Land Cover Project Office, Dep. of Geography, FSU Jena, Loebedergraben 32, 07743 Jena, Germany – m.h@uni-jena.de.
[b] Dep. of Geography, University of California Santa Barbara, Ellison Hall, Santa Barbara, CA, 93106, USA – (jeff, dietzel, kclarke)@geog.ucsb.edu.

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ABSTRACT:

This paper presents an addition to urban theory through a time-series analysis of remotely sensed imagery using spatial metrics. Results from the research are used to support the theory that urban areas are formed through an oscillatory growth process that switches between phases of urban coalescence and diffusion. In testing for the presence of this theory in a real-world context, the urban evolution of the Central Valley of California (USA) was recreated through the use of historical remotely sensed imagery. To test hypotheses about variation over geographical scale, multiple spatial extents were used in examining a set of spatial metric values including an index of contagion, the mean nearest neighbor distance, urban patch density and edge density. Through changes in these values a general temporal oscillation between phases of diffusion and coalescence in urban growth was revealed. Additionally a simple model of urban dynamics is presented, which has the ability to replicate some of the changes in urban form observed within imagery of urban areas. While the results are still preliminary, the research demonstrates the importance of urban remote sensing in the formulation and evaluation of urban theory.

1. INTRODUCTION

Understanding the evolution of urban systems, and addressing questions regarding changes in the spatio-temporal patterns of intra- and inter-urban form are still primary objectives in urban research. Remote sensing, although challenged by the spatial and spectral heterogeneity of urban environments, seems to be a suitable source of reliable information about the multiple facets of the urban environment (Jensen and Cowen, 1999, Donney *et al.*, 2001, Herold *et al.*, 2003). Despite proven advantages, urban remote sensing has widely remained "blind to pattern and process" (Longley, 2002). The spatial and temporal detail provided by space and airborne remote sensing platforms have yet to be broadly applied for the purposes of developing understanding, representation and modeling of the fundamental characteristics of spatial processes.

There are essentially two perspectives from which to view spatio-temporal urban patterns (Figure 1). The traditional perspective follows a deductive top down perspective: isolating urban structures as the outcomes of pre-specified processes of urban change (from process to structure). This point of view is common in the fields of planning, geography, and economics. The main criticism of this perspective is that it is only marginally representative of the spatial and temporal complexities of urban change. Early demographic and socio-economic research was limited by the ability to conduct detailed spatio-temporal pattern analysis at anything other than aggregate levels, leading to conclusions based on a top-down chain of causality. This era generated significant contributions and raised compelling questions regarding urban theory, but one question persists: how do cities form over time? More recent studies within these genres of urban research have started to address dynamics (White *et al.*, 2001, Batty, 2002). Research has become more focused on isolating the drivers of growth rather than solely the emerging geographic patterns. While new urban models have provided insight into urban dynamics, a deeper understanding of the patterns and processes associated with urbanization is still limited by the availability of suitable data and the lack of compatible theory (Longley and Mesev, 2000).

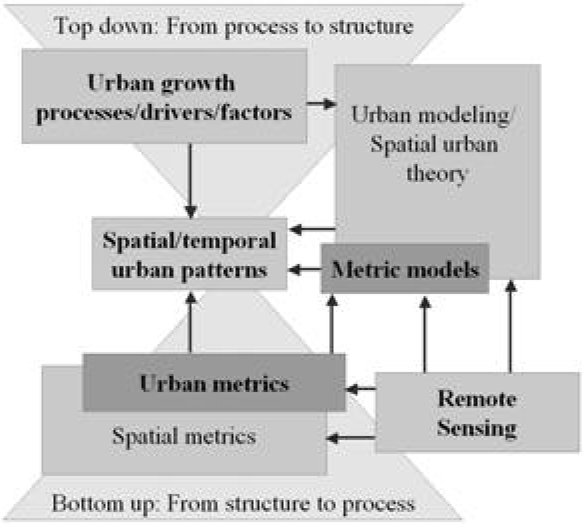

Figure 1: Conceptual approaches for studying spatial and temporal urban dynamics.

It is well understood that good models and good theory necessitate reliable measurements that capture spatio-temporal dynamics. This need is emphasized in the inductive, bottom up perspective. Empirical observations of actual spatial structures in spatial and temporal detail and linking changes over time to specific hypotheses about the processes involved (from structure to process) necessitates consistently available data. Remote sensing provides a freeze-frame view of the spatio-temporal pattern associated with a time series of urban change. Sequential snap-shots can be used to generate quantitative descriptors of the geometry of urban form. Geometric indices are used to quantify structure and pattern in thematic maps (including those of urban areas). These indices are commonly used in landscape ecology where they are referred to as landscape metrics. Recently researchers interested in understanding geographic phenomena have combine remote sensing, spatial analysis and spatial metrics to establish the link between urban form and process, and link empirical observation with urban theory (Dietzel *et al.*, 2005, In Press, Herold *et al.*, 2003, 2005).

A hypothetical framework of spatio-temporal urban expansion in terms of alternating processes of diffusion and coalescence is presented as part of this study. The framework hypothesizes that urban growth can be characterized as having two distinct processes generally follows a harmonic pattern. This hypothesis has been explored and at least partially confirmed using spatial metrics signatures of spatial-temporal urban growth dynamics for three centers of urbanization in the Central Valley of California (Dietzel, *et al.*, 2005). The conceptual model has now started to evolve into an urban modeling framework, with the goal being to bridge the inductive, bottom up, remote sensing observations with the top down perspectives in urban theory and urban growth models.

2. REMOTE SENSING OBSERVATIONS AND SPATIAL METRIC GROWTH SIGNATURES

The empirical observations of urban growth patterns were derived from time series remote sensing observations. The study area is California's Central Valley, encompassing the cities of Stockton-Modesto, Fresno, and Bakersfield (Figure 2). This study area was chosen because it contains one of the most rapidly urbanizing regions in the western world (State of California Department of Finance, 2004). The time span of the data ranges from 1940 to 2040 with historical observations for 1940, 1954, 1962, 1974, 1984, 1992, 1996 and 2000. The time span of the data series was extended using outputs from the SLEUTH urban growth model (Clarke *et al.*, 1997) for 2010, 2020, 2030, and 2040 (Dietzel *et al.*, 2005). Buffers (2, 10, 30 and 90 miles) around the central urban cores of the cities listed above, as defined by the Census 2000 urban areas dataset, were used to conduct the multi-scale analysis (Figure 2). Scaling in this context is changing the spatial extent encompassed by the buffers, not changing the spatial resolution which was fixed at 100 m x 100 m grid cell size.

Simple urban/non-urban categorization represents the urban expansion process in the time series data used in this study. The sequential snap-shots permit the application of quantitative descriptors of the geometry of urban form to be computed and compared over time. Geometric indices for quantifying the structure and pattern of thematic maps (including those of urban areas) are commonly used in landscape ecology where they are referred to as landscape metrics (O'Neill *et al.* 1988, Gustafson 1998). Calculation of spatial metrics is based on a categorical, patch-based representation of the landscape. The landscape perspective assumes abrupt transitions between individual patches that result in distinct edges. These measures provide a link between the detailed spatial structures that result from urban change processes that are captured by remote sensing (Luck and Wu 2002, Herold *et al*. 2003, 2005). Recently there has been an increasing interest in applying spatial metric techniques to the analysis of urban environments, where they have been used to examine unique spatial components of intra- and inter-city urban structure as well as the dynamics of change (Alberti and Waddell 2000, Herold *et al.* 2002). These more recent efforts have built on the fractal measures previously used to measure form, and have employed a variety of metrics to describe urban form (Herold *et al.* 2005).

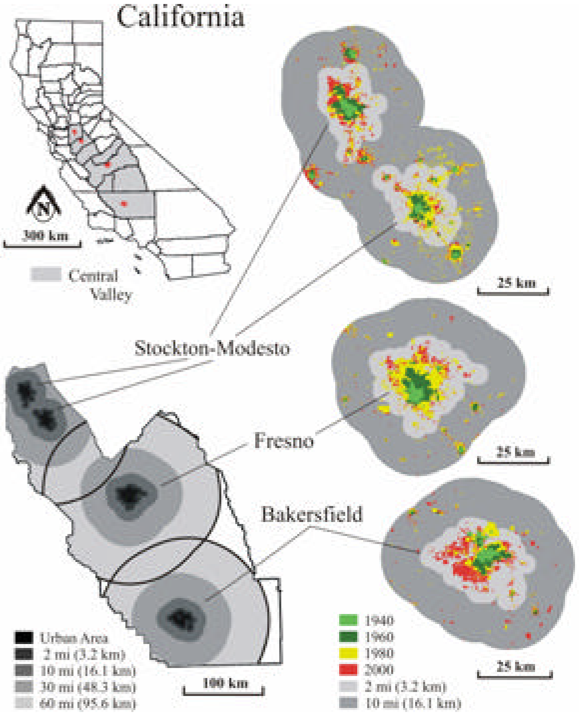

Figure 2: Study area location map showing the historical urbanization of Stockton-Modesto, Fresno, and Bakersfield (Dietzel *et al.*, 2005).

The metric calculations were performed using the public domain software FRAGSTATS version 3.3 (McGarigal *et al.* 2002). Most metrics have fairly simple and intuitive values, such as the urban patch (PD) and edge density (ED), and the measures of mean Euclidean distance (ENN_MN) between individual urban areas. The contagion index (CONTAG) is a general measure of landscape heterogeneity and describes the extent to which landscapes are aggregated or clumped (O'Neill *et al.* 1988). Landscapes consisting of relatively large contiguous patches have a high contagion index. If a landscape is dominated by a relatively large number of small or highly fragmented patches, the contagion index is low. A detailed description spatial metrics can be found in McGarigal *et al.* (2002).

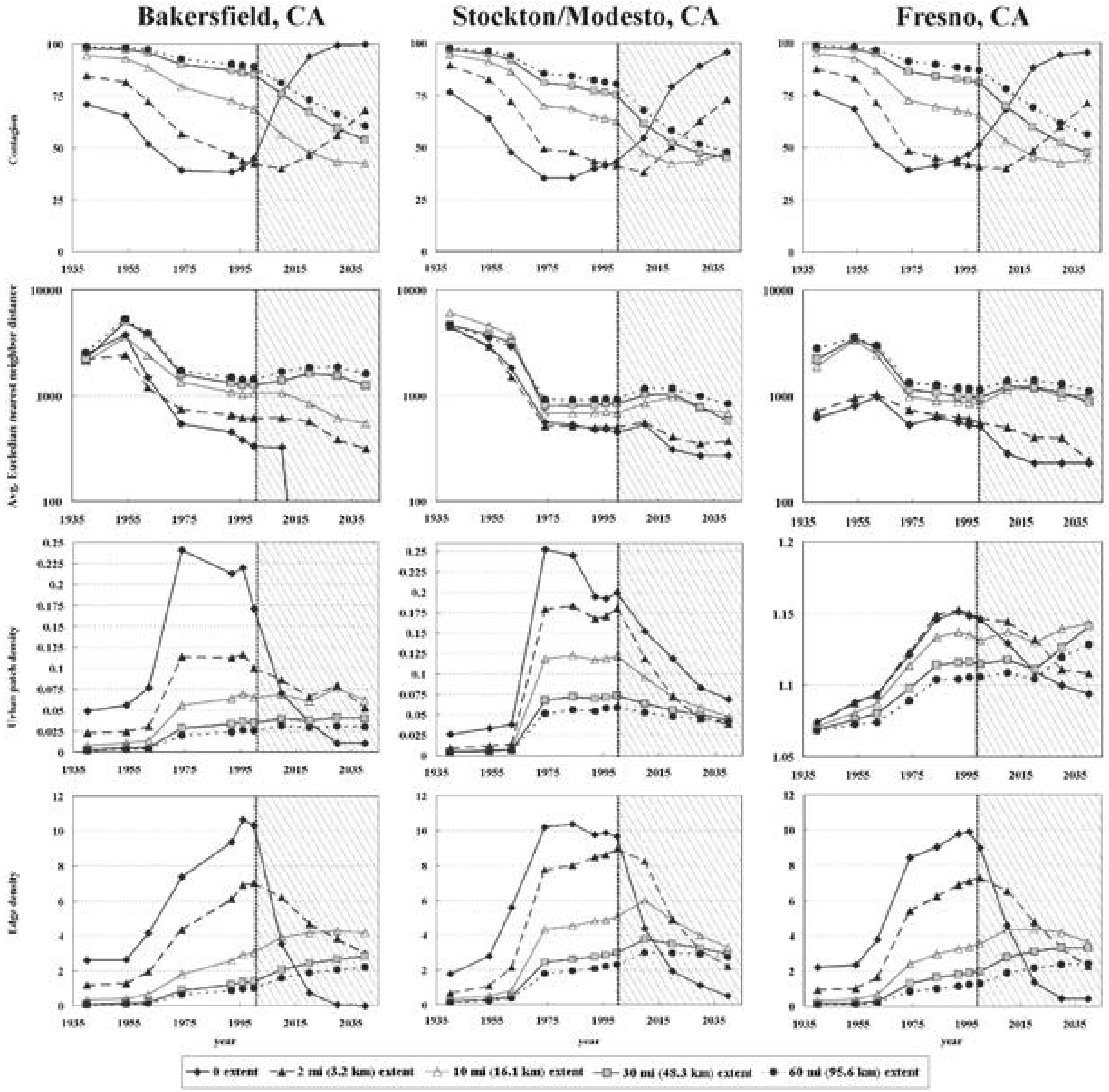

Figure 3: Spatial metric growth signatures for Bakersfield, Stockton-Modesto, and Fresno for multiple concentric ring buffers. The metric values until 2000 were obtained from remote sensing, 2010-2040 is based on model outputs.

Four spatial metrics were used in this study to compare growth signatures for three urbanizing areas (Figure 3.) The different line styles in each graph represent the metric signatures derived for the four different spatial extents, plus the central core as defined by the 2000 Census. The contagion metric is a general measure of landscape heterogeneity and is lowest when the urban/rural configuration is most dispersed and fragmented. For the central area the lowest contagion is found for the year 1974, when the landscape was most heterogeneous. With further expansion of the urban core notice that contagion increases as the landscape homogenizes. The spatio-temporal signature of the contagion metric follows a pattern similar to a sine wave. The general wave shape is evident for all extents, but with varying wavelengths. The wavelength represents the stage of urbanization for each scale, and generally increases with distance from the central core. The average nearest neighbor distance shows a peak in the 1950s and 1960s for all scales. This time period represents the initial phase of diffuse allocation of new development units which are separated by large distances. With the major spread of distinct new urban development units in the late 1960s and 1970s the Euclidian nearest neighbor distances shows an accordant decrease. The system of urban areas grows increasingly dense until the year 2000. For the central urban area the number of patches significantly increased between 1962 and 1974. This increase coincided with the highest rate of diffusive urban sprawl for these areas. The urban expansion is characterized by the diffuse allocation of new development units around the central core. The patch density metric decreases after 1974 as the new individual units grow together and become spatially connected to the urban center. This development results in larger more heterogeneous and fragmented urban patches. The spatial process that generates this general fragmentation pattern is reflected by the edge density metric which peaks in the mid-1990s.

The process of coalescence and expansion into open spaces continues towards the later stage of urbanization. This later stage is indicated by decreasing patch density and edge density in later dates. Also observed in the contagion metric, the patch density metric, and edge density metric, is that they all appear to have similar wave-like shapes for all spatial extents. Except for the ENN-metric, the metric values peak first in the smallest scale and in chronological order the larger scales respond as urbanization progresses outwards from the central core. The sequence of metric development with an early peak of the nearest neighbor distance, followed by a peak in patch density and then in the edge density is evident in each of the metropolitan areas studied.

3. THEORETICAL FRAMEWORK OF URBAN GROWTH

Given a hypothetical schema, the spatial evolution of cities can be described using a general conceptual representation (Figure 4). Urban area expansion starts with a historical seed or core that grows and disperses to new individual development centers. This process of *diffusion* continues along a trajectory of organic growth and outward expansion. The continued spatial evolution transitions to the *coalescence* of the individual urban blobs. This phase transition initially includes development in the open space in interstices between the central urban core and peripheral centers. As this conceptual growth pattern continues, the system progresses toward a saturated state. This "final" agglomeration can be seen as an initial urban core for further urbanization at a less detailed zoomed-out extent. In most traditional urbanization studies this "scaling up" has been represented by changing the spatial extent of concentric rings around the central urban core.

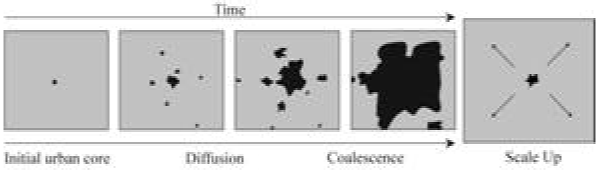

Figure 4: Conceptual sequence of the spatial evolution.

Reconsidering the perspective employed when discussing Figures 3 and 4, this theoretical sequence of growth emulates processes as they are reflected by the signatures of four different spatial metrics (Figure 5). The contagion metric shows the cyclic pattern among the different scales. Urbanization, as it is reflected by the contagion metric, results in a transformation from homogenous non-urban to a heterogeneous mix of urban and non-urban. At some time in the progression of development there is a transition to a homogenous urban landscape. The other three spatial metrics, average Euclidian nearest neighbor distance, urban patch density and edge density, capture spatio-temporal phases. The phases of diffusion and coalesce can be differentiated into two diffusion phases and two coalescence phases. The *first phase, diffusion*, represents the seeding of new development centers. This was referred to earlier with regard to the discussion of the conceptual growth sequence. This first diffusion phase is characterized by a peak in the nearest neighbor distance metric indicating the establishment of peripheral development centers around the original core. The *second phase, diffusion*, is the allocation of a large number of new urban areas in the nascent urban system comprised by the original core and peripheral development centers. The nearest neighbor distance drops and the patch density peaks during this second phase of diffusion. The amount of urban land in the largest patch is the lowest at this point. At the end of this phase the coalescence process starts to show its first significant contribution to the landscape structure.

The low point in the contagion metric marks the transition from diffusion to coalescence. *Coalescence* starts as urban areas aggregate. This is reflected by a decrease in the patch density and edge density metrics and nearest neighbor distances. The terminal point of coalescence is complete urban build out when all, or nearly all, of the available land has been urbanized.

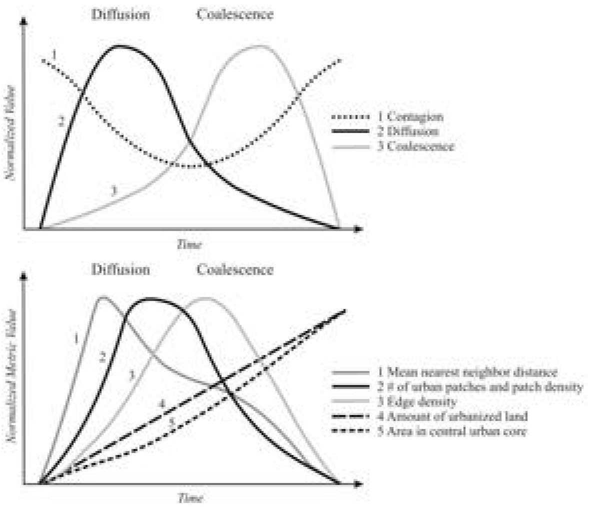

Figure 5: Theoretical spatial metric signatures for a full cycle of urbanization for uniform isotropic growth at a specific scale.

However, the link between empirical measurements (Figure 3) and this theoretical concept (Figure 5) 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 in light of the fact that urban growth is not constant over time and among 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. Exogenous factors (both spatial and thematic) are also playing a part. However, the local variations yield important information about the ongoing processes. The general processes of urbanization (diffusion and coalescence) are evident in the spatial metrics, but the local growth characteristics that contribute to the evolving spatial pattern are not, hence they can be interpreted as “distortions” i.e. amplifications, lagging, or damping in the metric signatures. As in other 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. Again, examples of factors that determine the spatial and temporal variations are the rate of urban growth, topographic constraints, road attraction, growth barriers, exogenous factors such as the business cycle, and planning efforts. Although these factors are quite diverse, there usually is sufficient information and appropriate datasets available to describe them. Therefore it may be possible to account for these distortions and relate observed and theoretical patterns as well as to account for residuals. Given a sufficient representation of local growth characteristics it should be possible to replicate the theoretical growth pattern under “ideal” conditions using a simplified abstract model.

4. A SIMPLE MODEL OF URBAN DYNAMICS

The theoretical framework developed thus far as it fits research perspectives described by Figure 1 has the potential to establish a quantitative link between empirical observation from remote sensing and urban theory. To further elaborate on this relationship a simplified geometric model will be presented that has the potential of generating comparative baseline pattern comparison templates. What is lacking in the framework as it has been developed is a mechanism to isolate the components of observed urban growth patterns analytically. Circles have a long tradition in urban geographic research. Shown in Figure 6 is an illustration of interacting city systems, intended to be descriptive of the interacting scales of socio-economic factors over time. Using circles as a basic geometric shape that represents interacting factors or ranges of influence is also prevalent in contemporary urban geographic research.

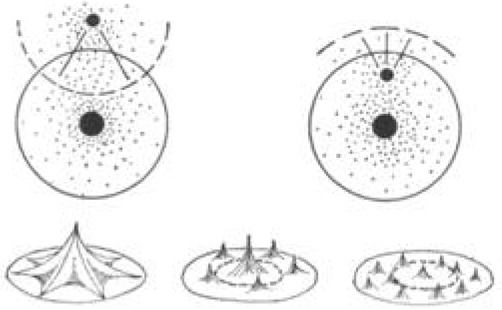

Figure 6: From Guttenburg (1964), *The Tactical Plan Explorations into Urban Structure*, this illustration shows theoretical interactions of two major city systems.

The use of circles to represent the spatial evolution of urban systems, like the hypothetical urbanizing area depicted in Figure 4, is an intuitive leap that superficially seems grossly oversimplified. Albeit abstract, a geographic model based on circles will enable further development of the theoretical framework by defining experimentally ranges of metric values for controlled situations where dynamics can be observed and manipulated.

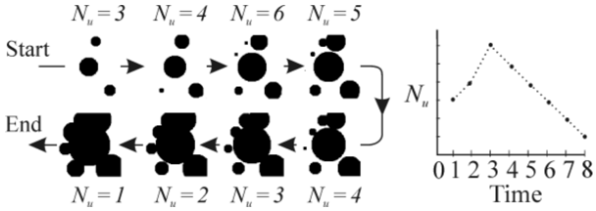

Figure 7: Sequential frames from the simple circle model. The graph on the right shows Nμ, number of agglomerations, through a sequence of time steps.

Figure 7 shows the sequence generated by the prototype model that generates patterns starting from a set of different sized circles dispersed randomly and grown in a varied sequence on an isotropic surface with uniform growth characteristics. This sequence mimics the process of diffusion and coalescence found within the spatial metric values from empirical observations (remotely sensed imagery) shown in Figure 3. This sequence can be seen as further support for the theoretical framework of urban growth harmonics (Dietzel *et al*., 2005, In Press). The outputs of this model can be used to assess spatial metrics based on their ability to capture spatial urban growth characteristics. Values for the number of circles, circle areas, overlap areas, separation distance, edge distance and other metrics can be measured.

This model will be used in future research to observe the pattern signature that results from differing arrangements of seed locations, circle sizes, and origin locations in simulated urban systems. An improved version of the model will contribute a simplified case as a baseline with which indicators can be derived that describe landscape pattern. With these base reference indicators it will be possible to assess different spatial measurement techniques. Beyond this overly simplified model, more complex geometric structures can be incorporated by integrating specific distortions (roads, topography, water, etc.) that constrain or contort patterns in urban development. The complexity of the experimental environment will be increased through the introduction of these distorting factors, which will alter the simplified growth pattern, and allow and understanding of the role that these factors contribute to urban form and structure.

5. CONCLUSION

Through the use of remote sensing, the spatial evolution of urban systems can be described, measured and modeled. This research summary has developed an integrative approach whereby empirical observations can be used for comparative analysis based on spatial metrics. Also incorporated in this research is a bridge between theoretical understandings of the spatial evolution of urban areas, the analytical modeling of systems, and the role at urban remote sensing can play. Contributions in the form of understandings regarding the spatial components of urban growth dynamics with this approach are potentially rewarding and uniquely insightful.

The main objectives of this research are all linked, and relied upon data from remote sensing: (1) use a historical set of remotely sensing imagery as the means of quantitatively assessing the spatial evolution of an urban system; (2) observe patterns in the spatio-temporal metric signatures for the three metropolitan areas within the study area; and (3) develop a theoretical framework helps explain the dynamic evolution of cities through time. An integral part of developing a method for assessing phase-related patterns will be experimenting with the manipulation of the simplified growth model shown in Figure 7, and introducing perturbations. Future research will be testing the hypothesized metric signatures shown in Figure 5 against multiple urban areas and developing an analytically solid means of diagnosing the phases of diffusion and coalescence, thus using remote sensing to validate urban growth theory.

With a controlled experiment it may be possible to characterize the spatial responses to factors that distort the overall patterns. Such a finding may lead to the identification and characterization of commonalities of the urbanization process as well as a means of isolating unique patterns that result from particular factors. Studying the dynamic nature of the urbanization process as it is captured by data sources that are themselves static snapshots, such as from time series remote sensing derived land cover products, involves a difficult set of assumptions. Difficult because they do not lend themselves well to unambiguous identification and description. Some assumptions are however necessary in order to address spatio-temporal dynamics. First, the process of urbanization is in reality continuous and non-uniform, and the temporal scale of analysis is fixed by the dates of the datasets used. Secondly, the spatial resolution of the data sources used for the comparative part of the analysis will also be fixed and thus impart uncertainty regarding any findings and most certainly will influence the calculation of spatial metrics.

The results of this research, and the preliminary development of the theoretical framework based on urban growth phases, provide encouragement for future research. Remote sensing delivers accurate urban mapping capabilities and a wide range of temporal and spatial scales, which are necessary for the validation of urban theory. What is necessary is the articulation of a theoretically sound approach with which to address cross-scale urban dynamics. The results presented make it clear that the combination of remotely sensed data and spatial measurements (metrics), have the potential to answer that cross spatial scales in urban geography and aid in the development and validation of new urban theory.

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