WORKING PAPERS

EAST-WEST CENTER WORKING PAPERS

Environment, Population, and Health Series

No. 2, October 2014

Quantify Spatiotemporal Patterns of Urban Growth in Hanoi Using Time Series Spatial Metrics and Urbanization Gradient Approach

Duong Nong, Christopher Lepczyk, Tomoaki Miura, Jefferson Fox, James Spencer, and Qi Chen

EAST-WEST CENTER
COLLABORATION • EXPERTISE • LEADERSHIP

Environment, Population, and Heath Series

No. 2, October 2014

Quantify Spatiotemporal Patterns of Urban Growth in Hanoi Using Time Series Spatial Metrics and Urbanization Gradient Approach

Duong Nong, Christopher Lepczyk, Tomoaki Miura, Jefferson Fox, James Spencer, and Qi Chen

Duong Nong is a PhD candidate at the Department of Natural Resources and Environmental Management at the University of Hawaiʻi at Mānoa and a recipient of the EWC-NSF Doctoral Fellowship Program.

Christopher Lepczyk is Professor of Ecosystem Management, Wildlife Ecology, Landscape Ecology, Human Dimensions in the Department of Natural Resources and Environmental Management at the University of Hawaiʻi at Mānoa.

Tomoaki Miura is Professor of Natural Resource Inventory Remote Sensing and GIS in the Department of Natural Resources and Environmental Management at the University of Hawaiʻi at Mānoa. His current works focus on Development of a satellite-based monitoring system of tropical ecosystem dynamics in Hawaiʻi.

Jefferson Fox is a Senior Fellow at the East-West Center in Honolulu. He studies land-use and land-cover change in Asia and the possible cumulative impact of these changes on the region and the global environment.

James H. Spencer is Professor of City & Regional Planning, and Chair of Clemson's Department of Planning, Development, and Preservation. His current research focuses on international urbanization and planning issues, with a particular focus on water supplies, infrastructure and inequality.

Qi Chen is Professor of Remote Sensing and GIS in the Department of Geography at the University of Hawaiʻi at Mānoa. Dr. Chen had his BS (1994) and MS (2001) in Geography from Nanjing University, and PhD (2007) in environmental science from UC, Berkeley.

This publication is a product of a doctoral dissertation funded by the EWC-NSF Doctoral Fellowship Program. The paper was supervised by and jointly written with UH Mānoa, EWC researchers, and other scholars.

EastWestCenter.org/publications

Publications Office| East-West Center
1601 East-West Road | Honolulu, Hawaiʻi 96848-1601

Tel: 808.944.7145 | Fax: 808.944.7376
EWCBooks@EastWestCenter.org

EAST-WEST CENTER
COLLABORATION • EXPERTISE • LEADERSHIP

Quantify Spatiotemporal Patterns of Urban Growth in Hanoi Using Time Series Spatial Metrics and Urbanization Gradient Approach

Duong Nong[(1)], Christopher Lepczyk[(1)], Tomoaki Miura[(1)], Jefferson Fox[(2)], James Spencer[(3)], Qi Chen[(4)]

[(1)]Department of Natural Resources and Environmental Management, University of Hawaii at Manoa, HI 96822, USA.
[(2)]East-West Center, 1601 East-West Road, Honolulu, HI 96848, USA
[(3)]Department of Planning, Development, and Preservation, Clemson University, SC 29634, USA
[(4)]Department of Geography, University of Hawaii at Manoa, Honolulu, HI 96822, USA

1. Introduction

The year of 2010 was the first time in human civilization that the urban population had reached 3.5 billion people or crossed the 50% mark and continued to grow with no sign of slowing down especially for developing countries in Africa and Asia (UN, 2011). In 1800, only few percent of the world population lived in urban areas, but quickly increased to 14% in 1900 and then 30% in 1950 (Platt, 1994). Clearly, urban areas have become one of our primary habitats; therefore, urban sustainability is becoming more important than ever.

The increasing share of the urban population has profound environmental, economic, and social implications for the world's future. The most notable aspect of urbanized areas is that they cover only about 3% of the earth's land surface but their influences on the functioning and services of local and global ecosystems are enormous (Alberti, 2005; Berling-Wolff & Wu, 2004; Grimm, Grove, Pickett, & Redman, 2000; Lester, 2002; Wu, 2004). Urbanized areas account for more than 50% of the world population, more than 78% of carbon emissions, about 60% of residential water use, and 76% of the wood used for industrial purposes (Brown, 2001; Grimm et al., 2008; Wu, 2008). The "ecological footprint"[1] of a city can be tens to hundreds of times as large as its physical size (M. A. Luck, Jenerette, Wu, & Grimm, 2001; Rees & Wackernagel, 1996). Increasing urbanization is also thought to be one of the human-induced changes of biogeochemical cycles, hydrologic processes, and landscape dynamics (Melillo, Field, & Moldan, 2003) and a cause of the rapid loss of farmland (Lin & Ho, 2003). Therefore, the relationships between urbanization and ecological effects have gained a great attention in

[1] The area of productive land and aquatic ecosystems that is required to produce the resources used, and to assimilate the wastes produced, by a defined population at a specified material standard of living, wherever that land may be located.

recent studies (Antrop, 2004; Carsjens & van Lier, 2002; Herold, Goldstein, & Clarke, 2003; Sui & Zeng, 2001). In many parts of the world, urbanization is also taking place with an increase of social inequity and poverty (Wu, 2010). Considering the immense impacts of urbanization on ecosystems and human in the foreseeable future, monitoring and understanding the changing patterns of urban growth is important.

The relationship of urban morphology and its function have been recognized in the context of urban planning, urban economics, urban geography, and urban sociology, much of which are confined to the spatially-explicit land-use models of Von Thunen (1875), Park et al. (1925), Muth (1961), and Alonso (1964) (Bertaud, 2004). Dynamics of urban pattern have been extensively studied in the past century and many urban theories developed, such as the concentric zone theory by Burgess (1925); the sector theory by Hoyt (1939); or multiple nuclei theory by Harries and Ullman (1945) (M. Liu et al., 2014). Since the 1960s, several new approaches from non-equilibrium and non-linear system perspectives have been studied and widely used to analyze, model and forecast the pattern of urban systems (M. Luck & Wu, 2002). These theories and approaches have provided a deeper understanding of urban structure and dynamics and have widely been used to model urban systems. However, most of the models remained hypothetical and are incapable of describing the spatiotemporal details of urban pattern dynamics. In reality, the urban systems have great complexity, i.e., spatial heterogeneity of various driving factors can cause different growth patterns among the different parts of the same city (Xu et al., 2007). Thus, planning and managing urban landscape must consider the ecological, physical and social components of the whole system (Botequilha Leitão & Ahern, 2002; Zipperer, Wu, Pouyat, & Pickett, 2000). The advancement of remote sensing technology, together with the development of landscape metrics, provides a potential way of understanding how urban patterns evolve and change over time (Herold, Couclelis, & Clarke, 2005; Herold et al., 2003; Herold, Scepan, & Clarke, 2002).

Pattern and process are well perceived as having a close relationship where “process creates, modifies, and maintains pattern and pattern constrains, promotes, or neutralizes process” (H. Li & Wu, 2004). Studies of landscape pattern and process are motivated by the concept that ecological processes are possibly connected to, and driven by coarse-scale ecological patterns (Gustafson, 1998). However, these studies seldom link temporal landscape patterns to gradient analysis to investigate the specific process-related differences (Yu & Ng, 2007). From an ecological point of view, the urban–rural gradient represents the structural and functional differences of transitional patches which can capture the spatio-temporal complexity of urban dynamics. Therefore, integrating ecological, social, and physical variables in different disciplines, the gradient approach is a useful tool for studying the ecological consequences of urbanization (Foresman, Pickett, & Zipperer, 1997; McDonnell, Pickett, & Pouyat, 1993; Medley, McDonnell, & Pickett, 1995).

The use of an urbanization gradient approach has improved our understanding of how organisms respond to the continuous process of urbanization with humans as an integral part of urban ecosystems (McDonnell & Pickett, 1990). The studies of urban-rural gradients have predominantly been quantified using concentric zones from the urban core outwards (Kroll, Müller, Haase, & Fohrer, 2012; Pillsbury & Miller, 2008; Sadler, Small, Fiszpan, Telfer, & Niemelä, 2006), and objective quantification using GIS methods (Hahs & McDonnell, 2006; Hunt et al., 2013; Lockaby, Zhang, McDaniel, Tian, & Pan, 2005; Williams, McDonnell, & Seager, 2005).

Combining landscape metrics with the gradient paradigm, the spatial properties of land use changes along the specific transect have been systematically investigated in recent studies (M. Luck & Wu, 2002; Zhang, Wu, Zhen, & Shu, 2004). However, the majority of spatially explicit landscape metrics studies focusing on the analysis of urban form are applied on a single U.S. city (Seto & Fragkias, 2005). For example, Jenerette and Wu (2001) used landscape metrics without partitioning space to describe urban form and to validate their urban growth simulation model for the Phoenix, Arizona metro area; M. Luck and Wu (2002) used gradient analysis for the static landscape study of the same metropolitan area; Herold et al. (2002) and (2003) utilized a time series of landscape metrics for test areas and city administrative units in Santa Barbara, California. Furthermore, only one single data set was employed for the urban-rural gradient so they did not adequately reflect the temporal differences of intra-city urban structure. Some recent studies have addressed this issue by evaluating a time series of gradients along multiple transects in China cities such as Schneider, Seto, and Webster (2005), Yu and Ng (2007), and Xu et al. (2007). To move forward, in our study we attempted to simultaneously quantify the speed, growth modes, and resultant changes in landscape pattern of urbanization across multiple spatio-temporal levels of Hanoi city. In doing so, we were able to re-examine some urban theories and hypotheses in a hierarchical context. For example, Dietzel, Herold, Hemphill, and Clarke (2005) noted that urbanization is a cyclic process of two alternating phases: diffusion (dispersed or spontaneous development) and coalescence (dominated by infilling). This hypothesis is conceptually related to the wave-like urban development (Boyce, 1966; Koreclli, 1970). Jenerette and Potere (2010) study also suggests that urbanization tends to increase the spatial homogeneity of urban landscape structure, which apparently repeats the hypothesis of biotic homogenization by urbanization (McKinney, 2006; Olden & Rooney, 2006). The geometric attributes as well as spatial distribution vary among the different growth types and more importantly, development direction and speed may be different. The study of urban typology is meaningful for urban theory and modeling (M. Luck & Wu, 2002).

In this paper, we combined multi-temporal remotely sensed data with landscape indices to investigate urban growth patterns of the Hanoi capital city of Vietnam from 1993 to 2010. Furthermore, the quantitative composition and distribution of the growth types were analyzed during the different periods. Afterwards, the distance effect on urban growth pattern from the center and fringe of urban patches was studied using buffering analysis. Our objectives were to quantify the speed, growth modes, and resultant changes in landscape pattern of urbanization and to examine the diffusion-coalescence and the landscape structural homogenization processes in Hanoi capital city.

2. Data Processing and Method

2.1. Study area and data sources

Our study analyzes the spatial pattern of the built-up land for Hanoi capital city. The land use land cover of the study area was first created using Support Vector Machine classification algorithm of Landsat multi-temporal image stacks from 1993 to 2010. Our land use and land cover maps include seven classes: water, forest, agriculture, built-up, urban change 1993-2001, urban change 2001-2006 and urban change 2006-2010. As we focused only on built-up land use categories, landscape heterogeneity was simplified and represented in four classes: (i) built-up (urban footprint) that existed before 1993 (including residential, commercial, park, and industrial areas); (ii) urban change between 1993 and 2001; (iii) urban change between 2001 and 2006; (iii) urban change between 2006 and 2010, and, we ignored other land cover classes such as water, forest and agriculture (for more detail about the study area and method, please refer to Duong et al., 2014).

2.2. Quantifying spatiotemporal patterns of urbanization using landscape metrics

Landscape metrics or indices can be defined as quantitative indices to describe structures and pattern of a landscape (McGarigal & Marks, 1995). 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) and Xia and Clarke (1997). Important applications of landscape metrics include the detection of landscape pattern, biodiversity, and habitat fragmentation (Gardner, O'Neill, & Turner, 1993), the description of changes in landscapes (Dunn, Sharpe, Guntenspergen, Stearns, & Yang, 1991; Frohn, McGwire, Dale, & Estes, 1996), and the investigation of scale effects in describing landscape structures (O'neill et al., 1996; Turner, O'Neill, Gardner, & Milne, 1989; Wu, 2004). Other investigations of landscape metrics 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 & Marks, 1995).

Literally, there are hundreds of quantitative measures of landscape pattern that have been proposed to quantify various aspects of spatial heterogeneity (Baker & Cai, 1992; McGarigal & Marks, 1994). As possible ambiguity might be introduced by landscape indices, we only chose those that have explicit meanings in relation to the behavior of urban patches (diffusion or coalescence) (H. Li & Wu, 2004; Tischendorf, 2001). In this study, overall changes in urban pattern were analyzed using a set of selected landscape indices: Patch Density (PD), Edge Density (ED), Landscape Shape Index (LSI), Largest Patch Index (LPI), Area-weighted Mean Euclidean Nearest-Neighbor Distance (ENN_AM) and Area-weighted Mean Patch Fractal Dimension (FRACT_AM) (McGarigal, Cushman, Neel, & Ene, 2002)). The landscape indices were calculated with public domain software FRAGSTATS version 4.3 (McGarigal et al., 2002).

Table 1: Landscape metrics selected for spatial pattern analysis

No	Landscape metrics	Range	Description
1	Patch Density (PD)	PD ≥ 0, without limit	PD equals the number of patches in the landscape divided by total landscape area, multiplied by 10,000 (to convert to hectares).
2	Edge Density (ED)	ED ≥ 0, without limit	Edge density (ED) equals the sum of the lengths (m) of all edge segments in the landscape, divided by the total landscape area (m^2), multiplied by 10,000 (to convert to hectares). ED standardizes edge to a per unit area basis that facilitates comparisons among landscapes of various sizes.
3	Landscape Shape Index (LSI)	LSI ≥ 1, without limit The larger LSI the more irregular shape of the landscape.	Normalized ratio of edge (i.e., patch perimeters)to area (class or landscape) in which the total length of edge is compared to a landscape with a standard shape (square) of the same size and without any internal edge; values greater than one indicate increasing levels of internal edge and corresponding decreasing aggregation of patch types.

4	Largest Patch Index (LPI)	0 < LPI≤100 The larger LPI, the larger share of the largest patch in the landscape and more compact landscape	LPI equals the area (m^2) of the largest patch of the corresponding patch type divided by total landscape area (m^2), multiplied by 100 (to convert to a percentage). LPI approaches 0 when the largest patch of the corresponding patch type becomes increasingly smaller. LPI = 100 when the entire landscape consists of a single patch of the corresponding patch type; that is, when the largest patch comprises 100% of the landscape.
5	Area-weighted Mean Euclidean Nearest-Neighbor Distance (ENN_AM)	ENN_AM ≥ 0, without limit The larger ENN_AM the more patch isolation	Nearest-neighbor distance is defined as the distance from a patch to a neighboring patch of the same or different class, based on the nearest cell center-to-cell center. That is, the distance between the two closest cells from the respective patches, based on the distance between their cell centers. Here, nearest neighbor distance is defined using simple Euclidean geometry as the shortest straight-line distance between the focal patch and its nearest neighbor of the same class. ENN is perhaps the simplest measure of patch context and has been used extensively to quantify patch isolation. ENN_AM equals the sum (m), across all patches in the landscape, of the nearest neighbor distance of each patch multiplied by the proportional abundance of the patch (i.e., patch area divided by the sum of patch areas).
6	Area-weighted Mean Patch Fractal Dimension (FRACT_AM)	1≤ FRACT_AM ≤2 The larger FRACT_AM the more shape complexity of individual patches	FRACT_AM equals the sum, across all patches of the corresponding patch type, of 2 times the logarithm of patch perimeter (m) divided by the logarithm of patch area (m^2), multiplied by the patch area (m^2) divided by total class area (sum of patch area for each patch of the corresponding patch type); the raster formula is adjusted to correct for the bias in perimeter (Li 1990). A fractal dimension greater than 1 for a 2-dimensional landscape mosaic indicates a departure from a Euclidean geometry (that is, an increase in patch shape complexity). FRACT_AM approaches 1 for shapes with very simple perimeters, such as circles or squares, and approaches 2 for shapes with highly convoluted, plane-filling perimeters.

As a non-spatial overall measure of urbanization in terms of its spatial extent, the annual growth rate of urbanized land was computed using the equation developed by (Puyravaud, 2003).

Equation 1: *Annual Urban Growth Rate*

$$r = \frac{1}{t2-t1} ln \frac{A_{t2}}{A_{t1}}$$

where A_{t2} and A_{t1} are the built-up land area in year t_2 and year t_1, respectively.

This formula has been standardized to calculate the annual rate of forest change (Puyravaud, 2003) and has been wildly used to quantify urban growth (Seto & Fragkias, 2005). The above equation assumes that urban growth is an exponential process, and is mathematically identical to the annual rate of compound interest.

2.3. Typology of urban growth

A Landscape Expansion Index (LEI) was applied to quantitatively distinguish the three growth types: infilling, edge expansion and spontaneous growth. In addition, the LEI can also be used to describe the process of landscape pattern changes within two or more time points. The LEI is determined by shared boundary between newly grown patches and previous urban footprint using the following equation:

Equation 2: *Landscape Expansion Index*

$$LEI = \frac{Lc}{P}$$

where Lc is the length of the common boundary of a newly grown urban area and the pre-growth urban patches, and P is the perimeter of this newly grown area (Fig. 1). Urban growth type is identified as infilling when LEI ≥ 0.5, edge-expansion when 0 <LEI< 0.5, and spontaneous growth when LEI= 0 which indicates no common boundary. The three growth types are illustrated in Fig. 1.

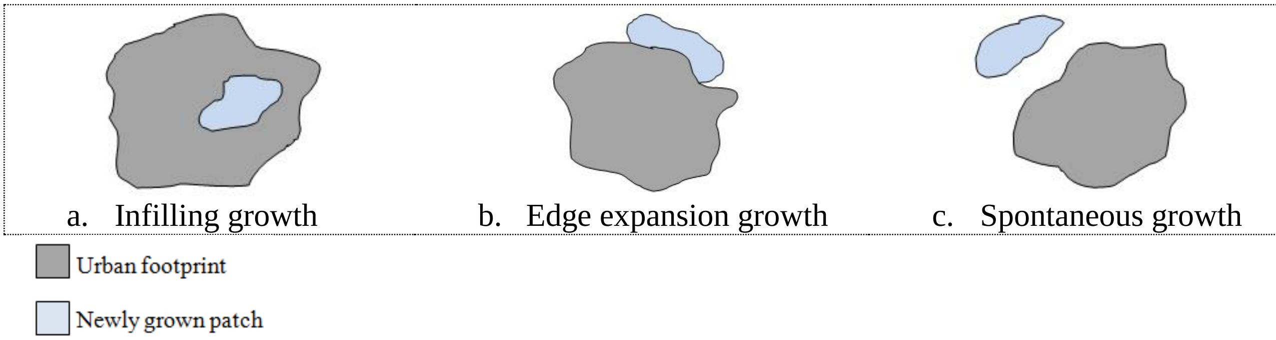


Figure 1: *Infilling, edge expansion, and spontaneous growth types*

To get a sense of the relative dominance among the different forms across a landscape or overtime, we computed the Area-weighted mean expansion index (AWMEI):

Equation 3: *Area-weighted mean expansion index (AWMEI)*

$$AWMEI = \sum_{i=1}^{N} LEIi * \left(\frac{ai}{A}\right)$$

Where LEIi is the value of LEI for a newly growth patch i, a_i is the area of this new patch, and A is the total area of all these newly growth patches. Larger values of AWMEI correspond to more compact urban growth while smaller values of AWMEI imply the prevalence of leapfrogging or spontaneous development or urban sprawl (X. Liu et al., 2010).

2.4. Urban-rural gradient analysis

In order to quantify the scale and impact of urbanization, this study applied the buffer gradient analysis. We used a predefined urban core located at Hoan Kiem Lake, Hoan Kiem district as it is one among the first four urban districts of Hanoi. Then, twelve buffer zones of five kilometers interval were created around the urban core until it completely covered the entire Hanoi boundary (Fig. 2). We defined a five kilometer buffer interval because the contiguous urban districts in 1993 (the beginning of our study period) are encompassed within a radius of five kilometers. Within each buffer zone, we calculated annual urban growth rate and analyzed the selected spatial metrics described in Table 1 and three landscape expansion indices (infilling, edge-expansion, and spontaneous growth) to understand their gradient changing characteristics.

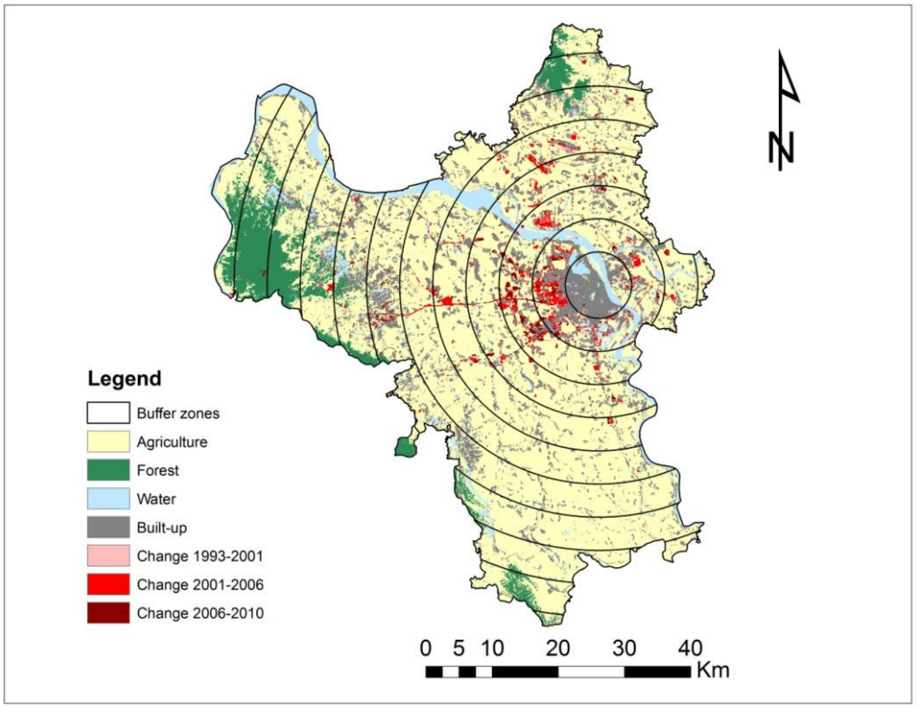


Figure 2: *Multiple buffer zones of 5 kilometers interval from the Hanoi center*

3. Results

3.1. Speed of urbanization at different buffer distances

Overall, from 1993 to 2010, the built-up land in the entire study area increased gradually from 503 to 631 km^2 which is from 15% to 20% of the total land area (Fig. 3). Then we computed the annual growth rate of built-up land for three time periods (1993-2001, 2001-2006, and 2006-2010) and for 12 buffer zones of 5 kilometers interval from the city center (Fig. 4).The results showed that speed of urbanization is different between the study periods and depending on distance from the urban center.

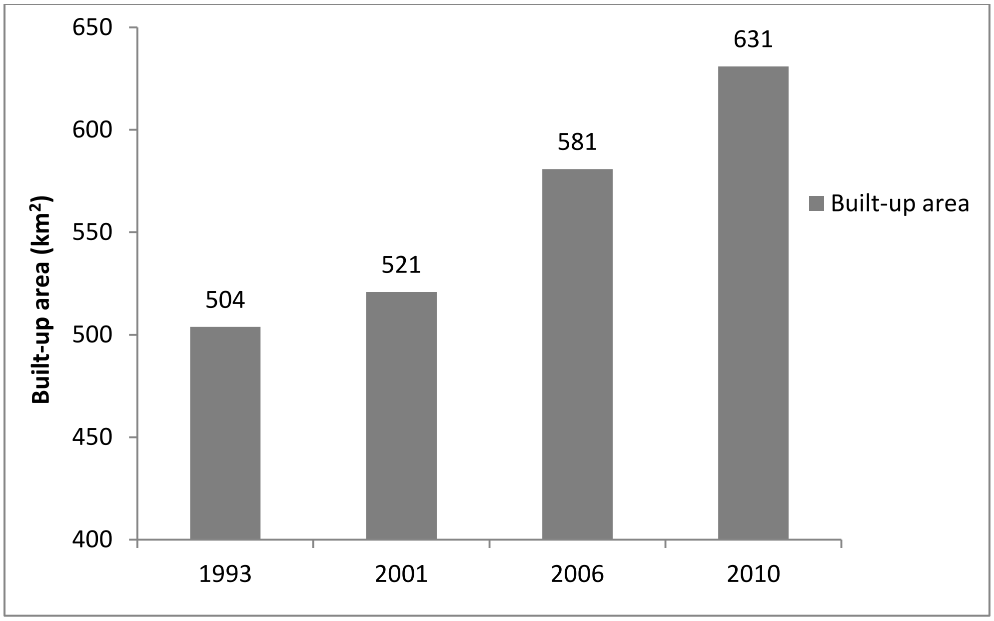


Figure 3: *Built-up area overtime of Hanoi*

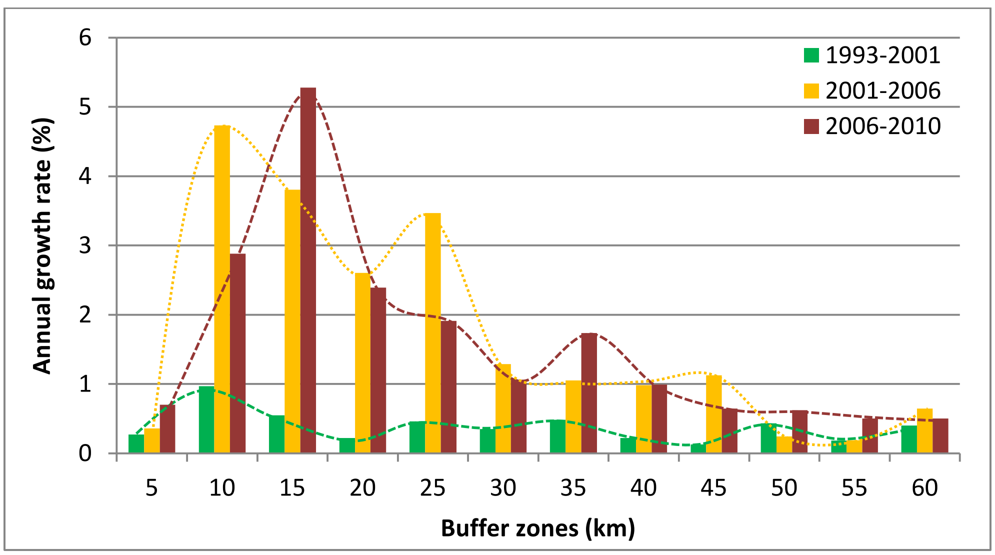


Figure 4: *Annual growth rate of built-up area across different buffer zones*

Across all 12 buffer zones and over three time periods, the annual growth rate ranged from as little as 0.12% to 5.27%, with substantially higher values for 2001-2006 and 2006-2010. The annual growth rate also differed with the highest value being between 10 to 35 km buffer zones and the lowest values being within 5 km buffer zone (urban core zone) and between 35 to 60 km buffer zones.

3.2. Different urban growth modes across distance and time

The urbanization in the study area resulted in a combination of all three urban growth processes (Fig. 1): infilling, edge-expansion, and spontaneous development which were classified according to the LEI values calculated from equation 2. Over 17 year period, from 1993 to 2010, the relative dominance of three urban modes of urbanization had changed whereas both the new urban areas emerged and the old ones expanded. As the result, urban cluster evolved, enlarged, and coalesced, and consequently formed the Hanoi urban agglomeration as today. Overall three periods, all over the landscape was dominated by edge expansion and followed by infilling growth mode in terms of both area and number of patches (Fig. 5). Overtime, the infilling growth decreased. In contrast, we observed an increasing trend of edge expansion mode. Spontaneous growth mode changed a little throughout 17 years.

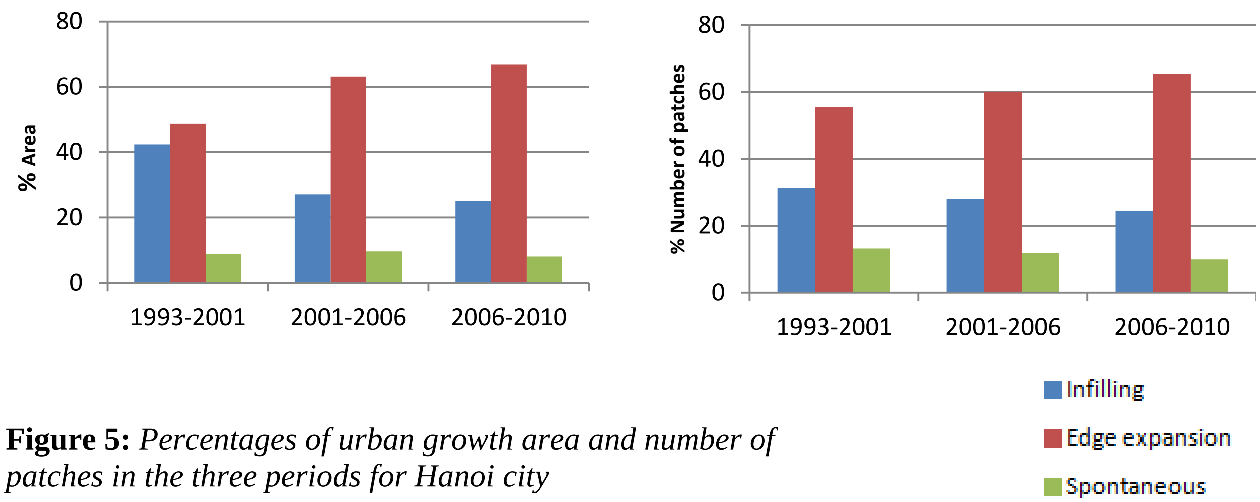
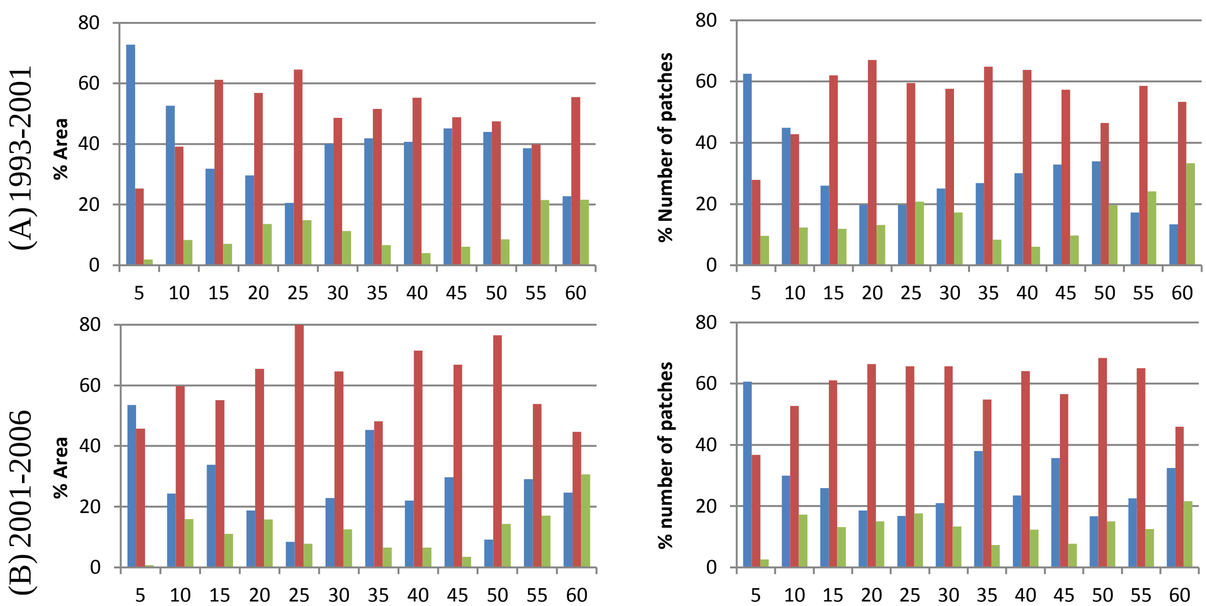


Figure 5: *Percentages of urban growth area and number of patches in the three periods for Hanoi city*

To understand the change behavior of urban growth mode with regard to distance to the urban center, we analyzed the urban growth modes in each buffer zone. In terms of urbanized area and number of patches, the urban landscape showed distinct growth patterns in different buffer zones (Fig. 6 [A], [B], [C]). In the first period (1993-2001), the 5 and 10 km buffer zones were dominated by the infilling growth types while the other buffer zones were dominated by the edge expansion growth type. In the second period (2001-2006), major urban growth mode of the 10 km buffer zone has shifted from infilling to edge expansion. Infilling still dominated in the 5 km buffer zone. In the third period (2006-2010), however, the urban growth mode in the 5 km buffer zone shifted to the dominance of edge-expansion growth mode and the 35 km buffer zone is in reverse trend where it shifted from edge-expansion to infilling dominance growth mode. Thus, there were temporal switches in urban growth in the 5, 10 and 35 km buffer zones between three time periods.

At different time periods, the relative dominance of the three growth modes in each buffer zone showed different proportions between the patch area and patch number representations (Fig. 6). For example, in the period 2006-2010, at the 35 km buffer zone, the percentage area of infilling is highest but the percentage number of infilling patches is not at the same level. This indicates the larger patch size of infilling growth mode as compared to other growth modes (edge-expansion and spontaneous growth). The complementary characteristic of percentage area and percentage number of patch of each growth mode allows us to justify different urban morphologies. The area-weighted mean expansion index (AWMEI) (equation 3) is a synthesized index where it takes into account different growth modes, number of patches and area of patches to justify the relative dominance among the three urban growth modes over three time periods and twelve buffer zones. The spatial and temporal profile of the AWMEI (Fig. 7), averaged for all communes in each buffer zone, showed a general descending trend of the AWMEI, except at the 35 km buffer zone where the trend is ascending. In the 10 to 25 km buffer zones, the urban morphologies reveal a distinct trend where they all showed a more compact growth in the third period (2006-2010) compared to the second period (2001-2006). In each buffer zone, the smaller AWMEI reflected the relatively higher dominance by edge expansion and spontaneous growth overtime, while the larger value of AWMEI indicated a more compact development trend due to the increased dominance by infilling overtime.



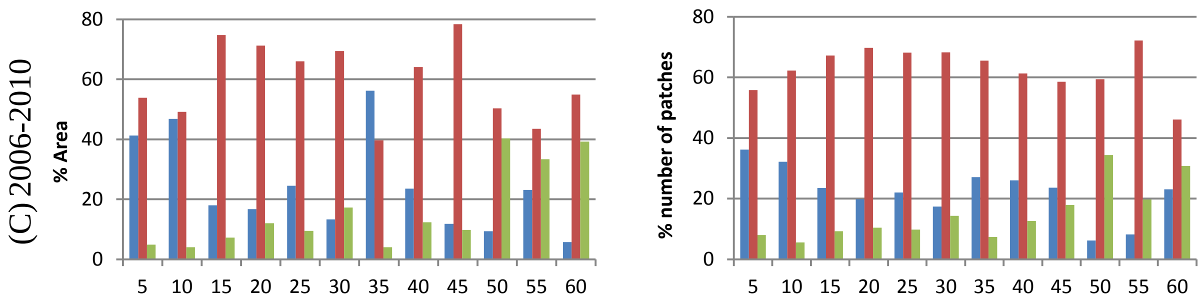


Figure 6: *Percentages of urban growth area and percentage number of patches for three urban growth modes in three time periods for twelve buffer zones*

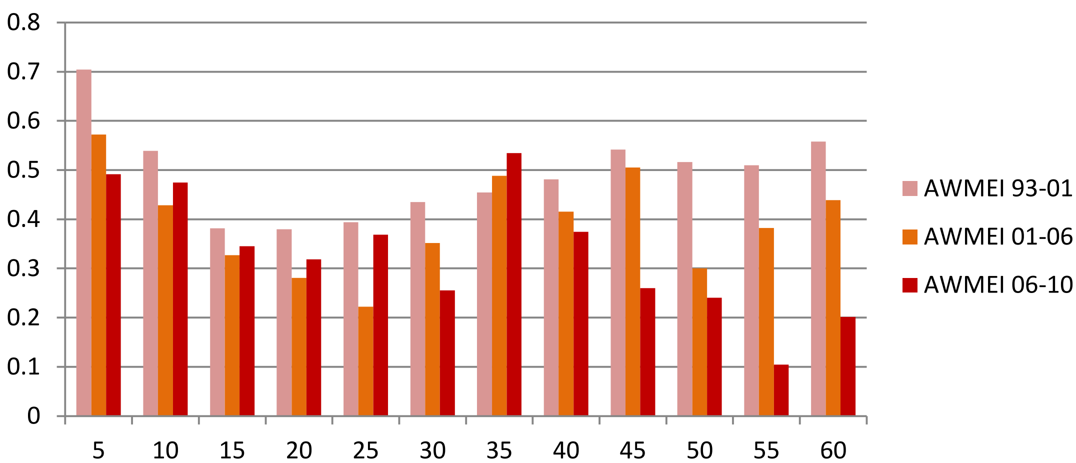


Figure 7: *Spatial and temporal profile of the area-weighted mean expansion index for twelve buffer zones*

3.3. Landscape structure and changes during urbanization

To understand the general landscape pattern of the study areas in different buffer zones, we calculated the mean for each selected landscape metric over the three periods (Fig. 8). The results showed that patch density and edge density increase as the buffer distance increase and the 5 km buffer zone has the lowest patch density and edge density. Landscape Shape Index is generally high between the 10 to 30 km buffer zone which indicates a more complicated landscape shape in these buffer regions as compared to others. The Largest Patch Index (LPI) is an indicator of degree of landscape fragmentation. The LPI values are smaller in between 15 to 30 km buffer zones. The largest patch in the 15 to 30 km buffer zones comprises only 4.5% to 10.6% of the landscape, whereas in the 5 km buffer zone it comprises 81.3% of the landscape. Thus, the LPI indicates that urban landscape is fragmented into smaller patches in the 15 to 30 km buffer zones as compared to the others. The Area-weighted Mean Euclidean Nearest-Neighbor Distance (ENN_AM) is a measure of landscape configuration because it deals explicitly with the relative locations and arrangements of patches. The values of ENN_AM appear to be higher in between 15 to 35 km buffer zones. As the result, patches in between 15 to 35 km buffer zones are further apart or more isolated from each other, especially at 20 and 35 km buffer zones. The Area-weighted Mean Patch Fractal Dimension (FRACT_AM) quantifies the degree of complexity of the planar shapes. The FRACT_AM values are higher in between the 5 to 35 km buffer zone. This indicates that the patch level shape complexity is higher where it closer to the urban center and reduced as it goes further from the urban center indicated by the increased buffer distance. The spatial profiles of different landscape metrics, therefore, have revealed a distinction landscape pattern along the urban-center based buffer gradient.

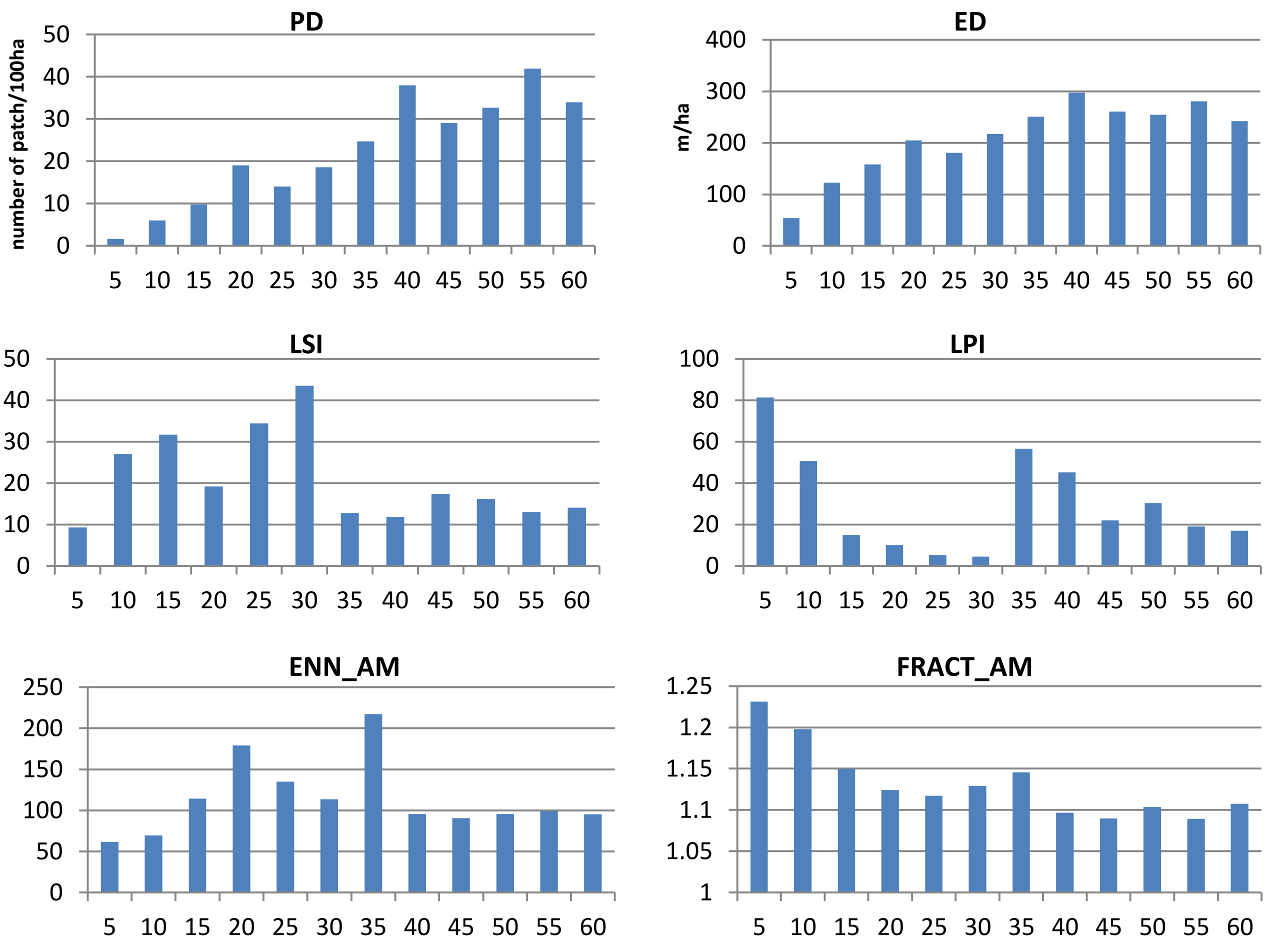
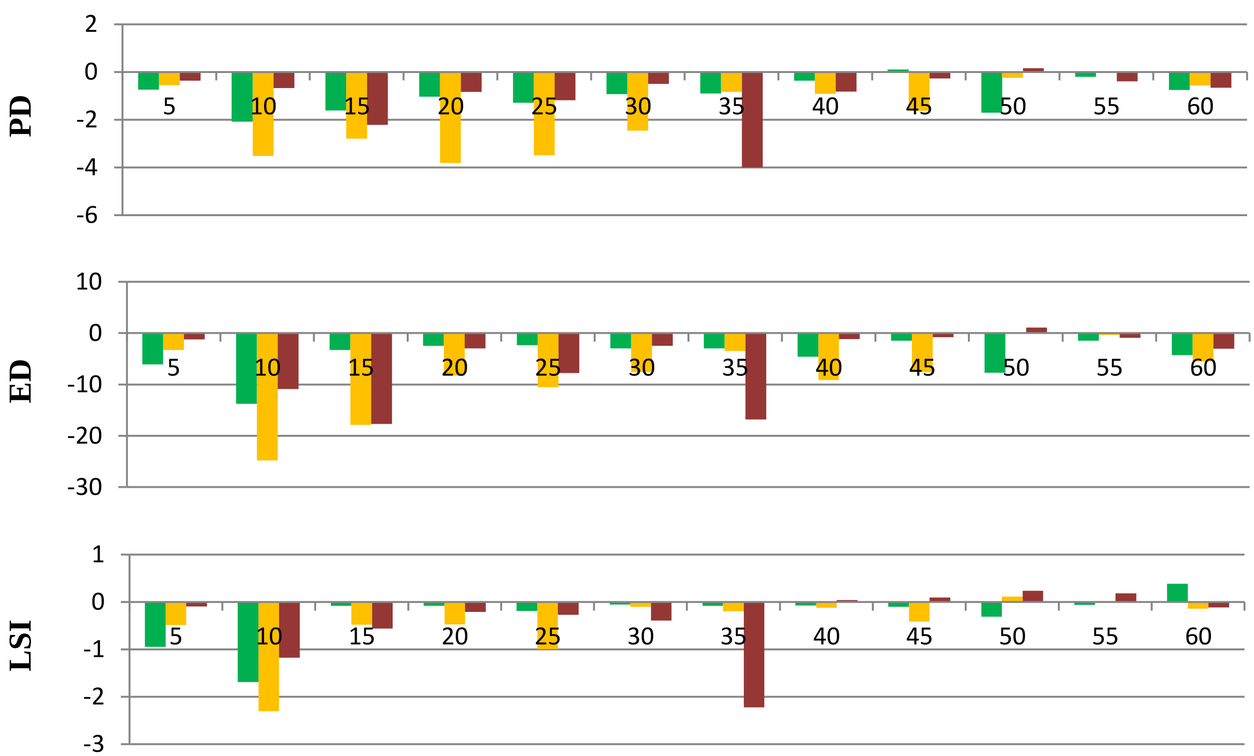


Figure 8: *Mean selected landscape metrics over three periods and across different buffer zones*

To quantify how landscape pattern changed during urbanization, we computed the difference in each landscape metric across the three time periods using following simple equation: Difference in landscape metric i = Landscape metric i (t_2) – Landscape metric i (t_1). For a given landscape metric, an increase in its value from t_1 to t_2 leads to a positive difference, and a decreases in its value from t_1 to t_2 results in a negative difference. Our results in Figure 9 show that major changes in represented landscape metrics happen in between the 5 to 35 km buffer zones. For each landscape metric, trend and magnitude of the changes are different among three time periods and across different buffer zones. Over three time periods, the patch density (PD) and edge density (ED) have decreased indicated by negative difference between time periods, except for the 35km buffer zone between the period of 2006-2010, the PD and ED have increased. These results suggest that the degree of landscape fragmentation have reduced overtime. The landscape shape index (LSI) also reduces within 5 to 40 km buffer zones and has some sign of slight increase from the 45 km buffer zone. The decrease of LSI in the 5 to 40 km buffer zones indicates that overtime the shape of the landscape become closer to the regular-square and circle shape. The largest patch index (LPI) has increased in the 10, 15 and 35 km buffer zones while it remains quite stable in other places. The increase of LPI overtime in these buffer zones reveals the prevalence of infilling and edge expansion during the urbanization process.



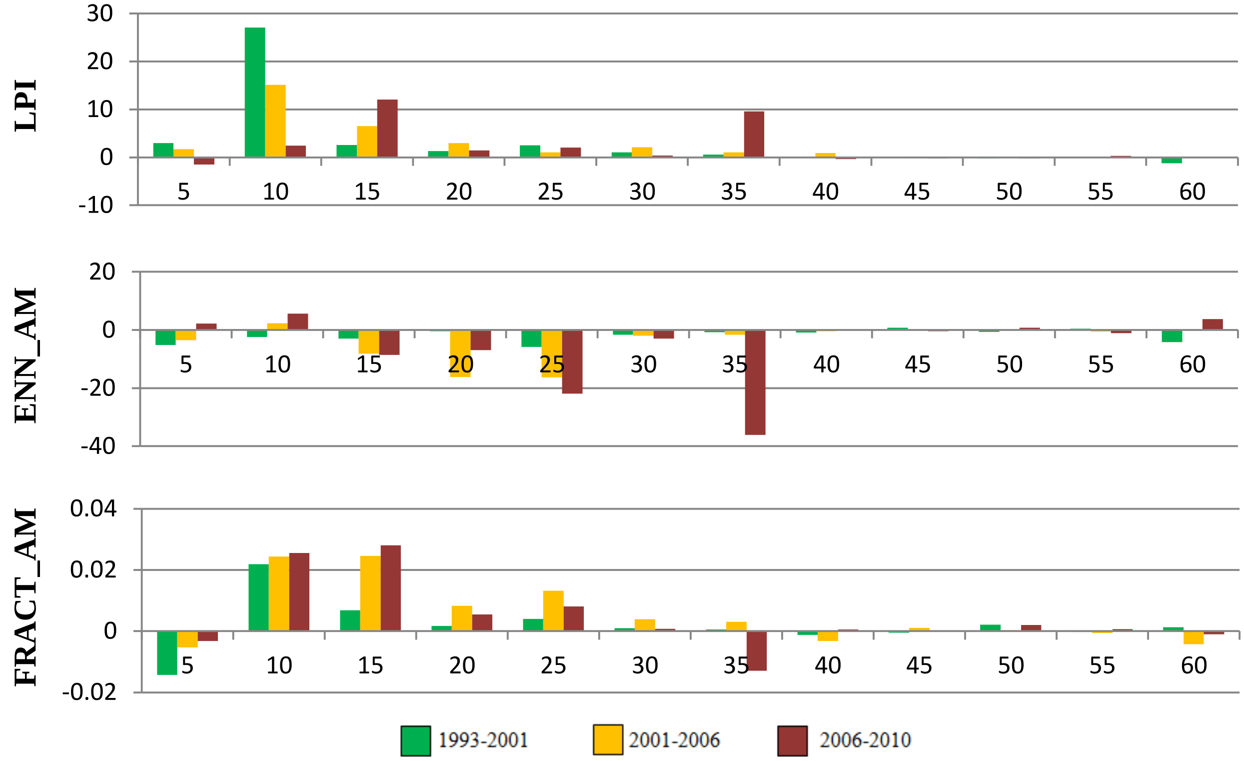


Figure 9: *Changes in landscape metrics at different buffer zones over three time periods*

The Area-weighted Mean Euclidean Nearest-Neighbor Distance (ENN_AM) has decreased overtime in the 15, 20, 25 and 35 km buffer zones and it slightly fluctuates in other buffer zones. The decrease of ENN_AM in these buffer zones signified an increase of patch isolation in these areas. The Area-weighted Mean Patch Fractal Dimension (FRACT_AM) has decreased at the 5 km buffer zone especially during between 1993 and 2001. This decrease indicates that, overtime, the shape of the urban patches has been conformed to a more regular and simple shape such as square or circle. Between the 10 to 30 km buffer zones, the patch shape has become more irregular and complexity indicated by the increase of FRACT_AM but the magnitude of increase is different among different periods and buffer zones. The patch shape index at the 35 km buffer zone had slightly increased in the first two periods but decreased in the third period indicating a more regular shape of urban patches. Changes of FRACT_AM in other buffer zones are negligible as the result of low urban growth rate (Fig. 4). The above results showed that major change in landscape metrics happened between the 5 and 35 km buffer zones which indicate a faster pace of urbanization process in these areas.

4. Discussion

4.1. Varying speeds at different buffer distances

Our study shows that urbanized areas in Hanoi capital city progressively increased over the 17 years from 1993 to 2010. The annual growth rate differed among the twelve buffer zones and three time periods. That is, urban growth rate was fastest at the 10 to 35 km buffer zones and in the period 2001-2006 and 2006-2010. By studying the spatial and temporal patterns of urban growth rate we were able to identify a hot zone of urbanization which is essential for urban modeling as well as city design and planning. According to the wave theory, the hot zone of the growth would move outwards from the city core with a particular periodicity (Schneider et al., 2005). In this study, the wave-like growth pattern was confirmed. Though, it was not clear due to low urbanization in the first period (1993-2001), the relationship between the growth area and the distance factor has clearly displayed the wave patterns especially in the second (2001-2006) and third period (2006-2010) (Fig. 4). The hot zone, indicated by the wave peak, has shifted through time and distance. The urban growth peaked at 10 km buffer zone between 2001 and 2006 and it shifted to 15 km buffer zone between 2006 and 2010. As the appearance of new growth center, some hot-spots would occur in further area, thus multi-peaked patterns were observed such as the peak at 25 km buffer zone where Quoc Oai and Quang Minh industrial zone project were laid their foundation between 2001 and 2006 and the peak at 35 km buffer zone where Son Tay, a new town of Hanoi, is being modernized as a satellite city and a recreation center.

4.2. The shift of different urban growth modes

The application of landscape expansion indices (X. Liu et al., 2010) and the landscape metrics in this study allows us to effectively detect and quantify three common urban growth modes (infilling, edge expansion and spontaneous growth), their temporal shifts in dominance, and the associated changes in landscape pattern in Hanoi capital city (Fig. 5, 6, 7, 8, and 9). The temporal shifts in relative dominance of three urban growth modes revealed by patch number may differ from those discovered by patch area (Fig. 6). These two measures are not independent, but complementary each other in a sense that the number of new urban patches is indicative of intensity/frequency whereas the area of new urban patches is indicative of urban footprint or extensiveness of urbanization. In addition, the area-weighted mean expansion index is also effective in quantifying the relative dominance among the three growth modes over different time period of urbanization (Fig. 7). Our study shows that using LEI and AWMEI together can facilitate the interpretation of seemingly complicated urban growth phenomenon. The idea of alternating urban growth phases had been proposed earlier in number of studies such as: Cressey (1938); Hoover and Vernon (1959); Duncan, Sabagh, and Van Arsdol Jr (1962); Winsborough (1962) and recently were supported by Dietzel et al. (2005), Seto and Fragkias (2005), and Xie, Yu, Bai, and Xing (2006). It has been proposed in the contemporary studies that the urban growth process may exhibit two alternate diffusion and coalescence phases, and that landscape metrics can be used to quantify this sequential process (Dietzel et al., 2005; Xu et al., 2007; Yu & Ng, 2007). The urbanization process of Hanoi during 17 year period has also experienced this oscillation. For example, in the urban core; the period of 1993-2001 and 2001-2006 can be seen as the coalescence phase which is evidenced by the dominance of infilling growth. As the growth continued overtime, the urban core became increasingly connected. This occurred mainly as a result of the establishment of several residential housing projects and offices driven by the increasing population density and economic opportunities in the urban center. The period of 2006-2010 can be seen as the diffusion phase which is demonstrated by the dominance of edge expansion and the increasing of spontaneous growth mode. Similarly, we also observed the switch between coalescence and diffusion phases in other buffer zones. But we noticed that the switches are not concurrent among buffer zones as some may have shorter or longer oscillation cycles depending on the speed of urban growth in each buffer zone. For example, the speed of urban growth in the 10 km buffer zone is higher than that in the 5 km buffer zone. As the result, the 10 km buffer zone quickly shifted from coalescence to diffusion phase in the period 2001-2006 while it was still coalescence phase in the 5 km buffer zone. Then in the third period (2006-2010), the 10 km buffer zone was in the transition to the coalescence phase while the 5 km buffer zone still continued with its coalescence. Thus, over 17 years, the coalescence and diffusion cycle had been repeated in the 10 km buffer zone, meanwhile the 5 km buffer zone had not completed one cycle yet. This investigation is important in the urban planning as it can support the modeling and prediction of urban growth. It is important to note that the two-phase diffusion coalescence concept can be easily misleadingly over simplistic because, in reality, all three urban growth modes present simultaneously in the same landscape (C. Li, Li, & Wu, 2013). One type of growth may dominate the others; therefore, it drives urban growth phases.

4.3. Changes in landscape patterns along the urbanization gradient

The urbanization, driven by infilling, edge expansion and spontaneous growth, has important effects on the spatial pattern of the entire urban landscape and the selected landscape metrics in our study has effectively described the structure and changes of the landscape for Hanoi area. The urban core appears to have lower value of the PD, ED, LSI, and ENN_AM but higher value of the LPI and FRACT_AM (Fig. 8). In addition, high urbanization zones can be also detected by examining the change of the landscape values as higher change was observed between 10 to 35 km buffer zone (Fig. 9) which is consistent with the urban growth rate (Fig. 4). In our study the high urbanization zones experienced a decrease of certain landscape metrics such as PD, ED, LSI and ENN_AM, but an increase of LPI and FRACT_AM. We found the urban growth characteristic of Hanoi is different from finding by C. Li et al. (2013) in Yangtze River Delta (YRD) in China from 1979 to 2008 and Jenerette and Potere (2010) study of 120 cities worldwide from 1990 to 2000. In their study, they found that the high urbanization rates tend to increase the values of PD, ED, and LSI. These differences brought us to a deeper comparison and we realized that spontaneous growth in YRD, driven by several cities at county and prefectural level, shares a significant amount of growth overtime whereas spontaneous growth is the least growth mode seen in Hanoi urbanization process over 17 years period. The low spontaneous development in Hanoi is the result of lacking social infrastructure, having a bad connection to the city center and lacking public services (Luan, Vinh, Brahm, & Michael, 2000). Most of the urban growth in Hanoi was within or adjacent to existing residential areas. Except the 5 km buffer zone, where the urban landscape already got saturated, the high urbanization zones in Hanoi can be considered as in the inception phase of urbanization. In the next several years, when the existing residential areas are filled up and old infrastructures become overloaded, the spontaneous growth/leapfrogging would be the dominant growth type and changes in landscape would be similar to what we've seen in YRD in China (C. Li et al., 2013) or general landscape changes of 120 cities worldwide (Jenerette & Potere, 2010). Our findings supported the suggestion by Jenerette and Potere's (2010) that urbanization tends to decrease the spatial heterogeneity of landscapes, resulting in homogenization of urban landscape structure. However, we argued that while this suggestion is true in the long run or as a final state of urbanization, during the urbanization process, the urban landscape structure change will follow a wave-like pattern where the coalescence and diffusion are simultaneously happening at different locations or switching each other in the same location.

5. Conclusion

Cities in Vietnam have been experiencing major urban transition since the country adopted the economic reform in 1986 which introduce liberal market mechanisms, encouraging private-sector initiatives, while retaining the government's role as the nation's strategic planner and enforcer. Hanoi, one of the two largest economic centers, has been experiencing a progressive urbanization during the 17 years between 1993 and 2010. Using gradient approach, our study has shown that the rate of urban growth was higher in between 10 to 35 km buffer zones. The growth modes and landscape structure changes of urbanization were also comprehensively captured and described using the landscape expansion index and selected landscape metrics. The process of urbanization was characterized by relative dominance of infilling, edge expansion, and spontaneous growth modes across the landscape. Our observation of the Hanoi urbanization in 17 year period could support the diffusion and coalescence phase dynamics. In addition, periodicity in the growing process, and the regularities of the shift of growth hot-zone revealed in this paper could be important implications for urban modeling and prediction. Through our landscape pattern analysis and comparison with other cities, it revealed that the urbanization of Hanoi is limited by its infrastructure systems which make the urban growth not evenly distributed, limiting their competitive advantage, disproportionately high transport costs, growing congestion and land market distortions. Therefore, strategic urbanization plan for future should consider improving urban transport and infrastructure systems, as well as strengthening its competitiveness in the region.

Reference:

Alberti, M. (2005). The effects of urban patterns on ecosystem function. *International regional science review, 28*(2), 168-192.

Antrop, M. (2004). Landscape change and the urbanization process in Europe. *Landscape and Urban Planning, 67*(1), 9-26.

Baker, W. L., & Cai, Y. (1992). The r. le programs for multiscale analysis of landscape structure using the GRASS geographical information system. *Landscape ecology, 7*(4), 291-302.

Berling-Wolff, S., & Wu, J. (2004). Modeling urban landscape dynamics: a case study in Phoenix, USA. *Urban ecosystems, 7*(3), 215-240.

Bertaud, A. (2004). The spatial organization of cities: deliberate outcome or unforeseen consequence?

Botequilha Leitão, A., & Ahern, J. (2002). Applying landscape ecological concepts and metrics in sustainable landscape planning. *Landscape and Urban Planning, 59*(2), 65-93.

Boyce, R. R. (1966). The edge of the metropolis: the wave theory analog approach. *British Columbia Geographical Series, 7*, 31-40.

Brown, L. R. (2001). Eco-economy. *Earth Policy Institute*.

Carsjens, G. J., & van Lier, H. N. (2002). Fragmentation and land-use planning—an introduction. *Landscape and Urban Planning, 58*(2), 79-82.

Cressey, P. F. (1938). Population succession in Chicago: 1898-1930. *American Journal of Sociology,* 59-69.

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

Dietzel, C., Herold, M., Hemphill, J. J., & Clarke, K. C. (2005). Spatio-temporal dynamics in California's Central Valley: Empirical links to urban theory. *International Journal of Geographical Information Science, 19*(2), 175-195.

Duncan, B., Sabagh, G., & Van Arsdol Jr, M. D. (1962). Patterns of city growth. *American Journal of Sociology*, 418-429.

Dunn, C. P., Sharpe, D. M., Guntenspergen, G. R., Stearns, F., & Yang, Z. (1991). Methods for analyzing temporal changes in landscape pattern. *Ecological studies: analysis and synthesis (USA)*.

Foresman, T. W., Pickett, S. T., & Zipperer, W. C. (1997). Methods for spatial and temporal land use and land cover assessment for urban ecosystems and application in the greater Baltimore-Chesapeake region. *Urban ecosystems, 1*(4), 201-216.

Frohn, R., McGwire, K., Dale, V., & Estes, J. (1996). Using satellite remote sensing analysis to evaluate a socio-economic and ecological model of deforestation in Rondonia, Brazil. *Remote Sensing, 17*(16), 3233-3255.

Gardner, R. H., O'Neill, R. V., & Turner, M. G. (1993). *Ecological implications of landscape fragmentation*: Springer.

Grimm, N. B., Faeth, S. H., Golubiewski, N. E., Redman, C. L., Wu, J., Bai, X., & Briggs, J. M. (2008). Global change and the ecology of cities. *science, 319*(5864), 756-760.

Grimm, N. B., Grove, J. G., Pickett, S. T., & Redman, C. L. (2000). Integrated Approaches to Long-Term Studies of Urban Ecological Systems Urban ecological systems present multiple challenges to ecologists—pervasive human impact and extreme heterogeneity of cities, and the need to integrate social and ecological approaches, concepts, and theory. *BioScience, 50*(7), 571-584.

Gustafson, E. J. (1998). Quantifying landscape spatial pattern: what is the state of the art? *Ecosystems, 1*(2), 143-156.
Hahs, A. K., & McDonnell, M. J. (2006). Selecting independent measures to quantify Melbourne's urban–rural gradient. *Landscape and Urban Planning, 78*(4), 435-448.
Herold, M., Couclelis, H., & Clarke, K. C. (2005). The role of spatial metrics in the analysis and modeling of urban land use change. *Computers, Environment and Urban Systems, 29*(4), 369-399.
Herold, M., Goldstein, N. C., & Clarke, K. C. (2003). The spatiotemporal form of urban growth: measurement, analysis and modeling. *Remote Sensing of Environment, 86*(3), 286-302.
Herold, M., Scepan, J., & Clarke, K. C. (2002). The use of remote sensing and landscape metrics to describe structures and changes in urban land uses. *Environment and Planning A, 34*(8), 1443-1458.
Hoover, E. M., & Vernon, R. (1959). Anatomy of a metropolis. The changing distribution of people and jobs within the New York Metropolitan Region.
Hunt, S. D., Guzy, J. C., Price, S. J., Halstead, B. J., Eskew, E. A., & Dorcas, M. E. (2013). Responses of riparian reptile communities to damming and urbanization. *Biological Conservation, 157*, 277-284.
Jenerette, G. D., & Potere, D. (2010). Global analysis and simulation of land-use change associated with urbanization. *Landscape ecology, 25*(5), 657-670.
Jenerette, G. D., & Wu, J. (2001). Analysis and simulation of land-use change in the central Arizona–Phoenix region, USA. *Landscape ecology, 16*(7), 611-626.
Koreclli, P. (1970). A WAVE-LIKE MODEL OF METROPOLITAN SPATIAL GROWTH†. *Papers in Regional Science, 24*(1), 127-140.
Kroll, F., Müller, F., Haase, D., & Fohrer, N. (2012). Rural–urban gradient analysis of ecosystem services supply and demand dynamics. *Land use policy, 29*(3), 521-535.
Lester, R. (2002). *Eco-economy: Building an Economy for the Earth*: Orient Blackswan.
Li, C., Li, J., & Wu, J. (2013). Quantifying the speed, growth modes, and landscape pattern changes of urbanization: a hierarchical patch dynamics approach. *Landscape ecology, 28*(10), 1875-1888.
Li, H., & Wu, J. (2004). Use and misuse of landscape indices. *Landscape ecology, 19*(4), 389-399.
Lin, G., & Ho, S. P. (2003). China's land resources and land-use change: insights from the 1996 land survey. *Land use policy, 20*(2), 87-107.
Liu, M., Xu, Y., Hu, Y., Li, C., Sun, F., & Chen, T. (2014). A Century of the Evolution of the Urban Area in Shenyang, China. *PloS one, 9*(6), e98847.
Liu, X., Li, X., Chen, Y., Tan, Z., Li, S., & Ai, B. (2010). A new landscape index for quantifying urban expansion using multi-temporal remotely sensed data. *Landscape ecology, 25*(5), 671-682.
Lockaby, B., Zhang, D., McDaniel, J., Tian, H., & Pan, S. (2005). Interdisciplinary research at the urban–rural interface: the West GA project. *Urban ecosystems, 8*(1), 7-21.
Luan, T. D., Vinh, N. Q., Brahm, W., & Michael, L. (2000). Urban housing. *Socioeconomic Renovation in Vietnam–The Origin, Evolution, and Impact of Doi Moi, IDRC and ISEAS, Singapore*, 65-113.
Luck, M., & Wu, J. (2002). A gradient analysis of urban landscape pattern: a case study from the Phoenix metropolitan region, Arizona, USA. *Landscape ecology, 17*(4), 327-339.

Luck, M. A., Jenerette, G. D., Wu, J., & Grimm, N. B. (2001). The urban funnel model and the spatially heterogeneous ecological footprint. *Ecosystems, 4*(8), 782-796.

McDonnell, M. J., & Pickett, S. T. (1990). Ecosystem structure and function along urban-rural gradients: an unexploited opportunity for ecology. *Ecology*, 1232-1237.

McDonnell, M. J., Pickett, S. T., & Pouyat, R. V. (1993). The application of the ecological gradient paradigm to the study of urban effects *Humans as components of ecosystems* (pp. 175-189): Springer.

McGarigal, K., Cushman, S. A., Neel, M. C., & Ene, E. (2002). FRAGSTATS: spatial pattern analysis program for categorical maps.

McGarigal, K., & Marks, B. J. (1994). Spatial pattern analysis program for quantifying landscape structure. *Dolores (CO): PO Box, 606*, 67.

McGarigal, K., & Marks, B. J. (1995). Spatial pattern analysis program for quantifying landscape structure. *Gen. Tech. Rep. PNW-GTR-351. US Department of Agriculture, Forest Service, Pacific Northwest Research Station*.

McKinney, M. L. (2006). Urbanization as a major cause of biotic homogenization. *Biological Conservation, 127*(3), 247-260.

Medley, K. E., McDonnell, M. J., & Pickett, S. T. (1995). Forest-Landscape Structure along an Urban-To-Rural Gradient*. *The Professional Geographer, 47*(2), 159-168.

Melillo, J. M., Field, C. B., & Moldan, B. (2003). *Interactions of the major biogeochemical cycles: global change and human impacts*: Island Press.

O'neill, R., Hunsaker, C., Timmins, S. P., Jackson, B., Jones, K., Riitters, K. H., & Wickham, J. D. (1996). Scale problems in reporting landscape pattern at the regional scale. *Landscape ecology, 11*(3), 169-180.

Olden, J. D., & Rooney, T. P. (2006). On defining and quantifying biotic homogenization. *Global Ecology and Biogeography, 15*(2), 113-120.

Pillsbury, F. C., & Miller, J. R. (2008). Habitat and landscape characteristics underlying anuran community structure along an urban-rural gradient. *Ecological Applications, 18*(5), 1107-1118.

Platt, R. H. (1994). The ecological city: introduction and overview. *The Ecological City: Preserving and Restoring Urban Biodiversity. University of Massachusetts Press, Amherst*, 1-17.

Puyravaud, J.-P. (2003). Standardizing the calculation of the annual rate of deforestation. *Forest Ecology and Management, 177*(1), 593-596.

Rees, W., & Wackernagel, M. (1996). Urban ecological footprints: why cities cannot be sustainable—and why they are a key to sustainability. *Environmental impact assessment review, 16*(4), 223-248.

Sadler, J., Small, E., Fiszpan, H., Telfer, M., & Niemelä, J. (2006). Investigating environmental variation and landscape characteristics of an urban–rural gradient using woodland carabid assemblages. *Journal of Biogeography, 33*(6), 1126-1138.

Schneider, A., Seto, K. C., & Webster, D. R. (2005). Urban growth in Chengdu, Western China: application of remote sensing to assess planning and policy outcomes. *Environment and Planning B: Planning and Design, 32*(3), 323-345.

Seto, K. C., & Fragkias, M. (2005). Quantifying spatiotemporal patterns of urban land-use change in four cities of China with time series landscape metrics. *Landscape ecology, 20*(7), 871-888.

Sui, D. Z., & Zeng, H. (2001). Modeling the dynamics of landscape structure in Asia's emerging desakota regions: a case study in Shenzhen. *Landscape and Urban Planning, 53*(1), 37-52.

Tischendorf, L. (2001). Can landscape indices predict ecological processes consistently? *Landscape ecology, 16*(3), 235-254.

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*(3-4), 153-162.

Williams, N. S., McDonnell, M. J., & Seager, E. J. (2005). Factors influencing the loss of an endangered ecosystem in an urbanising landscape: a case study of native grasslands from Melbourne, Australia. *Landscape and Urban Planning, 71*(1), 35-49.

Winsborough, H. H. (1962). CITY GROWTH AND CITY STRUCTURE†. *Journal of Regional Science, 4*(2), 35-49.

Wu, J. (2004). Effects of changing scale on landscape pattern analysis: scaling relations. *Landscape ecology, 19*(2), 125-138.

Wu, J. (2008). Toward a landscape ecology of cities: beyond buildings, trees, and urban forests *Ecology, Planning, and Management of Urban Forests* (pp. 10-28): Springer.

Wu, J. (2010). Urban sustainability: an inevitable goal of landscape research. *Landscape ecology, 25*(1), 1-4.

Xia, Z., & Clarke, K. (1997). Approaches to scaling of geo-spatial data (pp. 309-360): Lewis Publishers: Boca Raton, FL, USA.

Xie, Y., Yu, M., Bai, Y., & Xing, X. (2006). Ecological analysis of an emerging urban landscape pattern—desakota: a case study in Suzhou, China. *Landscape ecology, 21*(8), 1297-1309.

Xu, C., Liu, M., Zhang, C., An, S., Yu, W., & Chen, J. M. (2007). The spatiotemporal dynamics of rapid urban growth in the Nanjing metropolitan region of China. *Landscape ecology, 22*(6), 925-937.

Yu, X. J., & Ng, C. N. (2007). Spatial and temporal dynamics of urban sprawl along two urban–rural transects: A case study of Guangzhou, China. *Landscape and Urban Planning, 79*(1), 96-109.

Zhang, L., Wu, J., Zhen, Y., & Shu, J. (2004). RETRACTED: A GIS-based gradient analysis of urban landscape pattern of Shanghai metropolitan area, China. *Landscape and Urban Planning, 69*(1), 1-16.

Zipperer, W. C., Wu, J., Pouyat, R. V., & Pickett, S. T. (2000). The application of ecological principles to urban and urbanizing landscapes. *Ecological Applications, 10*(3), 685-688.