URBAN GROWTH CHARACTERIZATION BY INTEGRATION OF REMOTE SENSING, SPATIAL METRICS AND POPULATION DATA: A CASE STUDY OF HANOI, VIETNAM

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ABSTRACT

Vietnam, since the ‘Doi Moi’ reform policy in 1986, has gone through several economic development phases, resulting in various transformations of the landscape. One of the most evident is urbanization, a loss of agricultural lands and open spaces. These rapid changes pose an enormous challenge for local populations as well as planning authorities. This three-essay dissertation seeks to develop an improved understanding of the spatiotemporal urban growth characteristics of Hanoi in order to strengthen the region’s urban planning and management system.

In the first essay, a method of monitoring built-up area changes in Hanoi from Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) was developed with a Support Vector Machine classification algorithm (SVM). The study showed that the SVM classification was an effective method to monitor built-up area changes over time with high accuracy. Most of the built-up area changes in Hanoi occurred between 2001 and 2006 and between 2006 and 2010, which were closely linked to population growth and major land management policies enforced in the beginning of 2000.

The second essay analyzed the spatiotemporal patterns and dynamics of the built-up land in Hanoi using landscape expansion indices, spatial metrics and a gradient approach. The study showed that the urban landscape from 10 to 25 km buffer zones was more fragmented and over time there were temporal switches between coalescence and diffusion phases corresponding to the high urban growth rate in these zones. The complicated urban growth dynamics were successfully characterized and captured through this essay providing important information for urban modeling and prediction.

The third essay explored the utility of spatial metrics and population data to delimitate peri-urban zone for Hanoi. Successfully identifying and mapping peri-urban zone is crucial to better manage this landscape where there is an intensification of conflict and where the governance and management are often neglected by both rural and urban administrators. The study showed that about 30% communes was rural, 38% communes was peri-urban and 32% communes was urban. The peri-urban zone showed a greater level of landscape fragmentation and population growth than urban or rural zones. The essay provided an effective method to map the rural-urban transition and to identify urbanization models of Hanoi where limited census data are available.

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CHAPTER 1. GENERAL INTRODUCTION

Urbanization is an integral part of any country to achieve high economic development and is an inevitable part of human progress (Rigg et al. 2009). Nearly all countries become at least 50 percent urbanized before reaching middle-income status and all high income countries are 70-80 percent urbanized (Vaidya 2009).

After more than two decades of 'Doi Moi' reform policy since 1986, Vietnam has achieved a notable result in socio-economic development and in the transition from a centrally planned to a market economy with socialism orientation. By 2008, with the GDP per capita of US$1,024, Vietnam has already reached the status of a middle-income country by the World Bank classification method (Ohno 2009). The country's poverty rate sharply decreased from 58% in 1993 to 12.3% in 2009 (Tarp and Markussen 2011). Vietnam has shifted from primarily agricultural-based economy to a multi-sector economy promoting industrialization (Tsokhas 2014). The 9th National Congress of the Communist Party of Vietnam in 2001 drew a wide attention by setting an ambitious goal that Vietnam would basically become an industrialized nation by 2020. To make this ambitious project happen, the government of Vietnam has placed a strong emphasis on improving and developing the urban system throughout the country. This intention can be seen in the explicit statement by the Deputy P.M. Nguyen Sinh Hung at the Vietnam National Urban Conference held on November 6 and 7, 2009, "*Vietnam will have only one chance to get urbanization right. If we fail at urbanization, we will fail at industrialization and modernization.*" Vietnam's future economic growth will depend on its ability to develop competitive, market-driven industrial and service sectors which are primarily urban-based activities (Coulthart et al. 2006).

Urbanization is rapidly transforming socio-economic, institutional and spatial structures of Vietnam and other developing world. While the urbanization can boost the industrialization and modernization goals of the country, local and foreign academics, professionals, and policymakers also raise concerns about the problems resulting from the urbanization process. As the urbanization proceeds, the size of cities will expand and the rural-urban fringe will become the zone of interaction where urban and rural forces meet and compete for land and other natural resources between new comers and old communities (Beesley 1994). The regions that combine elements of both "rural" and "urban," are referred to as *peri-urban*, *exurban*, *urban tract*, *rurban*, *urban fringe*, *semiurban*, and even *suburban*, all of which are well-established terms in the literature (Iaquinta and Drescher 2000). The term ‘peri-urbanization’ refers to the process through which rural areas located on the outskirts of established urban areas are physically and/or functionally incorporated into the urban system (Graham et al. 2004; Webster et al. 2003; Webster and Muller 2002b). This is a complex and dynamic process that involves radical, structural changes in physical, economic, and social terms, and often in piecemeal fashion (Webster and Muller 2002b). There is no doubt that peri-urban areas will be the key sites for urban growth and industrial-based activities in the future. Therefore, planning for these transitional areas and for the transition from agricultural to manufacturing-based economies receives great attention in all developing countries in Asia and Africa.

For decades, Vietnam inherited a top-down/centralistic planning system from the Soviet Union. This planning system is known to be fragmented and overlap, and be no longer suitable with the country’s condition after more than 20 years of reform. The fragmentation in the planning system occurs between ministries and between different levels of government. Three types of plans have been applied to urban areas (socio-economic development plans; spatial plans-commonly referred to as master or construction plans; and sector development plans) and different ministries have been responsible for each (Coulthart et al. 2006). For example, socio-economic development plans are prepared at all levels of government, for which the Ministry of Planning and Investment is responsible; master plans are administered by the Ministry of Construction; and for sector development plans, respective lines of ministries are responsible. It is widely recognized that the master plans prepared for city and provincial levels in Vietnam are no longer effective. The term “quy hoach treo” or “hanging plan” has become popular among planning sectors in Vietnam. Plans were neither linked to budgets, nor to other resources and capacities needed to achieve them. Those beautifully drafted plans and maps hanging in the offices of People’s Committee tend to represent what planning experts and city administrators would like their city to become if unlimited resources were available (Coulthart et al. 2006). In addition, timeframes for planning were unrealistically short, making public participatory and evidence-based planning exercise impossible (Charlier 2014). Therefore, an urgent reform in urban planning system in Vietnam is needed where planning should more accurately respond to the dimensions and locations of demand and market forces. An integration and coordination across functional and/or spatial jurisdictions should also be strengthened in planning systems. It is recognized that Vietnam is entering a crucial period of urbanization corresponding to its present stage of economic development. As the nation's capital city and second largest agglomeration after Ho Chi Minh City, Hanoi is one of the key sites of this urban transition. Vietnamese Government, in its strategic development plan, emphasizes that the growth of Hanoi and other cities is essential for the shift from agriculture to manufacturing and higher order services (Labbé 2010).

Given the importance of urbanization for industrialization and modernization goals and the challenges facing local populations as well as planning authorities, this dissertation seeks to develop an improved understanding of the past and current spatiotemporal urban growth characteristics of Hanoi in order to strengthen the region's urban planning and management system. This dissertation consists of three essays where Support Vector Machine classifications (Burges 1998) of Landsat multi-temporal image stacks, spatial metrics, population data and a rural-urban gradient approach were used to examine urban land cover change in Hanoi from 1993 to 2010. The first essay aims to provide a method of monitoring the built-up land feature changes in Hanoi using Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+). The second essay analyzes the spatiotemporal pattern of the built-up land in Hanoi. While the first two essays focus on quantifying the changes of built-up land and its spatial patterns using a rural-urban gradient approach, the third essay aims to map the rural-urban transition in Hanoi using cluster analysis of spatial metrics and population data.

Monitoring urban built-up features has been a challenge, i.e., conventional image processing algorithms and techniques which are largely built upon parametric statistics do not provide accurate results when mapping urban built-up features (Myint and Lam 2005; Yang 2011). In addition, urbanization in Asia often occurs onto prime agricultural land, making it more challenging to distinguish between fallow farmland and built-up areas, since both show high reflectance in the visible-infrared wavelength regions. This problem is even more serious in the study area where the farmland usually supports multiple crops per year with high inter and intra-year variability. The first essay will address this problem where a new method of mapping the built-up land features in Hanoi using the Support Vector Machine classification algorithm was applied. The built-up area change analysis will be accompanied by a rural-urban gradient approach and a population change analysis.

The second essay concerns with spatial patterns and dynamics of the urban growth in Hanoi. The urban growth, especially in its undesirable form has negative impact on natural and human systems and the sustainability of cities. This often results in sprawling patterns of cities causing high cost of transport, public infrastructure and residential and commercial development. Sprawling patterns also demand more energy, metal, concrete and asphalt than do compact patterns because homes, offices and utilities are set further apart (DiMuzio 2012). Urban areas are approaching rural areas causing decrease in agricultural lands, wild forests and open spaces as well as disruption of ecosystem structure (Marshall and Shortle 2005). Given the continuous change in the structure and pattern of urban growth, characterizing and understanding the changing patterns is critical to ensure a balance development of socio-economic, ecological, and physical components and to support urban system modeling. The physical process of urban land use changes as the result of urbanization is still under study and research (Seto and Fragkias 2005). The second essay will analyze the spatiotemporal patterns and dynamics of built up land in Hanoi using landscape expansion indices, spatial metrics and a gradient approach, therefore, providing a new perspective about Hanoi urbanization over the last two decades.

The third essay involves delimitating peri-urban landscape in Hanoi. How to define rural and urban nature is a fundamental question that has attracted the attention of geographers, ecologists, and other scientists interested in various urban phenomena for decades (Rashed et al. 2001). While the nineteenth-century landscape showed a clear boundary between the city and the countryside, the twentieth-century developments have complicated this division (Zenner 2002). Peri-urban zones often involve social, physical and economic transformations in non-contiguous transitional zones between urban centre and the countryside (Oduro 2010). The separation of peri-urban from rural and urban entity is important to help identify useful policy interventions where there is an intensification of conflict and a necessity for negotiating and resolving competing claims (e.g., in residential versus agricultural land use debates, or between competing customary institutional forms and values). Such conflicts occur at all levels such as family, neighborhood, organizational, community, regional, and national levels (Iaquinta and Drescher 2000). Without a clear distinction, it will be more challenging to address the problems and to manage this complex and dynamic landscape. The third essay proposes and evaluates a new cluster analysis-based classification approach to delimitate the peri-urban landscape. The proposed methodology utilizes spatial metrics that are derivable from any medium to high resolution remotely sensed images and population data – the basic social data that are often available at various levels such as communes, districts, provinces and/or countries.

CHAPTER 2. BUILT-UP AREA CHANGE ANALYSIS IN HANOI USING SUPPORT VECTOR MACHINE CLASSIFICATION OF LANDSAT MULTI-TEMPORAL IMAGE STACKS

Abstract

Vietnam is experiencing one of the greatest urban transitions over the last two decades after the embankment of 'Doi Moi' policy in 1986. The urban transition is vividly manifested in social, economic and physical aspects. While the urbanization can boost the industrialization and modernization goals of the country, it can cause adverse impact on natural environment as well as society and economy. To support a sound urban development plan, it is important that data and analysis on urban built-up areas are accurate and timely available. In this study, the Support Vector Machine Classification Algorithm (SVM) was applied to the multi-temporal image stacks of Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) from 1993 to 2010 to quantify the changes of built-up areas over three time periods, 1993-2001, 2001-2006, and 2006-2010 and across twelve buffer zones. Our SVM classification algorithm produced a highly-accurate map of land cover change with the overall accuracy of 95%. The study showed that most of the urban expansion occurred in the periods 2001- 2006 and 2006 – 2010. The analysis was strengthened by the analysis of population census and other socio-economic figures. Throughout this study, correlations between the urban growth, the spatial expansion and other socio-economic factors can be proposed. Results of this study would allow urban planners and policymakers to timely assess and adjust accordingly the urban growth and be aware of the sustainable use of the cropland and other associated environmental, social and economic problems.

Keywords: *urbanization, built-up areas, support vector machine, remote sensing, GIS, gradient approach.*

Introduction

In this 21st century, we have witnessed the world's fastest-growing cities in Asia, Africa and Latin America (Satterthwaite 2007) where urbanization is faster than what governments and city planners can manage. Vietnam, a new economic dragon in Southeast Asia (Welle-Strand et al. 2013), is experiencing one of the greatest urban transitions in the world. This remarkable achievement has been largely attributed to the ‘Doi Moi’ or ‘Renovation’ reforms program initiated in 1986 which introduces liberal market mechanisms, encouraging private-sector initiatives, while retaining its role as the nation’s strategic planner and enforcer (World Bank 2011). Vietnam has now embarked on an ambitious 10-year plan with the aim to become a fully industrialized nation by 2020 (Welle-Strand et al. 2013). In which urbanization was considered as an integral part to promote the country’s goals of industrialization and modernization (World Bank 2011).

These policy reforms and economic vitalities led to several economic development phases resulting in various transformations of the landscape. One of the most evident is urbanization, the loss of agricultural land and the flood of rural migrants into urban areas. Rural – urban migration by people seeking employment is steadily increasing. At the national level, urban population has increased from 23.7% in 1999 to 29.6% in 2009 (with 25.4 million urban residents out of the country’s 85.8 million people) (Population and Housing Census 2010). The urban population continues to grow at an unprecedented rate and is projected to increase by 45% by 2020, which translates to more than 30 million urban resident population (Campbell 1999). Consequently, the development of public amenities and infrastructure will require increasing areas of land, which will in turn have the effect of increasing the pressure on land uses. Cities are often located on the most productive agricultural lands (L Imhoff et al. 1997), so any expansion of urban areas will compromise not only food production, but also the provision of ecosystem goods and services that are derived from these landscapes (e.g. climate regulation, water infiltration, etc.) (Foley et al. 2005). Expanding urban, in the way out of control and changing land use pattern, will bring about new issues (Brook et al. 2000), including both positive and negative impacts on the natural environment as well as society and economy.

Vietnamese government, in its strategic development plan, emphasizes that the growth of Hanoi and other cities is essential for the shift from agricultural to industrial-based economies and for the material well-being of the national population (Labbé 2010). Given the importance of the urbanization in Hanoi, timely and accurate data on the spatial expansion of built-up areas are of great importance for urban planners and policymakers. Fortunately, satellite remote sensing technology offers considerable promise to meet this requirement. With different spatial and spectral resolutions, the satellite observations can provide globally consistent and repetitive measurements of the Earth's surface conditions.

While the administrative boundary and area of Hanoi were well documented over time as provided in the background, its spatial entities are not always updated. At certain level, data on land uses are available in census format but lack consistency, are of limited access to users and have non-spatial references. The objective of this study was to provide a comprehensive understanding of the urban expansion around Hanoi using multi-temporal image stacks developed from freely-available Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) data from 1993 to 2010. To archive this objective, the Support Vector Machine Classification Algorithm was applied to the image stack to quantify the changes of built-up areas across temporal and spatial scales. We evaluated the impact of urban expansion on open land especially in the peri-urban environment using a rural-urban gradient approach. Finally, changes in population were analyzed to provide an insight into how urban expansion corresponds to population growth in the study area. Results of this study would allow urban planners and policymakers to timely assess and adjust accordingly the urban growth and be aware of the sustainable use of the cropland and other associated environmental, social and economic problems.

Historical overview of land change in the study area

Vietnam has developed two independent and dominant core-periphery urban systems: Hanoi, the capital city of Vietnam and Ho Chi Minh, the largest metropolitan in the south. Vietnam's rapid economic growth is strongly driven by these two urban systems with high growth and industrial concentration within these cities and their surrounding areas. Hanoi is a typical example of rapid urbanization in Vietnam in particular and in Asian countries in general. In this section, we describe the land change of Hanoi since its initial establishment with a focus on major turning points in the past and current stages.

Throughout the history, the Vietnam's capital city has changed its name and administrative boundary several times. Its name has changed over time such as "Thăng Long" in 1010, "Đông Đô" in 1397, "Đông Quan" in 1408, "Đông Kinh" in 1427, "Bắc Thành" in 1787. In 1805 King Gia Long renamed it again "Thăng Long". "Hà Nội" was first named in 1831 by King Minh Mang as a province which included the ancient "Thăng Long" Citadel and four other districts. In 1888, French colonialist established Hanoi City (Vien et al. 2005). Hanoi became the Capital of the Democratic Republic of Vietnam in 1945 which comprised five wards (Lang Bac, Dong Da, Me Linh, Dai La and De Tham) and 120 suburban villages. In 1954 Hanoi was liberated from the French Colonial Regime. By then the capital city had four urban districts (Ba Dinh, Hoan Kiem, Dong Da, and Hai Ba Trung) and four peri-urban ones (Gia Lam, Dong Anh, Thanh Tri and Tu Liem) with an area of 152 km^2 (Logan 2000). In 1960 Hanoi expanded to 586.13 km^2 but remained the same number of urban and peri-urban districts. In 1978 Hanoi's area increased to 2,123 km^2 as there were seven districts and one more town was added to Hanoi's administration: Soc Son, Me Linh, Ba Vi, Phuc Tho (taken from Vinh Phu province) and Thach That, Dan Phuong, Hoai Duc and Son Tay town (taken from Ha Tay province) (Vien et al. 2005).

In 1991, the land was adjusted to only 913.8 km^2 (from the earlier 2,123 km^2) with same four urban districts (Ba Dinh, Hoan Kiem, Dong Da, and Hai Ba Trung) and only five peri-urban districts (Gia Lam, Dong Anh, Thanh Tri, Tu Liem, and Soc Son). From 1995 to 1997 Hanoi had expanded its urban area further to include part of Thanh Tri and Tu Liem peri-urban districts. Thereafter, two new urban districts, Tay Ho and Thanh Xuan, were established, making Hanoi's urban area 62.15 km^2. In 1998 Hanoi took more land of Tu Liem peri-urban district to make up Cau Giay urban district. It brought the urban area to 82.78 km^2. In November 2003, two new urban districts named Hoang Mai and Long Bien were established (Vien et al. 2005).

In sum, from 1991 to 2003 more urban districts have been established, which are Tay Ho, Thanh Xuan, Cau Giay, Hoang Mai and Long Bien. Those are mostly formed from taking land of peri-urban districts: Tu Liem, Thanh Tri and Gia Lam. In general, the number of urban districts of Hanoi has increased more than twice since 1995 with the land area increased nearly four times from 47.22 km^2 in 1995 to 185.72 km^2 in 2003.

In 2008, the administrative boundaries of Hanoi were again adjusted to include the neighboring province of Ha Tay as well as a number of districts and communes that formerly belonged to the provinces of Vinh Phuc and Hoa Binh. As a result, the capital reached 3,300 km^2 which is 3.6 times the size of the previous area increase (Labbé 2010). In doing so, Hanoi absorbed wide areas of agricultural land that now constitute two-thirds of its area. This expansion also resulted in a doubling of the official population of the capital city, from 3.2 to 6.4 million inhabitants. A large part of this new population is classified as "rural" (3.7 million people, against 2.5 million classified as "urban") (HSO 2009). Hanoi's population comes just after HCMC (6.8 million) but the city is now far ahead of Hai Phong (1.8 million) and Da Nang (822,000). Although encompassing less densely settled areas, Hanoi's population density has now reached an average of 1,926 persons per km^2 (HSO 2009). With the massive wave of immigrants from other provinces to Hanoi, mostly from other rural in the North of Vietnam and other nearby provinces, the real number of population in Hanoi is increasing at an accelerated speed and this upward trend does not seem to cease in the foreseeable future.

Methods

Remote sensing of built-up areas

Urban areas represent the most heterogeneous landscape making it challenging for remote sensing specialists to derive highly accurate mapping results especially when conventional image processing algorithms and techniques are employed which largely built upon parametric statistics (Myint and Lam 2005; Yang 2011). In addition, urbanization in Asia often occurs onto prime agricultural land, making it more difficult to distinguish between fallow farmland and built-up areas, since both show high reflectance in the visible-infrared wavelength regions. This problem is even more serious in study areas where the farmland usually supports multiple crops per year with high inter and intra-year variability (Kontgis et al. 2014) such as the Red River Delta and the Mekong River Delta in Vietnam. Urban mapping often demands the selection of an appropriate scale of observation. There is a certain trade-off between the detail of very high resolution remote sensing imagery and the generalizing nature of moderate to high resolution sensors such as the 30 meter of Landsat data (Griffiths et al. 2010) as well as the temporal and spatial coverage. The long historical archive and continuing acquisitions is an advantage of Landsat data (Wulder et al. 2008) compared to very high resolution sensors. Therefore, Landsat data was considered the most suitable in our study.

Recent studies have shown that the use of several Landsat images can provide additional information on land cover types (Hilker et al. 2009; Huang et al. 2010; Kennedy et al. 2007; Verbesselt et al. 2010). The high image density of the stack allows for the detection of a change through its multi-temporal signature in spectral space (Schneider 2012). Integrating multi-temporal information helps distinguish urban from non-urban surfaces as urban spectral responses are largely persistent over time compared to non-urban surface phenology (Griffiths et al. 2010). Capitalize on this strategy; we utilized dense stacks of Landsat TM and ETM+ images from 1993 to 2010. The satellite images were acquired from the Global Land Cover Facility (GLCF) archive at the University of Maryland (GLCF-UMD) and from the United States Geological Survey (USGS)-Earth Resources Observation and Science (EROS) Center. Hanoi capital is covered by 2 Landsat tiles: p127-r045 and p127-r046. To avoid the effect of scene noise on the classification, we excluded cloudy and SLC-off scenes. Landsat images and dates of acquisition are listed in Figure 2.1.

To prepare the image stacks, we selected all visible and infrared bands (1-5, 7) of each Landsat and compiled them into a single image stack for each tile, then we subset each tile via the study area's boundary.

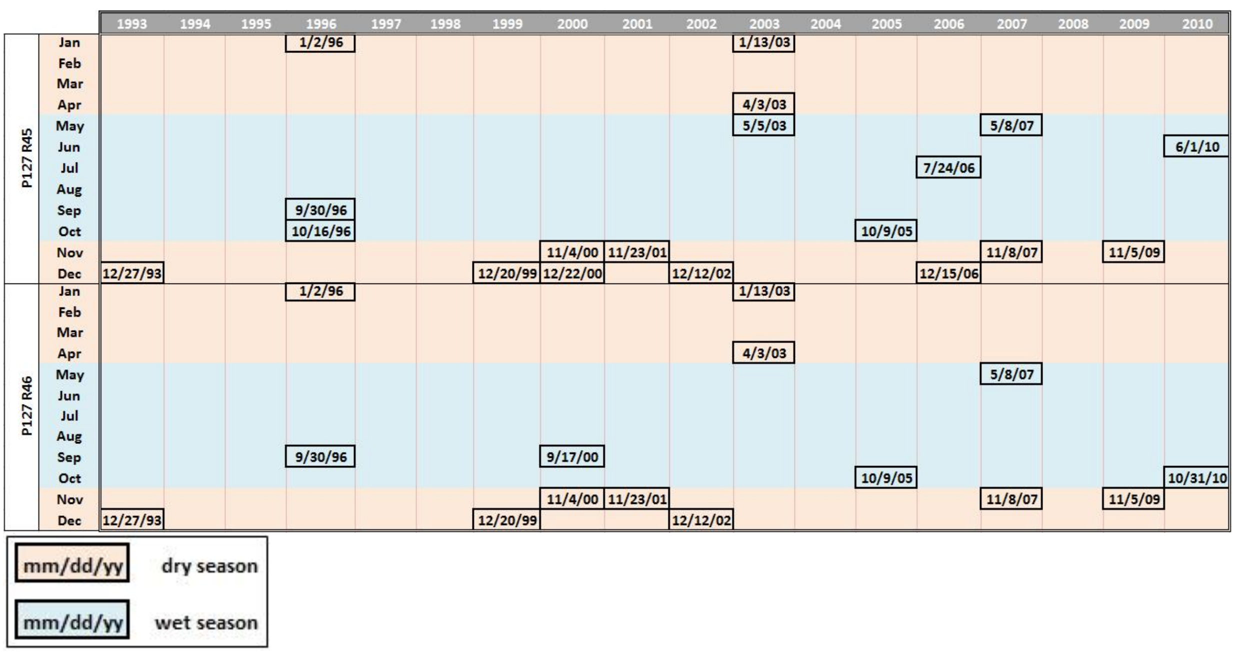

Figure 2.1. Landsat scenes selected for multi-temporal image stacks.

The Support Vector Machine (SVM) supervised classification was applied to the dense stacks of Landsat TM and ETM+ images for mapping the land use/cover of the study area. Note that radiometric correction was not performed since this step is only necessary when images are analyzed individually (Song, Woodcock, & Seto, 2001), but not simultaneously as we did here. The advantage of Support Vector Machine is that it can handle a large volume of data by processing a stack of multiple-year remotely sensed imagery at one time. In addition, SVM is a supervised non-parametric statistical learning technique, therefore, there is no assumption made on the underlying data distribution (Mountrakis et al. 2011). Instead, they obtain their decision directly from the training data in a suitable space that is described by a kernel function. Although some studies have underlined that kernel selection can be crucial in the production of satisfactory classification accuracy by SVMs (Kavzoglu and Colkesen 2009), very little guidance exists in the literature concerning the criteria to be used in selecting kernel-specific parameters (Carrão et al. 2008; Li and Liu 2010), that may need more expert judgment.

Our method for image analysis and classification was intellectually stimulated by a strategy outlined in Schneider (2012). First, our classification scheme was formulated which includes seven classes: agriculture; built-up; forest; water; and three change classes (agriculture to built-up) between the time periods of 1993-2001, 2001-2006 and 2006-2010. Our decision to use the above classification scheme was based primarily on photo interpretation of the high resolution imagery acquired from Google Earth, assisted by historical and present field photos and our familiarity with the study region from previously conducted work in the same site. We determined these three time periods in order to match them with the dates of the national census surveys for the convenience of comparison and combination of these two datasets.

Second, ground truth points representative of each of the above classes were collected from visual interpretation of high resolution imagery from Google Earth and Bing Maps with an acquisition date close to that of our Landsat imagery following both random and strategic sampling strategies. Approximately, about 130 pixels per class (in total 927 pixels) were identified as the ground truth points representing the classes identified in our classification scheme.

Third, the SVM algorithm was implemented in ENVI 4.4 (Exelis Visual Information Solutions, Inc., Boulder, CO, U.S.A.) using the training dataset which was made by randomly-selecting a subset from the ground truth data collected during the previous steps. The SVM classifier has four kernels namely linear, polynomial, Radial Basis Function (RBF) and sigmoid. We chose the RBF kernel as it generally requires defining a small number of parameters and is also known to generally produce good results (Huang et al. 2008; Petropoulos et al. 2011).

After classification of each subset, we mosaicked them together and performed accuracy assessments based on the computation of the overall accuracy (OA), producer accuracy (PA), user accuracy (UA) and the kappa coefficient (Kc) statistic (Congalton and Green 2008). Ten-fold cross validation was applied (Steele 2005) to obtain relatively realistic accuracy estimates using limited number of reference data samples for both training and accuracy assessment. We randomly divided our groundtruthing data into training and validation samples with a proportion of 80% and 20% respectively. We repeated this process ten times to generate ten independent sets for training and validation. Then the classification and accuracy assessment were performed for each training and validation set. The average value of all validation iterations represents the estimated accuracy of the map. In reality, a ten-fold cross-validation allows the user to estimate the repeatability of the classification model. Our supervised classification was an iterative process that involved evaluating the misclassified points, editing point labels and locations, and then re-running the classifier. Once the classification was satisfactory, several post classification steps were performed to obtain final maps (Figure 2.2).

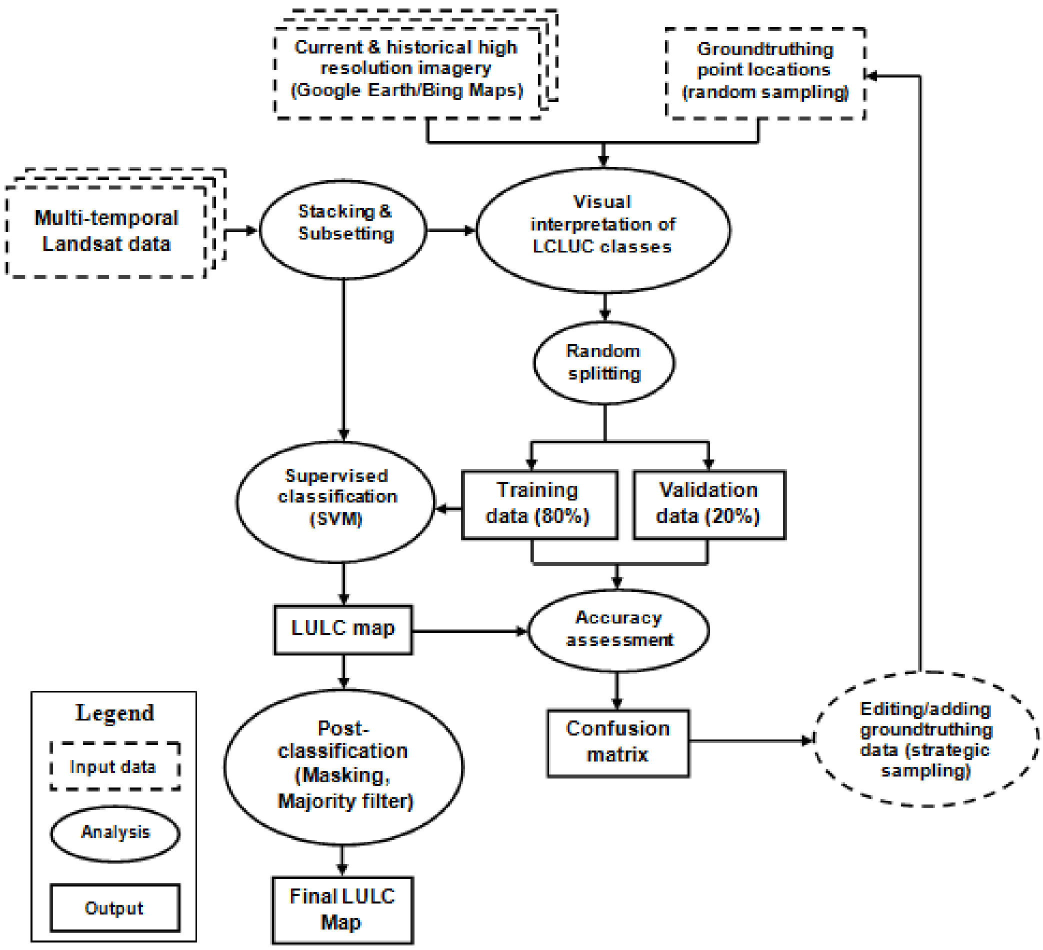

Figure 2.2. Workflow for supervised classification.

Rural-urban gradient analysis

GIS-based buffer analysis was adopted in our research, which involved circular buffer zones surrounding the city center (Figure 2.3). Each buffer zone was employed as a basic spatial unit to characterize distance-dependence of urban growth. Rural-urban gradients have predominantly been quantified using concentric zones from the urban core outwards (Kroll et al. 2012; Pillsbury and Miller 2008; Sadler et al. 2006), and objective quantification using GIS methods (Hahs and McDonnell 2006; Hunt et al. 2013; Lockaby et al. 2005; Luck and Wu 2002; Williams et al. 2005). In this study, we defined a center point located in Hoan Kiem district because this is one of the first four urban districts of Hanoi. Then, multiple buffer zones of five-kilometer interval were created from the center point until it covers the entire Hanoi boundary. We defined the five-kilometer interval buffer zones because the contiguous urban districts in 1993 (the beginning of our study period) were encompassed within a radius of five kilometers.

To reinforce our understanding of how land cover changes in and around the urban core, we used an urban transition map developed for Hanoi by Saksena et al. (2014) as an independent gradient system which does not depend on the distance from the city center (Figure 2.3). Saksena et al. (2014) used a cluster analysis of socio-economic and biophysical variables to map the urban transition in Vietnam (for a detailed account of the classification methodology, see Saksena et al. 2014). According to Saksena et al. (2014), within Hanoi, 106 administrative units were classified as urban core communes, 32 as urban communes, 230 as peri-urban communes and 204 as rural communes. There are two communes with missing data that were excluded in our analysis. Finally, to gain an insight into how the urban expansion corresponds to the population growth in the study area, we relied on 1999 and 2009 population census.

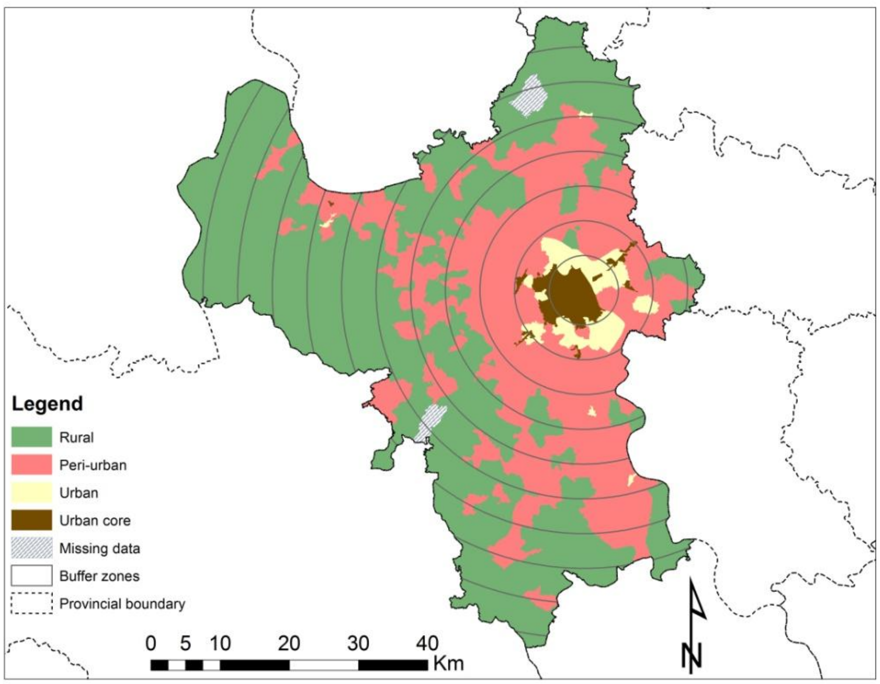

Figure 2.3. Gradient analysis using five-kilometer interval buffer zones and a commune classification by Saksena et al. (2014).

Results and discussion

Land cover classification

Our resultant map of land cover includes seven classes; agriculture, forest, water, built-up and three classes of change. The built-up land is pretty clear and well separated from other land cover classes as we saw many built-up areas appearing as small “islands” surrounded by agriculture (Figure 2.4). The SVM classification of the land cover for Hanoi resulted in a high overall accuracy ranging from 93.85% (kappa coefficient = 0.92) to 95.37% (kappa coefficient = 0.94). Comparing with our previous study using similar method (Castrence et al. 2014), we obtained higher accuracy in this study. This was accounted for by the smaller study area and the richer historical archive of Landsat images and high resolution image in Google Earth in the study area that assisted us in labeling the land cover classes more accurately. Accuracies of each class slightly vary; we found that three classes of change (1993-2001; 2001-2006; 2006-2010) generally have lower accuracy than other stable classes (agriculture; built-up; forest; water) (Table 2.1). Accuracies also greatly depend on an appropriate land cover classification scheme, spatial resolution of satellite images and study's objectives. The urban landscape of Hanoi is heterogeneous but we simplified our land cover classification scheme that met our study's objectives and was suitable with 30-meter spatial resolution Landsat images. Accuracies may also depend on the temporal coverage of the Landsat images as we found the higher temporal coverage tends to result in higher accuracy of that particular period. Therefore, our most recent change class, with lower temporal coverage, often has lower accuracy. We had gaps in time (Figure 2.1) because we omitted several cloudy and SLC-off images. Our decision was made based on Castrence et al. (2014) that shows the SVM classifier is sensitive to noise and missing data such as cloudy and SLC-off images. Even though recent advanced remote sensing techniques may help to fill the un-scanned gaps for SLC-off images and therefore provide a better temporal coverage, this would require a considerable amount of time and effort that is beyond the scope of our study.

Table 2.1. Overall accuracy, kappa coefficient and average producer's and user's accuracies of the ten-fold cross validation for all land cover classes.

Land cover classes	Prod. Acc.	User Acc.
Agriculture	95.60%	95.11%
Built–up	95.34%	95.12%
Change 1993-2001	94.10%	93.86%
Change 2001-2006	93.01%	93.15%
Change 2006-2010	92.86%	92.85%
Forest	94.61%	95.61%
Water	94.90%	95.38%
Overall Accuracy	94.5%	
Kappa Coefficient	0.93	

Due to the seasonal change of water levels in the 'Red River' or 'Song Hong', some of the alluvial plain areas were misclassified as built-up change classes. To resolve this misclassification issue, a layer of the Red River for Hanoi was manually digitized as a masking layer, and then the 'raster calculator' tool was used to merge the original land cover map with the masking layer. In addition, we also observed numerous one-pixel outlying patches misclassified as change classes in agricultural areas resulting in 'salt and pepper' patches that would lead to an overestimation of urban spatial patterns and configuration. This problem is quite common when using medium resolution satellite image such as Landsat and was seen as a disadvantage of the SVM classifier (Fung et al. 2008). Therefore, the SVM classification is necessarily followed by post-classification methods such as using a sliding-window majority vote (Soergel 2010). In this study, a 4x4 majority filter kernel was applied. The final land cover map of Hanoi revealed that although the built-up land is becoming rapidly expanded and the size of the city core is growing, the city's landscape is still largely occupied by agriculture.

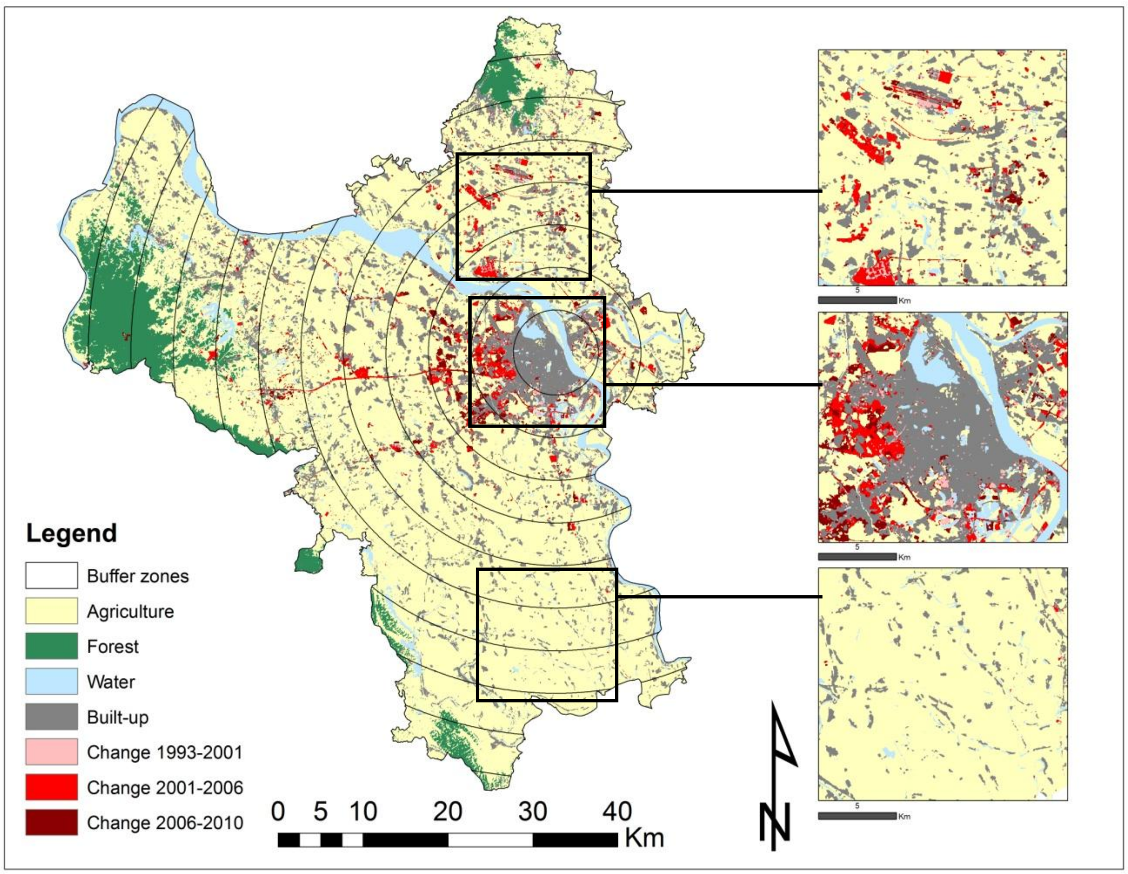

Figure 2.4. Land cover map of Hanoi using the Support Vector Machine Classification.

Gradient analysis of urbanicity and land cover changes in Hanoi

To understand the urbanicity of Hanoi along the rural-urban gradient, we summarized the number of communes of each category for each buffer zone. In order to do this, we generated commune centroids using 'feature to point' function in ArcGIS, and then the commune centroid layer and the buffer zone layer were overlaid. The overlaid result showed that within a radius of five km, 91.1% of the communes are classified as urban core and none of them is rural. As the buffer distance increases (above five km), the share of urban and urban core communes reduces and the number of peri-urban and rural communes grows. The number of peri-urban communes peaks between 10 and 20 km. From 20 km outward, the share of peri-urban communes reduces and the number of rural communes starts rising and remaining the majority in other buffer zones till it reaches the boundary (Figure 2.5).

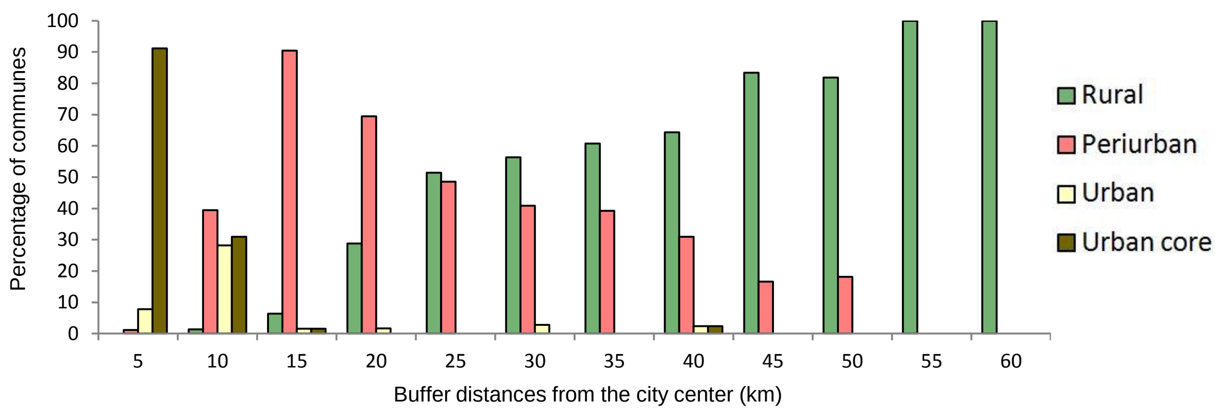

Figure 2.5. Urbanicity along the rural-urban gradient of Hanoi.

It is clear that the urbanicity of Hanoi has an inverse relationship with the distance from the city center. Over time the urban core has been expanded to meet its growing demand as the cultural, social and economic center of Vietnam. In 1993, the concentric zone of Hanoi was covered by four districts with an area of 47.27 km^2 (Vien et al. 2005). In 2006, the number of urban core districts increased to 10 and covered an area of 228.55 km^2. Just in 2013, two new urban districts (Bac Tu Liem and Nam Tu Liem) were added to the core increasing the number of urban districts to 12 and covering an area of 304.17 km^2. Along with the expansion of the urban administrative area, the conversion of agricultural land to urban built-up land is rapidly occurring along the rural-urban gradient.

To quantify the location and change of built-up land over time and along the rural-urban gradient, we used the pre-defined buffer zones. The result showed that, over the course of the study, the growth of built-up areas occurred mainly between10 and 25 km buffer zones (Figure 2.6). Within 10 to 25 km buffer zones, the changes between periods are also distinctive difference; the largest growth has generally taken place between 2001 and 2006. The core zone (within five km) and over 35 km buffer zones have lower amount of change over the three periods and differences between periods are also negligible. However, the question of whether the built-up change in different buffer zones conforms to the built-up change in different commune categories is worth to explore. We quantify the newly built-up land using the commune classification by Saksena et al. (2014) (Figure 2.7). The result showed that the urban core and urban communes experienced a very modest change over three time periods and the growth in the peri-urban category is the most remarkable. Most of the changes occurred in between 2001 and 2006 in all commune categories. The largest growth in peri-urban communes is 30 times higher than that in urban core communes in the same period (2006 to 2010). Both of our approaches of built-up change analysis reveal a distinction of urban growth in different commune categories and along the rural-urban gradient. This comparison suggested that the urbanization in Hanoi is driven by both the distance to the urban center and the socio-economic and natural characteristics of each commune.

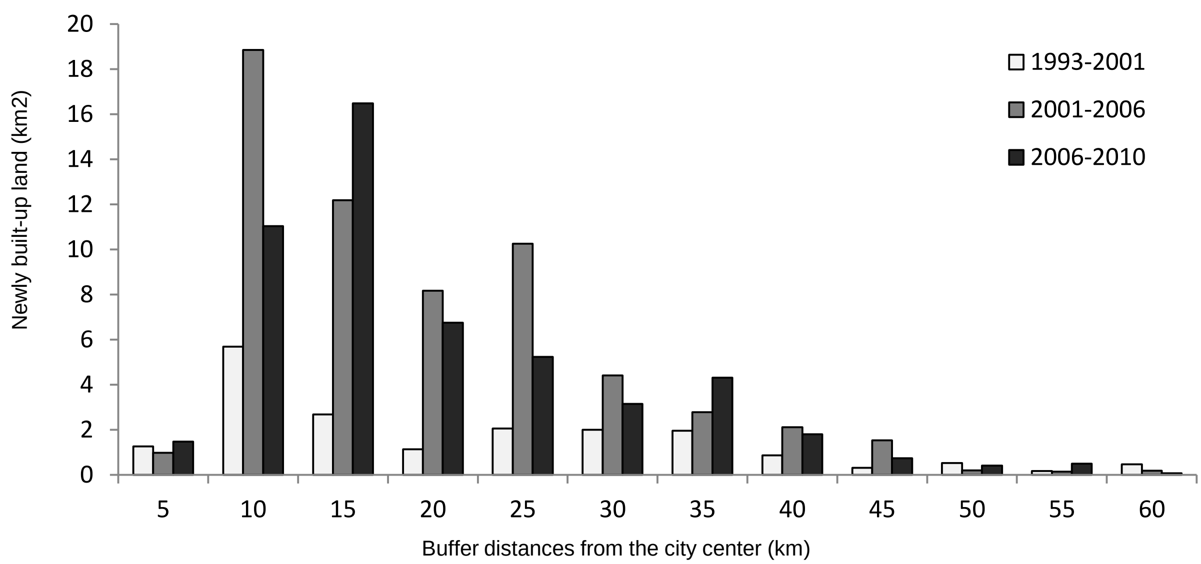

Figure 2.6. Newly built-up land in different buffer zones for three periods.

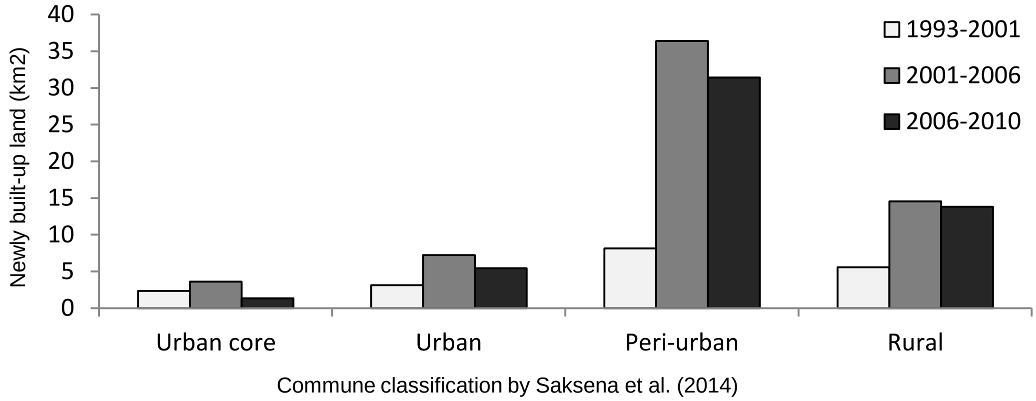

Figure 2.7. Newly built-up land in different commune categories for three periods.

Together with the expansion of built-up land in peri-urban areas; a similar pattern of population growth was also found in here. The data showed a relatively same pace of built-up and population change in peri-urban areas but a gap/disproportion in urban, urban core and rural communes (Figure 2.8). According to the population and housing census, in ten years period, 1999 to 2009, population of Hanoi has increased more than a million people, of which over 50% was added to peri-urban communes (Figure 2.8). Even though the population data was captured in a shorter time period (10 years), within five and ten km buffer zones, the population growth exceeds the growth of built-up land which indicates an increase of population density in these intrinsically high density areas. Of the total amount of population and built-up change, the largest amount was added to the ten and 15 km buffer zone (Figure 2.9).

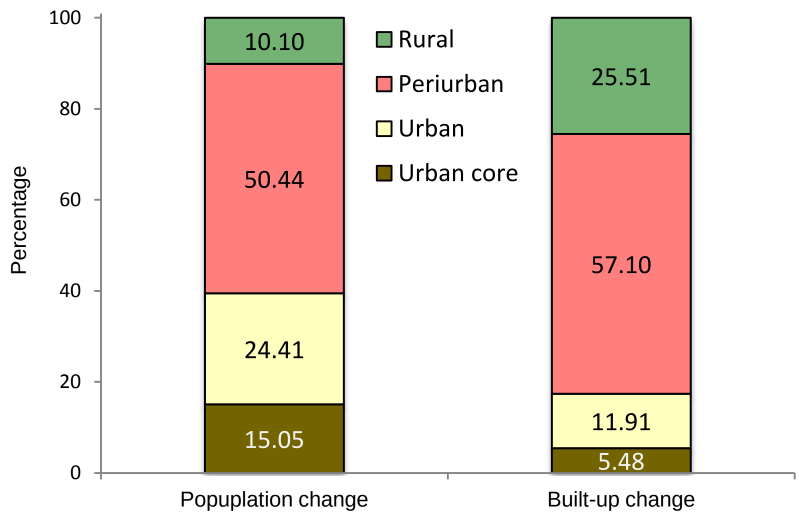

Figure 2.8. Percentage of population change and built-up change in each commune category: Percentage was computed based on the total amount of built-up growth during the study period and total population increase between two census data.

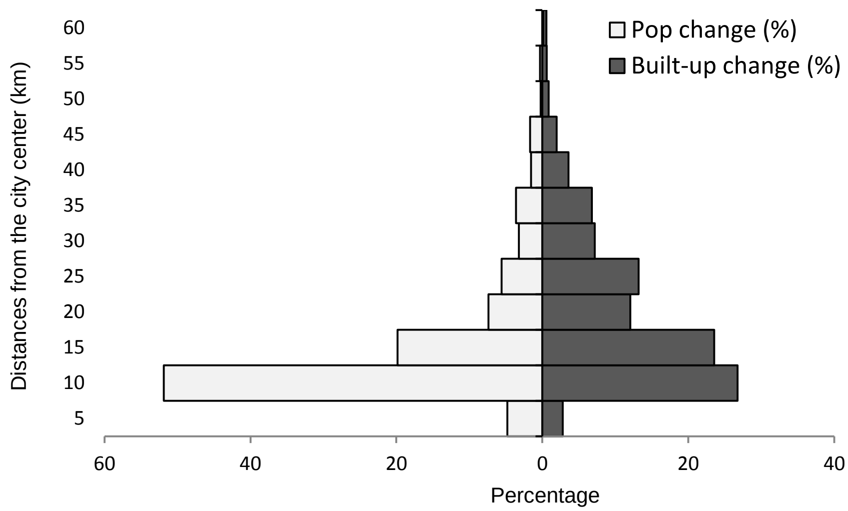

Figure 2.9. Percentage of population change and built-up change in each buffer zone: Percentage was computed based on the total amount of built-up growth during the study period and total population increase between two census data.

This study showed that the growth of built-up areas in Hanoi is closely linked with the growth of economy and population. The introduction of the ‘Doi Moi’ policy in 1986 was a significant turning point into considerable transformation of Hanoi. The GDP of Hanoi increased 11.2 times in the period of 1985-2000 and 3 times between 2000 and 2008 (Labbé 2010). The current target for GDP in 2014 is US $2,726. The city’s poverty rate sharply decreased from 62.7% in 1993 to 3.4% in 2010 and the target of 2% poverty rate has been set for the year 2015 (Biau, D. 2010). The change of built-up land detected by remote sensing data is reflected in some economic values. For instance, increase in built-up area is influenced by housing development on one hand and also industrial infrastructure development. The GDP growth for industry sector of Hanoi is estimated for 15% per year between 1996 and 2000 while GDP for agriculture sector has gone down from 5.13% in 1996 to 3.8% in 2000 (Duong et al. 2003).

The expansion of Hanoi in both administrative areas and built-up areas over the last two decades was manifold. The urban growth of Hanoi is important to consolidate the city’s position as the center of politics, culture, education, science, economics, and international exchanges of the country. In addition, the extended capital city is expected to contribute to the economic and functional development of the city by encouraging investment, including official development aid (ODA) and foreign direct investment (FDI), and by supporting the expansion and modernization of the surrounding infrastructure system. It is expected to attract the city’s population and redistribute the overcrowded urban core. While the former expectation might be achieved, the later might not readily be an effect. The result in this study showed an increase of population density in the urban core area. Most of the new population in the city are rural migrants from neighboring provinces, with a minor share of natural growth (Labbé 2010). The increase was spontaneous due to the migration to the cities by farmers who have lost their land and employment (Quertamp and de Miras 2012).

During the 1990s, large scale conversion of agricultural land to urban land was tightly restricted and controlled by the state; requiring approval from the Ministry of Natural Resources and Environment. At the beginning of the 2000s, the state relaxed its power on the management of these lands and, in 2006, decentralized to provincial and municipal governments (Labbé 2010). This stimulated a real estate market boom all over Hanoi's peri-urban areas. In the same vein, by the late 1990s, the central government ratified an orientation for general planning of urban development in Vietnam up to 2020 with the goal of fostering economic development (Decision 10/1998/QD-TTg). This decision has literally promoted the urban expansion through the conversion of agricultural to urban land uses and revitalization in slum areas. These policies have immense consequences for local communities and even migrants from neighboring areas, especially the loss of agricultural occupations of many local people and the difficult housing access for migrant workers. By the late 1990s, the central and municipal authorities developed an urban development model referred to as 'Khu Đô Thị Mới' or 'New Urban Areas' (NUAs) such as Trung Hoa - Nhan Chinh, My Dinh, Nam Trung Yen or Dinh Cong Living Quarters which are located within 10 to 15 km of the historic center (Labbé and Boudreau 2011; Waibel 2004). These NUAs were mainly developed between 2000 and 2005 and some of which are still under construction. These carefully planned new sites, provided with a well-equipped infrastructure, are good targets for upper and emerging middle classes of Hanoi searching for a dwelling. Even though it was planned that about 30 to 50% of new housing units built in NUAs be accessible to low-income population, it is still too far to reach for low-income cases and because of several legal barriers[1]. Many rural migrants and land lost farmers from neighboring areas or other provinces that are in the informal or private sectors and illegal migrants are certainly disqualified for this housing project. Therefore, large urban area of Hanoi turned into marginal settlement zones with slum-like buildings and became the destination of impoverished city residents as well

[1] Among several other criteria, it is required by policy that only permanent residents of Hanoi or temporality registered residents with a secured-labor contract of more than 12 months are eligible to buy low income apartments. In addition, in order to register as permanent resident of Hanoi, one has to own a house.

as rural migrants (Boothroyd and Phạm 2000). Consequently, the flood of population both legality and illegality to Hanoi for the convenient of work and services makes this area particularly high density.

Conclusions

The supervised non-parametric statistical learning techniques of SVM produced a highly-accurate map of land cover change with the overall accuracy of 95%. We found that built-up areas in Hanoi have expanded rapidly over the last two decades. Especially, most of the change occurred between 2001 and 2006 and between 2006 and 2010 which correspond to major policy changes in the beginning of 2000 when the state relaxed its grasp on the management of the land and, in 2006, decentralized the power to approve and convert land uses down to provincial and municipal governments stimulating a real estate market boom all over Hanoi. A large part of Hanoi's economic growth comes from FDI which consequently goes to industrial and infrastructural development projects in the peri-urban areas. In 2008, Hanoi received close to US$18.8 billion in FDI, accounting for 7% of the total investment in Vietnam (HSO 2009). Several housing development projects between 2000 and 2005 also contributed to the expansion of the city between ten to 15 km to the West and Southwest portions. Since major source of urban expansion in Hanoi came from cropland, large rural population has been squeezed out of the agricultural sectors and became unemployed. Therefore, massive migration to city in searching for alternative incomes is indispensable if social welfares and post-urbanization plan for these people are not taken into consideration and if the urbanization is haphazardly taken place. The analysis is supported by other statistical data such as the population structure of Hanoi over the years. Through this study, correlations between the urban growth, the spatial expansion of the city and other socio-economic factors can be proposed. Knowing how, where and when the urbanization occurred would allow urban planners and policymakers to timely assess and adjust accordingly the urban growth and be aware of the sustainable use of the cropland and other environmental, social and economic problems.

CHAPTER 3. QUANTIFYING URBAN GROWTH PATTERNS IN HANOI USING LANDSCAPE EXPANSION INDICIES AND TIME SERIES SPATIAL METRICS

Abstract

For anytime period, the spatial arrangement of urban areas provides a snapshot of various economic, social, and political factors that influenced land use decisions. This study aimed to quantify urban growth rates, growth modes, and resultant changes in landscape patterns of urbanization in Hanoi from 1993 to 2010 and to evaluate the extent to which the process of urban growth in Hanoi conforms to the diffusion-coalescence hypothesis. We analyzed the spatiotemporal patterns and dynamics of the built-up land in Hanoi using landscape expansion indices, spatial metrics and a gradient approach. The results suggested that high urbanization occurred in the periods of 2001-2006 and 2006-2010 from 10 to 35 km buffer zones. The seemingly complicated spatiotemporal dynamic of urbanization was successfully captured by its time series spatial metrics. Over the 17 year period the urban expansion in Hanoi was dominated by infilling and edge expansion growth modes. The spatiotemporal patterns of urban landscape found in this study support the diffusion-coalescence theory of urbanization. The findings from this study provide important information about the urban growth process and cycle through the shift of the growth hot-zone and the changing behavior of spatial metrics; thereby, support urban modeling and prediction. The resultant spatial patterns could also be used to evaluate urban planning policies and initiate measures against urbanization issues.

Keywords: *Urbanization, spatiotemporal patterns, spatial metrics, diffusion-coalescence theory, gradient approach.*

Introduction

Urbanization is known as one of the most powerful, irreversible, and visible human impacts on earth causing landscape and ecosystem transformations and exacerbating global environmental problems (Brown and Kernaghan 2011). Today, more than half of the world's population lives in an urban area (Un-habitat 2010). Considering the immense impacts of urbanization on ecosystem and human population in foreseeable future, monitoring and understanding urban patterns, dynamic processes, and their relationships is a primary research focus of scientists, resource managers, and planners.

For any time period, the spatial arrangement of urban areas provides a snapshot of various economic, social, and political factors that influenced land-use decisions (Seto and Fragkias 2005). Central questions concerning the urban patterns and dynamic processes are how cities are spatially growing and organized and how urban growth results in a specific pattern, and ultimately what will be the consequences of such patterns and processes (Bhatta 2010). Addressing these questions will help us to better balance various competing goals of sustainability while making policies and planning for future urban development.

Dynamics of urban patterns have been a long-standing interest of many scientists in the past century. Many urban theories were developed such as the Concentric Zone Theory (Park and Burgués 1925); the Sector Theory (Hoyt 1939); the Multiple Nuclei Theory (Harris and Ullman 1945); and the Wave Theory Analog Approach (Blumenfeld 1954; Boyce 1966). These theories have provided a better understanding of urban structure and dynamics and have been widely used to model urban systems. However, the spatiotemporal dynamics of urban patterns have not been adequately tested and described in these theories (Dietzel et al. 2005b; Lee 1973; Lee 1994; Ulfarsson and Carruthers 2006). Recent increased computational power, improved sources of remotely sensed data, landscape pattern analysis and geographic information systems provide a powerful approach to modeling and testing urban morphological theories (Luck and Wu 2002; Xie et al. 2006; Zhu et al. 2006).

In recent studies, spatial metrics have been used extensively as a means of quantifying spatial characteristics at patch, class or landscape levels, and therefore have potentials in helping to understand the process of urban development at various scales and to inform models of urban growth (Dietzel et al. 2005a; Dietzel et al. 2005b; Martellozzo and Clarke 2011). Dietzel et al.

(2005b), using spatial metrics to develop theory of spatiotemporal growth dynamics for the Houston Metropolitan Area, suggests that the spatial evolution of cities can be described as an oscillatory of a two-phase process of diffusion and coalescence (Figure 3.1). In the urban growth context, the term 'diffusion' refers to the dispersed expansion of new urban areas from the origin point or 'seed' location (Dietzel et al. 2005b) and is represented by the dominance of 'edge expansion' and 'spontaneous growth' (Liu et al. 2010; Xu et al. 2007). Meanwhile, the term 'coalescence' refers to the union of individual urban patches (Dietzel et al. 2005b) or the 'infilling' of open spaces within the urban complex (Liu et al. 2010; Xu et al. 2007). Three urban growth processes (infilling or gap-filling; edge expansion; and spontaneous or outlying growth) have been widely discussed in the literature (Berling-Wolff and Wu 2004; Clarke et al. 1997; Liu et al. 2010; Xu et al. 2007). These three urban growth processes occur concurrently, but the abundance of each type varies within the urbanization cycle, therefore, determine the urban growth phases (Francis and Chadwick 2013; Li et al. 2013).

Hanoi, after the 'Doi Moi' reform policy in 1986, has considerably transformed in both socio-economic and physical forms. The annual growth rate of GDP during 1995-2000 was 10.7%, substantially higher than the national rate of 7.1% (Khuong and Haughton 2004). The city's GDP increased three-fold between 2000 and 2008 (HSO 2009). Along with the economic growth, the city population has substantially grown at an annual rate of 3% and reached 3.2 million in 2007 (Danielle 2010). The expansion of the administrative boundary in 2008 has doubled the population of the city-region to 6.4 million and become the second largest city in Vietnam after HCM city (HSO 2009). While much has been known about the socio-economic achievements after 'Doi Moi', spatiotemporal patterns of the urban growth are poorly understood. Given the need of understanding the spatiotemporal patterns of urban growth in Hanoi, the objectives were to quantify the growth rates, growth modes, and resultant changes in landscape patterns of urbanization by using spatial metrics (McGarigal and Marks 1995) and landscape expansion indices (Liu et al. 2010; Xu et al. 2007) and to evaluate the extent to which the process of urban growth in Hanoi conforms to the diffusion-coalescence hypothesis by Dietzel et al. (2005a, b).

Methods

Study area and data sources

To address the main objectives, the study focused on the city and surrounding landscape of Hanoi. We used pre-existing land cover map from the previous study (see Chapter 2) to generate spatial metrics for the study area. The original land cover map include four stable classes (classes which remain unchanged throughout study period): (i) water, (ii) forest, (iii) agriculture, (iv) built-up before 1993, and three classes of built-up change in three following periods: (i) 1993-2001, (ii) 2001-2006, and (iv) 2006-2010. We attempted to map built-up changes in these time periods in order to synchronize with the national socio-economic census for the convenience of combining and analyzing these two datasets together. As we focused only on built-up land categories, we excluded other land cover classes in the spatial analysis such as water, forest and agriculture (for detail about the land cover classification method, please see Chapter 2). Based on the field observation, we assumed that all changes to built-up land in Hanoi come from agricultural land and other sources of changes are negligible.

Hypothetical model of urban growth

To identify patterns and processes in the agricultural to urban landscape transitions, we focused on a hypothetical model of spatial evolution by Dietzel et al. (2005a), in which urban land area increases through a combination of diffusion and coalescence processes (Figure 3.1). In this hypothetical model, a predominantly agricultural landscape becomes more fragmented over time as new developments are established in the periphery of an urban core. As they expand in size, these patches begin to aggregate until most of the land has become urbanized. We can quantify and track these changes by examining spatiotemporal patterns of urban patches through their spatial metrics and urban growth typologies.

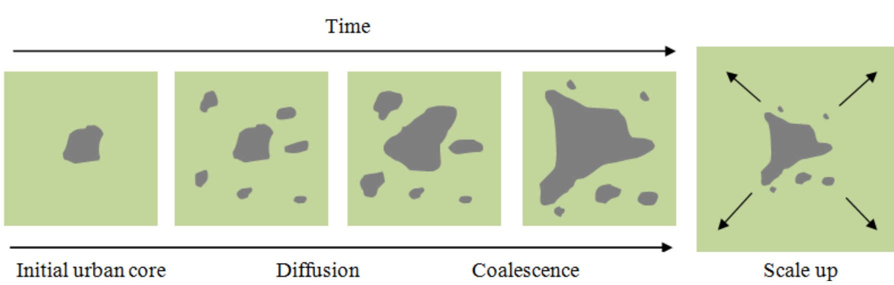

Figure 3.1. Hypothetical sequence of the spatial evolution of an urban area (Adapted from Dietzel et al. (2005a).

Quantifying spatiotemporal patterns of urbanization using spatial metrics

There are a large number of quantitative spatial metrics available, but many of them are highly correlated with one another, therefore; containing redundant information. (Baker and Cai 1992; McGarigal and Marks 1994). Riitters et al. (1995) examined the correlation among 55 spatial metrics and found only five independent metrics which were able to detect meaningful structure of urban landscape. Geoghegan et al. (1997), Alberti and Waddell (2000) and Herold et al. (2005) compared a range of different metrics and suggested that there is not any unique set of metrics for use in urban environments and the metrics selected for analysis must be based on the objectives of the studies. In this study, we used a set of spatial metrics which were known to have explicit meanings in relation to the diffusion and coalescence processes of urban growth (Dietzel et al. 2005b; Li et al. 2013; Tischendorf 2001; Wu et al. 2011). These spatial metrics include: 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) (Table 3.1). The landscape indices were calculated with public domain software FRAGSTATS version 4.3 (McGarigal et al. 2002).

Table 3.1. Spatial metrics selected for spatiotemporal analysis.

No	Spatial metrics	Range	Description	Diffusion	Coalescence
1	Patch Density (PD)	PD ≥ 0, ∞	Number of patches per hectare (ha).	Increasing	Decreasing
2	Edge Density (ED)	ED ≥ 0, ∞	Sum of the lengths (m) of all edge segments in the landscape per ha.	Increasing	Decreasing
3	Landscape Shape Index (LSI)	LSI ≥ 1, ∞ (The larger LSI the more irregular shape of the landscape)	Normalized ratio of edge (i.e., patch perimeters) to area of a class or landscape.	Increasing	Decreasing
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)	Proportion (%) of the largest patch in a class or landscape.	Decreasing	Increasing
5	Area-weighted Mean Euclidean Nearest-Neighbor Distance (ENN_AM)	ENN_AM ≥ 0, ∞ (The larger ENN_AM the more patch isolation)	Distance from a patch to a neighboring patch of the same or different class, based on the nearest cell center-to-cell center.	Increasing	Decreasing
6	Area-weighted Mean Patch Fractal Dimension (FRACT_AM)	1≤ FRACT_AM ≤2 (The larger FRACT_AM the more shape complexity of individual patches)	Complexity of a patch by a perimeter area proportion.	Increasing	Decreasing

We calculated the annual growth rate of urbanized land as:

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

Equation 3.1. Annual growth rates of urbanized land

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

Equation 3-1 has been standardized to calculate the annual rate of forest change (Puyravaud 2003) and has been wildly used to quantify urban growth (Seto and Fragkias 2005). Furthermore, Equation 3.1 assumes urban growth is an exponential process that is mathematically identical to the annual rate of compound interest.

Typologies of urban growth

Based on the relationship between newly grown urban patches and pre-growth urban patches, Xu et al. (2007) proposed a quantitative method to distinguish three urban growth types: infilling, edge expansion, and spontaneous growth. The dominance of each growth types is meaningful to describe the process of landscape pattern changes between two or more time points (Francis and Chadwick 2013; Li et al. 2013). Whether a growth patch is called infilling or edge expansion or spontaneous growth is determined by shared-boundaries between newly grown patches and pre-growth patches in the following equation:

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

Equation 3.2. Landscape Expansion Index

where *LEI* is Landscape Expansion Index, *Lc* is the length of the shared-boundary of a newly grown urban area and the pre-growth urban patches, and *P* is the perimeter of this newly grown patch.

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 shared-boundary. The three growth types are illustrated in Figure 3.2.

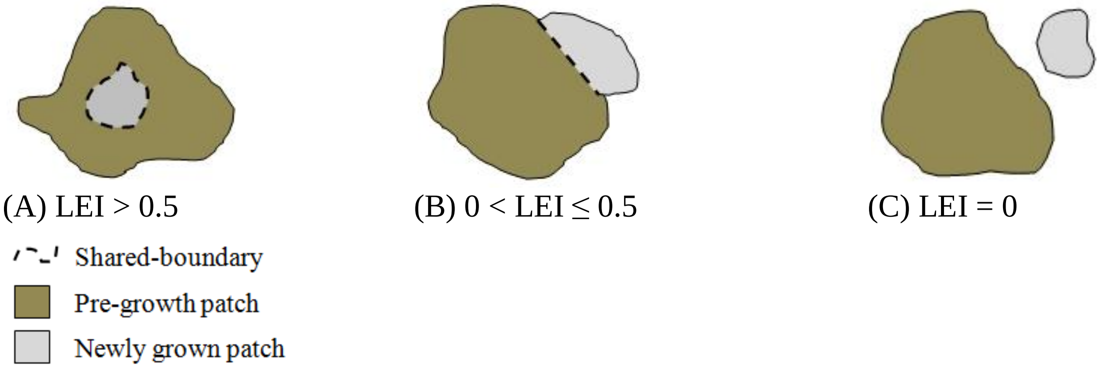

Figure 3.2. (A) Infilling growth which occurs within urbanized open space & increases contiguity of built-up area by filling in that space; (B) Edge expansion which refers to non-infill development intersecting the urban footprint & extending outward from previous development; and (C) Spontaneous growth which does not intersect the urban footprint, is not contiguous with previously developed areas and has greatest effect on fragmentation of open lands.

To get a sense of the relative dominance among the different forms across a landscape or over time, Liu et al. (2010) has further developed an Area-Weighted Mean Expansion Index (AWMEI) expressed in the following equation:

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

Equation 3.3. Area-Weighted Mean Expansion Index

where *LEIi* is the *LEI* value 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 grown patches.

Larger values of AWMEI correspond to more compact form of urban growth while smaller values of AWMEI imply the prevalence of leapfrogging or spontaneous development or urban sprawl. Increase of AWMEI over time signifies a coalescence phase while decrease of AWMEI signifies a diffusion phase.

Rural-urban gradient analysis

In order to quantify the scale and impact of urbanization, we created multiple buffer zones from Hanoi center. First, we defined a center point located in Hoan Kiem district because this is one of the first four urban districts of Hanoi and where other studies also refer to as the center point (Pham and Yamaguchi 2011; Quang 2013). Then, multiple buffer zones of five-kilometer interval were created from the center point until it covered the entire Hanoi boundary (Figure 3.3).

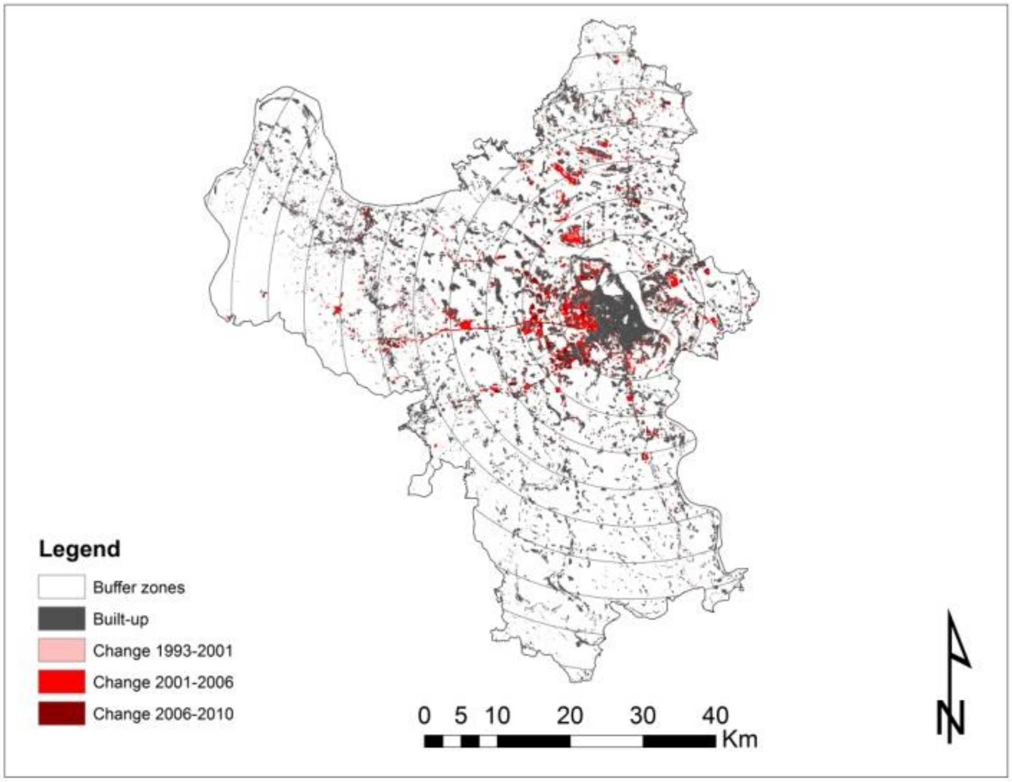

Figure 3.3. Multiple buffer zones of five-kilometer interval from the Hanoi center.

We defined the five-kilometer interval buffer zones because the four initial urban districts in 1993 (the beginning of the study period) was contained within the five kilometer radius. Within each buffer zone, we calculated annual urban growth rates and analyzed the selected spatial metrics described in Table 3.1 and three landscape expansion indices (infilling, edge-expansion, and spontaneous growth) for three time periods to understand their changing behaviors along the gradient. Because of the different size among the buffer zones, we standardized all measures by their mean values and percentages to make them comparable.

To quantify how landscape patterns changed during urbanization, we computed the difference in each spatial metric across the three time periods using following simple equation: Difference in spatial metric i = Spatial metric i (t_2) – Spatial metric i (t_1). For a given spatial metric, an increase in its value from t_1 to t_2 leads to a positive difference and a decrease in its value from t_1 to t_2 results in a negative difference.

Results

Annual urban growth

Between 1993 and 2010 the built-up land increased from 504 km^2 to 631 km^2, rising from 15% to 20% of the total land area. The annual growth rate of built-up land for three time periods and for twelve buffer zones showed that speed of urbanization is different between the study periods and depends on distance from the urban center. The annual growth rate ranged from as little as 0.12% to 5.27%, with higher growth rates found in the two later periods (2001-2006 and 2006-2010) and in the distance of 10 to 35 km buffer zones (Figure 3.4).

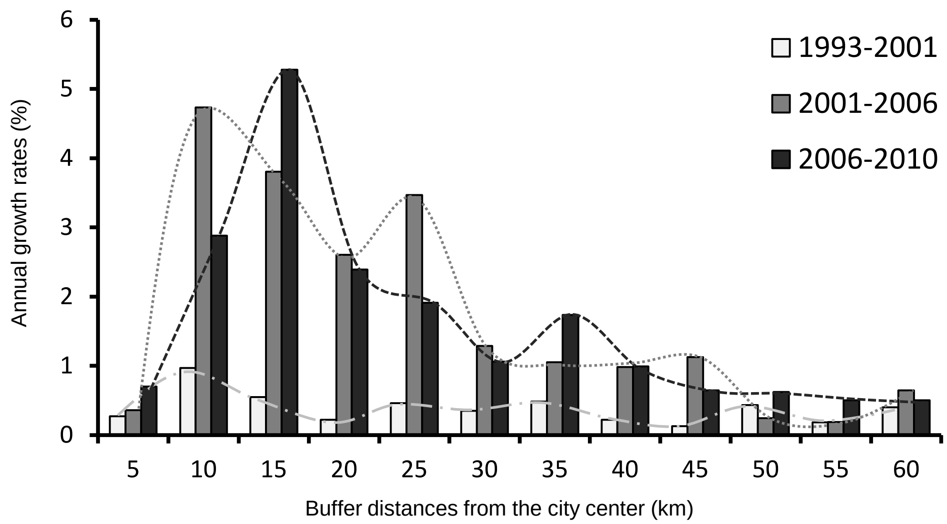

Figure 3.4. Annual growth rates of built-up area across different buffer zones

Urban growth modes

Over the 17 year period the relative dominance of infilling, edge expansion and spontaneous growth changed whereas both new urban patches emerged and the old ones got expanded. These changes led to urban clusters enlarging and coalescing, ultimately forming the Hanoi urban agglomeration. Across all time periods the landscape was dominated by edge expansion, followed by infilling growth in terms of both area and number of patches (Figure 3.5). Infilling growth exhibited a decrease, whereas edge expansion growth exhibited an increase and spontaneous growth was relatively constant.

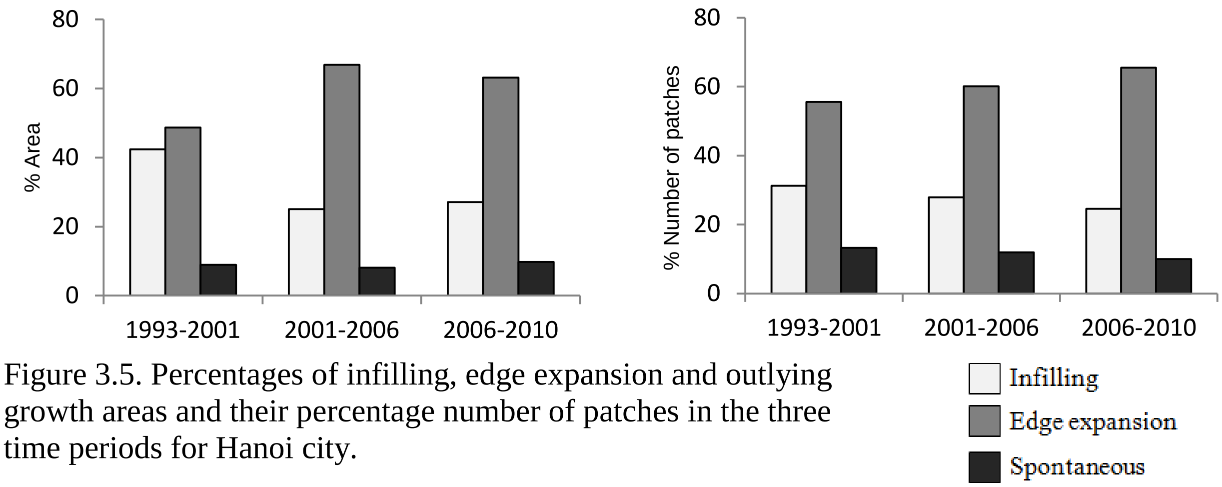

Figure 3.5. Percentages of infilling, edge expansion and outlying growth areas and their percentage number of patches in the three time periods for Hanoi city.

Across the urban landscape, the relative dominance of growth patterns is different across space and time (Figure 3.6). For example, in the first period (1993-2001), the five and ten km buffer zones were dominated by the infilling growth mode while the other buffer zones were dominated by the edge expansion growth mode. In the second period (2001-2006), major urban growth mode of the ten km buffer zone has shifted from the infilling to the edge expansion. The infilling still dominated in the five km buffer zone. In the third period (2006-2010), however, the dominance of urban growth mode in the five km buffer zone shifted to the edge-expansion and the 35 km buffer zone is in reverse trend where it shifted from the edge-expansion to infilling growth mode. Thus, there were temporal switches in urban growth modes in the five, ten and 35 km buffer zones over the three periods.

At different time periods, the relative dominance of the three growth modes in each buffer zone also showed different proportions between the patch area and patch number representations (Figure 3.6). For example, in the period 2006-2010, at the 35 km buffer zone, the infilling grew in a larger area but had a smaller number of patch as compared to other growth modes (edge-expansion and spontaneous growth). Therefore, the temporal shifts in relative dominance of three urban growth modes revealed by patch number may differ from those revealed by patch area (Figure 3.6). These two measures are complementary each other, therefore; providing more information when examined together. For example, a landscape with a small patch area and a large patch number is often more fragmented and vice versa. The AWMEI (Equation 3.3) is a synthesized index where it takes into account different growth modes, patch area and patch number to justify the relative dominance among the three urban growth modes over three time periods and twelve buffer zones. The study suggested that using LEI and

AWMEI together can facilitate the interpretation of seemingly complicated urban growth phenomenon.

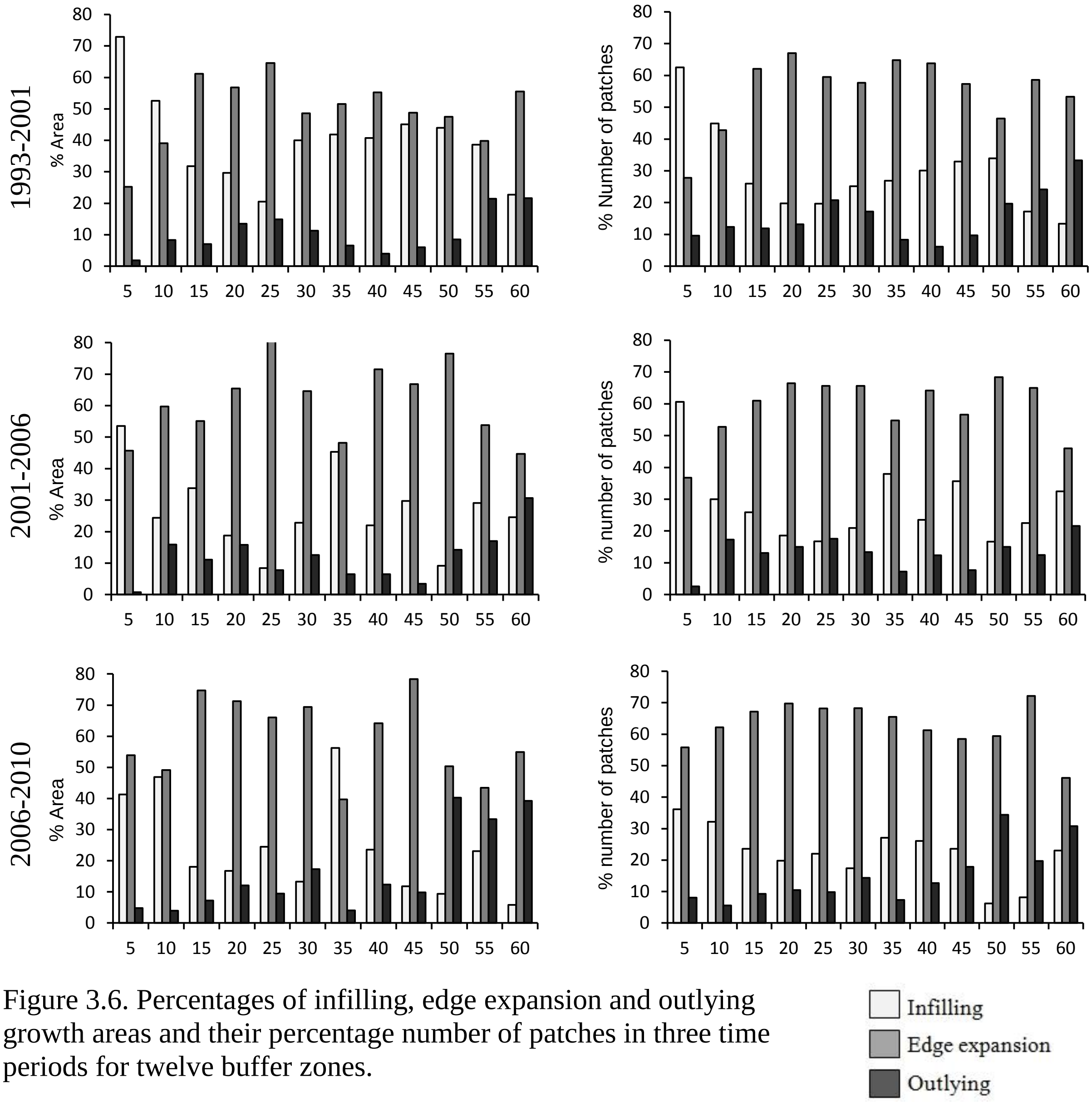

Figure 3.6. Percentages of infilling, edge expansion and outlying growth areas and their percentage number of patches in three time periods for twelve buffer zones.

The spatial and temporal profiles of the AWMEI (Figure 3.7), averaged for all communes in each buffer zone, showed three particular trends: The AWMEI decreased over time in the 5, 30, and 40 to 60 km buffer zones. At the 35 km buffer zone, however, the AWMEI ascended over time. In the 10 to 25 km buffer zones, the urban morphologies reveal a distinct trend where all their AWMEI values decreased in the second period (2001-2006) but increased again in the third period (2006-2010).

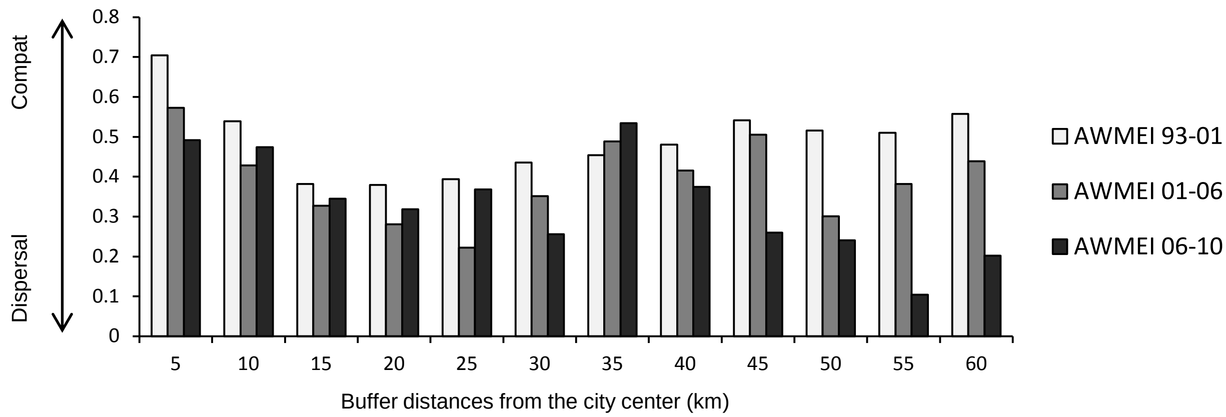

Figure 3.7. Spatial and temporal profiles of the area-weighted mean expansion index for twelve buffer zones.

Landscape structures and changes during urbanization

Patch density and edge density increase as the buffer distance increased (Figure 3.8 A&B). The landscape shape index was greatest between 10 to 30 km buffer zones; indicating a more complicated landscape shape in these zones as compared to others (Figure 3.8C). On the other hand, the largest patch index was smaller between 15 to 30 km buffer zones (Figure 3.8D). As such, the largest patch in the 15 to 30 km buffer zones comprises only four to ten percent of the landscape, whereas in the five km buffer zone it comprises 81 percent of the landscape (Figure 3.8D). 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 values of ENN_AM appear to be higher in between 15 to 35 km buffer zones (Figure 3.8E). 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 (Figure 3.8E). The FRACT_AM values are higher in between the 5 to 35 km, indicating 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 (Figure 3.8F).

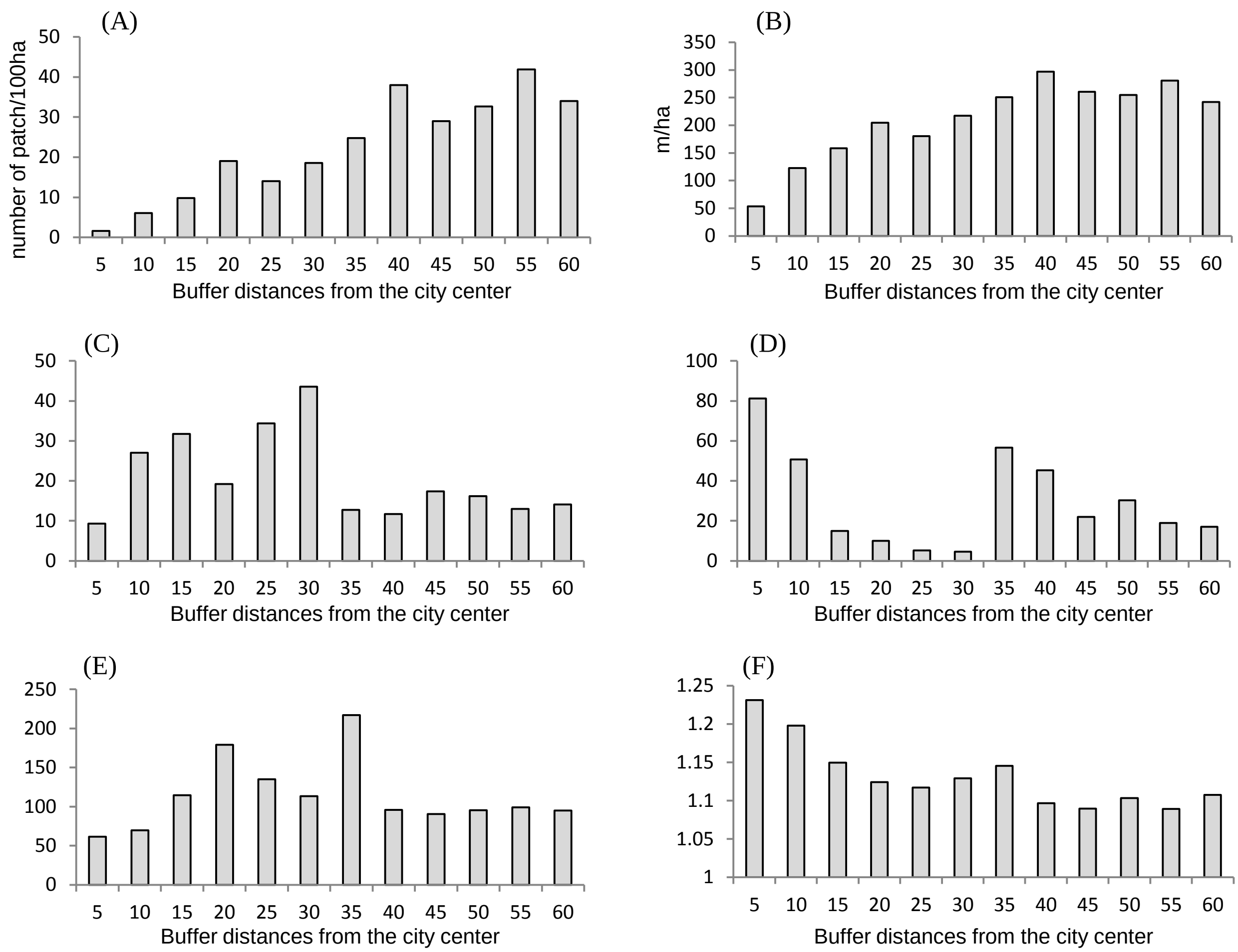

Figure 3.8. Mean selected spatial metrics showing general landscape patterns over three time periods and across different buffer zones: (A) Patch Density; (B) Edge Density; (C) Landscape Shape Index; (D) Largest Patch Index; (E) Area-weighted Mean Euclidean Nearest-Neighbor Distance; (F) Area-weighted Mean Patch Fractal Dimension.

For each spatial metric, trend and magnitude of the changes are different among three time periods and across different buffer zones (Figure 3.9). Over three time periods, the PD and ED have decreased indicated by a negative difference between two consecutive time periods. These results suggested that the degree of landscape fragmentation have reduced over time. The LSI also reduces within 5 to 35 km buffer zones. The decrease of the LSI in these zones indicates that over time the shape of the landscape become closer to the regular-square and circle shape. The LPI has increased in the 10, 15, 25 and 35 km buffer zones while it remains quite stable in other places. The increase of the LPI over time in these buffer zones reveals the prevalence of infilling and edge expansion during the urbanization process.

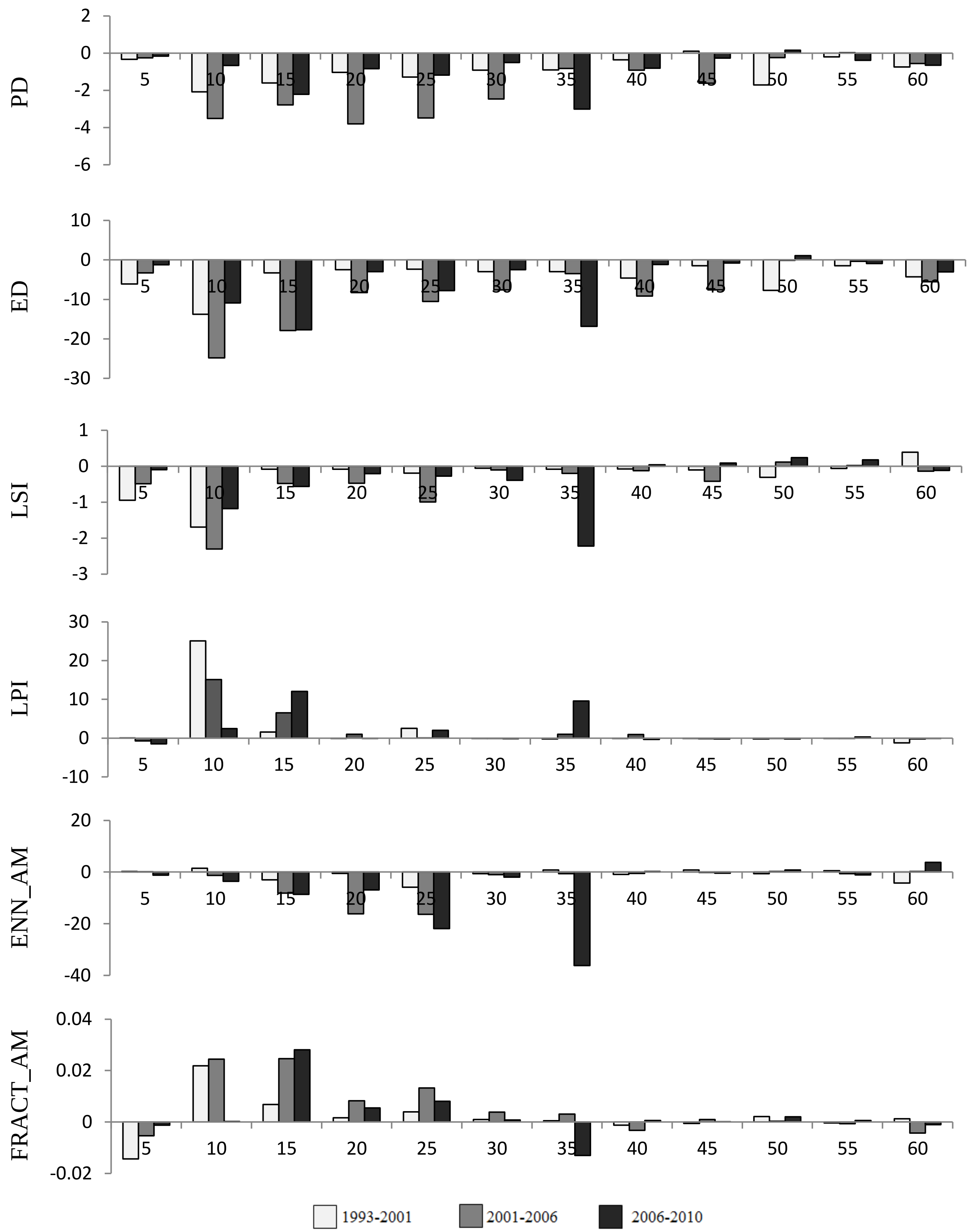

Figure 3.9. Changes in mean values of the spatial metrics at different buffer zones over three time periods.

The ENN_AM has decreased over time in the 10 to 35 km buffer zones and it slightly fluctuates in other buffer zones. The decrease of ENN_AM in these buffer zones signified a decrease of patch isolation in these areas. The FRACT_AM has decreased at the five km buffer zone. This decrease indicates that, over time, 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 25 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 then 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 rates (Figure 3.4). The above results showed that major change in spatial metrics happened from the 10 to 25 and at 35 km buffer zones which correspond to the faster pace of urbanization in these areas.

Discussions

Varying urban growth rates across different buffer zones

The study showed 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, the annual urban growth rate was highest at the 10 to 25 and 35 km buffer zones and in the period 2001-2006 and 2006-2010. By studying the spatiotemporal growth rate of built-up land we were able to identify a hot zone of urbanization which provides important information for urban planning and development. 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) (Figure 3.4). The hot zone, indicated by the wave peak, has shifted through time and distance. The urban growth peaked at ten 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 projects 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.

Diffusion and coalescence phases of urban growth

The idea of alternating urban growth phases has a long history of support such as: Cressey (1938); Hoover and Vernon (1959); Duncan et al. (1962); Winsborough (1962) and recently were supported by Dietzel et al. (2005a), Seto and Fragkias (2005), and Xie et al. (2006). Contemporary research suggested that the urban growth process may exhibit two alternate diffusion and coalescence phases, and that spatial metrics can be used to quantify this sequential process (Dietzel et al. 2005a; Xu et al. 2007; Yu and Ng 2007). The urbanization process of Hanoi during the 17 year period has also experienced this oscillation. But we noticed that the switches between diffusion and coalescence phases are not concurrent among buffer zones as some may have shorter or longer oscillation cycles depending on the urban growth rate in each buffer zone. For example, the urban growth rate in the ten km buffer zone is higher than that in the five km buffer zone (Figure 3.4). As the result, the ten km buffer zone quickly shifted from the diffusion to coalescence phase between the second and third periods while the five km buffer zone still continued with the coalescence phase throughout the whole study period (Figure 3.7). Thus, over 17 years, the coalescence-diffusion cycle had been repeated in the ten km buffer zone, meanwhile the five km buffer zone had not completed one cycle yet. This investigation is important for 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 (Li et al. 2013). One type of growth may dominate the others; therefore, it drives urban growth phases.

Changes in spatial patterns along the rural-urban 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 spatial metrics in this 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 (Figure 3.8). In addition, high urbanization zones can be also detected by examining the change of the spatial metric values as the higher change was observed between 10 and 35 km buffer zone (Figure 3.9) which is consistent with the urban growth rate (Figure 3.4). The result showed that the high urbanization zones experienced a decrease of certain spatial metrics such as PD, ED, LSI, ENN_AM and an increase of LPI. Trends of these spatial metrics support the diffusion and coalescence theory in Dietzel et al. (2005). However, the study found an increase of FRACT_AM in the high urbanization zone that is different from what Dietzel et al. (2005) concluded. The increase of FRACT_AM may suggest the absence or poor planning activities of the city causing uncoordinated development. Comparing with other studies, we found the urban growth characteristic of Hanoi is different from findings by Li et al. (2013) in Yangtze River Delta (YRD) in China from 1979 to 2008 and by Jenerette and Potere (2010) in a 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 in China, driven by several cities at county and prefectural level, shares a significant amount of growth over time 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 et al. 2000). Most of the urban growth in Hanoi was within or adjacent to existing residential areas. Except the five 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 (Li et al. 2013) or general landscape changes of 120 cities worldwide (Jenerette and 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.

Conclusions

Cities in Vietnam have been experiencing a major urban transition since the country adopted the economic reform in 1986 which introduced free market approaches and encouraged 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 undergoing rapid urbanization between 1993 and 2010, especially in the periods of 2001-2006 and 2006-2010 from 10 to 35 km buffer zones. The spatiotemporal dynamic of the urbanization in Hanoi was successfully described by its time series spatial metrics. The process of urbanization was characterized by relative dominance of infilling, edge expansion, and spontaneous growth modes across the landscape in which infilling and edge expansion are the dominant growth modes. Our observation of the Hanoi urbanization supports the diffusion and coalescence phase dynamics. In addition, the oscillation cycle in the urban growth process, and the regular shift of growth hot-zone found in this paper could provide important information for urban modeling and prediction. Through the spatial pattern analysis and comparisons with other cities, the study showed that Hanoi is limited by its inadequate 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, a future urbanization plan should consider improving urban transport and infrastructure systems, as well as strengthening its competitiveness in the region.

CHAPTER 4. MAPPING RURAL-URBAN TRANSITION IN HANOI, VIETNAM USING REMOTE SENSING, SPATIAL METRICS AND POPULATION DATA

Abstract

While the nineteenth-century landscape showed a clear boundary between the city and the countryside, the twentieth-century developments have complicated this division. The separation of peri-urban from rural and urban entity is important to help identify useful policy interventions where there is an intensification of conflict and where the governance and management of this landscape are often beyond the capacity of rural administrators and neglected by urban authorities. This study explored the utility of spatial metrics, population data and cluster analysis to map the rural-urban transition zone and to identify urbanization models of Hanoi. The analysis showed that about 30% communes was rural, 38% communes was peri-urban and 32% communes was urban. The peri-urban zone showed a greater level of landscape fragmentation and population growth than urban or rural zones. We found that urbanization models of Hanoi represented both transportation-corridors and dispersed-sites models; two least eco-friendly models. This study provided an alternative and effective method to map the rural-urban transition and identify urbanization forms of Hanoi where limited census data are available. However, we suggest that, where possible, the combination of landscape patterns, socio-economic and even biological data would provide a better description of these different categories.

Keywords: *spatial metrics, cluster analysis, rural-urban transition, urbanization models.*

Introduction

How to define rural and urban nature is a fundamental question that has attracted attentions of geographers, ecologists, and other scientists interested in various urban phenomena for decades (Rashed et al. 2001). In history, pioneering studies of urban development modeled urban growth in two-dimensional space by using a gradient outward from the city center and demographic and economic variables. Notable are the Central Place Theory (von Thunen 1875), Concentric Zone Theory (Park and Burgués 1925), or Monocentric City Model (Alonso 1964; Mills 1967; Muth 1969). These studies simplify the city to a central business district (CBD) that acts as a job center, decentralized by trip distance from center along with decline of land price and population density. Other attempts to delineate city centers have relied on measures of employment (Giuliano and Small 1991; Redfearn 2007) or on commuting for the purpose of employment (Cladera et al. 2009; Hughes 1993). One common limitation among these models is their focus on employment because it reduces the entire experience of urban place to a simple journey-to-work exercise. Employment is indeed important to urban form, but it is not the only factor that needs to be considered for studying the landscape structure of cities (Krueger 2012).

While the nineteenth-century landscape showed a rigid dichotomy between the city and the countryside, the twentieth-century developments have blurred this division (Zenner 2002). Distinction between agricultural communities and industrial urban centers is no longer as sharp as it once was. The advance of transportation (cars and highway), communication technologies as well as changing land tenure policies have soften the distinction between urban and rural areas. Webster and Muller (2002a) defined this phenomenon as a peri-urbanization in which rural areas located on the outskirts of established cities become more urban in character, in physical, economic, and social terms, often in piecemeal fashion.

In East and Southeast Asia, peri-urbanization often involves rapid social and environmental changes, as small agricultural communities are forced into an industrial way of life in a very short time (Webster and Muller 2004). The definition emphasizes that peri-urbanization is a complex and dynamic process that involves radical, structural changes in the demographic characteristics of the peri-urban region, including rapid population growth, changes in the structure of the peri-urban local economy. These include changes in both the composition of the regional gross domestic product (GRDP) and the share of the labor force employed in each sector. Peri-urbanization often involves a shift from an agricultural-based to a manufacturing-dominated production and employment. The change in the structure of the peri-urban economy also translates into a change in land uses, namely the rapid conversion of agricultural and formerly marginal lands (e.g., wetlands) to industrial and residential uses.

Because of the complex and dynamic nature of peri-urban areas there has been a great deal of attention on describing and mapping these areas since the early 1990s. McGee (1991) used a term "Desakota" to describe the corridor development consisting of an intense mixture of agriculture, cottage industry, industrial estates, residential development and other uses co-existing side-by-side. Similarly, using different approaches, Rigg (2006) characterized the urban transition as a process of "deagrarianization" where the following trends are commonly occurring over the landscape: (1) diversification of occupations and livelihoods becoming more common and more pronounced; (2) balance of household income shifting from farm to non-farm; (3) livelihoods and poverty becoming delinked from land (and from farming); (4) lives becoming more mobile and livelihoods correspondingly delocalized; (5) a growing role of remittances vs. agricultural income in household; (6) average age of farmers rising; and (7) cultural and social changes being implicated in livelihood modifications and in new ways. More recently, built on the variables identified by McGee (1991), Webster (2002), Rigg (2006), and Spencer (2013), Saksena et al. (2014) had classified and mapped the rural-urban transition in Vietnam based on four characteristics: (1) fraction of households whose main income is from agriculture, forestry and aquaculture; (2) fraction of land under agriculture, forestry, and aquaculture, across households and enterprise ownership; (3) fraction of houses using modern forms of toilet (pour flush or septic); and (4) vegetation density measured by NDVI derived from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS). These studies suggested that several socio-economic and biophysical factors could be considered as potential drivers affecting the nature of rural-urban continuum. However, mapping rural-urban transition is often challenged by data availability. Especially in developing countries, not many countries have a comprehensive census database like Vietnam. Instead, our previous study (see Chapter 3) suggested that landscape metrics (e.g., patch density) are important indicators to characterize the urban spatial pattern and could also well represent the nature of rural-urban continuum. Instead of mapping the urban transition using those socio-economic and biophysical indicators, we hypothesize that we can achieve the result by examining the landscape pattern of built-up land.

The increasing ability to measure spatial arrangement and distribution of land uses through the use of geographical information system (GIS), remote sensing and spatial metrics has facilitated general interest in measuring and using landscape configurations. Taking this advantage, in this study, our objectives are to investigate the utility of spatial metrics and population data to delimitate the rural-urban transition zone and to explore urbanization models of Hanoi city. Our attempts are first to map the rural-urban transition zone in Hanoi using cluster analysis of spatial metrics and population data. Second, we seek to compare our resultant map with those obtained by Saksena et al. (2014) as a validation method. Third, we aim to describe the spatial pattern and population structure of peri-urban area. Finally, based on the spatial distribution of each cluster and four major spatial models of urbanization in Forman (2008), we aim to understand urbanization models of Hanoi. Successfully identifying and mapping peri-urban zone is crucial to better manage this dynamic landscape where often exists an intensification of conflict. In addition, the governance and management of this landscape are often beyond the capacity of rural administrators and neglected by urban authorities.

Methods

Data

Variables that we used in cluster analysis including five out of six spatial metrics which were calculated in our previous study (see Chapter 3). Five variables are Patch Density, Largest Patch Index, Landscape Shape Index, Area-weighted Mean Patch Fractal Dimension, Area-Weighted Mean Euclidean Nearest Neighbor Distance. We did not include the Edge Density in the cluster analysis because it showed a high correlation with Patch Density that would affect the cluster analysis (Table 4.1).

In addition to spatial metric variables, we included an estimate of the human population size. Rapid population growth is one of the four characteristics of peri-urbanization (Webster and Muller 2002b). Among all socio-economic variables, population data are the most easily available and accessible in many countries and regions and usually having a good historical archive. Since 1979, Vietnam has conducted decennial censuses, which are detailed at the commune level and this is considered the best and most reliable information about demographic information for the whole country (Banens 1999). The minimum mapping unit is commune, the smallest administrative unit for which census data are collected and spatial metrics were aggregated. We calculated the annual growth rate from the 1999 and 2009 general population census using following equation:

$$PGR\ (\%) = \frac{(P_{2009} - P_{1999})/P_{1999}}{10} * 100$$

Equation 4.1. Annual population growth rates

where *PGR (%)* is the percentage annual population growth for period 1999 – 2009, P_{2009} is the population in 2009, P_{1999} is the population in 1999.

Classification method

We used cluster analysis to classify the communes into three categories (rural, peri-urban and urban). Our choice of three clusters was based on our preliminary exploration which suggested that there typically exist three zones with differed spatial patterns which were 0 – 10 km, 10 – 35 km, and 35 – 60 km (see Chapter 3). Cluster analysis identifies and classifies objects, individuals or variables on the basis of the similarity of the characteristics they possess and seeks to minimize within-group variance and maximize between-group variance. The result of cluster analysis is a number of heterogeneous groups with homogeneous contents. We used a form of hierarchical clustering with the Squared Euclidean Distance measure and the average linkage between groups. All the variables were standardized to a 0 – 1 range using a simple data transformation equation:

$$Zi = \frac{Xi - \min(X)}{\max(X) - \min(X)}$$

Equation 4.2. Data transformation

where *Zi* is the i^{th} standardized value, X_i is the i^{th} value in the population, *min(X)* is the minimum value of the population, and *max(X)* is the maximum value of the population.

Because cluster analysis assumes no high correlations among variables (Sambandam 2003) we first used multivariate test to test for correlations among variables. With an exception of a high correlation between Patch Density and Edge Density (r = 0.895), all other correlation coefficients among variables are considered as low correlation (Taylor 1990) and acceptable for the cluster analysis (Table 4.1). Based on the correlation coefficient, we excluded Edge Density variables in the cluster analysis.

Table 4.1. Pearson correlation (r) between variables used in cluster analysis.

	PD	ED	LPI	LSI	FRACT_AM	ENN_AM	Pop. growth
PD	1	.895**	-.347**	.126**	-.397**	.262**	-.150**
ED		1	-.516**	.279**	-.320**	.206**	-.276**
LPI			1	-.483**	.439**	-.097*	.304**
LSI				1	.276**	-.217**	-.006
FRACT_AM					1	-.334**	.304**
ENN_AM						1	-.130**
Pop. growth							1

**. Correlation is significant at the 0.01 level (2-tailed).

We assumed that three clusters would distribute in a hierarchical/nested order where the first cluster would be in the center and called urban, the second cluster would be in between and called peri-urban, and the third cluster would be outermost and called rural. We expected that urban patches would be more clumped at the urban center, but fragmented toward the periphery due to newly developed urban patches at the edge. To validate our classification method, we compared with the result obtained by Saksena's et al. (2014); we used overlay tool in ArcGIS to identify the agreement and disagreement between two methods (Table 4.3; Figure 4.1A, 4.1B).

Urbanization models

To identify urbanization models of Hanoi, we relied on the classification result and major road networks in 2010 and compared with the urbanization models in Forman (2008).

Results and discussions

Cluster results

In 2010 Hanoi was close to evenly split among urban, peri-urban and rural communes (Table 4.2). Comparing the spatial characteristics of each cluster reveal that the peri-urban category has highest values of PD, ED, LSI, ENN_AM and population growth rate, but lowest LPI and medium value of FRACT_AM (Table 4.2). As our expectation, the peri-urban communes show a high degree of landscape fragmentation indicated by the greater values of PD, ED, and ENN_AM, and smallest LPI value (Table 4.2). The configuration of built-up features in peri-urban category is also more complicated than rural and urban categories indicated by the greater values of LSI.

Table 4.2. Characteristics of rural, urban, and peri-urban communes.

Cluster class	Number of commune	Percentage of commune	PD	ED	LPI	LSI	FRACT_ AM	ENN_ AM	Pop. Growth
Rural	170	30	15.05	191.50	62.30	4.3	1.09	154.24	0.7
Peri-urban	219	38	34.13	266.64	32.15	5.9	1.12	159.50	3.2
Urban	185	32	9.05	148.41	90.46	3.6	1.14	101.00	1.8

Model validation

Two communes with missing data in Saksena's classification were classified as rural in our classification. However, these two communes were not included in the comparison. We combined urban and urban core categories in Saksena's classification to compare with our urban category. In general, there was a good agreement between our approach and Saksena's et al. (2014) (Table 4.3). Although the comparison is only relative and is limited by the different time frame of two classifications as we based our classification on 2010 landscape metrics and 1999-2009 population growth rates, while Saksena et al. (2014) used the census data and NDVI in 2006, the comparison reveals that the disagreement occurred between only two contiguous categories such as between urban and peri-urban or rural and peri-urban. There is no disagreement between urban and rural categories. The comparison may suggest that over four years - the gap between the two classifications - some of the peri-urban communes have been advanced to urban category and some rural communes have been advanced to peri-urban category.

Table 4.3. Spatial metrics and population-based model vs. Census and remote sensing-based model by Saksena's et al. (2014).

		Saksena's et al. (2014) model				
		Rural	Peri-urban	Urban & Urban core	Total	User's Acc.
Spatial metrics & population - based model	Rural	148	20	0	168(*)	88.09%
	Peri-urban	56	163	0	219	74.42
	Urban	0	47	138	185	74.59%
	Total	204	230	138		
	Producer's Acc.	72.54%	70.86%	100%		

(*) Two communes with missing data were excluded.

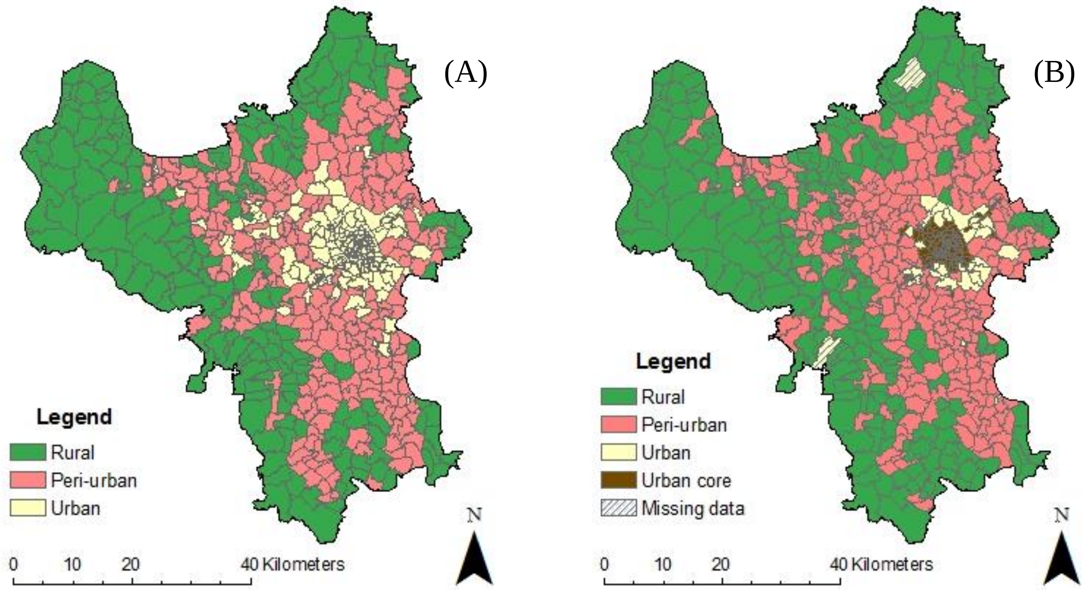

Figure 4.1. (A) Urban transition classification using 2010 spatial metrics and population growth between 1999 and 2009. (B) Urban transition classification using 2006 census data and NDVI by Saksena's et al. (2014).

Spatial patterns and population structure of peri-urban area

The spatial pattern of peri-urban landscape are well perceived as having a close relationship with their socio-economic characteristics (Greene 2004; Hillier 2007; Karimi and Parham 2012; Omer and Goldblatt 2012; Penn et al. 1998; Rodriguez et al. 2012; Vaughan 1999). Lower land price and a more flexible environmental legislation in the peri-urban areas have attracted foreign funds to invest in industrial parks and housing projects (Fanchette 2012). Winarso and Firman (2002) showed new housing projects, in proposing new developments, oftentimes search for locations with abundant and inexpensive vacant land. Developers may not consider the adequacy of the existing infrastructure as they are financially able to create new infrastructure subsequently (Winarso and Firman 2002). As a result, the new urban infrastructure that is independently built by the private developers is often not integrated into the existing regional infrastructure network provided by the government; for example, new sections of roads are often disconnected from broader transportation network systems (Hudalah et al. 2007). In addition, the governance and management of peri-urban areas are often neglected by both rural and urban administrators (Saksena et al. 2014) which eventually causes uncontrolled peri-urbanization and infrastructure deficiency, particularly at the regional level. Lack of transport infrastructure, especially integrated public transportation, is a classic example of a deficiency that can isolate peri-urban areas from their surrounding regions (Hudalah et al. 2007). It can also be more expensive to provide adequate environmental infrastructure (e.g. solid waste and waste-water systems and watershed management) to industrial estates at long distances from cities (Webster 2002). Furthermore, the construction of environmental infrastructure is often not a priority, since public investment is largely allocated to other infrastructure systems that can directly support the industrial activities. For example, 88% of public investment for the development of Eastern Sea Board, Thailand, was allocated to industrial-support infrastructure, including two world-class seaports and an express way (Webster 2002).

Rapid population growth around city centers is a common characteristic of peri-urbanization in Southeast Asian countries (Webster and Muller 2002b). In this study, the average population growth of the peri-urban communes is nearly as twice as urban communes (Table 4.2). In other study by Kontgis et al. (2014) using the same population census for Ho Chi Minh City found that of ten years population growth, nearly 50% of the population was increased in communes defined as peri-urban category. Most of the population increase is due to migration from rural area with natural growth plays only a minor role (Labbé 2010). Dang Nguyen Anh (2005) highlighted three main driving factors of migration to peri-urban areas of Vietnam since 1986. First, the increasing commercialization of agriculture and the replacement of labor with capital investment have been major reasons in releasing the rural workforce and encouraging them to leave rural areas. Second, in the emerging industrial and technology sectors, Vietnam’s incorporation in the global economy has resulted in an increase of foreign direct investment into the country. As the result, migrant workers are attracted to areas where foreign investment has created industrial hubs. Third, the development of transport systems, telecommunications, and mass media across regions has facilitated spatial mobility and enhanced social contacts between rural and urban areas.

Urbanization models of Hanoi

The spatial configuration allowed us to identify urbanization models of Hanoi. Park and Burgués (1925) estimated that cities would progressively expand and would form as five concentric rings, with areas of social and physical deterioration concentrated near the city center and more prosperous areas located near the city's edge. Forman (2008) inherited the concentric ring interpretation and describes three additional models of urbanization. Four urbanization models described in Forman (2008) are: (i) Concentric-rings model where built-up is evenly distributed around the central core; (ii) Satellite-cities model where smaller cities become prominent in addition to the urban center; (iii) Transportation-corridors model where urbanization occurs along the main radial highways; (iv) Dispersed-sites model where built-up occurs in equal-sized small dispersed patches (Figure 4.2). Each of the above urbanization models has varying ecological effects. Forman's (2008) study of thirty-eight urban regions worldwide concluded that, in terms of ecological impacts, urbanization models are, from best to worst: satellite cities, concentric rings, transportation corridors, and dispersed sites.

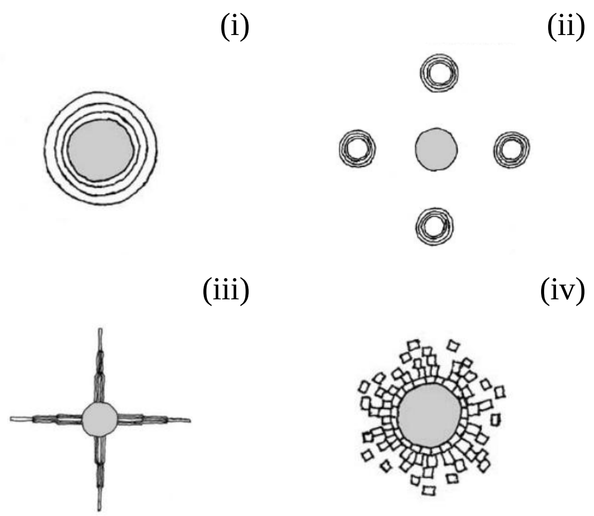

Figure 4.2. Four major urbanization models adapted from Forman (2008). (i) Concentric-rings model, (ii) Satellite-cities model, (iii) Transportation-corridors model, (iv) Dispersed-sites model.

Comparing the urban form of Hanoi with those discovered by Forman (2008), we found that urbanization in Hanoi represented both transportation-corridors and dispersed-sites model. With regards to dispersed-sites model, we saw a number of communes in predominantly rural area classified as peri-urban communes. Many of these peri-urban communes are home to industrial, energy, or natural resource projects (e.g., mining) (Saksena et al. 2014). This finding supported Saksena's et al. (2014) argument that proximity to city itself does not define peri-urban; rather, it is the co-existence of both rural and urban characteristics, rural-urban linkages, and the flows of goods and services between rural and urban areas.

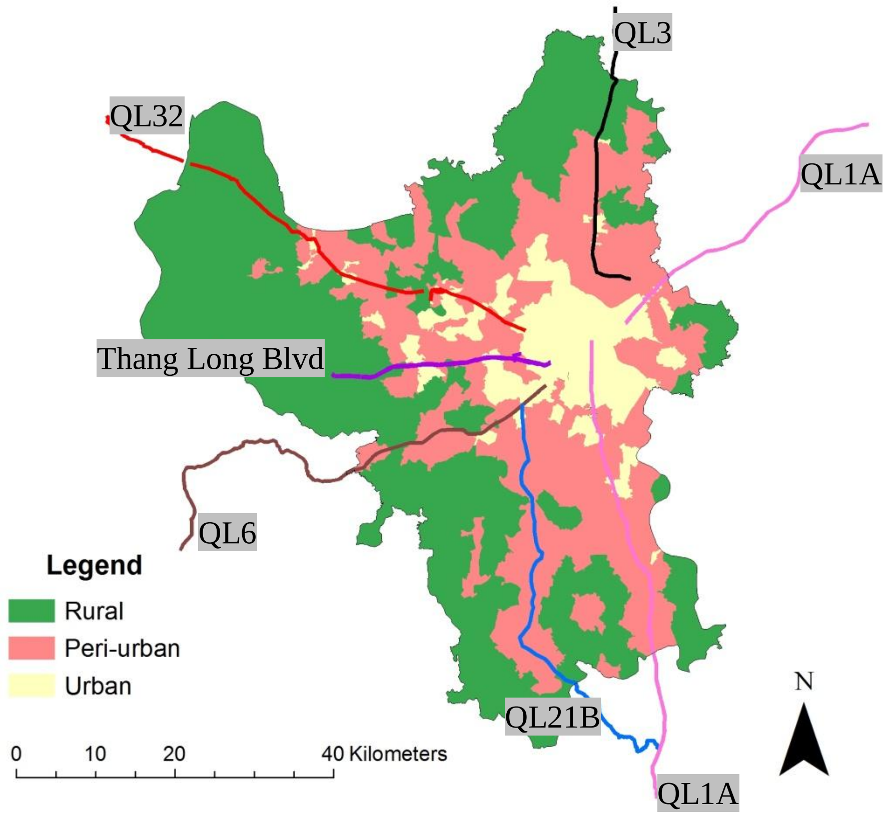

Figure 4.3. Urban and peri-urbanization along the major transportation corridors in Hanoi.

The distribution of peri-urban communes was also drawn by transport systems. In Asia, peri-urbanization tends to incorporate small towns along urban corridors spreading out from metropolitan regions, for instance, in China's coastal regions, Bangkok's metropolitan region, the Lahore-Islamabad highway, and in Viet Nam's craft and industry villages in the Red River Delta (Martine and Marshall 2007). Saksena et al. (2014) found a statistically significant association between peri-urban settlement and highway density in Vietnam. In case of Hanoi (Figure 4.3), we observed that the peri-urbanization to the south of Hanoi was led by two major national highways; QL1A and QL21B. The QL1A runs north-south connecting Hanoi to number of cities in the south such as Hung Yen, Phu Ly, Thai Binh, Thanh Hoa. Whereas, the QL21B is parallel with QL1A and is an important route connecting west towns of Hanoi to Huong Pagoda, a famous tourist and historical attractions. It is also the route to access to national highways QL1A, QL38, and provincial highways TL71, TL73, TL75, and TL76. To the west and northwest, the peri-urbanization of Hanoi clings on to national highway QL6, Thang Long Boulevard and QL32. These are important routes connecting Hanoi to provinces in the west and northwest such as Hoa Binh, Son La, Dien Bien, Phu Tho, Yen Bai, Lai Chau and more. To the north, the peri-urbanization of Hanoi follows national high way QL3 that connects Hanoi to provinces in the north such as Thai Nguyen, Bac Kan and Cao Bang. Our recognition of urbanization models in Hanoi has a significant contribution for development plan. The urban region of Hanoi unfortunately exhibits urbanization patterns extending from an urban core to dispersed sites and discontinuously along some major transportation corridors. These are considered as the least eco-friendly models (Forman 2008). However, certain immediate solutions emerged that may apply to Hanoi city. For example, developing a ring road system could gradually convert or direct the current urban growth to the concentric rings model or developing a multi-polar urban regions consisting of satellite cities dispersed around the existing agglomeration would help to reduce the pressure on the existing urban infrastructure and environment.

Rural and urban dichotomy is, in most cases, no longer sharp, instead, often blurred (Webster and Muller 2002b). Structure, culture, and lifestyles of urban and rural areas are mingling quite intensely. This intense mixture of urban and rural areas is not always visible in a physical form, but may be taking place in the activities that local inhabitants engage in. Therefore, a limitation in this study is that the peri-urban nature was only captured in terms of its spatial characteristics through the landscape metrics and the population without considering other socio-economic factors such as changing economic structure (a shift from agriculturally based to a manufacturing dominated economy) and employment structure (a shift from agriculture to manufacturing). This limitation is, however, opening questions and opportunities for further study of peri-urbanization to explore. Our study proved that landscape metrics are significant variables attributed to urban and peri-urban and rural nature in Vietnam. But we suggest that, where possible, the combination of physical, socio-economic and even biological data would provide a better understanding of intrinsic nature of these different categories.

Conclusions

The study identified the potential utility of common landscape metrics and population data for delineating urban, peri-urban and rural areas in Hanoi in response to the process of urbanization. The study suggested that cluster analysis of landscape metrics and population data is an effective way to map the rural-urban transition. We found that in 2010 about 30% of communes was rural, 38% of communes was peri-urban, and 32% communes was urban. The peri-urban communes show a higher level of landscape fragmentation indicated by the greater values of PD, ED, and ENN_AM, and smallest LPI value. The configuration of built-up features in peri-urban is also more complicated than rural and urban categories indicated by the greater values of LSI. Population growth has been greater in peri-urban communes than in urban and rural communes during the study period. We found a good agreement between our method and Saksena's et al. (2014) method. The exploration of urbanization models revealed that the city has experienced two least eco-friendly models of urbanization. Because peri-urban areas of Hanoi will be the sites of significant population growth, land use and land cover changes in the foreseeable future; these findings have important implications for policy-makers. Finally, urban landscape planning often requires strengthening structures and ecological functions of urban landscapes. This study showed that spatial metrics and variables of urban land use forms can serve as alternative representations of ecological factors in urban models. Such information will help planning authorities and policymakers in modifying the landscape in order to achieve a sustainable use of resources.

CHAPTER 5. SUMMARY AND CONCLUSIONS

Summary

The findings of this dissertation have demonstrated that integrating remote sensing, spatial metrics, and population data are valuable for characterizing urban growth in Hanoi, Vietnam. In particular, the findings from the research can help provide insights into a wide variety of concerns about urban and peri-urbanization raised by local and foreign academics, professionals, and policymakers. Specifically, the second chapter demonstrated how Support Vector Machine classification can map and track changes in built-up land features in a heterogeneous urban landscape, providing new insights into urban growth in Hanoi. Likewise, the third chapter demonstrated how spatial metrics and the gradient approach could be used to characterize the urban growth in Hanoi as well as provided new findings that contribute to improving our scientific understanding of spatiotemporal patterns and dynamics of urban landscapes in Hanoi. The resultant spatial patterns could be used to evaluate urban planning policies and initiate measures against urbanization issues. Finally, the fourth chapter showed the utility of spatial metrics and population data to delimitate the rural-urban transition zone which improves our scientific understanding of peri-urban landscape structures and how to map it where limited census data are available.

Planning implications

The urban growth dynamics and forms of urbanization discovered in this dissertation provide essential information for land use management and planning authorities. For instance, there has been a lengthy discussion on whether it is more beneficial to manage for compact or diffuse cities (Wu et al. 2011) as there are both advantages and disadvantages in each approach. Because Vietnam's urban areas are currently being developed it is critical to consider what form it should take. More diffuse urbanization may lead to leaving native habitats that are networked and thus can support diverse species and that provide accessible green spaces throughout the city (Wu et al. 2011). Compact cities are, in contrast, better in terms of land use efficiency and energy consumptions (Frey 2003), but may have reduced ecosystem functions and services (Tratalos et al. 2007). The compact model has been widely adopted as a planning approach in developed countries, especially in European countries (Ng et al. 2013). However, compact cities often require a strong governmental leadership for policy implementation and involve a radical change in the lifestyle of residents such as enhancing the saving of resources, minimizing waste discharge, and recycling. These pose a challenge for developing countries to adopt a compact growth model and to achieve in a sustainable manner. Past studies have suggested that cities around the world are becoming less dense as they grow (Olsen 2013). But a recent World Bank study on urban expansion in East Asia found that population is growing faster than urban footprints in most East Asian cities (World Bank Group 2015) and the findings from Hanoi supports this conclusion. The compact growth (high density) of cities in many developing countries does not draw them to sustainable growth. Instead, these are the consequences of large families living together due to high housing price, housing shortage, poor infrastructure, and public transportation that restrict population to expand to surrounding regions (Kaji et al. 2003). Therefore, opting for the compact or diffuse model of urban growth needs to be based on past and current data of urbanization as well as the role government will play in the decisions and management.

The different urban growth phases discovered for Hanoi city provide important information for policymakers and planning authorities. On the one hand, where urbanization is in the coalescence phases, the urban form will be more compacted by the dominance of infilling growth process. As such, planning authorities should be aware of the surrounding areas that will likely receive much pressure from land transformation. On the other hand, where urbanization is in the diffusion phase, urban growth tends to disperse far from the existing urban areas causing landscape fragmentation, biodiversity losses and disruption of ecosystem functions. Studies have shown that green belt and remnant forest areas are critical for providing habitats and maintaining ecosystem functions (Christian et al. 1998; Lindenmayer et al. 1999). Therefore, maintaining natural habitats, green belts, and remnant forest areas would help to mitigate the negative impacts of the urbanization and should be highly prioritized in any urban development plans.

In many developing countries, urban agriculture contributes significantly to livelihoods of urban populations. Located in the heart of the Red River delta, Hanoi is a largely agricultural dominated landscape. About 80% of fresh vegetables and 40% of eggs are produced by urban and peri-urban agriculture surrounding Hanoi (Corbould 2013). This level of production can be attributed to the large proportion of the population involved. The rapid conversion of agricultural land to urban uses has raised a concern about food provision for urban populations and livelihoods of peri-urban famers (Pham et al. 2014). In fact, the findings of this dissertation indicated that agricultural land in Hanoi is not only shrinking but also becoming more fragmented. Fragmented agricultural land are largely known as having negative impacts on crop productivity, increasing labor and other expenses, and preventing the use of modern and mechanized equipment. Because agricultural land is finite and there is also competing interests in what to use the land for (e.g., industrial and infrastructural projects), integrated land use planning is needed to balance different development goals. Agricultural land should be broadly classified on the basis of ecological conservation and economic efficiency (An 1995).

Migration to Hanoi is another related planning focus. Questions have been raised as to whether policies to reduce and control rural-to-urban migration are either desirable or practical. Experiences from other developing countries indicate that such policies are largely ineffective at reducing the rural-to-urban migration and can have devastating consequences. The population increase in Hanoi over the last two decades is largely due to migration. Migrants to the city bring both advantages and challenges for policymakers and the public. Even though there are concerns that rural migrants may bring poverty and other social issues to the city, the fact is that most of the workers in Hanoi's industrial parks are migrants from rural areas. Remittances also have a very important role in development and poverty reduction for migrants' origins. From the perspective of city authorities, migrants should be seen as a great potential labor source for the growing industry rather than problems to the city. However, policies to accommodate migrants are a challenge. Migrants in Hanoi generally have low incomes, poor benefits, unstable employment, and lack traditional family support systems that often make them particularly vulnerable, especially in the case of women (Thao 2013). Only 11% of migrant workers have work contracts compared with 90% of local residents and only 30% of private companies pay health insurance fees for their workers, with 90% of migrants have no social insurance (Taylor 2011). Migrants are also struggling for state support for their legal migration status. In theory, migrants can obtain official permission to change their registration. But in reality, large numbers of them are unable to fulfill the conditions required, which inhibits their rights to access housing and other public services. Most of migrants live in shelter settlement with poor sanitation conditions (Vu 2007). It is therefore advisable that restricting migration is not the solution. Rather, it would be more practical to focus on meeting the basic infrastructural needs for the migrants and create political will to accommodate them.

Further study

Although the objectives of the study have been met, there remain unanswered questions and opportunities for further study. First, while Landsat data generally provides a good temporal coverage its medium spatial resolution has limitations mapping urban features in detail when applying the Support Vector Machine classification method. Therefore, the spatial pattern analysis did not take into account internal changes of agricultural land uses such as from paddy rice to vegetable. Such changes in land uses could serve as indicators of urban and peri-urbanization process. In addition, different built-up features and their density could have been mapped if higher resolution satellite imagery were used. These pieces of information are meaningful for urban pattern analyses and can support our understanding of population density vs. built-up density change dynamics. Future studies should consider using higher resolution satellite images for a greater detail of LCLUC mapping and for a better understanding of LCLUC dynamics.

Second, due to limited satellite data availability in the study area, the observation of urban growth in this study was rather short (17 years) which limits the study to link the spatial growth with policy objectives and spatial planning policy implementation. The current construction master plan for Hanoi has a planning horizon of 30 years and a projection to 50 years with multiple short-term to mid-term plans of 5 to 10 years. Therefore, long-term monitoring data and practices are essential to understand change over time in urban landscape and to guarantee policy objectives. Future studies should continue with longer monitoring and observation periods to have a better prediction and to understand consequences of the urban growth.

Finally, the urban ecosystem will only be optimized when all components are balanced and linked together which include human-social system, urban land use planning process, and ecological system. Although this study already addressed the relationship between land change and population change in Hanoi, its spatial pattern and socio-economic linkages have not yet been adequately addressed. Therefore, linking these more completely is an important area for future studies to explore.

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