UNDERSTANDING SPATIAL AND TEMPORAL PATTERNS OF URBAN EXPANSION IN WESTERN CHINA DURING THE POST-REFORM ERA

by

Chaoyi Chang

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Small service is true service while it lasts:
Of humblest friends, bright creature! scorn not one:
The daisy, by the shadow that it casts,
Protects the lingering dew-drop from the Sun.

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Abstract

Cities in China have exploded in size, population, and impact during the last three decades after economic reforms in late 1970s. Several investigations have documented the impacts of ongoing urban transition, but the majority has focused on rates and patterns of development in coastal cities first targeted for reforms in the late 1970s and early 1980s rather than those in China's western region. This thesis investigates the ongoing urban transition in Western China over the past two decades (1988-2009), focusing on four extended metropolitan regions: Chengdu, Xi'an, Kunming, and Urumqi. The analysis relies on data from time series land cover change maps, very high resolution satellite images, disaggregated socioeconomic data, and urban planning maps for each city, and draws on measures from geography, urban planning, and land change science to estimate urban patterns through space and time. The results show that average rates of change are indeed high: all four cities grew at annual rates near 2 percent for the earliest period (1988-2000), but climbed to 5-7 percent after 2006. The extent of urban expansion corresponding to these changes is staggering: each city has more than doubled in size during the study period. In addition, the location of new urban land is primarily outside the contiguous urban core area, being located near small town seats and planned development zones. This finding suggests the emergence of a multinucleated urban form consistent with trends reported for coastal cities. Within each city, the land use pattern is differentiated by planned industrial, high-tech, and residential zones, corresponding to the government master plans. Quantitative analysis using landscape metrics and an urban-rural gradient approach in each zone suggests that rates and amounts are highest in areas designated for tertiary activities and housing. Further estimation on land use pattern over time identifies a monumental morphology in the newly developed area that may be a consequence of strong urban planning aimed at development. Monumentality in urban expansion has led to more land consumption, and further more to an urban form that is changeable in a short time period and results in a lower average population density. An assessment of population growth relative to urban land expansion at the county-level reveals that the increase in population has led to decreasing population density in counties and districts surrounding preexisting core city area, at the same time population densities in the core city districts tend to reach the same level. Overall, the results suggest that urban expansion in Western China does not fit traditional models of urban growth and development based on U.S. and European cities, but is similar to the typology of growth in China's coastal cities. Given the disadvantageous geographical location of these Western cities, this rapid urban expansion could be tied to strong central planning and to the enormous and long suppressed demand for housing. This pattern of urban expansion has consumed a large amount of arable land, which is environmental hazardous, and leads to social inequalities, including but not limited to the reallocated farmers, floating workers, educated youth, and homosexual group. These findings need to be taken into account in the future planning and management of urban land, for such efforts will impact social, economic, political and environmental systems.

Table of Contents

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

1. Introduction

Cities in China have exploded in size, population, and impact during the last three decades. Since the economic reform in 1978, China's urban population has grown from 172 million to 691 million in 2012, boosting the urbanization rate from 16 to over 50 percent (Chinese Statistical Bureau, 2012). During the same period, annual GDP growth has averaged 10 percent (Chinese Statistical Bureau, 2011), with the majority of economic activity focused in densely populated coastal areas and special economic zones targeted for development by the Chinese government (Lin, 1999). Several investigations have documented China's rapid urban transformation following reforms in the 1970s and 1980s, which has led to unprecedented rates of land development in coastal provinces (Wu and Yeh, 1997; Seto and Fragkias, 2005; Yu and Ng, 2007; Han et al, 2009). In the early 1990s, China's leaders began to coordinate economic development in western regions as a means to reduce inequality in development and living standards between coastal and inland areas (Lin, 1999). While a handful of studies have assessed the impact of these policies (e.g. Rural-Urban Integration, Chinese Western Development Program) on industrialization and urbanization in Western China (Vermeer, 2004; Liu et al., 2005; Schneider et al., 2005), urban expansion, which is the land conversion to the urban land led by this urbanization process, in the western region (Figure 1) has not been widely studied or well-understood.

With its large area, rapid development and burgeoning population, urban expansion in China will have a significant regional and potentially global impact on land use and the environment (Grimm et al., 2000; Grimm et al., 2008). Urban expansion has profound environmental impacts that extend beyond the city core, including changes to microclimate, conversion of natural ecosystems, loss of agricultural land, fragmentation of natural habitats, contamination of air, soil and water, increased water use and runoff, reduced biodiversity, and introduction of non-native species (Pickett et al., 1997; El Araby, 2002; Shepherd, 2005). In China, recent investigations in coastal cities have revealed that urbanization has a significant and lasting impact on local precipitation and temperature (Weng, 2001; Kaufmann et al., 2007), expansion of the urban heat island effect (Zhou et al., 2004), reduced water quality (Shao et al, 2006), and air pollution (Shao et al, 2006). Moreover, many environmental impacts are exacerbated when new growth is expansive and fragmented in form (Alberti, 2005), such as the low density, dispersed or even decentralized forms of urban expansion now common in the U.S. and other developed countries (Ewing, 2003). The western region of China is environmentally fragile, yet the information about urban expansion remains unclear for years. Accurate, up-to-date information on the rate, form, and pattern of China's urban expansion is therefore crucial to answering a wide range of research questions related to the influence of urbanization on climate, ecology and environmental processes.

Urban expansion takes place in different forms, and in each form it would have different environmental impact with regard to compactness or dispersions (Grossman and Krueger, 1995; Alberti, 2005). Previous studies show that as a city spread out, the new expansion is likely to result in a handful of typical geometric forms, or a mixed form of some of them (Ewing, 1997; Angel et al., 2005). Three geometric forms are typical and fundamental: leapfrog or scattered development, strip development, the expanses of low-density and single family houses (Ewing, 1997; Antrop, 2004). And discontinuous development, multi-centered development, and corridor development are mixed forms of them (Ewing, 1997).

Work to understand changing urban form in China has taken one of two perspectives – epistemological/qualitative and positivist/quantitative – in terms of research method. First, a large number of studies have focused on spatial restructuring of Chinese cities in the context of urban economics, urban planning, and urban sociology (Yeh and Xu, 1996; Gaubatz, 1999; Zhang, 2000; Lin, 2001; Wu, 2002; Ma, 2004; Vermeer, 2004; Ding, 2007; Wei and Zhao, 2009). These researches provides a mostly theoretical and qualitative understanding of urban dynamics that is crucial for understanding rural-urban demographic shift, social progress in rapid urbanization era, and spatial restructuring with respect to marketization and major institutional changes. However, they are not well documented with sufficient data, especially with regard to the changing spatial patterns. Second, a growing body of work has centered on use of empirical data to measure urban land use trends (Weng, 2001; Seto and Fragkias, 2005; Xie et al., 2007; Xu et al., 2007; Yu and Ng, 2007; Deng et al, 2009; Feng and Chen, 2010; Yue et al., 2010; Pham et al., 2011). These studies rely on geospatial analysis of urban land, often using satellite observations to measure rates and amounts of urban growth. To quantify patterns of urban expansion, empirical studies have relied exclusively on spatial analyses, especially the spatial metrics originally developed in the landscape ecology arena (O'Neill et al., 1988; McGarigal and Marks, 1995). Current studies in coastal cities show that: first, urban expansion in coastal cities had been rapid (Wu and Yeh, 1995; Liu et al., 2005; Seto et al., 2011), and the urban form can change in a short period (Seto and Fragkias, 2005); second, as the cities grew larger, a multinucleated form and corridor expansion emerged (Wu, 1998; Yue et al., 2010). Nonetheless, a monumental form was observed in the new developments in Chinese coastal cities (Ford, 2008), as well as expansive development with declining population density (Deng et al., 2009). These findings have extended the scope of diverse urban expansion patterns by complicating the three typical geometric forms.

With these issues in mind, the primary goal of this work is to understand the spatial and temporal pattern of cities in Western China, with a specific focus on empirically validating whether these urban forms observed in the coastal cities occurred in cities in Western China. I selected four extended metropolitan regions – Chengdu, Xi'an, Kunming, and Urumqi (Figure 1) as the study areas to measure the patterns quantitatively. And to better understand this overarching research question, five hypotheses are tested in this research. I will state them more fully in section 5, with detailed evaluation, but here is a preliminary statement.

(1) Following implementation of reforms in the western region, rates and amounts of urban growth have increased.

(2) All study areas have experienced expansion of built-up lands outside the city core. Each city has transitioned from a monocentric to a multi-nucleated urban form, with new development has occurred discontiguous from the edge of the urban core, in the outlier independent zones.

(3)Maps and documents published by urban planners in western municipalities (Figure 2) have included development of corridors extending outward from each city core. These plans designate specific areas for industrial, commercial, high-tech and residential development, which in turn has resulted in distinct spatial patterns within each corridor. Specifically, there is a convergence of spatial patterns across residential corridors from different cities, and across high-tech corridors from different cities.

(4) Urban expansion since the late 1990s has been monumental (Schneider et al., 2005, Seto and Fragkias, 2005; Ding 2007), resulting in new urban development taking the form of large block structures, and road networks laid out on increasingly large road grid patterns.

(5) Expansion of built-up lands has been faster than population growth in each study area. The new expansion exhibits a more expansive and fragmented form than that in the city core before the reforms.

To test these questions, this study relies on unique datasets of land cover change derived from remotely sensed data (Schneider, 2012) for five key time periods: the period immediately after the land reform, 1988-1995, two periods following the wave of development zones, 1996-2000 and 2001-2003; and two periods after the China Western Development programs have been in place, 2004-2006, and 2007-2009. Drawing on measures used in the urban planning, geography, and transportation studies literature, this work exploits simple, straightforward measures from a variety of spatial analyses, landscape metrics and urban study indicators to estimate urban patterns through space and time.

In the following sections, I review past research on urban form in China (including a synthesis of how landscape metrics have been used), describe the study regions, introduce the datasets and methodology, and present my findings. The paper concludes with a discussion of the trend of urban expansion in Chinese cities, its implications, and limitations of applying theoretical models into this study area, as well as the importance of possibilities by modeling land cover and land use changes.

2. Background

2.1 Previous investigations of urban spatial form

The spatial form of cities and patterns of urbanization have been investigated across multiple disciplines for nearly a century, especially by urban economists (Burgess, 1927; Hoyt, 1939; Blumenfeld, 1954; Muth, 1961; Batty, 1991). Early theories include the concentric zone (Burgess, 1927), the sector (Hoyt, 1939) and the multiple nuclei (Harris and Ullman, 1945) models, which show sectoral specialization and rent-seeking competitions could shape urban spaces in different forms. Ideas of primary (or basic) industry and the division of labors continued to dominate in economic base theories (Haig, 1928; North, 1955; Thompson, 1965), growth pole theories (Perroux, 1950; Hirschman, 1958) and ideas of cumulative causation (Myrdal, 1957; Kaldor, 1957) contributed to the understanding of changing urban forms driven by pursuit of development. As long as the city still takes advantage in gaining economic efficiency by scale and agglomeration effects, it would continue to grow economically usually along with land conversions to built-up areas.

Many studies have investigated urban spatial structure using population density or housing prices. These studies model urban growth in two-dimensional space by using a gradient outward from city center. Von Thünen (1875), Park et al. (1925), Alonso (1964), Mills (1967), and Muth (1969) developed spatially-explicit land-use models to analyze the spatial organization of cities (Bertaud, 2004), as known as monocentric model. These theories simplify the city to a central business district (CBD) that acts as a job center, decentralized by trip distance to it along with decay of land price and population density. The spatial form of the city was driven by sectoral rent-bid in the land market. The city expands when high land value at the perimeter put simultaneous pressure on all land owners in the fringe to convert to urban use (Gaffney, 1969). In reality, several socioeconomic and physical factors were considered to be potential drivers affecting urban form, such as topography, urban planning, infrastructure construction and so forth. The revised polycentric model includes labor market at multiple locations in the city, but still relies on the same theory that the demand for housing decreases as distance to the labor market increases. Because the existing urban form resilient to be changed, the new demand could only be met by a large amount of land conversions on urban fringe. A decay of transmission to built-up areas was hypothesized to appear extended from preexisting labor market in urban space, the old core city and nucleus in this case.

Although many of these theories have not been tested using empirical data, they do provide a foundation for understanding the spatial expansion of urban and built-up land. In this study, because the population density and house price at very fine spatial scale at multiple time points are not available, the changing form of urban land is analyzed as an indicator and spatial existential form linking to these urban economic theories.

2.2 The role of landscape metrics for understanding urban form

A large number of studies within geography and urban planning are now dedicated to the use of landscape metrics to understand changes in urban form and morphology. Originally developed for use in landscape ecology (O'Neill et al., 1988; McGarigal and Marks, 1995), landscape metrics or spatial pattern metrics were designed to quantify and categorize landscape patterns (McGarigal et al., 2002). The metrics first appeared in urban studies in late 1990s to understand residential housing prices in the Washington DC region (Geoghegan et al., 1997) and early 2000s to understand changes in urban structure in California (Herold et al., 2002). Following these initial applications, researchers and practitioners across a range of disciplines have adopted spatial metrics for use (Bockstael, 1996; Hargis et al., 1998; Luck and Wu, 2002; Leitão and Ahern, 2002). A survey of peer-reviewed literature from the last decade reveals nearly 90 articles that have used landscape metrics to quantify urban structure. These studies have all relied on maps derived from satellite data, often at medium spatial resolution (e.g. 30-m Landsat data). The contiguous impervious pavements that is delineated as urban land on these land cover land use maps is defined as urban patches. A suite of metrics are typically estimated to show increasing fragmentation, changing composition, or varying spatiotemporal patterns in various urban landscape dominated by these urban patches (Herold et al., 2005; Seto and Fragkias, 2005; Lewis and Plantinga, 2007).

Table 1. Most frequently used landscape metrics in peer-reviewed literature pertaining to urbanization.

Abbreviation	Landscape metric	Frequency of use (total: 87)	Equation	Relevance and meaning within urban studies	Spatial consistency
PD	Patch density	37	$\frac{n}{A}$	Density of continuous settlements. Could be meaningful as an indicator of patchness. May not be meaningful in urban studies due to its inconsistency with new settlement and infilling process.	Consistent with extent and grain size
NP	Number of patches	36	n	Number of continuous settlements in the study area. May not be meaningful in urban studies due to its not normalized by area and inconsistency with new settlement and infilling process.	Varies with extent
MPS	Mean patch size	31	$\frac{\sum_{i=1}^{n} a_i}{n}$	Mean size of continuous settlements. It stands for average size of urban settlement in the extent. Can be meaningful because its direct correlation to settlement size and patchness. High value means continuous, large settlement, while low means possible small patches or more patchy landscape.	Consistent with extent and grain size
CONTAG	Contagion	31	$1+\frac{\sum_{i=1}^{m}\sum_{j=1}^{m}(p_i \frac{g_{ij}}{\sum_{j=1}^{m} g_{ij}}) \ln(p_i) \frac{g_{ij}}{\sum_{j=1}^{m} g_{ij}}}{2\ln m}$	Relative clumpiness of continuous settlements. May not be meaningful in urban studies because it is hard to understand how it is calculated with specific meaning in urban studies and different software packages use different formula.	Consistent with extent and grain size
ED	Edge density	31	$\frac{\sum_{i=1}^{n} e_i}{A}$	Density of settlement edges. Can be meaningful in urban studies because it is simply another measure of patchness. May not be straightforward as MPS.	Varies with extent and grain size
LPI	Largest patch index	31	$\frac{\max(a_i)}{A}$	Percentage of the largest settlement to the extent. It means how dominate the largest urban settlement exist in the extent. May not be meaningful because it not necessarily mean for continuous development.	Varies with extent
LSI	Landscape shape index	26	$\frac{.25\sum_{i=1}^{n} e_i}{\sqrt{A}}$	Total settlement edges divided by edge of the minimum settlement. May not be meaningful in urban studies due to its unclear meaning to urban morphology.	Varies with extent and grain size
SHDI	Shannon's diversity index	24	$-\sum_{j=1}^{n} p_j \ln(p_j)$	Abstract index to measure the diversity of land types. It provides a reference to measure the abundance of land use types. Could be meaningful if detailed land use information is available. May not be meaningful in some urban studies due to remote sensing images cannot provide enough detail on land use types.	Consistent with extent and grain size

Letters in equation

n: number of patches in the extent

A: total area of the extent

a_i: area of patch i

p_i: proportion of the extent occupied by patch type i

m: number of patch types in the extent

e_i: length of all edge segments of patch i

g_{ik}: number of adjacencies (joins) between pixels of patch types i and j based on the double count method

e_{ij}: tot al length of edge of patch type i in the extent

To better understand which metrics may be useful and/or meaningful for this work, I tallied the frequency with which metrics were used across literature in the arena of urban studies, ranging from urban geography, transportation studies, landscape architecture, and urban planning disciplines until 2010 (Table 1, Appendix 1). The results show that patch density (PD) is the most widely used landscape metrics, followed by the number of patches (NP) and the mean patch size (MPS). The consistencies of those metrics, as well as their meaning in urban studies, are also investigated here, in order to find a parsimonious set of landscape metrics that are meaningful in urban studies and consistent with scale and extent.

Only 35 percent of these studies provided a justification of why the metrics were useful in an urban setting. The majority of landscape metrics are meaningful for ecological studies (e.g. measurement of forest patch perimeter to determine its impact on edge-sensitive species) (McGarigal et al., 2009), but less so for studies that attempt to measure fragmentation of the city (Schneider et al., 2005). For instance, edge density is crucial to edge-sensitive species in ecology, but it is unclear how this is meaningful for urban land. Another example is that patch density can indicate the fragmentation of urban patches but not the size of each patch. There are several characteristics of urban areas that are often useful in planning and policy-making, including accessibility of neighborhood to the roads, distance of new settlement to existing urban areas, commuting distance to workplace and connectivity of sidewalks. These features are difficult to characterize with landscape metrics, however. Other characteristics are of importance to contrast over time could be documented, such as the average size of urban blocks, the configuration of land cover at urban fringe, and the degree of fragmentation in urban land.

The consistencies of metrics across scale and extent are also essential to be comparable across the studies using various spatial resolution of satellite imagery, and the studies covering different spatial extent (Gustafson, 1998; Remmel and Csillag, 2003; Li and Wu, 2004; Cushman et al, 2008). Common metrics such as the number of patches (NP) and total class area (TA) are sensitive to changing scale (grain size and extent size) (Cain et al, 1997; Wu, 2004). Furthermore, many of the metrics provide redundant information. For example, patch density (PD) is equivalent to the number of patches (NP) divided by areal extent, and is numerically correlated to mean patch size (MPS).

Given the insufficient and inconsistent studies, simple, parsimonious and straightforward sets of measure are needed to estimate urban patterns through space and time. Among available metrics, a few metrics, such as TA and MPS, have been shown to be suitable for use in urban studies (Luck and Wu, 2002; Carrion-Flores and Irwin, 2004; Seto and Fragkias, 2005; Schneider et al., 2005; Yu and Ng, 2007; Wu et al, 2011). TA provides an intuitive means to investigate the amount of urban land, yet it is not robust across extent. As long as the extent of landscape has been accurately defined, TA could provide comparable estimation but also the differences of it between consecutive time points could also yield the growth rate. MPS captures the average size of continuous urban settlement in a given landscape mathematically, as well as consistent with variations of spatial scale and extent. Since urban expansion is unidirectional, the growth of an urban patch exhibits three spatial patterns: edge expansion, infilling, and leapfrog development (Forman, 1995; Ellman, 1997; Hoffhine Wilson et al, 2003; Xu et al., 2007; Sun et al, 2013). The first two patterns of growth lead to area increase of an urban patch, which further result in an increase of the metric in the landscape. The leapfrog development of small isolated settlements leads to a decrease of MPS in the landscape. Therefore, once the city started expanding as observed in the satellite image, increasing of MPS indicates the patterns infilling and edge expansion in the landscape, while being constant or decreasing stands for a more fragmented development.

2.3 Past work to understand urban form in China

A growing body of evidence shows that the rates and patterns of urban expansion in China differ from those in more developed countries like the U.S. and E.U. countries where the majority of work has been conducted and most theories established (McGee, 1989; Ginsburg, 1990; Lin, 2001; Ma, 2004; Schneider and Woodcock, 2008; Deng et al, 2009). Previous studies have shown that medium to large-sized cities (those over 1 million in population) in China have experienced core expansion and the rapid growth of satellite cities outside the core, as well as the development of transportation corridors extending outward from the city that have led to peri-urban expansion (Schneider et al., 2005; Seto and Fragkias, 2005).

Massive urban expansion was first observed in coastal regions, mostly documented in the Pearl River Delta and Yangtze River Delta, Beijing and the Bohai Rim area. Previous studies have suggested that metropolitan areas in China's coastal area now exhibit these trends as a result of rapidly increasing international trade, the influx of floating workers following hukou reforms, tremendous infrastructure construction, reform to a market-oriented economy, increasing foreign direct investment and newly established development parks (Wu and Yeh, 1997; Wu, 1998; Wang, 2002; Ma, 2004; Yue et al., 2010).

A number of studies have suggested that the reforms first witnessed on the coast may lead to a spatial restructuring of cities (Wu and Yeh, 1997; Ma, 2004), and several empirical studies have shown that Beijing, Shanghai, Guangzhou, and Hangzhou experienced rapid polycentric urban development including the core city and nearby nucleus (Yeh and Li, 2001; Ma, 2002; Xu et al. 2007; Yue et al., 2010). Similar reform policies were adopted in Western China in the late 1990s and early 2000s. With gradual transition to market oriented economy, vast infrastructure construction and newly built industrial parks may generate similar spatial restructuring in the region. However, China's Western provinces have lagged behind the coastal regions in resource allocation from the central government and sectoral transformation (Lai, 2002). In addition, the lack of proximity to ports has likely contributed to the lack of foreign direct investment (Chadee et al., 2003). In sum, these differences in socioeconomic conditions, investment, and historical context may significantly impact the spatial evolution of cities in Western China.

The state and municipal government played an important and active role in shaping urban landscapes. Reforms (the Land Administrative Law in 1986 and 1998, the Constitutional

Amendment for land reform in 1988, the tax reform in 1993 that led municipal government to leverage the land market to offset government spending) toward a market-oriented economy have not only established the land (i.e. land use right) and real estate market, but the government has also been leading land acquisitions for the past years to meet the increasing land demand in those markets (Ding, 2007). The acquired land was designated to a variety of development zones (e.g. industrial, high-tech, commercial, logistics, university, even government), state, regional, or urban public projects, as well as real estate projects. The planned development zones, large scale infrastructure construction, and preferable policies spurred urban growth, as well as stimulated specialization in manufacturing, commercial districts and large scale housing developments (Gaubatz, 1999; Ma, 2004; Vermeer, 2004).

Empirical analysis of the urban transformation in China has been increasing since remotely sensed imagery began to be widely used (Li and Yeh, 1998) to quantify the extent of urban land as well as the rates of change. With the increasing availability of satellite data sources and semi-automated processing streams, there has been an explosion of work (>140 publications, Appendix 2) during the last decade dedicated to mapping change in China's cities and settlements. The bulk of work has been dedicated to mapping three regions in particular: (a) Beijing and the Bohai Rim (Zhang et al., 2002; Liu et al., 2004; Tan et al., 2005; Wu et al., 2006; An et al., 2007; Dong et al., 2008), (b) Shanghai and the Yangtze River Delta (Zhang, 2001; Zha et al., 2003; Liao et al., 2008; Yue et al., 2010), and (c) Guangzhou and the Pearl River Delta region (Weng, 2001; Seto et al., 2002; Fan et al., 2007).

Despite the differences of the time horizon and spatial extent of city's limit (some studies only mapped the change to the urban core, or part of the city), these studies reveal that changes in urban extent vary by region: the annual growth rate of urban land in extended Beijing, Shanghai, and Guangzhou metropolitan area peaked over 10% in the period of 1980 to 1990, followed by the rate of 5% to 10% in the period of 1990 to 2010. In addition to case study analysis, work to map urban expansion across all of China has shown that other cities in coastal areas and some cities in central and western China have also experienced fast urban growth since 1990s, with an accelerating growth rate in the late decade (Wang, 2010). Their findings suggested that urban expansion in all Chinese cities might have occurred at different waves when Beijing, Shanghai, and Guangzhou were observed having rapid expansion in 1980s. However, due to less developed economic and social conditions, most qualitative and quantitative studies have overlooked urban expansion in Western China, leading to a lack of understanding the urban form of cities there.

3. Study areas

This study focuses on four urbanizing regions in Western China: Chengdu, Sichuan Province, Xi'an, Shaanxi Province, Kunming, Yunnan Province, and Urumqi, Xinjiang Province (Figure 1). While clear commonalities exist across the four metropolitan regions, these areas have been selected for study because of their differences in development trajectories, history, physical geography, and land cover types.

Each of the four cities is long lasting in history and has been a center of the region's economic, cultural, and political life. Chengdu and Xi'an are located in a fertile flood plain and a densely populated region. After a massive irrigation project - Dujiangyan system – was built in 256BC and sent water to the broad fertile plain, Chengdu has been the most populous city of Sichuan due to its agricultural wealth. Xi'an is known for its culturally rich history, as it had been agglomerated as an important city for over three thousand years, and symbolized as Chinese capital for 13 dynasties, approximate a thousand years. Farms gradually replaced forest to dominate in this plain region. Rich natural resources such as coal and natural gas reserves are generously warranted as well. In contrast, Kunming and Urumqi are settled at a strategic location in an ethnic region. Kunming is seated at a mountainous plateau in southwestern China, and has been a significant military base and trade center for a thousand years. It links international trades between Han dominated central China and southeastern Asia. Urumqi was home to native Uygur population in history but outnumbered by Hans today. The oasis city in a desert region has been a port on the route of the Silk Road, connecting China to Europe in history and known rich for petroleum, natural gas, and other energy resources today.

Physical geographies determine strong possibilities for a large population in each city. Chengdu sits in a broad plain in the Red Basin, with small mountains in its east boundary and great mountains of foothills of Tibetan Plateau lie in the west. Xi'an is also located in vast Guanzhong Plain, bounding the mighty Qingling Mountains on the north. Thanks to the fertile soil of flood plain and periodic precipitation brought by monsoon climate, the agricultural production has long been well developed in both Chengdu and Xi'an. The triple cropping with rotation of rice, wheat, and vegetables predominates in Chengdu, and textile industry has been prosperous given to its sizable number of labors and sufficient resources. With a drier and colder weather, a rotation of maize and wheat is typical in Xi'an. Manufacturing and heavy chemical industries were the pillar industries before the reform. Kunming, in contrast, has been resource-poor, partly due to its location in the rugged landscape of the Yungui Plateau. Thus, Kunming has a small amount of agriculture near the core city on the edge of Dianchi Lake, but is surrounded primarily by forest. The transport of people and goods was difficult but also embarked Kunming to be an important trade port on Ancient Tea Route. Urumqi is seated in a narrow valley with alluvial plain, bisecting Urumqi River and Toutun River. Its southern side is the giant Tianshan Mountains and its northern side is the Junggar Basin and desert. The extremely continental arid climate encapsulates the way in which agricultural productions – grazing and crop farming – are largely constrained by timely snowmelt.

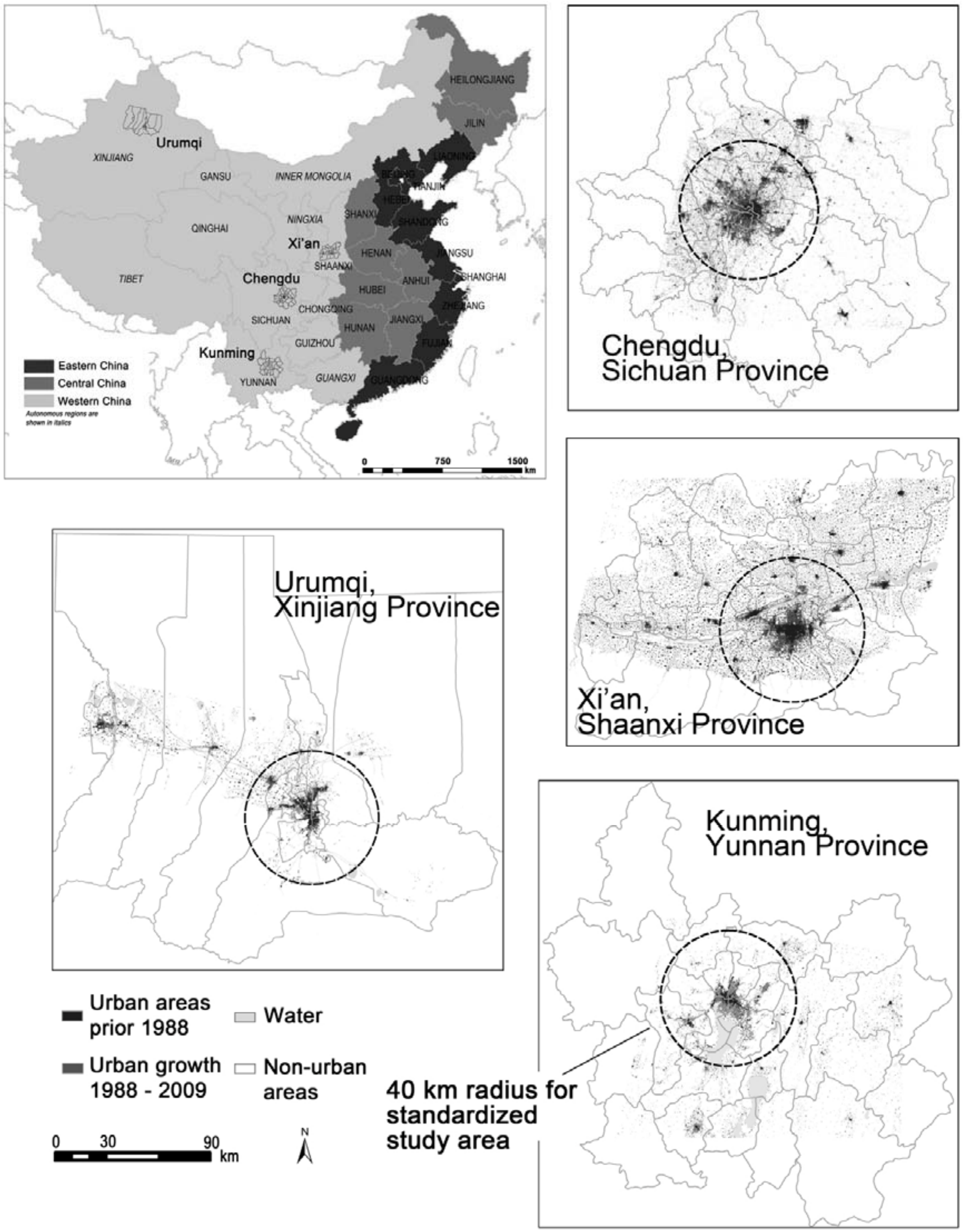

Figure 1. The location of each metropolitan area within China (upper left) and the extent of each study area in Xi'An, Shaanxi Province, Chengdu, Sichuan Province, and Kunming, Yunnan Province. The small maps of each study area illustrate three periods of urban expansion from 1988 to 2010 (note that the full classification scheme was collapsed for ease of viewing).

Each city is surrounded by a densely settled region that has grown significantly in the twenty year period following reforms (1990s to present): the population in each extended region ranged from 4 to 9 million in 1990, but climbed to 6 to 11 million by 2009 (Table 2, Chinese Statistical Bureau, various years). The population in the city proper grew even faster than that in the extended region in each city. And for both scales the population of the city at least increased a half in the two decades.

Second, all four regions have witnessed incredible rates of economic development, with a noticeable shift away from agrarian-based economies to secondary and tertiary industry based on percent GDP. Despite these similarities, there are also important differences in policy and development as well: Chengdu was designated early on as a western ‘Gateway City’, Xi’an has emerged as a leader in telecommunications and aerospace industry, and Kunming has been designated a primary tourist destination within China.

Table 2. Demographic, socio-economic, and land cover characteristics of the three study areas, 1990-2009.

		Chengdu, Sichuan		Xi'An, Shaanxi		Kunming, Yunnan		Urumqi, Xinjiang	
		1988	2009	1988	2009	1988	2009	1988	2009
Population[a]									
	City proper	2,000,600	3,171,498	2,506,560	3,685,300	1,482,000	3,080,000	1,548,662	2,505,000
	Extended metro area	19,355,4000	22,703,260	12,368,270	16,286,060	3,849,000	6,059,000	2,218,744	3,448,400
Household Number[b]		2,626,100	4,052,000	2,165,175	N/A	921,957	1,884,900	339,300	783,100
Gross Domestic Product[c]									
	GDP (10,000 yuan)	1,940,857	39,009,857	1,165,100	21,900,400	1,152,588	16,053,993	532,664	11,025,884
	GDP per capita (yuan/person)	2,123	34,873	N/A	26,259	2,413	25,826	3,440	44,016
	GDP by sector (% of total GDP)								
	Primary	20.9	6.9	12.0	4.8	11.2	6.5	N/A	2.0
	Secondary	39.7	46.6	43.1	43.4	52.9	46.1	N/A	42.7
	Tertiary	39.4	46.5	45.0	51.9	35.9	47.4	N/A	55.3
Land Cover[d]									
	Urban extent (km^2)	577.7	1,237.7	553.2	1,016.7	211.3	532.1	278.4	456.0
	Cropland (km^2)	3,805.6	3,145.5	3,635.7	3,172.2	2160.0	1839.2	1205.8	1096.5
	Major crops	rice, wheat, vegetables		wheat, corn, vegetables		rice, wheat, corn, tobacco		cotton, wheat	

a Population statistics are from the Provincial Statistical Bureau , various years. The *city proper* includes the core city (defined by political boundaries), while the *extended metropolitan area* consists of the core and surrounding counties (typically, the municipality).

b Household statistics are from the Provincial Statistical Bureau, various years. The number includes the core city (defined by political boundaries) only.

c. Miscellaneous GDP are from Chinese Statistical Bureau, various years.

d. Land cover statistics are derived from maps produced in this research, while crop information is from agricultural census data for crops with greatest yields for the 1990-2009 period (Chinese Statistical Bureau, various years).

Population and economic changes have been spurred by major policy and institutional shifts during the reform period (Table 2). Over the last two decades, Western China has been targeted by the Chinese government for reforms designed to bring China's economic transformation to inland regions (Lai, 2002). The extraordinary rates and patterns of land use change in Shanghai, Beijing, Guangzhou and other open cities in coastal region exemplify the first 'wave of growth' that occurred as a result of reforms that liberalized the household registration system (aka. *Hu Kou*) to allow greater mobility to the population, gave freer rein to market forces (which in turn led to a rapid rise in GDP and per capita income), and provided preferential policy to spur growth in a small number of Open Door cities and Special Economic Zones (Lin & Ho, 2005). These early reforms included The Household Contract Responsibility System for rural land lease, which was introduced in the early 1980s and allowed for the privatization of land use right in rural areas (Ho, 2001). In the late 1980s, controls on population mobility were largely released throughout China (including the West), permitting migration from rural to urban area (Chan and Zhang, 1999).

By the 1990s, China's leaders began to coordinate economic development in central and western regions to reduce inequality in development and living standards between coastal and inland areas (Long et al., 2008). Following the regional development goals outlined in the Ninth Five-Year Plan (1996-2000), western cities began to experience China's "second wave" of industrialization, urbanization and urban growth. This growth was spurred in part by the establishment of economic and industrial zones in the West, beginning as early as 1991 in Chengdu (Lai, 2002; Chengdu municipal government, 2011). These areas provided cheap land, tax exemptions and reductions, and the new firms in these areas helped foster faster GDP growth during the 2000-2009 period than witnessed a decade earlier (Ding, 2007). The Chinese Western Development policies adopted in 1999 had profound impacts in Western China on infrastructure construction, investment, economic adjustment, environmental protection and the welfare of residents (Lai, 2002; Fan and Sun, 2008). Finally, the Grain for Green policy designed to return grazing land to forest or natural vegetation was implemented in 2003, instituting land protection that affected where and how the urban regions in the West were able to expand/grow (Lai, 2002; Tan et al., 2005). More recently, policies favoring economic development, the real estate market and public infrastructure development have been extended to include cities throughout the central and western regions, with evidence of increasing flows of government-led investment to high-performing cities such as Xi'an (Vermeer, 2004).

The major shifts in policy and institutional governance have had a profound impact on each of the four study areas, although changes have occurred at different times and at times, have fostered different outcomes (Demurger et al, 2002; Ni et al., 2005; National Bureau of Statistics, various years). Chengdu was one of the first western cities designated for 'open' status, also receiving the first national-level high-tech zone in 1991 (Chengdu municipal government, 2011). Chengdu also benefited from major road/highway construction projects that connected the city to nearby prefectural-level cities, such as Mianyang, Guanghan. In comparison, Xi'an was favored by same bundle of national-level policies as Chengdu but failed to attract as much FDI as Chengdu (Xi'an municipal government, 2011). Instead, Xi'an boosted its economy by high-tech industry, export-oriented industry and tourism. Aside from these, it was labeled as a national center for space technology and energy exploitation, along with a regional center for financial service and logistics. In comparison, Kunming was not favored by national-level policies as much as Chengdu and Xi'an. Kunming is unique among the study areas in that its development was spurred by major investment and infrastructure development for the International Horticultural Expo held in 1999. Following these changes, Kunming planned a new town in Chenggong in order to break the geographical constrains for urban growth. Tobacco industry, biochemistry, tourism, mining and electricity production sparkled in Kunming as mainstay industry. Urumqi was also benefited from the state government with the national-level economic zone and high-tech zone in 1994. Because of the barren soil quality, limited water supply, and petroleum transportation hub to central Asia, Urumqi emphasized on developing energy industry and other resource based industry.

In addition, all four cities established ambitious urban planning by developing city to a leading position in Western China. Corridors are planned along major arterial roads and functional satellite cities are designed based on county seats or industrial parks. For example, primary and secondary developing axes were planned in Chengdu from north to south and from northwest to southeast. At least six satellite cities with different functions were planned around the core city. The underlying goal of recent urban planning efforts has been to shift each city from a traditional monocentric form to a polycentric urban region (Chengdu Planning Bureau, Xi'an Planning Bureau, Kunming Planning Bureau, and Urumqi Planning Burea, 2011).

4. Datasets and definitions

4.1 Remote sensing of urban expansion in Chinese cities

This study was possible in part because of recent work to monitor land cover change in Chinese cities using remote sensing data with high spatial and temporal detail (Schneider, 2012). The maps of land cover change for each study area were obtained through historical analysis of 30 m spatial resolution Landsat TM and ETM+ data for five time periods (1988-1995, 1996-2000, 2001-2003, 2004-2006, 2007-2009). Although great strides have been made to accurately map land cover change using satellite imagery, remote sensing of urban areas remains a complex challenge because of the many combinations of materials present and the variations in size/shape of urban features that can lead to different 'mixtures' within pixels (Small and Lu, 2006). These issues are further compounded in developing countries such as China, since new development is often small, patchy in nature, and located in peri-urban areas up to 100 km from the urban core (Webster, 2002; Long et al., 2009).

To deal with these issues, the remote sensing analysis relied on a supervised multi-date composite change detection technique that exploited training data of stable/changed areas interpreted from Google Earth images, and a 'brute force' approach of providing all cloud-free Landsat data as input (typically 35-50 scenes for each city). All Landsat scenes were stacked and used as input to a boosted decision tree classifier (C4.5, Quinlan, 1993) to detect changed areas for the five periods of interest. This approach is built on the premise that information from before a given period helps establish land cover classes, while information from after the period helps confirm that change occurred.

Selection of training sites was performed in-lab for each case study city through visual interpretation of Landsat data and Google Earth very high resolution (1-4 m) imagery (multiple dates, 2000-2011) and through on-the-ground visits to each location. On-site visits (multiple visits, 2009-2011) confirmed that the only land lost to urbanization was agricultural land, and other land cover transitions (e.g. forest to urban land) were negligible. Thus, this work focused specifically on the transition from cropland to urban land in each region for the five time periods. In addition, unchanged or ‘stable’ classes such as natural vegetation, forest, and water bodies were mapped, as well as agriculture and urban land that remained unchanged throughout the study period. Note that a lack of cloud-free Landsat data for Urumqi in 1995 required estimation of land cover amounts for this time point using linear interpolation of the 1990 and 2000 classes.

The final maps were calibrated and assessed for accuracy using Google Earth imagery, on-site visits, and photo interpretation of test sites by multiple analysts (for details see Schneider, 2012). The overall accuracies of the maps averaged 90-94 percent, and the methodology proved particularly effective for monitoring peri-urbanization outside the urban core, capturing >98 percent of village settlements.

4.2 Defining 'urban land' and 'urban expansion'

Before outlining the approach, it is important to clearly define 'urban land'. In the remote sensing based maps, a definition based on the physical environment was required: here, urban land refers to places dominated by the built environment. The 'built environment' includes all non-vegetative, human-constructed elements, such as roads, buildings, runways, etc., and 'dominated' implies coverage greater than 50 percent of a given spatial unit (the pixel). When vegetation (e.g. a park) dominates a pixel, these areas are not considered urban, even though in terms of land use, they may function as urban space. Finally, the definition also includes a minimum mapping unit: urban areas are contiguous patches of built-up land greater than 1,800 m^2 (because the classification algorithm screens out single pixel urban land with classification errors, the minimum size of contiguous urban patch should be two 30m-by-30m pixels. See details in Schneider, 2012).

Given the definition of urban land described above, it is now possible to define 'urban expansion'. In this research, expansion of urban areas refers to wholesale conversion of land within a 30-m pixel (it is assumed that the entire pixel area is converted). Since new development near the urban core has a similar spectral signature to lands converted to urban uses outside the city, all areas converted to built surfaces are labeled 'urban expansion', regardless of location. To distinguish different types and locations of new development therefore required additional processing, as described below.

There are three forms of new development taking place in terms of location, observed in land cover maps (Figure 1). First, a major development in scale is the continuous expansion extended from the old city core. Behind it, the increasing demand of land for urban use encourages municipal government to acquire surrounding land, pave infrastructure, and enlarge city's limit. Second, a noticeable amount of development is situated close to county seat, towns, and planned development zones. They are either attractive to nearby farmers with short distance to their villages, or attractive to employers with favorable policies. Third, the rest of developments in piecemeal form, such as new settlements next to existing villages or emerging villages, are categorized as rural development here.

The remote sensing work was also able to characterize the large number of settlements that dominate the Chinese landscape (Schneider, 2012). The most appropriate label for these areas is that of 'village': these areas are comprised of a dense configuration of buildings, houses and tree cover, and vegetation typically differs from surrounding agricultural areas. The presence of buildings and materials characteristic of urban environments makes it easy to include these areas as part of the urban class, and most remote sensing studies that focus on the geophysical environment follow this convention. From the perspective of urban planning, however, these areas neither essentially function as a part of city economically nor have the minimum population size to be administratively designated a city or town.

To fully address the research questions and hypotheses, areas of built-up land had to be separated into core urban land, nuclei cities/towns (i.e. the small satellite cities that surround the core city), and all other built-up areas (typically, villages or rural industry). The urban core was delineated for each time point using visual interpretation and heads-up digitizing. To define the nuclei cities, three criteria were used: (1) the area had to be a county seat or a planned industrial or high-tech zone; (2) the area had to be connected to the core city with major transportation networks; and (3) the built-up area had to rank in the top one percent of all urban patches in the region. With this definition, 27 satellite cities were designated for Chengdu, 19 for Xi'An, 14 for Kunming, and 5 for Urumqi circa 2009. Similar to the core, the nuclei cities were then digitized for each time point. Finally, any remaining urban land outside the core or satellite cities was designated as 'other built up land'.

4.3 Defining the extent of each study area

Defining the extent of what constitutes a city is challenging for several reasons: (a) the jurisdictional extent usually does not coincide with boundaries used for economic and social functions of city (e.g. the extent of sewage and water supply may not align with administrative boundaries, Kelly, 1984; Leutwiler, 1987); (b) the extent of the city – both in physical and administrative terms – often changes as the city grows and expands (Lin, 2001; Brenner, 2004); and (c) including all areas that function as part of the city (whether socially, politically or economically) can be difficult (Benguigui et al, 2000).

Although population measures are widely used to define urban versus rural areas, demographic data for Chinese cities are problematic due to the discrepancy and inconsistency of surveying approaches across time and generality of spatial scale in early years. One approach that was used by statistic bureaus in 1980s and early 1990s were absolutely relying on counting hukou permits of the city's residency, leaving two main concerns for reflecting the real number for urban population. First, the statistics failed to include floating population with other cities' residency (Zhou and Ma, 2005). Second, while the hukou permit divides population dichotomously into the agricultural and non-agricultural population, a large fraction of rural residents who live and work in the city and hold the hukou permits of the same city were also misreported in the urban population of the statistics (Tan et al, 2008). The other approach for the statistics was surveying or sampling all residents within a city's limit that was delineated by municipal authorities. This approach overcame the problem of floating population but left two other issues. First, it overly counted urban residents by even including peasants who lived on lands that were delineated into the urban boundary (Yew, 2012). Second, it did not cope well with changing urban boundaries, given the duration between population censuses was usually longer than boundary changes (Fan, 1999; Chan, 2007). Considering the land conversion is essential to the process of urbanization in China, using the extent of built-up environment is an alternative to define city's extent and incorporate socioeconomic data consistently.

To balance the trade-offs described above, I used two measures to determine the overall extent of each city and its surroundings. First, the study extent is normalized by using a standardized area across all four regions. Based on a review of relevant literature, a 40 km radius is selected to buffer the original CBD (Wang and Meng, 1999; Dietzel et al, 2005; Seto and Fragkias, 2005; Ji et al., 2006; Haase et al., 2007; Schneider and Woodcock, 2008), since this value has been shown to reach the realm of jurisdictional and economic functioning of a city, and the area in this radius covers all zones and corridors in each city's master plans, it was used here to define the extent of each city.

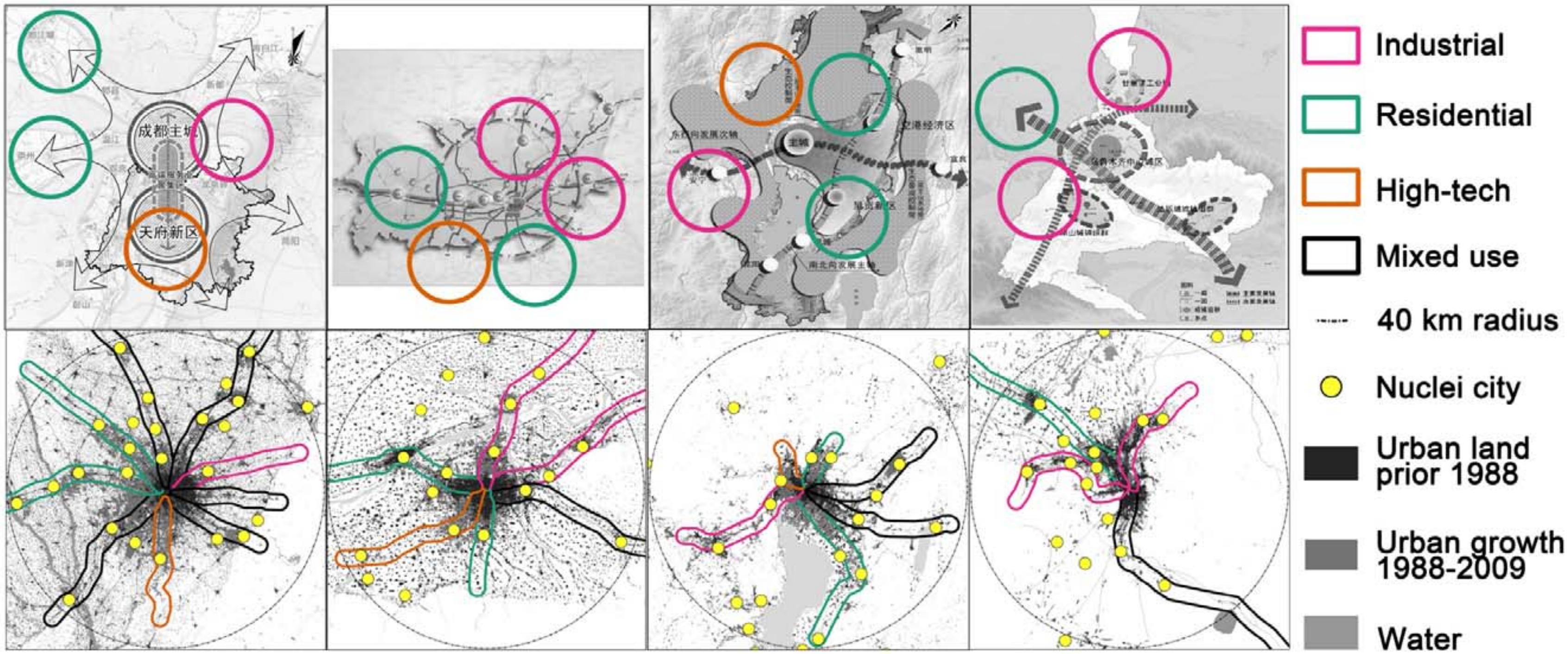

Figure 2. Planning maps, corridors, nuclei cities, and urban growth for each city. From left to right, they are Chengdu, Xi'an, Kunming, and Urumqi respectively. Top row is the planning maps across cities and bottom row is the defined nuclei and corridors using planned development zones, county seats, and townships.

Second, I selected the counties that comprise the standardized area (i.e. the counties whose majority land area fell within the 40 km buffered area). For Kunming, Chengdu, and Urumqi, the selected counties correspond roughly to the municipal boundary as well, while in Xi'an, the selected counties comprise the municipality and six neighboring counties as well. Those six counties are under jurisdiction of Xianyang municipality that is functioning as a part of great Xi'an area. In addition, I chose one measure to delineate a more constrained urban core than the standardized area or municipality provide. Here, I selected the county that overlapped the urban core (Figure 2). The data within the urban core county was important because the number of total population using here stands for the urban population within traditional urban center constantly, since agricultural activities barely exist in those first-core-county-then-core-districts. Also, the total population instead of urban population in statistics is used for matching up with the standardized urban extent in each city for further comparison. Due to the considerably low fertility rate and the diminishing input of labors for farming in China, population migration explains the demographical shift. The rural household permit holders within jurisdiction of municipalities were likely to work in the nearby cities, or at least capitalize their agricultural products or services (e.g. work at the farmers' market), with increasing demand of labors in those cities. Thus, the matching counties and districts are arguably defined as the extent of the city in this research.

4.4 Additional datasets

The goals of this research required comparison of urban expansion to socioeconomic characteristics, such as population density, as part of a larger objective to connect urban expansion to socio-economic drivers of change (see Schneider et al., *in prep*). Population data is available at different administrative levels for each city, so the first step was to determine the most appropriate source/level of data to align with the land cover analysis. While municipal-level data published by National Bureau of Statistics of China contain the most complete set of variables and consistency is maintained across provinces and through time, two caveats prevent applying it to this study: 1) the variation in terms of municipal boundary lacks necessary continuity for data quality; 2) taking one municipality as a whole fails to differentiate the change of built-up areas detected in this study.

Disaggregated, district-level data, on the other hand, were not available prior to 2000 and the statistical variables collected/published by each city varied widely, making comparison across cities before 2000 impossible. To fill the gap of time horizon, I turned to the county-level data that make up each municipality (Sichuan Bureau of Statistics, Shaanxi Bureau of Statistics, Yunnan Bureau of Statistics, and Xinjiang Bureau of Statistics, multiple years). The multiple districts with newly delineated jurisdictional boundaries in post-2000 period that shaped the city proper were usually one or two counties/districts prior 2000. As described above, the counties corresponding to the built-up extent of the city and its surrounding nuclei were selected and the population data aggregated to one metropolitan-level statistic.

It is important to note that Chinese socioeconomic data have been shown to be problematic due to the manner in which data were collected, and due to possible adjustment of figures by local officials (Fan, 1999, 2005; Chan, 2007). The term 'city' remains unclear in China, in terms of population or jurisdictional spatial scale. The *hukou* system (household registration system) divides population into rural and urban based on residence, and statistical data is collected accordingly. Prior to 2000, this system did not record persons with rural hukou who moved to the city as urban residents. This 'floating population' has been estimated as high as 10 percent of the total population in medium and large sized cities (Liang and Ma, 2004). Moreover, Chinese statistical agencies changed their survey methods in the year 2000 to include some of these persons in the urban population data (Zhou and Ma, 2005; Chan, 2007). Because these issues make the urban and rural population data particularly unreliable, I chose to use the total population at the county level, and aggregate the county-level data to one metropolitan statistic as the core districts. With regard to deflation of data before 2000, the results of this study should be considered in light of the bias introduced by these issues. Fortunately, some studies suggest that since the large population migration mostly started from inner small sized cities and rural areas to coastal large metropolitan areas, the floating population before 2000 in those medium sized cities specifically from other municipalities was limited (Liang and Ma, 2004; Wang et al., 2008).

Finally, political boundary data of counties and districts were acquired in GIS format from the Socioeconomic Data and Applications Center (SEDAC), China Dimensions at Columbia University (http://sedac.ciesin.columbia.edu/data/collection/cddc). A few new districts were established in or near the core for some cities. Since disaggregated data were available for the new districts, it was possible to adjust all socioeconomic data to the baseline GIS political boundaries.

5. Methods and results

5.1 Hypothesis 1: Rapid expansion of built-up land.

The first hypothesis I explore is centered on one fundamental question: what the rates and amounts of urban transformation in each study area are. In addition to a visual assessment of each map, these trends were quantified using one simple and straightforward approach: the amount of new urban land within the 40 km normalized study extent was measured for each period to estimate city-specific rates of change (Figure 3).

Regional views of each map (Figure 1) reveal that each study area has expanded rapidly, with large amounts of new urban land appearing in the most recent time period (2006-2009). New urban land, rather than sprawling out from the core city, extended further out to even 20-40 kilometers away from the city center. Visual inspection suggests that not only the growth rate in each period is fast but in a trend of accelerating. The growth of all four cities in the latest period was immense.

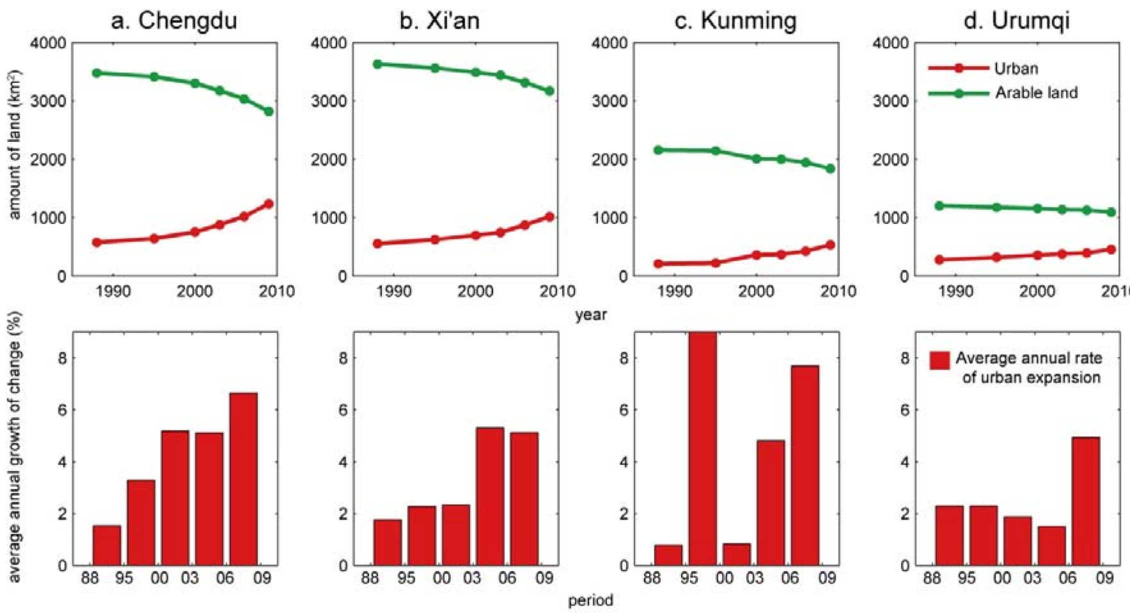

Figure 3. Rates and amounts of new urban land, agricultural land, 1988 - 2009. The top row is the urban expansion at the expense of arable land. The bottom row is the average annual rate of urban expansion in each period.

Quantifying these trends, Figure 3 shows that rapid expansion has indeed occurred in all four study areas. Studies that measure rates of urban expansion in cities across the globe suggest an average annual rate of change of 2 percent per year (Angel et al., 2005; Schneider and Woodcock, 2008; Seto et al., 2011). The results here reveal that all four cities grew at rates near 2 percent for the earliest period (1988-1995), but climbed to over 3 percent expansion in the 1995-2000 period for all cities except Xi'an. While none of the cities developed rapidly during China's "first wave" of growth in the late 1980s and early 1990s, this jump in the late 1990s suggests that Western cities may have undergone a "second wave" of growth. Both Chengdu and Urumqi were targeted for growth during this period, with favorable investment/policies, state infrastructure construction, etc.

Finally, a "third wave" of growth may be apparent in the results as well: all cities jumped to average annual rates of expansion of 5-7 percent in the 2006-2009 period. This third wave has not yet been discussed in the literature on Chinese urban development, but the consistency of this trend across study areas suggests that policies aimed to develop the West have been effective in establishing new buildings and infrastructure outside the core during this period (Lai, 2002).

Compared to average annual rates of change over 30% for coastal cities (Schneider and Woodcock, 2008), rates in Western cities are clearly not as high. Rates of change on the order of 5-7 percent are equivalent to significant amounts of land, however (Table 3). In Chengdu, for example, more than 200 km^2 were developed between 2006 and 2009, the overall total amount of expansion-- cities tripled in size from 88-09 (27 years), while cities on the coast tripled in a shorter amount of time (88-96, Seto et al., 2003).

When estimating the rates and amounts of new urban land, one additional trend became clear. Across all four cities, all new urban land developed between 1988 and 2009 occurred at the expense of farmland or arable land. This trend is clear in Figure 3, which shows a decline in the amount of agricultural land coincident with the increase in urban land.

The findings of hypothesis one suggest that none of these cities experienced rapid urban expansion during 1988 to 1995, as they grew at 2% annually on average, which approximately equals to the average annual growth rate of cities throughout the world (Angel et al, 2005; Schneider and Woodcock, 2008). From mid-1990s to early 2000s, the average growth rate of these cities was much faster (at 5-7%) than early period. Also, the new expansion was discontiguous and located as far as 10 kilometers away from the edge of preexisting urban core area.

Table 3. The average annual growth rate in two periods compared to other studies

	Average annual growth rate of urban land, 1990 - 2000	Average annual growth rate of urban land, 2000 - 2010
Chengdu		
This research	2.3%	5.6%
Wang et al., 2012	7.3%	8.1%
Xi'an		
This research	1.9%	4.2%
Wang et al., 2012	4.6%	6.9%
Kunming		
This research	4.6%	4.4%
Wang et al., 2012	5.4%	5.5%
Urumqi		
This research	2.1%	2.8%
Wang et al., 2012	3.7%	4.6%
Other cities*		
Anging	3.8%	N/A
Changzhi	4.1%	N/A
Guangzhou	8.0%	N/A
Leshan**	7.0%	N/A
Yiyang	7.4%	N/A

* The numbers were calculated from results by Angel et al.. The extent of city in Angel et al., 2005 is approximately the core city area, which is much smaller than the other two studies.

** Leshan is a city in Western China, close to Chengdu in this research.

5.2 Hypothesis 2: Transition from monocentric to multi-nucleated urban form.

Given that the rates and amounts of the expansion are fast, the question is where the new urban land is located with regard to the preexisting core city. Instead of delineating artificial gradients at certain directions, I applied a series of 1-km buffers to the city at each time point (Figure 4). As shown in Figure 4, the core urban area was not held constant through time, but rather updated for each time period, and the buffers re-estimated accordingly. This approach is similar to transect analysis along the urban-rural gradient (Luck and Wu, 2002), but I modified it so that transects in all directions could be considered.

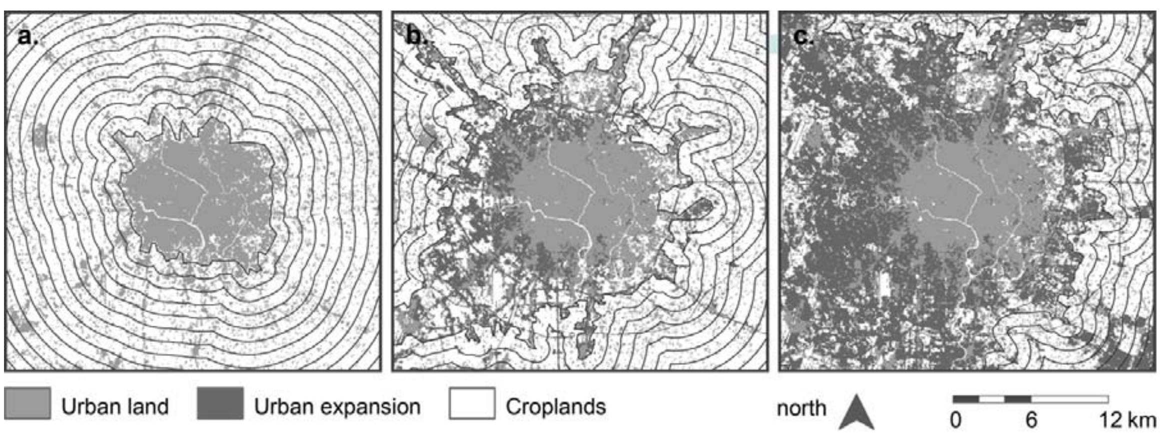

Figure 4. Examples of the buffers used in the analysis of each city (Chengdu is shown above), where the buffers were modified for each time period based on the extent of urban land for a given period.

To estimate the amount of new urban land within each consecutive buffer extending outward from the city, the total area (TA) of urban land at each time point is a simple and straightforward measure, yet not consistent across scale as reviewed in the use of landscape metrics. Instead, TA at each time point is normalized by the amount of land available in each buffer area for development in each period (note that available developable land was defined as the total land, minus any built-up areas, water, and forest, for nuclei expansion, exclude the core city). In this analysis, a steep slope for a given period indicates that all new urban land was developed very close to the original city core, while a flattening of the slope with distance indicates that development occurred farther from the edge of the city (specifically, the city edge as defined in that period). It is important to note that, although the buffers are adjusted to account for the growth of the core, the actual area within the buffer is not standard across a city or across cities. Therefore, the percentage of new urban land in the buffer (the percentage) will always be higher for the early periods (20-40 percent or higher), while in later periods, the large core size means that the first buffer ring is substantially larger, and the percentage of urban land is correspondingly low.

The results for the core urban area of each city show that in the early periods (1988-1995, 1995-2000), the slope for the amount of new urban land is indeed steep; nearly all new urban land developed during these two periods occurred within 4-5 km of the original city core in Chengdu and Xi'an, and within 2-3 km of the core in Kunming and Urumqi (Figure 5, top row). In later periods, this drop is less apparent, and the trend lines are indeed flatter, revealing that consecutive buffers all had a large amount of development take place. The later trend lines are also higher along the y axis, since a greater amount of available land was developed in later periods. Kunming exhibits the extreme case: nearly 10 percent of available land was developed in every buffer between 5 and 13 km from the core during the 2006-2009 period.

Given the sizable amount of new urban land that was developed far away from the core city, more efforts have been made to investigate changes in spatial patterns over the past two decades – whether they are simply sprawling outward from the monocentric city center or shifting to a multi-nucleated urban form. Planned development zones, new towns, and county seats are defined as nuclei cities in each study area, with the assistance of planning maps published by each municipality (Figure 2). Within a development zone, essential infrastructure, including roads, sewage lines, electricity, is well accommodated by the government. And certain type of land use (e.g. high-tech manufacturing in high-tech zone) is encouraged, if not limited, by favorable policies, such as subsidies for land purchase, favorable tax policies and so forth. The number of nuclei cities differs as mentioned in section 4. The other development, including village and town expansion, and piecemeal rural housing extension, is defined as rural transformation.

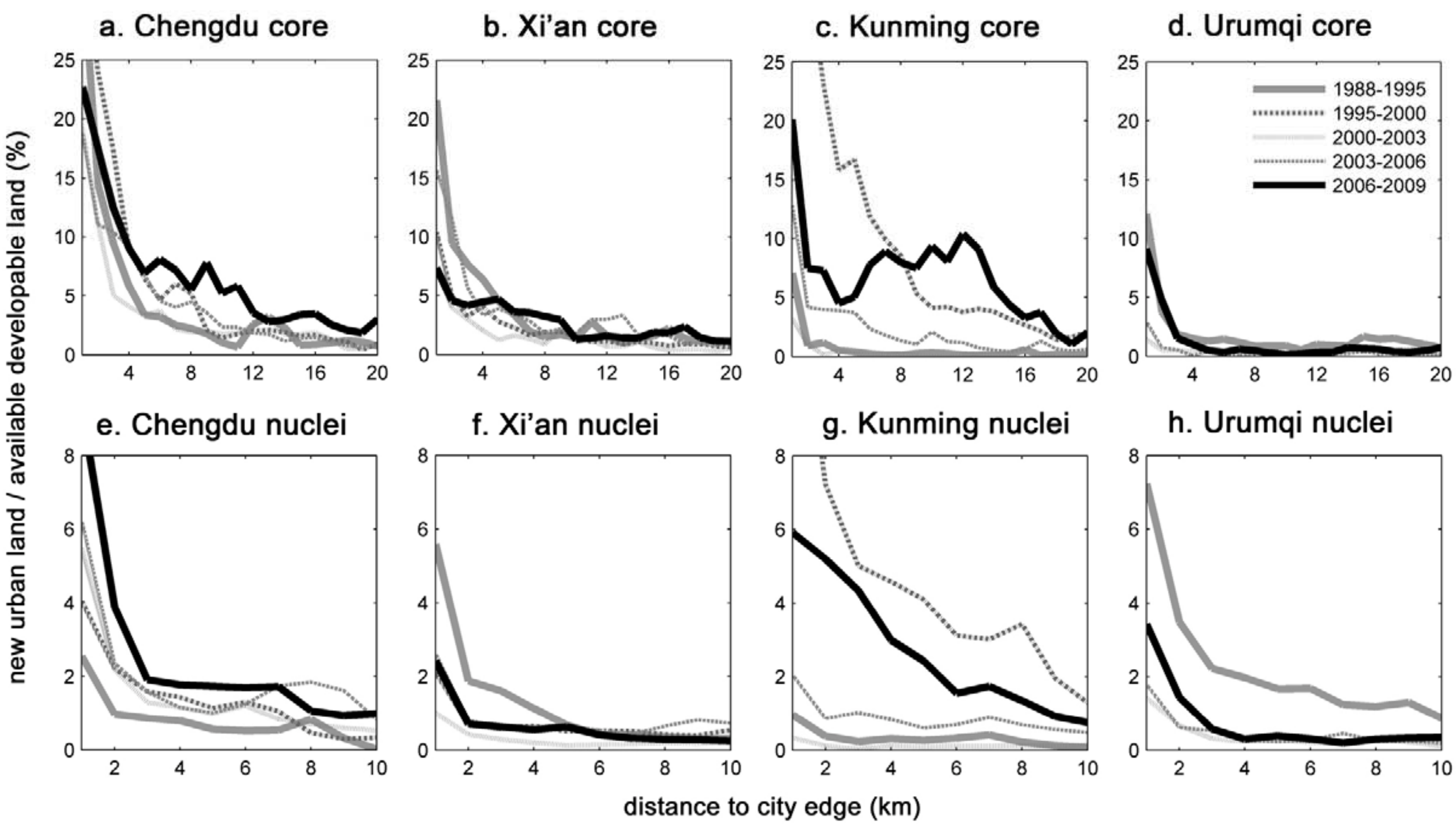

Figure 5. Ratio of new urban land to the amount of developable land in 1 km rings/buffers extending outward from the core city (top row) and from the nuclei outside each core city (bottom row) for the three metropolitan areas. In this analysis, the buffers vary for each period (see Figure 4 for an example).

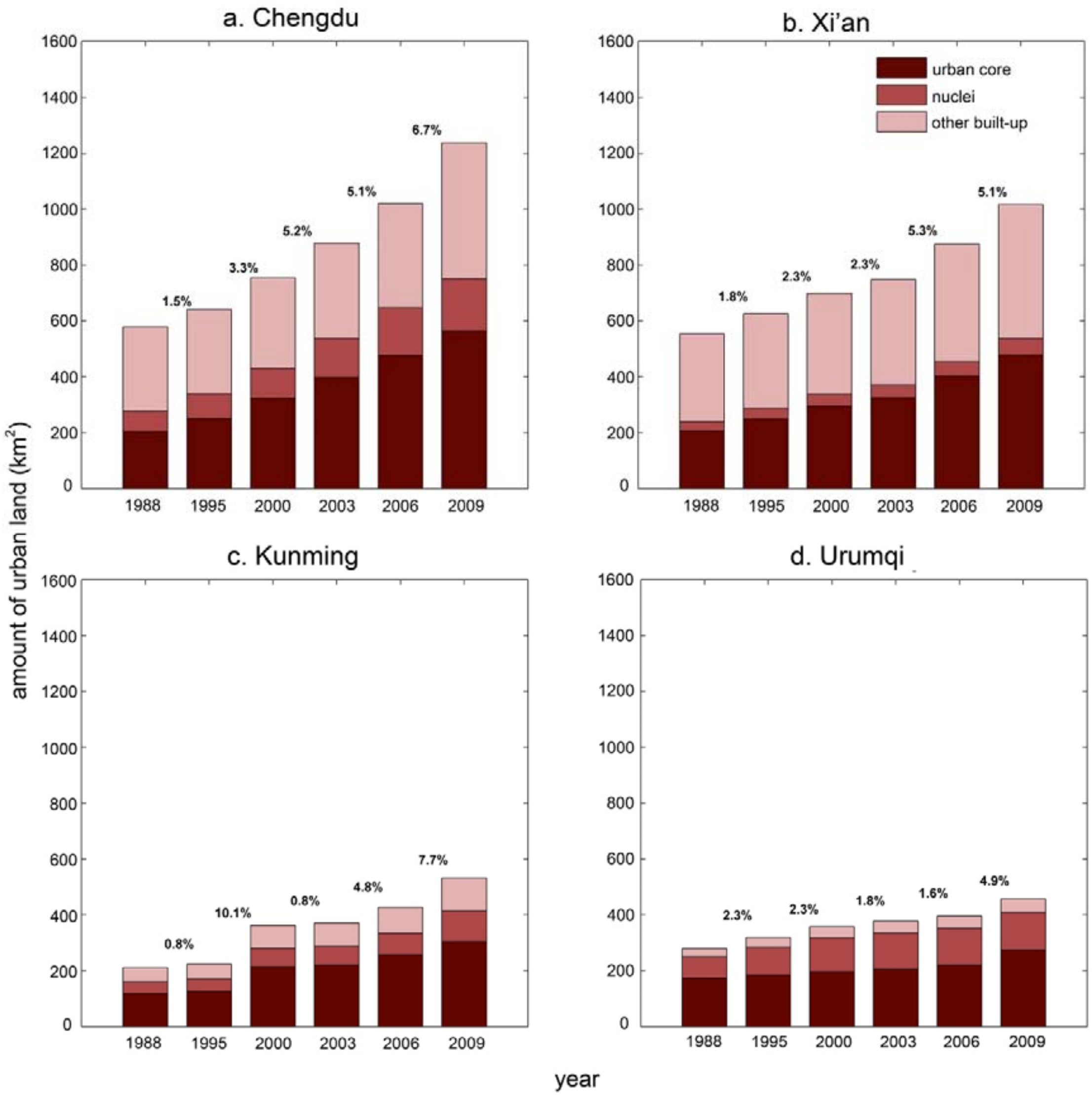

Figure 6. Rate and amount of urban land in core city, satellite cities, and villages. The rate between two bars indicates the average annual growth rate for all urban land during that period.

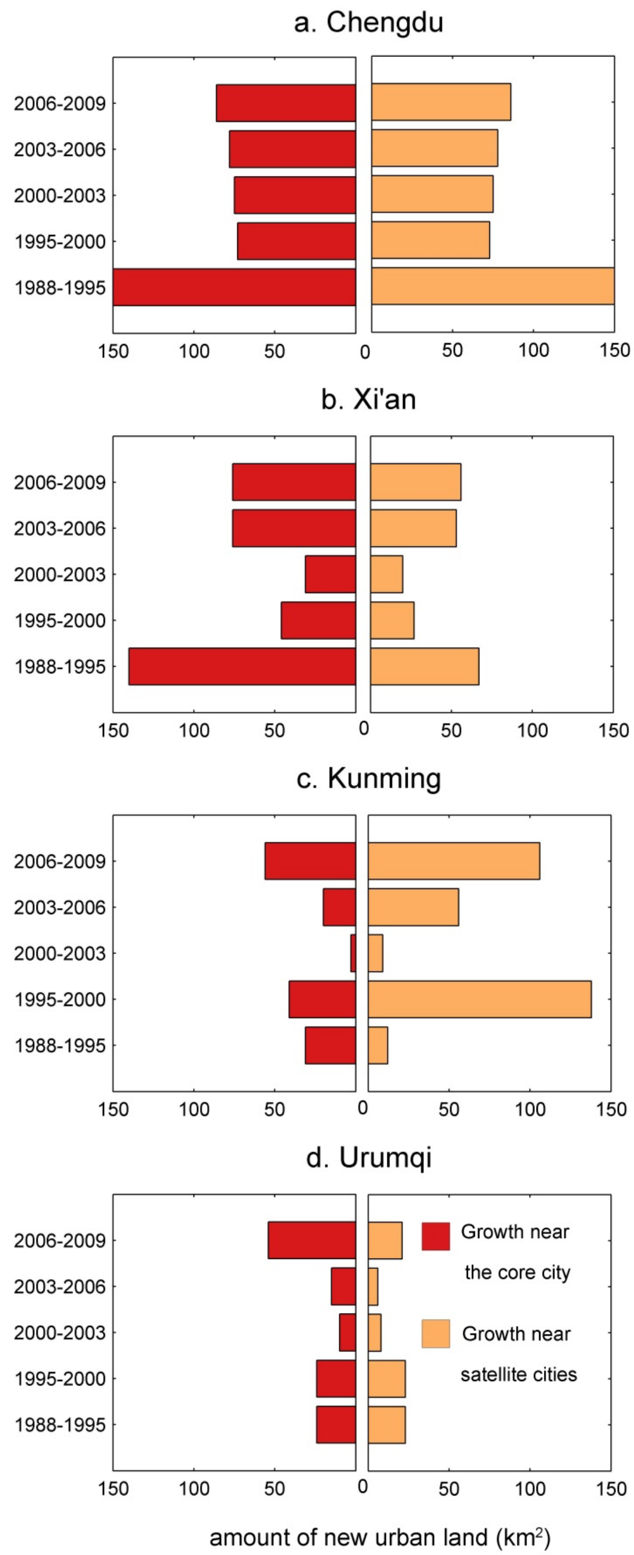

Figure 7. Amount of new urban land near core city and satellite cities

The same buffer analysis was applied to the nuclei cities in each region, to determine if the trend toward expansive growth near the city core was also apparent in small- and medium-sized cities in each region (Figure 5, bottom row). The results show that for Chengdu and Kunming, this is indeed the case: new urban areas have been developed as far as 10 km from the city edge. In Xi'an and Urumqi, however, the line remains steep over time, suggesting that any growth that occurred in the small cities occurred consistently within 2 km of the city's edge. The results suggest that, over time, development has occurred farther and farther from existing built-up spaces in China's western cities. It is no surprise, then, that my next question focuses on the transition from the monocentric to a multi-nucleated urban form that is likely underway in each study region.

An alternative way to understand this trend is to look at the amount of new urban land that has occurred near the core, compared to the amount of new land developed near satellite cities (small cities located between 10-40 km from the original CBD) (Figure 7). If I look at the total urban land in both the core and nuclei cities, the year-to-year trends are actually masked - the amounts of urban land change varies little year to year relative to one another. Some new urban land near nuclei cities here is counted both as core expansion and nuclei expansion even though some nucleus merged into the core city eventually.

Even in these raw (unnormalized) numbers, an interesting story begins to emerge. All the core cities exhibit an initial jump in urban land growth during the 1988-1995 period (the lowest bar), followed by a drop to lower amounts of growth in subsequent periods. Later, the trend was followed by increasing amounts of urban land in the 2003-2006 and 2006-2009 periods (note the 'C' shape in graphs for the core, right side). The amounts of new urban land added to the satellite cities (left side graphs) actually mirror what occurred in each core city. In both Chengdu and Xi'an, the amounts of urban land added to the core are nearly the same as the combined amount of new urban land added to the satellite nuclei cities. In several cases, the amount of new land added to the satellite cities is actually greater than that for the core for the 2006-2009 periods: Chengdu and Kunming added 86 and 46 km^2 to the core, respectively, while the combined amount of urban land added into the satellite cities outside Chengdu and Kunming was 118 and 56 km^2, respectively. Overall, the growth near the nuclei cities is staggering in years.

Also, clear contrast between satellite cities and rural transformation suggests differences across the cities (Figure 6). In both Chengdu and Kunming, rural transformation almost coincided the growth near satellite cities and the core city. In Chengdu, the built-up in the rural area increased in every period, and in Kunming, it grew significantly in the 1995-2000 and 2006-2009 periods, where the expansion near satellite cities increased the most in these two periods. However, in Xi'an, the settlements in rural area widely outnumbered the total amount of urban land in the satellite cities at the beginning, so the growth of rural transformation outpaced the growth near satellite cities in each period. There was very little urban growth occurring out of the core city and satellite cities in Urumqi, due to the sparsely populated surrounding areas. Given the rural transformation is the house extension of grassroots farmers benefited from economic growth, it is a bottom-up growth other than government-led core and nuclei expansion.

Finally, it is worth noting that, in some extreme cases, the amount of new urban land in the nuclei might actually be quite a bit larger than the amount of new land added to the core, indicating that all urban expansion is occurring far from the core. Urumqi in the early 1990s is a good example of this trend, as well as Kunming during the 2006-2009 period.

The finding of hypothesis two indicates that the newly expanded urban land in all four cities is located discontiguous from the preexisting core city. A sizable amount of this new urban land is clustered around the planned development zones, county seats and other townships, which is addressed as nuclei expansion here. Because of the nuclei expansion, the transition of the urban form is clear: all four cities are transitioning from a form with one core city to a new form with a large core city and several satellite cities.

5.3 Hypothesis 3: Development of corridors with specific spatial patterns related to designated land use.

The third hypothesis for investigation is related to the corridor expansion that was visually detectable in each city. In addition to exploring the expansion in terms of location near the core and nuclei cities, it is more specific to compare and contrast the expansion that economically links specific nuclei cities with certain land use in urban planning. Major roads and massive road construction in later years linked nuclei cities with the core city. A handful of literatures suggest that road construction drives urban expansion in China, not like the reverse way in the U.S (Fan and Chan-Kang, 2005). After the roads and ancillary infrastructure are built, other developments are filled in accordingly. For the road construction, land acquisition and the favorable policies in development zones are predominately designed by the government (Ding, 2007), which suggest that the government plays a large role in the development that is worth further examination. Therefore, a few gradients along the arterial roads in each city were examined specifically to understand how road construction fosters new urban growth and what kind of specific spatial pattern could be linked to designated land use type of nuclei expansion.

According to the master plan of each city, several development zones were planned, such as the high-tech zone, the industrial/manufacturing zone, and the new town/residential zone, where the designated land use in the zone is encouraged by favorable policies, but not necessarily regulated by zoning and construction ordinances. To accommodate the potential large load of commuting between the historical core city to its development zones, arterial roads were built to connect them with the core city. Along with the arterial roads, road networks and other infrastructures were appropriated and formed corridors, inviting certain businesses related to designated land use of the zone. The growths of certain land uses are hypothetically likely to expand along these corridors.

To measure the expansion, a four-kilometer wide corridor was therefore defined along the arterial roads to connect the core city to the satellite cities. Among all the landscape metrics, the mean patch size was used here to capture the increasing average size of the urban settlement as well as the fragmentation of development in the circular moving windows (2 kilometers radius) from the city centers to the urban fringes within the corridors. It is worth noting that the maximum value of MPS ideally is 12.56 km^2 when the entire moving window is occupied by one urban settlement, and the minimum value is 0 and not shown in the figure.

A trend shows that in early period (1988-2000), the expansion in the corridor was near the core city, not near the nuclei cities. The area in between the two lines stands for the expansion during the period in Figure 8. The line of 2000 curves but simply moves to the right, illustrating how the expansion remains close to the core. In the later period (2000-2009), the expansion of the core city continued by externalizing the peri-urban area, while a few rapid expansions near the nuclei cities emerged, as the spikes show in the figure.

The results also show distinctions among different planned corridors, in spite of certain designated land use across the cities. For both the high-tech and residential corridors, significant expansion in1988-2000 period was pronounced near the city center (within 10 kilometers), as is shown in the first and last two columns from left to right (Figure 8). The trend diverged in the 2000-2009 period. The growth in the high-tech corridors extended further out close to existing urban area, due to the fact that the available land closer was fully consumed. In contrast, in the later period, growth appeared in spikes even over 30 kilometers far from the city center, as is shown in the right two columns, indicating large expansion near the nuclei cities further out. For the industrial corridors, the growth was initialized in early period, but was not prominent as expected in the later period.

Corridor expansion differed across cities in terms of magnitude. The expansion in Chengdu and Xi'an was larger than that in Kunming. In Urumqi, there was not much expansion for all the designated corridors compared to other cities. Taking the residential corridors as an example, the expansion was 15 kilometers away from the city center in Chengdu and Xi'an by 2000, and even beyond 30 kilometers by 2009. In Urumqi, the development was not as much about urban expansion but the fragmentation of urban land.

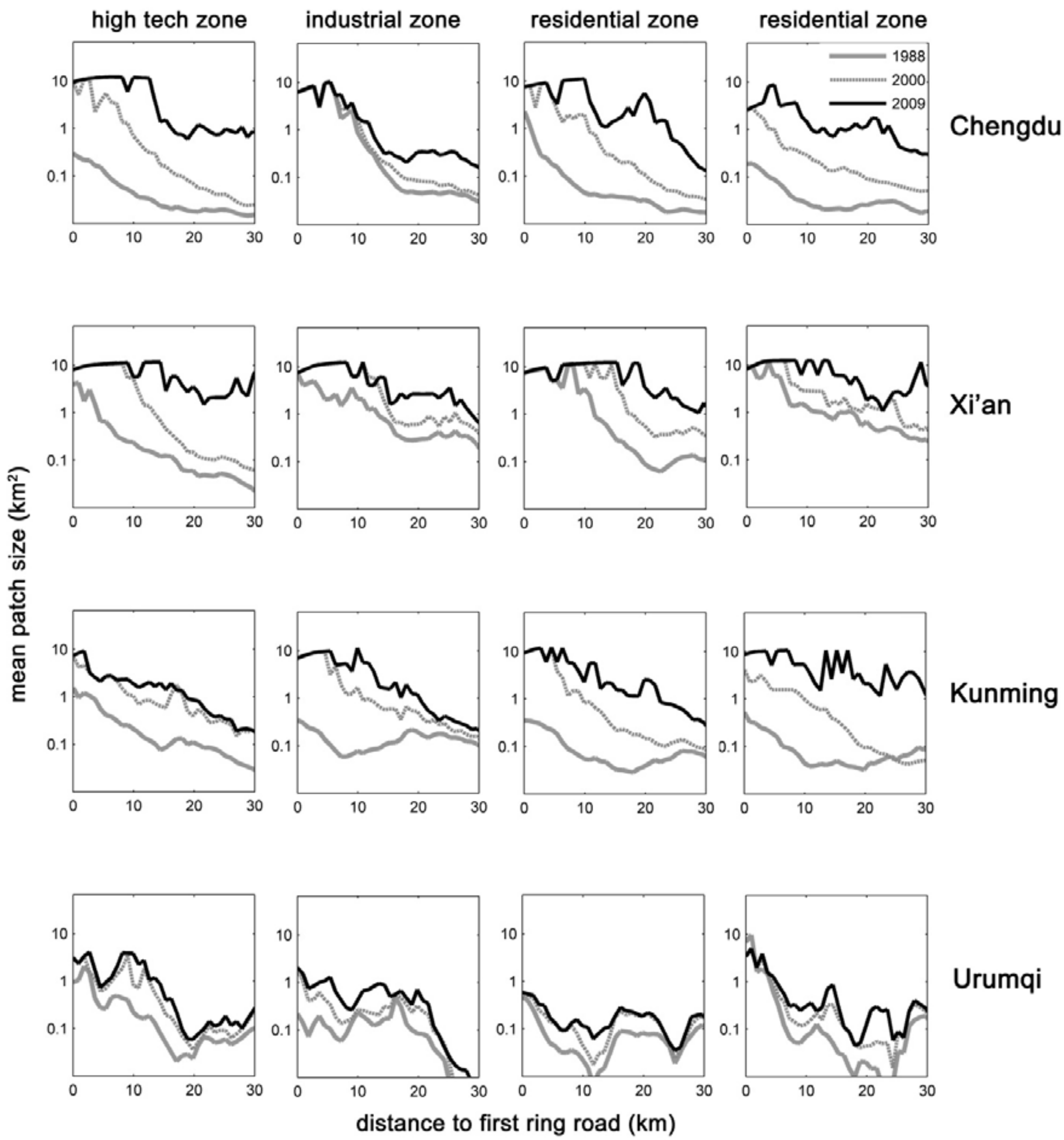

Figure 8. Average size of urban patch in designated corridors across cities, displayed in log scale. It is worth noting that corridor b. is industrial corridor and corridor d. is mixed-use corridor in Urumqi.

The finding suggests that, first, the corridor expansion widely occurred in western China during the urban expansion. Second, it is closely related to the nuclei expansion, and the form varies by the difference of development zones. For high-tech zones, corridor expansion is extended outward from the core city. For residential zones, it is spread from both the core city and the nuclei cities. For industrial zones, there is not much expansion in the corridors. Last, the extent of corridor expansion in each city responds to the magnitude of urban expansion in the city as discussed in hypothesis one.

5.4 Hypothesis 4: Trend toward monumentality in urban form.

Besides of the spatial patterns of the expansion, the fourth urban model I explore is the expansive nature of new development in these cities over a relatively short period, which is closely related to large consumption of land, such as wide street block structure, and enormous real estate projects. The ideology of expansive urban form could trace back to the concept of monumentality in the Paleolithic or Neolithic period where the early form of the city started to be crystallized. The religious and royal monuments, such as the Egyptian pyramids, and the Greek and Chinese palaces emerged to magnify social privilege and power as urban order formed (Mumford, 1961 pp.64). With the rise and development of capitalism, the idea of monumentality has repeatedly appeared in urban planning (Le Corbusier, Daniel Burnham) and landscape architecture (Frederick Law Olmsted) in search of the utopian aesthetics, economic growth and competiveness.

The monumentality has reappeared recently in urban geography literature (Ford, 2008; Smith, 2008; Adams, 2008; Ben-Joseph, 2009; Trumbull, 2010). From the singular imperialism that incites religious monuments, to the manifold mechanisms which, in the areas of economy, political symbolism, and aesthetics, distribute and institutionalize the monumentality, an immense verbosity of monumentality is what each municipality has required and pursued. The term monumentality refers to any urban development projects that are at a larger scale than their surrounding neighborhood, and in an emblematic and distinguished form that can be singled out in the urban fabrics. For instance, the grand boulevards of Paris, Central Park of New York, and the downtown Abu Dhabi, could be considered as urban monuments. Sometimes, these monuments are referred to as 'megaprojects' or 'megastructures', which are those that transform landscapes rapidly, intentionally, and profoundly in a visible way that can be observed by satellites.

Although it is difficult to quantify the significance and magnitude of these urban monuments, there is enough uniformity in how new urban areas and new zones are planned to be less dense but with large-scale forms that could be quantified. What I am trying to measure is the movement toward new urban areas that are less dense than the core urban at a certain level of dispersion, or areas becoming less dense, and buildings and road design become more large scale, involving more land.

One way to measure the monumentality is the density of road intersections, which is a proxy for the area of an urban neighborhood given that the pedestrian accessibility and communicable proximity are largely cut off by highways (Jacobs, 1961; Southworth, 1997). Higher the intersection density is, smaller the average neighborhood is. Here I selected sample circles with 1.5 kilometer radius from each period, within which 90% or more urban expansion occur during that period (Figure 9). Overlying them with Google Earth (Figure 10), all intersections were digitized using points and the average number of intersection per square kilometers was estimated as the results in Table 4.

The results show that in early periods, such as 1988 and 1995, the first amounts of settlement developments were quite dense. The wave of development exhibited similar intersection density as the urban core area before 1988. The expansion in the late 1990s for Chengdu and Xi'an appeared to be expansive in form, as the sharply dropping intersection density suggests in Table 4. At the same time, Kunming and Urumqi continue dense development as a form of their historical urban core. Intersection density in Kunming and Urumqi began to sharply decline in the early/middle 2000s. Since then, new development in all four cities has been expansive, such as large condo blocks, multiple lanes boulevards, and spacious squares.

The observed monumentality of urban development did not vary with land use types. The selected sample circles across the cities all have designated associated land uses. However, not quite different density of intersection was observed across the cities. It suggests that, for all sectoral development, including manufacturing, high-tech, and residential/service, has a similar expansive form of development emerged in the cities in Western China as the cities expanded.

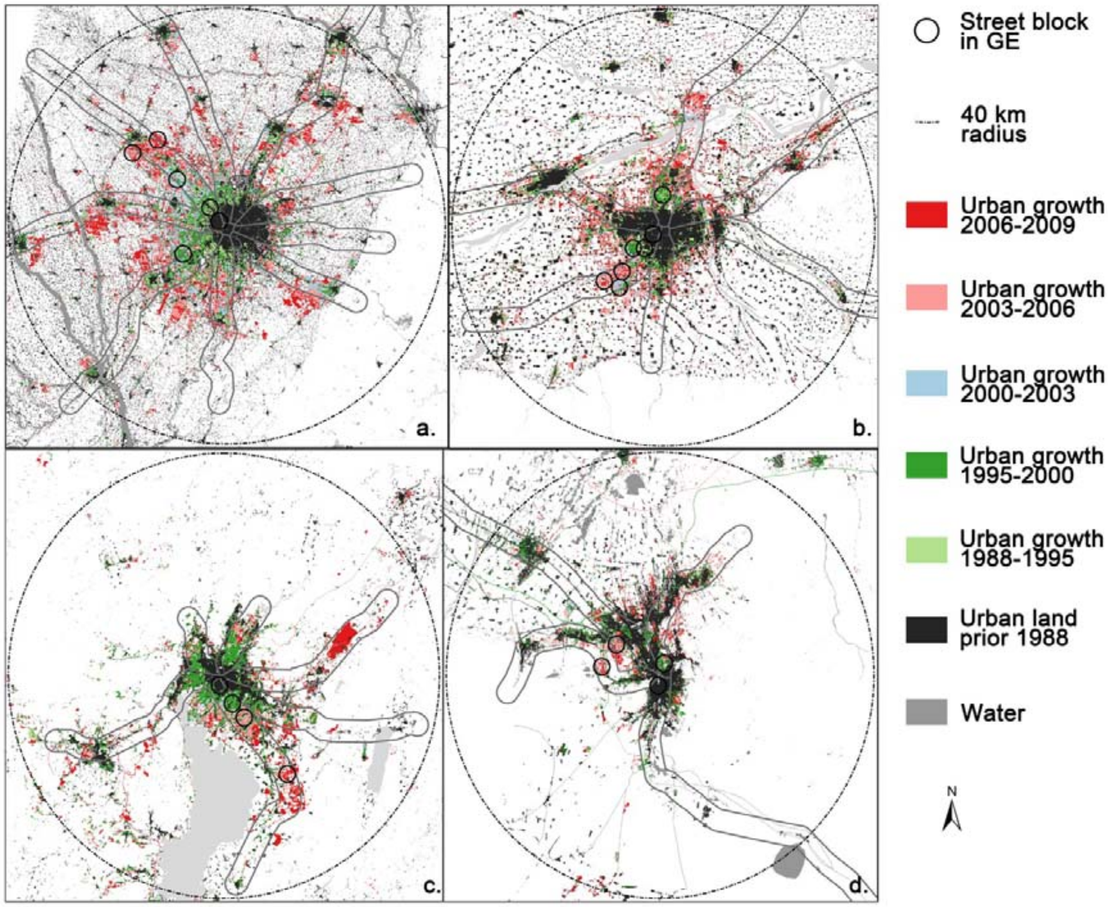

Figure 9. Selected sample circles for estimating number of road intersections at each time point across cities. Alphabetically, the letter stands for Chengdu, Xi'an, Kunming and Urumqi respectively. The small black circles are the sample circle with 1.5 kilometers radius for counting intersections in each period.

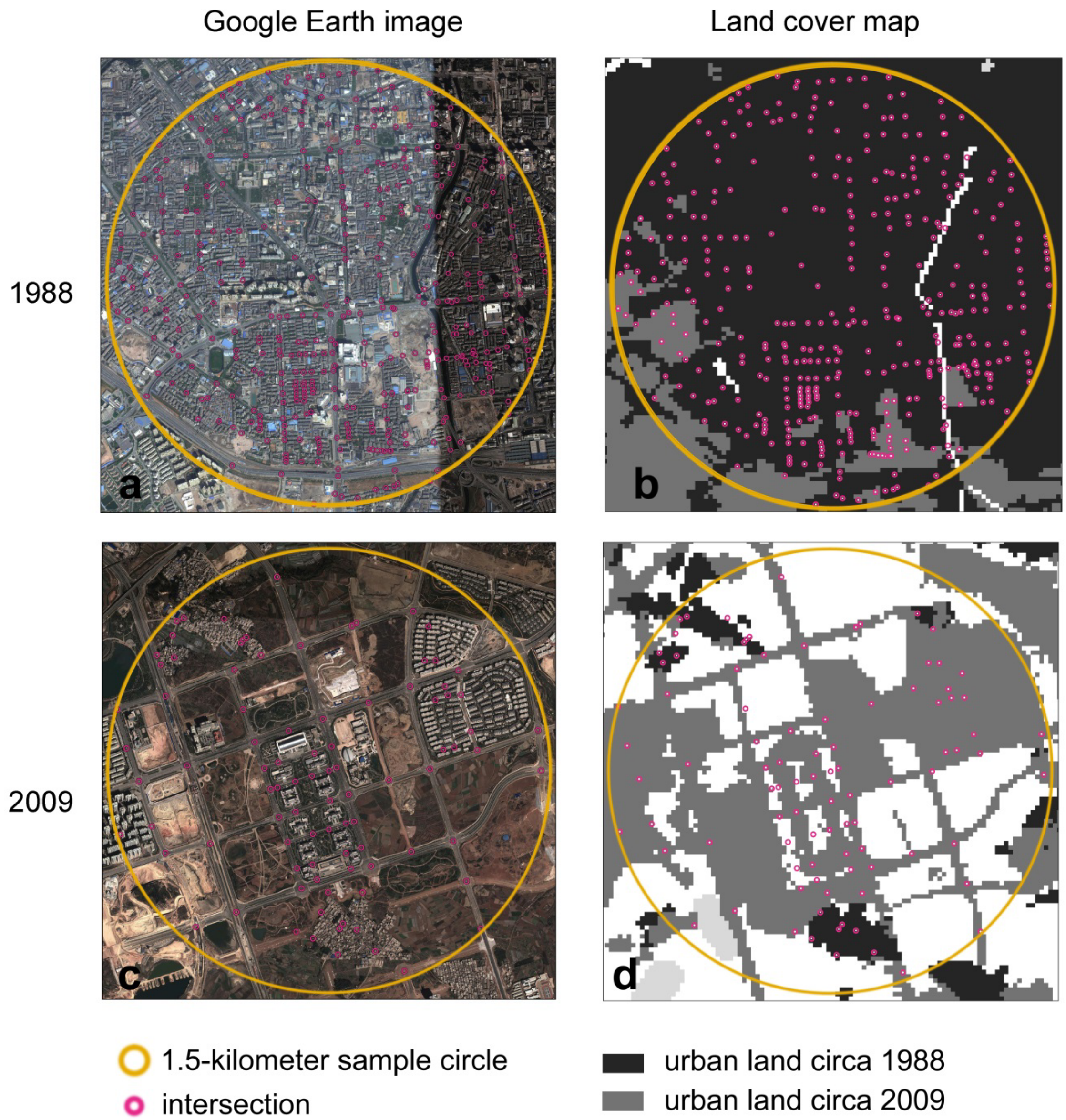

Figure 10. Digitizing road intersections – example of roads from Google Earth, compared to Landsat. The top panels (shown as **a** and **b**) are regarded as urban area circa 1988, and the bottom panels (shown as **c** and **d**) are regarded as urban area circa 2009.

Table 4. Density of intersections in different period for all four cities (1.5km buffer)

	1988	1995	2000	2003	2006	2009
Chengdu	54	42	10	9	3	7
Xi'an	31	33	18	17	15	7
Kunming	57		42		18	13
Urumqi	37		41		7	6

* Unit: count of intersections per square kilometer
** The count of intersections is estimated based on circles in each period with 1.5 km radius

5.5 Hypothesis 5: Expansion of urban land is greater than population growth.

The last urban model that was examined related to the change of population density in all four cities in response to the changing spatial form. Previous results show that the rate of urban expansion in these cities was unprecedented and accelerating. An interesting question is raised here – whether the population growth was as fast as urban expansion so that the population density remained the same.

The amount of urban land and the number of urban residents were carefully matched at two levels – counties and districts in the core city that was administratively defined as the city proper, as well as the city extent in the 40 kilometers buffer that was defined in this study. The raw numbers and cumulative changes of both urban land and population were shown in Figure 11.

The results show two sets of plots that illustrate the relationship between population growth and urban expansion, in jurisdictional core districts and a consistent 40 kilometers buffer separately. The first row of panels finds an explicit trend of both population increase and urban land increase in every period, at both core districts level and farther 40 kilometers buffers. The trends of four cities could be split into two categories. Chengdu and Xi'an are at a larger size as shown in the second plot, while Kunming and Urumqi are at a smaller size. It is notable that the growth of Kunming in core districts was exaggerated because the size of its core districts is comparatively much bigger. Also, the period 2000 – 2003 has the least expansion for all four cities.

For Chengdu and Xi'an, population density has been constantly decreasing for all periods. Even for Kunming, because of constraints of physical geography, the trend is noisier than the first two study regions but still pronounced. The trend of the core districts of Urumqi is exceptional. In this case, the population growth outpaced the urban expansion.

The second row of panels shows the same trend as of cumulative percent change, but only in two main periods, 1988 – 2000 and 2000 – 2009. It is clear to compare and contrast the trend in inner core districts and a larger extent. For all four cities, the slope of these periods varies. The slope of Urumqi is the flattest in both core districts and 40-kilometer extent. The slope of Kunming is steeper than that of Urumqi. And those for Chengdu and Xi'an are the steepest. The steeper the slope is, the lower population density of the city becomes. The development in inner districts has been denser in population than that of outer peri-urban areas. The rate of urban expansion outpaces the rate of population growth and the difference is increasing. The latest period is the fastest period for urban expansion in all four cities.

An alternative method to show the expansive form is measuring the population density at county level. Instead of using total land area within the jurisdictional boundary, the total built-up area in each county/district is used here. Even without available data in a few counties and districts in early periods, an interesting story emerges as the choropleth maps were shown in 1988, 2000 and 2009 (Figure 12).

The results show decreasing population density, especially in counties and districts closely around the city center. The population density was relatively high in 1988 in all four cities where urban expansion had not started yet and rural dwellers were living in traditional compact rural houses. The density started declining in a few counties and districts near the core city in 2000. And this trend spread to other surrounding counties and districts that were even further to the core city in 2009. The deceasing population density in later periods suggests that all cities were extended out in a more expansive form that the form in the city center prior to 1988.

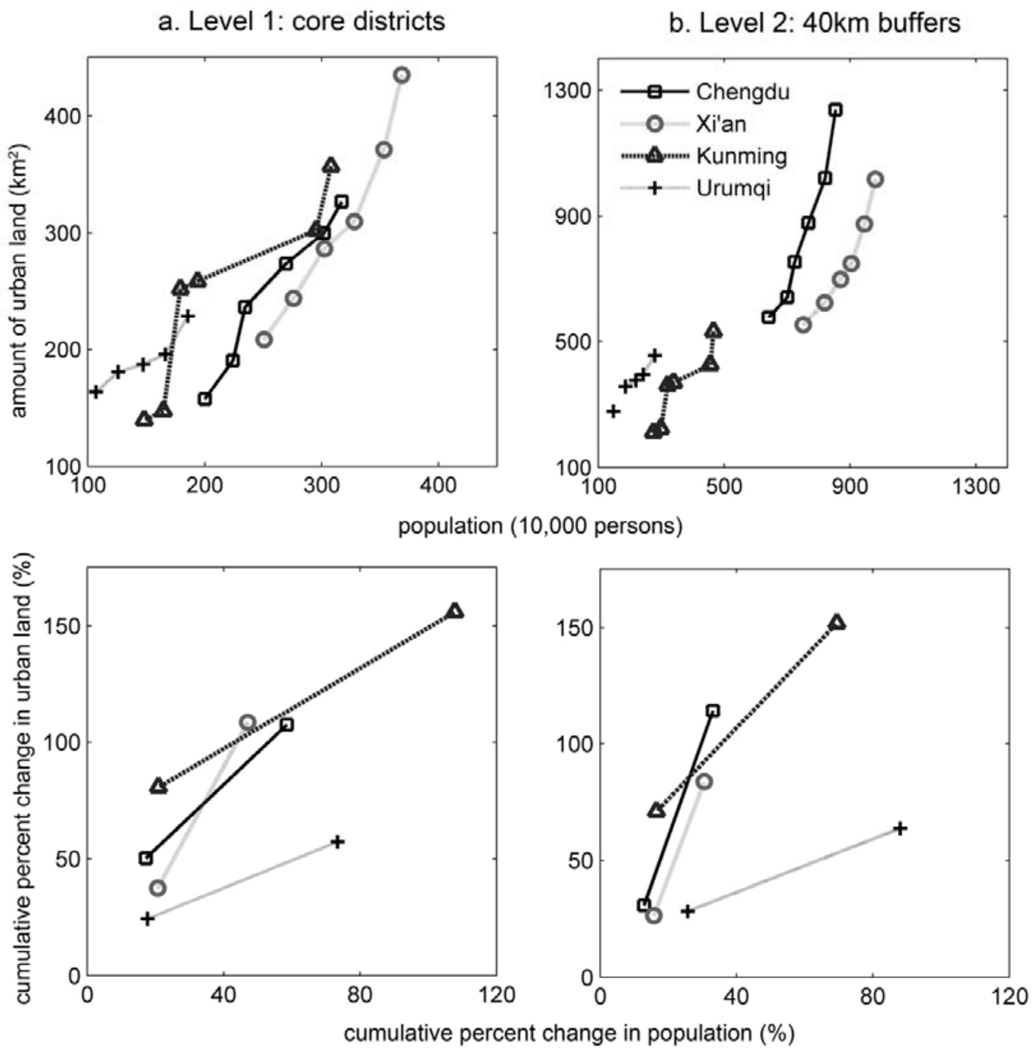

Figure 11. The growth of urban land versus the growth of population in all four cities. The top panels are the raw number of urban land and population in each time point at two spatial levels. The bottom panels are the cumulative percent changes in two major periods at two spatial levels.

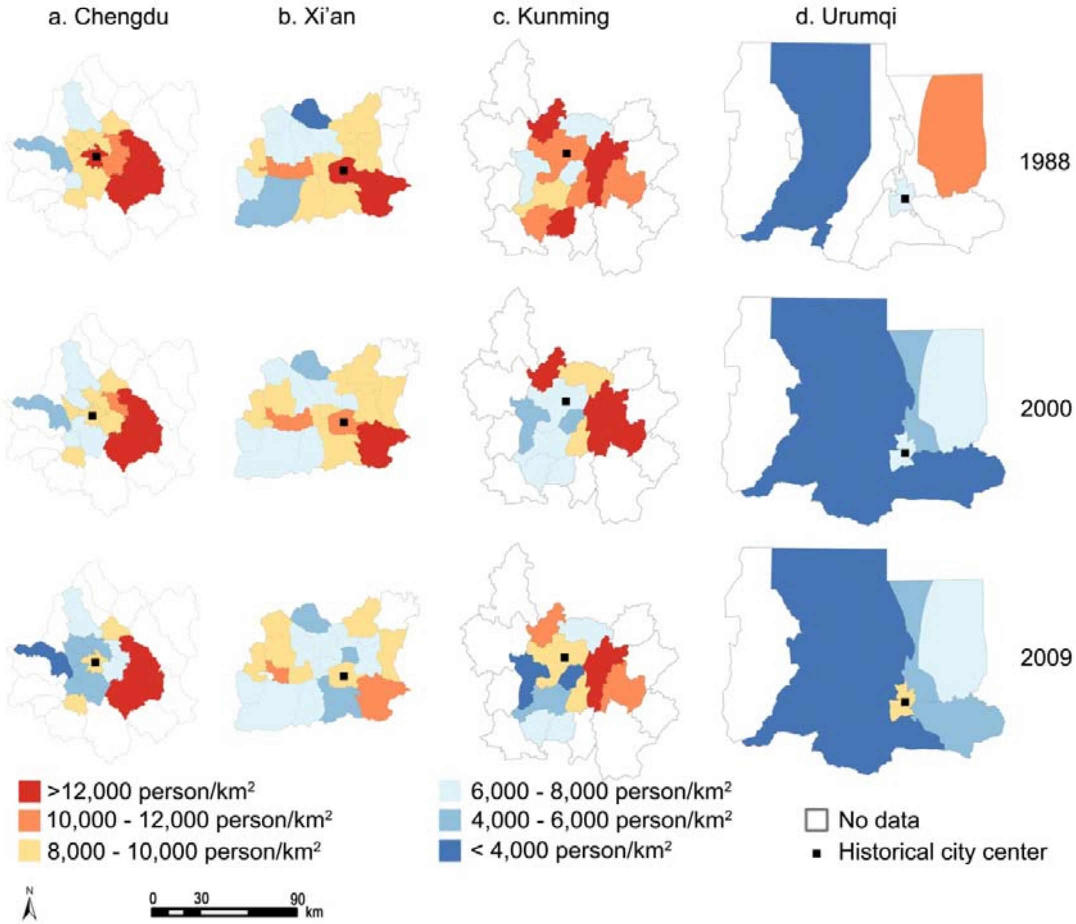

Figure 12. Chloropleth maps illustrating the population normalized by the area of urban settlement by county in three years: 1988 (top row), 2000 (middle row), and 2009 (bottom row). It is worth noting that the population of Hongta in Kunming and core districts in Urumqi circa 1988 is interpreted from later years (1990-1995). Also, the numbers for a handful of counties at the urban fringe are slightly adjusted due to the short of Landsat imagery footprint.

The trend in the core districts varies by cities. For Chengdu and Xi'an, the population density declined consistently during the past two decades. For Kunming, it declined from 1988 to 2000 then increased in the later period. For Urumqi, the population in the core districts increased during the whole period. Considering there are a large amount of non-urban land in Kunming and Urumqi that can be developed, the increasing population density in Kunming and Urumqi might be because they tend to utilize the available land in the core districts first. However, the population density in the core districts for all four cities reached same level – 8,000 to 10,000 persons per square kilometers built-up land – by the end of 2009, which may indicate the bottleneck of population density in the developed urban area under current city building in China.

The findings of the final hypothesis show that the growth rate of urban expansion and population is different across cities over period. In Chengdu, Xi'an and Kunming, urban expansion is faster than population growth, while in Urumqi, it is the reverse way. Also, it is noticeable that the core districts have been experiencing both population growth and urban expansion, and eventually their population density reaches a similar level. In contrast, the counties around the core districts, where the population density was high in the rural area, have also experienced both population growth and urban expansion. But the population density has been declining.

6. Discussion

6.1 Trends in urban expansion of cities in Western China

I have given a detailed account of trends in urban expansion in Western China. Here I recapitulate a number of these trends so as to raise certain socio-economic issues. In the following section (6.2), I will broach the topic of explanations: What caused the expansion? How important was central planning at state, provincial, and local levels as distinct from market forces – the role of the invisible hand? Seeking causes requires one to look backward. One can also look forward, that is to say, ask how urban expansion is affecting non-urban land use, especially agriculture, what are its current and future impact on soil degradation and air pollution, and what are the social consequences – for example, the gap between rich and poor? Naturally I cannot even begin to do justice to these important questions. I wish only to say two things: first, I am aware of them and wish to explore them in the future; second, I believe that such exploration requires detailed spatio-temporal mapping and analysis of what actually happened on the ground in Western China. My contribution lies primarily in this necessary, preliminary step.

The rapid expansion of Western cities is in different waves. None experienced rapid growth right after the land reform in the late 1980s when coastal cities took off. The pattern of expansion is not simply one of sprawling from the core city. Satellite cities emerged, with urban types of land use surrounding them. One may characterize this expansion as from monocentric to multi-nucleated. Multi-nucleated pattern has a dominating center surrounded by smaller cities. It is not to be confused, therefore, with polycentric pattern in which the multiple centers are approximately of the same size. In the multi-nucleated pattern, the core city, which is usually the historical center, does not suffer from having satellites. On the contrary, it remains strong and even becomes stronger with growing residents, jobs, and services. It is in services – health, business, and social – that the smaller satellite cities cannot compete. In the development of the multi-nucleated pattern, governmental planning has clearly played a role in acquiring land, reallocating rural residents, and laying out essential infrastructure. Government may begin by establishing development zones. In just a few years, these can turn into satellite cities, gobbling up land once used for agriculture and non-urban purposes. Obviously, other forces – social, cultural, and economic – must also be at work. So far, little is known about them – little that is precise and quantitative. But perhaps the social and, particularly, the cultural forces need a different approach, one that is more like a narrative than a statistical algorithm.

6.2 Possible explanations of urban expansion and limitation of quantitative urban methods

What drives urban expansion? One drive is the increasing demand for urban/nonagricultural services. Satellite cities did not grow with villages, but from preexisting county seats or government planned, development zones. Similarly, corridors did not grow out of pre-existing roads, but were connections required by core and satellite cities. The craving for housing seems to drive people to move from core city to spacious apartment complexes along these corridors. The newly built structures take up land that was once occupied by villages and workers' condos, resulting in a mixed landscape of modern housing and slums. Who live in the new complexes along the corridors? Government officials, entrepreneurs, and well-paid professionals. Who live in the collectively owned condos? Floating workers and the urban poor. Who live in the villages that remain and need upkeeping? Elderly peasants who lack the initiative and resource to move into the city and other underprivileged groups.

Government planned development zones can turn into satellite cities, as we have seen. The speed of the transformation seems to depend on the type of industry. Thus high-tech zones give rise to cities rapidly because they promote growth in secondary and tertiary economies. Zones devoted to the more traditional industries, by contrast, promote mixed city growth, successful in some areas, not successful in others. Urumqi, however, is an exception. It has an energy industrial zone, and energy is not high technology. Nonetheless the industrial zone, supported to an unusual degree by such services as management and finance, is promoting the growth of new towns and the new towns themselves are plentifully supplied with restaurants, house care, schools, and hospitals, to minimize the need to commute.

Even though the planning policies have an effect on urban form, it is not easy to separate the roles that different levels of government have from decision making to implementation. One problem is that cities and corridors have stretched beyond the jurisdiction of any district and county, sometimes even the jurisdiction of the municipality, as is the case with Xi'an. It also happens that sometimes a project requires the participation of all levels of government. A case in point is urban expansion following major road construction. Remotely sensed images have captured major roads constructed in various periods in all four cities, roads that extend beyond the city's limit. These are phenomenally wide and long; they are super highways built at the state level of government. Along their side and the side of the development zones are large street blocks and other types of built-up areas. These require input from the lower levels of government – provincial, municipal, and county. Success is clearly a challenge, for it requires all levels of government to make and carry out the urban plans seamlessly.

6.3 Implications: what I learned from urban expansion in Western China

Unlike other developing countries where urban expansion occurs near a few major cities, the expansion in western China, the interior hinterland, is expansive and occurring in many small cities outside large metro areas. This is similar to the coastal cities. This finding has posed an interesting question: Whether the urban development in western China would follow the same development path as coastal cities in terms of spatial forms? The rapid urban expansion is concurrent with Chinese economic restructuring, unbalancing geographic development, and decentralizing political system. As the share of agricultural production diminishes, manufacturing and services are increasing in demand. The port cities on the coast began taking off due to the proximity to the global market. While the state government decentralized its fiscal and administrative power to municipal governments, the municipal governments capitalized its power on establishing land market on one side, on the other side simply pursued economic growth by promoting real estate development, to gain advantages in political rewarding system. The strategies involved adaptive urban planning to the market economy, deficit-financing infrastructure construction, and large scale privatization. It also helps spatial differentiation in terms of sectoral restructuring and income segregation (Leaf, 1995; Yeh, 1995; Zhang et al., 2003). Urban planning has been adaptive to the dynamics of spatial forms, shaping the corridors and satellite cities associated with certain land uses. The multiple satellite cities planned seem working well; not only they are expanding, but also the corridors connecting them are filling with new residents especially from the end near the core city. Manufacturing is booming. Spatial differentiation continues, in terms of not only land use types, but also housing.

After the liberalization reforms, Chinese economy developed fast by marketization, privatization, and integrating international trades, and initialize the transformation from totalitarian and egalitarian poor society to early stage of capitalism – state capitalism (Panell, 2002; Harvey, 2005; Hsing, 2007; Huang, 2008; Naughton, 2011). Under the political economic circumstance, the municipal governments in this study established growth-led policies and urban master plans in order to mimic the economic success in coastal regions. Not just setting the path for economic growth, government actually worked closely with developers, entrepreneurs, and foreign investors to ensure the development happening over space and time. Setting up development zones could attract investments and create jobs, so does promoting real estate development, as results show that master plan successfully promote urban growth near satellite cities and along radial corridors. The massive development further away from city center and the monumental development observed in later periods were appropriations to western urban form, where the commuting mode is mostly individual vehicle and the large green space could attract new offices and residents.

However, this means of production raises challenges in two ways. First, the development largely relies on a controversial regulation over individual mobility – the hukou system. Instead of reallocating labors to coastal regions to increase the efficiency, it allocates capital inland, which inevitably increase the transportation cost and decrease the competitiveness. With technical advances and increasing competitiveness, the Fordism in the interior area will break down first in crisis. Second, the urban expansion has almost reproduced the hierarchy of Chinese political system – large development near the core city, and satellite cities, and even rural areas. However, without equivalent amenities and public goods, creative services, the benefits from economic growth in remote areas, including satellite cities far away from the core city and rural areas, are limited. As the capital further accumulated, it would be spatially skewing towards large cities, where resources like education, medical care, and public recreation are concentrated. This restructuring would further encourage the geographical rural-urban migration, therefore, leave the settlements in rural area and satellite cities abandoned.

6.4 Limitations and uncertainty in the various data sources

The main purpose of this study is to find the appropriate and manageable level of resolution – the appropriate scale and detail – of the facts, to understand the rapid expansion of built-up land in Western China. A few limitations and uncertainties that relate to my findings are aware of. First, it is impossible to capture the constructions at one pixel level (that is 900 square meters). And developments smaller than 2 to 3 pixels (less than 1,800 or 2,700 square meters) are highly possible to be missed. However, self-constructed houses in rural China could fall into this category, especially in mountainous areas. That means rural development in Kunming and Chengdu could be slightly underestimated in the results. Also, small linear features, such as mud road connecting villages, are sometimes missed.

Even though I cautiously examined the socioeconomic data and matched to the land cover changes, a certain level of uncertainties remains that are elusive to assess. The jurisdiction boundaries of districts and counties have been changing quite often at fine level. These sub-county level changes of boundaries can shift the results but are not reflected in my results. The survey approach used (census sampling size, statistical approach, etc.) and the data published in yearbooks (published variables at county level) vary slightly by each municipality. In addition, after the rigid hukou system was lifted in early 1990s, a fraction of floating population in urban spaces and private sectors were missing in yearbooks around 2000. Considering the uncertainty is systematically biased toward underestimation like the built-up land, the ratio of population to the built-up land in examining the last hypothesis is less biased than expected.

The urban expansion is a three dimensional process. Constrained with the limited land in historical urban center, a handful of urban renewal projects replaced Soviet style, and six to eight story building with high-rise buildings or even skyscrapers with elevators. The population density, therefore, was further concentrated. However, because remote sensing mapping does not capture change in height of buildings, this trend of change is missing in this work. Also, urban expansion in China can be overly rapid, thus it requires more frequent satellite observations to fully capture the temporal variations.

6.5 Future work

A few unresolved questions need further researches. First, based on the findings, why are there differences in the form of urban expansion? Why do these cities in Western China take different form of satellite cities, as well as corridors? Because pattern links to process, in this study, I have been trying to connect the morphological change to the change of land use, economic restructuring, social restructuring. However, further data is required and it needs modeling to connect the dots. The urban planning policies strongly intervene the urban growth but more work needs to be done to study the effect of these policies. Policies from state and municipal level of government were clear having huge impacts on urban growth, while role of provincial and county level government remains unknown in this process. Liberalization reform in late 1970s and early 1980s unleashed population migration and initialed land/housing market to some extent, as well as leveraged FDI and domestic investment to stimulate the expansion (e.g. development zones and large infrastructure projects). The effect of policy on the expansion is not always clear. For example, it is unclear to tell how the land use plan and master plan in each city impact on expansion. And it is hard to tease apart impacts of municipal development zones from provincial or state zones. Another example is that "Great West Development" had a share of budget on building highways and railways. They were also encouraged by municipal and provincial policies. And it is difficult to distinguish the impact from each policy. The dramatic expansion accompanied with a great deal of land acquisitions. It is still unclear that how the public and private sectors in urban and rural area coup with the acquisition, especially in the process of emerging land use right and land market.

In addition to understanding different reasons behind the expansion across cities, the different pattern of two specific expansions also needs further investigation. On the one hand, there was no decay in these Chinese cities, in contrast with the history of decay, followed by gentrification and rejuvenation, in many American cities. On the other hand, the expansion along a corridor invites businesses around it, increasing neighborhood population, so the population density should accordingly increase. Yet the population of the countryside – the neighborhood – actually decreases. Why are these Chinese cities exceptions in these two aspects? The answer may lie in the rural transformation unique to densely settled Asian countries, but requires further analyses.

Furthermore, the impact and future scenarios of urban expansion in China are significant and worth studying. It is clear to show transportation network has been changed in response to the expansion. It would be interesting to show how the commuting means, land use, and urban society are shifting due to this change. It is also interesting to incorporate globalization to the state, regional and local development and build up possible scenarios. Also, the urban climate, biodiversity, and carbon cycles were changed accordingly, and require more efforts to understand these impacts.

7. Conclusions

Understanding the spatial and temporal patterns of urban expansion provides valuable information for exploring the possible reasons behind the process, as well as estimating its impact on the environment, economy, and society. Remotely sensed imagery opens the opportunity to map the expansion for a large area for the past three decades, which could not possibly be surveyed by human power. The results from the satellite based maps provide a powerful tool for illustrating the spatial expansion of built-up areas across decades.

The findings in this study show that urban expansion in Western China has occurred at an unprecedented rate for the past three decades. Even it is slightly slower than that in coastal regions, the rapid process of urban expansion associated with arable land loss is not negligible. The expansion exhibits a multi-nucleated form, along with several planned corridors. Unlike the urban sprawl of the United States and European countries, the expansion still take forms in high-rise apartment buildings, factories, and office buildings as relatively high population density suggests. However, the newly constructed urban spaces all exhibit a monumental form of development, relating to wide boulevards, large urban blocks, and other planned megaprojects.

Across provinces, the urban development occurred in waves. The cities with larger population base and higher GDP at the initial stage took off to expand earlier. Physical geography like the geomorphology and climate constrains the spatial expansion of cities to some extent. However, in terms of rates and spatial forms, urban expansion in Western China does not seem different than that in coastal regions.

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Appendix 1. Literatures in applying landscape metrics in urban studies

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Appendix 3. Literatures in spatial differentiation and polycentricity

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