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Research Paper

The changing spatial form of cities in Western China

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HIGHLIGHTS

- Four western Chinese cities expanded 2% annually, 1988–2006, and 5–7%, 2006–2009.
- Chengdu, Xi'an, Kunming, and Urumqi, China, each more than doubled in size, 1988–2009.
- In Western China, one-third of new urban land is outside the core, in small towns.
- The results suggest a multinucleated urban form similar to coastal Chinese cities.
- Rates/amounts of expansion are highest in areas with tertiary residential activities.

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ABSTRACT

Cities in China have exploded in size, population, and impact during the last three decades. The combined effects of liberalization, decentralization, rapid industrialization, and globalization have led to an unprecedented urban transformation. Several investigations have documented the land-based impacts of this transition, but the majority focus on coastal cities first targeted for reforms in the 1970s–1980s. Urban expansion and restructuring in China's western region have not been widely studied or well-understood. This research investigates the ongoing urban transformation in Western China (1988–2009), focusing on four cities: Chengdu, Xi'an, Kunming, and Urumqi. The analysis relies on land change maps, satellite images, socioeconomic data, and master plans, and draws on a variety of measures to estimate urban patterns through space and time. The results show that the pace of change is indeed high: all cities grew at annual rates near 2% from 1988 to 2000, but climbed to 5–7% after 2006. Each city has more than doubled in size during the study period, and nearly one-third of new urban land is outside the core, in small towns. This result suggests the emergence of a multinucleated or polycentric urban form consistent with trends reported for coastal cities. Analysis using landscape metrics along urban–rural gradients suggests that rates and amounts are highest in areas designated for tertiary activities and residential growth. Overall, the results suggest that urban expansion in Western China may not fit models of urban development based on U.S.-European cities, but aligns more closely with new models based on Chinese coastal cities.

1. Introduction

Cities in China have exploded in size, population, and impact during the last three decades. Since the implementation of liberalization policies in 1978, China's urban population has grown from 172 million to 665 million in 2010, boosting the urbanization rate from 16 to over 50% (NBS, 2012). During the same period, annual GDP growth averaged 10% (NBS, 2012), with the majority of economic activity focused in special economic zones and open cities targeted for development by the Chinese government (Lin, 1999). Several investigations have documented China's rapid urban transformation following reforms, which have led to unprecedented rates of land development in coastal provinces (Han, Hayashi, Cao, & Imura, 2009; Seto & Fragkias, 2005; Wu, Hu, Wan, & Wan, 2006; Yu & Ng, 2007), as well as critical changes to the structure and urban morphology of cities (Yeh & Wu, 1995; Gaubatz, 1999). 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, as well as for strategic military and national development interests (Lin, 1999). While a handful of studies have assessed the impact of these

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Table 1
Reforms put in place in China, 1978–2009, relevant to this research.

	Coastal China		Western China	Study areas affected
1978	Agricultural reforms			
1980	Special economic zones established in cities			
1984	Coastal open cities ('gateway cities') established	Economic technology development zones (ETDZs) established		
1985	Early coastal open economic zones established (3 areas)			
1988	Coastal open economic zones (10 provinces) established			
1990			Eighth five-year plan recommends labor coordination between coast and west	
1991	High-tech industrial development zones (HTDZs) established			Chengdu
1992	Provincial capitals, border cities designated as open cities			All
	State tourist districts established			Kunming
1999			Western development program established	All
2005	Urban–rural integration policies advanced			All
2008	Development zone reform; all areas opened			All
2009			Western triangle economic zone established	Chengdu, Xi'an
2010				

Fig. 1. Map showing four regional zones within China (National Bureau of Statistics, 2010), as well as the location of the four metropolitan areas investigated in this research (from north to south): Urumqi, Xi'an, Chengdu, and Kunming.

policies (Table 1) on industrialization and urbanization in Western China (Liu et al., 2005; Schneider, Seto, & Webster, 2005; Vermeer, 2004), urban expansion and urban restructuring in the western region (Fig. 1) have not been widely studied or well-understood.

A review of recent literature suggests that urban expansion in China does not fit traditional models of urban development, but may, in fact, be a unique typology of growth (Lin, 2007; Whitehand & Gu, 2006; Wu, Xiang, & Zhao, 2014). The motivation for this work stems from the complex and significant ways that urban development and urban form impact social, economic, political and environmental systems. Changing spatial structure has a direct effect on where people live, work and play, thus implying a social impact. In economic terms, the size of a city, the location of new development, the level of fragmentation, as well as specialization of land use each affect the provision of goods and services, the profitability of firms, as well as the movement of people, information, and products. Change in urban form can also lead to fragmentation of city governance; as cities expand into new political divisions, decision-making is fractured, making it difficult to put policy in place that coordinates growth and development. Polycentricity can further hinder coordination of urban planning, since multiple local governments may have differential goals within one agglomeration (Vogel et al., 2010). Finally, changes in urban form are known to have significant impacts on land use and the environment (Grimm et al., 2008). Environmental impacts often extend far beyond the city core, including a significant and lasting impact on local precipitation and temperature (Kaufmann et al., 2007; Weng, 2001), expansion of the urban heat island effect (Zhou et al., 2004), reduced water quality (Shao, Tang, Zhang, & Li, 2006), and air pollution (Shao et al., 2006). Moreover, many environmental impacts are exacerbated when new growth is expansive and/or fragmented in form (Alberti, 2005), such as the low density, dispersed or even decentralized forms of urban expansion common in the U.S. and other developed countries (Ewing, Pendall, & Chen, 2002), and emerging in many rapidly developing nations as well (Kontgis, Schneider, Fox, Spencer, & Castrence, 2014; Schneider et al., 2014).

With these issues in mind, this study assesses the magnitude and form of urban expansion in China over the past two decades, with a specific focus on the spatial and temporal patterns of urban expansion in four western cities – Chengdu, Xi'an, Kunming, and Urumqi (Figs. 1 and 2). We test four hypotheses, drawn from an extensive review of the literature on urban development and urban form in China, but which have not yet been addressed for cities in Western China:

(1) All study areas have experienced urban growth and expansion of built-up lands outside the city core. Following implementation of reforms in the western region in the early 1990s, rates and amounts of urban growth have increased, and new development has occurred increasingly far from the edge of the contiguous built-up urban core.
(2) Each city has transitioned from a monocentric to a polycentric or multi-nucleated urban form, with increased amounts of built-up land in satellite cities and towns up to 40 km from the original central business district (CBD).
(3) Land use specialization has occurred in each city following the creation of development zones, often in corridors and areas outside the original urban core.
(4) Corridors in each study area have witnessed differential rates and patterns of urbanization specific to the dominant land use within the corridor. High tech and residential corridors, in particular, have experienced a greater amount of land conversion than industrial corridors.

While these hypotheses have been discussed at length in the context of Eastern China, none has been applied to the ongoing urban transformation in Western China. The goal of this work is to test these hypotheses using empirical datasets, including unique, Landsat-based maps (Schneider, 2012), detailed satellite images (1–4 m resolution), demographic and socioeconomic data, and master planning documents (Fig. 3). This research focuses on five key time periods: the pre-reform period in the West, 1988–1995; two periods immediately following reforms, 1996–2000 and 2001–2003; and two periods after reforms were in place, 2004–2006, and 2007–2009. Drawing on techniques used in the urban planning, geography, and transportation studies literature, this work measures urban changes through space and time.

This paper is organized as follows. Section 2 begins with a literature review designed to show how the four hypotheses have been developed from the growing body of empirical work on urban morphology in the Chinese context. The study regions and datasets are introduced in Sections 3 and 4, respectively. In Section 5, data for the four study areas are used to test the hypotheses above. The paper concludes with a summary of the research findings and a discussion of their implications for Chinese urbanization.

2. Background – urbanization in China

2.1. Overview

There is an extensive body of literature investigating urban spatial form, beginning with early ideas that characterize the city using concentric zones (Burgess, 1927), sectors (Hoyt, 1939), or multiple nuclei (Harris & Ullman, 1945), and continuing through approaches that test the monocentric model (Alonso, 1964; Mills, 1967; Muth, 1969), quantify the spatial equilibrium model (Fujita, Krugman, & Venables, 1999; Krugman, 1995), or utilize spatially-explicit land use change models (Irwin & Geoghegan, 2001). Until recently, the majority of work has been conducted on cities and metropolitan areas in the U.S. and Europe. While many aspects of these foundational ideas are relevant to the Chinese experience, there is growing consensus that Chinese cities are undergoing a unique and significant transition, with many characteristics that cannot be explained by Western models (Lin, 2007; Whitehand & Gu, 2006). The following review traces the evolution of cities in both pre-reform and post-reform China, and documents the literature that has begun to establish the dominant processes and patterns that have emerged. Although much of the literature remains focused on China's coastal areas, many of the concepts and processes are relevant in Western China as well.

2.2. Pre-reform urbanization

Recent development in Chinese urban form can be understood, in part, by investigating the historical forces that shaped city development. The location, size, shape, and structure of Chinese cities can be traced to early imperial city layout, with ceremonial and administrative buildings concentrated in the center, and common people scattered outside (Lynch & Kevin, 1981; Yeh & Wu, 1995). After 1949, these features were retained, although state control and economic planning began to play a significant role in shaping cities during the Mao era. Because Chinese leaders gave priority to industrialization throughout the 1950s, '60s, and '70s, cities became the primary location of heavy industry (Ning & Yan, 1995; Yeh & Wu, 1995). Since land rent was non-existent, a relatively large amount of land was dedicated for industry (25–30%) in most cities. There was typically no CBD, but rather, daily services were provided by work units designed to be self-contained spaces in multiple locations throughout each city. Cities were undifferentiated by function, with each neighborhood or district providing services for its residents (Gaubatz, 1999). The result was a generalized city form, consisting

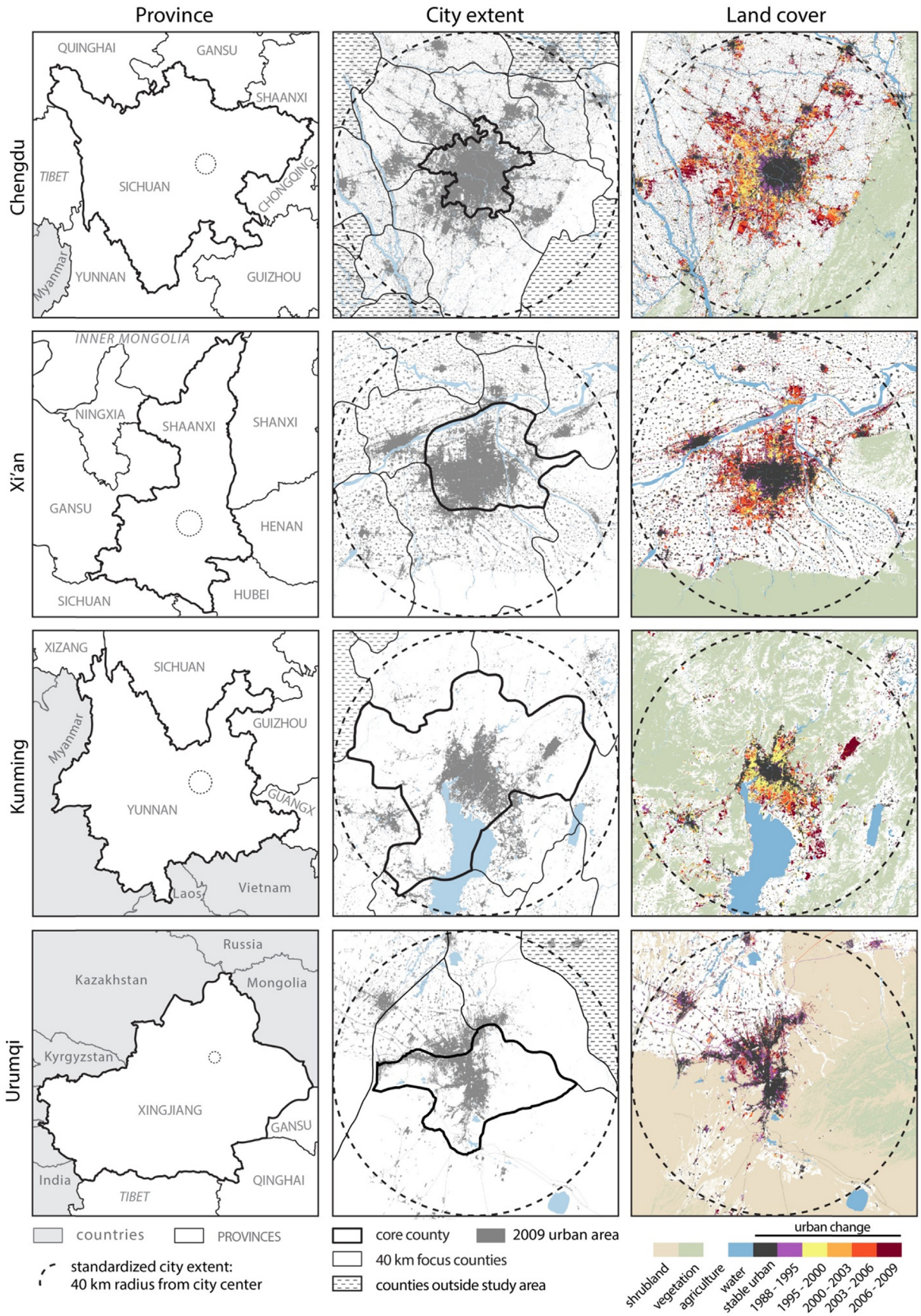

Fig. 2. Maps of each study area illustrating the location of the city within each province (left); the counties included in each study area and the 40 km buffer applied to the central business district to standardize the study areas for comparison (middle); and the maps of land cover change for five periods, 1988–2009 (right).

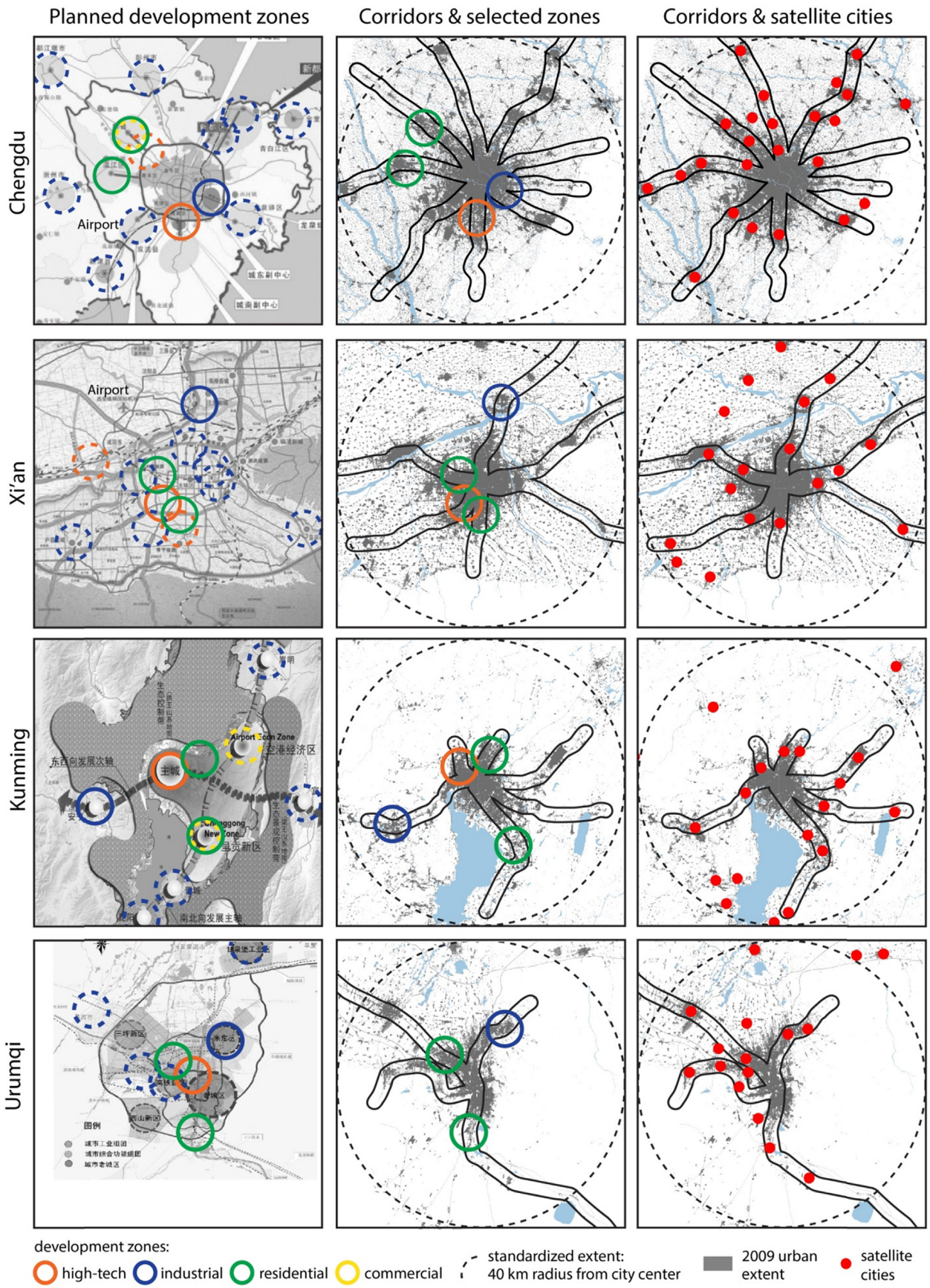

Fig. 3. Maps illustrating examples of the master planning maps for each study area, including development zones (left); the zones and corridors delineated for analysis (middle); and the satellite cities outside each city core (right, corridors are shown for reference). *Note that while the zones are designated with rings in the figure, the rings on the planning maps may denote a small or medium-sized city rather than a development zone.* (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

of a dense core surrounded by self-sufficient neighborhoods and communities (Pannell, 1977), often of lower density, but still part of the core. The role of socialist ideology in the development of Chinese urban structure cannot be understated: cities were highly centralized and standardized, with uniform social organization, and equal access to facilities and services by all (Lo, 1989; Lin, 2002).

Because capital construction focused on industry before 1980, the construction of urban infrastructure and housing was neglected, leading to traffic congestion, housing shortages, and pollution. These problems were seen as impediments to growth, and thus the government has focused its attention on urban infrastructure, public utilities, and communications during the last three decades (Ning & Yan, 1995).

2.3. Post-reform urbanization

It is generally understood that China experienced a fundamental social and economic shift following reforms in the late 1970s (Lin, 2007; Pannell, 2002). Reforms began in rural coastal areas with structural and economic policies that stimulated farmers' productivity (Ho, 2001; Lin & Ho, 2005), which led to increased income that allowed, for example, the building of new homes. Increased productivity also led to a surplus agricultural labor force, which the central government dealt with by relaxing rural–urban migration laws (Chan & Zhang, 1999). Migration to large cities remained under tight control, but migration to small towns was permitted after 1984. The result is phenomenal urbanization that has been based on the numerous small towns throughout China rather than growth in large cities. Many towns exceeded the thresholds for town designation, in fact, and were upgraded to small cities (NBS, various years).

Concurrent with these changes, the government moved to reduce the dominance of central state planning by decentralizing decision-making and fiscal powers, permitting a more market-led economy (including marketization of land use rights, and development of a real estate market), privatizing urban enterprises and housing, and opening China to the world market and foreign direct investment (FDI) (Ma, 2004; Yeh & Wu, 1995). These reforms were first realized in urban areas in 1979 after four Special Economic Zones (SEZ) were designated in Shenzhen, Zhuhai, Xiamen, and Shantou. Despite criticism, the SEZs were considered successful and used as a model for economic development. In 1984, 14 coastal 'gateway cities' were opened to foreign investment. In contrast to SEZ cities, these municipalities were chosen due to their relatively higher economic base and existing transportation infrastructure. Thereafter, economic technology development zones (ETDZ) were established in many open cities, enabling provincial governments to develop better infrastructure for foreign investors. By 1985, China began opening large areas as Coastal Open Economic Zones, eventually extending these areas to all coastal provinces (Cho & Tung, 1998).

In addition to the use of development zones, two early policies in particular had major impacts on the creation of new urban space, and the reorganization/restructuring of existing cities and towns (Ma, 2004). First, a variety of housing options became available as housing reforms enacted in 1982 allowed housing to be commodified and new housing built with foreign and domestic capital. Second, urban land use values were introduced in 1987, leading to the emergence of an urban land use market. As a result, urban land use rights can be obtained from the government, and the importance of real estate location has led to land rent gradients similar to those in Western cities (Ma, 2004). In recent years, the transfer of land use rights has been a source of capital formation for many local governments (Lin, 2007). Land sales and the leasing of land use rights often form 30 to 70% of municipal budgets. These budgets, in turn, have been used to finance urban development projects, including new development zones. The result is an even greater increase in urban land development than in previous periods, although there is increasing evidence that some areas are effectively empty due to lack of demand (Evans-Pritchard, 2012; Larmer, 2012). The ability of officials to make money off rural-to-urban land conversion is now a leading factor fostering land conversion in China (Lichtenberg & Ding, 2009).

By the 1990s, China's leaders began to expand economic development to western regions in an effort to reach 'balanced' growth across coastal and inland areas (Long, Liu, Wu, & Dong, 2009; Yeung & Jianfa, 2004). Following the goals outlined in the Ninth Five-Year Plan (1996–2000), western cities began to experience industrialization, urbanization and urban growth. This growth was spurred by the establishment of ETDZs as well as High-Technology Industrial Development Zones (HTDZ) in provincial capitals, beginning as early as 1991 in Chengdu (Lai, 2002). These areas provided cheap land, tax exemptions and reductions, and new firms in these areas played a crucial role in rapid GDP growth during the 2000–2009 period (Ding, 2007). Given the success of national development zones, local governments began setting up their own development zones by seizing land from farmers to create large areas with paved roads, utilities, landscaping, and even commercial building space (Wong & Tang, 2005).

More recently, policies favoring economic development, the real estate market and 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 Chinese Western Development program adopted in 1999 led to further investment in construction, as well as policies aimed at environmental protection (Fan & Sun, 2008; Lai, 2002). In particular, the Grain for Green program was implemented in 2003 to return grazing land to natural vegetation, resulting in land protection that significantly impacted the rate and form of urban development in Western China (Lai, 2002; Tan, Li, Xie, & Lu, 2005).

2.4. Impacts on urban expansion and morphology

Overall, expansion in cities and towns has been described as both top-down, where policies from the central government have led to rapid urban development, as well as bottom-up, whereby the expansion of local economies has resulted in rapid, unplanned development near cities (Ma & Fan, 1994). While the exact influence of the factors described above (transition to a market-driven economy, institutional changes, decentralization, globalization, socio-demographic changes) continues to be debated (Heikkila, 2007; Wei, 2012), the outcomes have been documented for China's coastal cities. The changes include not only rapid rates of land conversion, but significant changes in the structure and form of cities, including the emergence of polycentricity and district specialization. These can be summarized as follows:

(1) Urban expansion has occurred at unprecedented rates: With the increasing availability of satellite data, there has been an explosion of work (>150 publications) during the last decade mapping China's cities and settlements. The majority have been dedicated to mapping three regions: (a) Beijing and the Bohai Rim (An, Zhang, & Xiao, 2007; Tan et al., 2005; Wu et al., 2006; Zhang, Wang, Peng, Gong, & Shi, 2002), (b) Shanghai and the Yangtze River Delta (Liao, Jiang, Lin, Huang, & Gong, 2008; Yue, Liu, & Fan, 2010; Zha, Gao, & Ni, 2003; Zhang, 2001), and (c) Guangzhou, Shenzhen and the Pearl River Delta (Fan, Weng, & Wang, 2007; Seto, Fragkias, Guneralp, & Reilly, 2011; Weng, 2001). These studies typically investigate one metropolitan area at a time, with limited comparative analysis. Because each study defines the urban extent differently (e.g. core, municipality, watershed), it is impossible to compare trends across space and time.

A more comprehensive view of urban expansion comes from Wang, Li, et al. (2012), who documented growth in 147 of China's largest cities for two periods, 1990–2000 and 2000–2010. With the exception of Shanghai, Beijing and Guangzhou, the results include only a limited area for each city; any satellite cities or peri-urban growth that may function as part of the metropolitan area were not assessed. Their results show that urban expansion 1990–2010 occurred at an average annual rate of 6.0%, with rates of 4.0% for Beijing, 5.6% for the greater Shanghai region, and 9.0% for the Pearl River Delta region. More than 1092.1 km^2 of land was developed in Shanghai, 1310.4 km^2 in Beijing, and 523.9 km^2 in the Pearl River Delta during the study period. These figures are phenomenal when compared with global averages of less than 2% expansion for mid- to large-sized cities annually (Angel et al., 2005; Schneider & Woodcock, 2008), and a circa 2000 mean city size of 560 km^2 (Schneider & Woodcock, 2008).

In addition, Wang, Xu, & Zhu (2012) show that the four SEZ cities have significantly higher growth rates than other cities, with average annual rates of change from 5.1 to 12.9%. Xiamen and Shenzhen, in particular, have consumed large amounts of land for urban uses, now covering 278.8 and 692.5 km^2, respectively. Several eastern cities also appear to have received significant effects from the open coastal zone policy: rates of growth average 8–12% per year in Hangzhou and Suzhou (near Shanghai), as well as in Dongguan and Foshan (in the Pearl River Delta).

(2) Development of polycentric or multi-nucleated urban form: The focus on regional expansion by authorities, the movement of industry to small towns, as well as policies that favored migration to small towns have led to massive growth in small cities proximate to major cities. This trend has been described not only as polycentric urban development, but also "population and employment decentralization" (Lin, 1999; Zhu, Zhang, & Chen, 2002), "suburbanization" (Zhou & Ma, 2000), "edge city development" (Wu & Phelps, 2011), "dispersed city form" (Sun, Wu, Lv, Yao, & Wei, 2013), and "urban cluster formation" (Fragkias & Seto, 2009). The defining feature across these studies is the rising importance of sub-centers outside the CBD, either within or outside the contiguous urban core.

Yao and Liu (1995) were among the first to note the emergence of polycentric urban form in China, with analysis of the port cities of Hangzhou, Fuzhou, Quanzhou, Xiamen, and Zhangzhou. This trend has also been documented in Guangzhou (Wu, 1998; Gaubatz, 1999), Panyu (Lin, 1999), Nanjing (Qian & Wong, 2012; Zhu et al., 2002), Beijing (Feng, Wang, & Zhou, 2009), Hangzhou (Yue et al., 2010), and more recently, in cities originally targeted for 'concentrated' growth, such as Shanghai (Lehmann, 2013). Most studies investigate this trend using population or employment data, since polycentricity is often tied to the subcentering of inhabitants and/or job activity. Statistical analyses based on population density functions are typically used to indicate the relative importance of various centers, and the factors responsible for subcenter formation (Feng et al., 2009; Wu, 1998; Zhu et al., 2002). In a few cases, satellite imagery has been used alone or to complement socioeconomic data (Wu, 1998; Yue et al., 2010). Studies based on remote sensing can show *morphological polycentricity* (the shape of the city as having multiple clusters), but remain limited for illustrating *functional polycentricity* (the function of the new subcenters, pulling economic activity from the core, Burger & Meijers, 2012).

While development has focused on small cities, many metropolitan areas have begun to reassert their position in the rapidly globalizing Chinese economy (Lin, 2007). Because Chinese city centers have continued to expand coincident with small city growth outside the core, much of what the literature describes as polycentric development in Chinese cities may in fact be multi-nucleated spatial structure (subcenters have a share of higher-order functions traditionally found in the CBD, Fujii & Hartshorn, 1995). In contrast, definitions of polycentricity from the U.S., Europe, and Japan describe regions comprised of multiple cities, each of which functions independently, but is linked in various ways to its neighbors (Kloosterman & Musterd, 2001). The early literature on Chinese cities suggests that these areas are transitioning toward polycentricity, but may not have achieved "fully functional" polycentricity that rivals their European or American counterparts (Yue et al., 2010).

(3) Land use specialization: Another aspect of Chinese cities – spatial differentiation of built-up areas by land use type – has been documented as a prominent feature of post-reform urban development (see Madrazo & van Kempen, 2012, for a review). This trend is often studied in conjunction with economic restructuring, since the shift toward industrial or service-sector activities often parallels the spatial shift in land use (Walcott & Pannell, 2006). Many factors are cited in the differentiation of urban space, including the role of FDI and different types of FDI, globalization, master planning focused on formation of development zones, and the influx of migrants requiring new housing (Lin, 2001; Wei & Li, 2002; Wei, Leung, & Luoa, 2006; Wu & Yeh, 1997; Wu, 2002; Yeh & Wu, 1995).

To illustrate land use specialization in Chinese cities, studies have assessed population density, labor, GDP, and other economic data by sector. Those that map specialized districts or zones rely on planning documents and simple diagrams (Gaubatz, 1999; Yao & Liu, 1995), with just a few case studies using detailed surveys and spatially-disaggregated mapping of specific land use types (Wei & Li, 2002; Yue et al., 2010). Empirical work has focused Beijing, Shanghai, Guangzhou, Shenzhen, and Nanjing; to date, there has been no study of land use specialization in small cities, nor those located in central or western regions. Together, the literature has established the following land use types:

- *Industrial areas.* To reduce pollution and provide space for tertiary activities, factories have been moved to large industrial estates on the city periphery (Gaubatz, 1999; Zhou & Ma, 2000).
- *Economic zones.* Much of the articulation of land use is the result of top-down planning to attract FDI by creating zones that provide tax breaks and other incentives to foreign investors (Cho & Tung, 1998; Walcott, 2002). These areas typically have a designation for specific economic activities, such as light industry, high-tech industry, financial centers, export-oriented activities, etc. (Wei et al., 2006).
- *New CBDs.* Again the result of master planning to promote tertiary activities, many cities have defined new subcenters for service sector activities (Gaubatz, 1999).
- *Residential areas.* Driven by the commodification of housing, residential areas have moved outside the urban core, where environmental conditions are better and where land acquisition has been easier and cheaper (Li & Siu, 2001; Yeh & Wu, 1995). Sometimes described as 'suburbs', these areas are often composed of high-rise apartment buildings, leading to high population densities (Lin, 2001). In addition, some cities have witnessed the rise of "housing estates", gated communities of single-family homes located at the urban fringe (Ma, 2004).
- *Green space.* A new focus on quality of life and environmental sustainability has led many cities to establish areas for parks, recreation, ecotourism, or environmental protection (He et al., 2011).

(4) Fragmentation of the urban fabric: Broadly defined, fragmentation refers to the relative share of open space in the urban landscape (Angel, Parent, &, Civco, 2012), such that an increase in fragmentation indicates a decrease in the density of built-up land with respect to open (often vegetated) space. The unit of analysis is often the *patch*, defined as a spatial entity composed of the same land use type at a specific scale (O'Neill et al., 1988). Analysis often

involves estimating the size, shape, and frequency of urban patches using spatial pattern metrics developed within landscape ecology (McGarigal & Marks, 1995). Landscape metrics are typically combined with buffering or urban–rural gradient analysis to provide the location of patches relative to the core (Zhang, Wu, Zhen, & Shu, 2004).

Studies on fragmentation in Chinese cities fall into one of three categories: (a) those that focus on macro-level changes in city shape and configuration to quantify cities as compact or sprawling (Ji, Ma, Twibell, & Underhill, 2006; Lv, Dai, & Sun, 2012; Yue, Liu, & Fan, 2013); (b) those that look at micro-level changes in built-up land within the city or at the city edge (Liu et al., 2010; Su, Jiang, Zhang, & Zhang, 2011; Yang et al., 2012; Zhang, Ban, Liu, & Hu, 2011); and (c) those that monitor environmental impacts (Long et al., 2009; Wang, Wu, & Wang, 2009). For (a), there are mixed results as to whether Chinese cities are witnessing urban sprawl; this may be an artifact of the wide variability in the metrics used to assess urban form (>100 metrics are available, McGarigal & Marks, 1995). Those studies that assess localized spatial patterns in Chinese cities (category b) rely on density metrics (e.g. patch density, mean patch size, etc.), measures of heterogeneity (e.g. density/mixture of land cover types), and shape (e.g. landscape shape index, etc.). Here, there is growing consensus that Chinese urban development often exhibits a patchy, or low density, form, followed by infilling over time (Liu et al., 2010; Su et al., 2011; Yang et al., 2012; Zhang et al., 2011).

While the use of landscape metrics to understand urban fragmentation may be growing, there are several issues that limit the conclusions drawn from these studies. First, these investigations typically treat urban expansion as a purely physical phenomena, and limited connections are drawn to urban geography and urban economics (e.g. agglomeration economies, economic restructuring, etc.). Second, the majority of metrics are meaningful in landscape ecology (e.g. measurement of forest patch perimeter to determine its impact on edge-sensitive species), but less so for studies that attempt to measure urban space (e.g. measurement of urban patch edge is difficult to connect to intra-urban processes; Chang, 2013). In addition, many metrics produce inconsistent results across changes in scale and extent (Cushman, McGarigal, & Neel, 2008; Gustafson, 1998; Li & Wu, 2004), but these problems are typically not addressed in urban applications.

3. Study areas

Each of the four study areas – Chengdu, Xi'an, Kunming, and Urumqi – has been a capital and principal city in Western China since the foundation of the People's Republic of China in 1949 (Fig. 1). These regions were selected because of clear commonalities, but also because of important differences in history, economics, demographics, and policies that have influenced their development trajectories.

Chengdu was established >2500 years ago, following development of irrigation systems northwest of the city. The combination of alluvial soils and subtropical monsoon climate makes the area the most fertile in southwest China and ideal to support a large variety of crops. In the 1950s and '60s, many heavy and military industries were moved to rural areas near Chengdu for strategic and defense reasons. Subsequently, many industries were moved to Chengdu's peri-urban area in the 1970s (Webster, 2002). With the lowering of strategic threats, modification of the military-industrial complex to civilian production, and expansion of the service economy, Chengdu has emerged as one of the most important industrial, service, knowledge, and distribution centers in Western China. Chengdu was one of the first western cities designated for 'open' status, also receiving the first national-level high-tech zone in 1991.

Located in a rich agricultural region, Xi'an has a similarly long history, dating back >3100 years. Xi'an held an important historic and strategic role as the eastern terminus of the Silk Road, and served as China's capital for >1000 years. Although the region has large seasonal fluctuations (cold winters and hot, humid summers), the fertile lands surrounding the city support maize, wheat, and vegetables. Xi'an also served as a key location for the military-industrial complex; Jiaotong University, a major engineering university, moved from Shanghai to Xi'an in 1956 to support military enterprises. The city's proximity to abundant coal and natural gas reserves solidified its importance during the Maoist era, and later, the city became a leader in heavy chemical industry (Yeung & Jianfa, 2004). Currently, Xi'an has become a major transportation, telecommunication, information, and finance center, and was recently designated as one of three regions to link development within Western China (Walcott, 2003).

Kunming's settlement can be traced back >2300 years, although the city was officially established in 765 as a nexus of caravan routes linking China to Southeast Asia. Kunming has been resource-poor due to its location in the rugged Yungui Plateau, which has made agriculture and transport of people and goods difficult. The city's subtropical highland climate supports some crops, but the city is surrounded primarily by forest and mountains that limit farming and development. The city first grew in prominence prior to WWII, when the Eastern China population evacuated to the Southwest, along with coastal industries and several universities, due to the Japanese invasion. The city has been relatively slow to expand until the 1990s, when most roads, bridges and buildings were constructed for the 1999 World Horticultural Expo (Feiner, Salmeron, Joos, & Schmid, 2002). The Expo effectively opened Kunming to outside trade and influence, and the city has become dominant in biochemistry, mining, and energy production during the last decade (Chunkai & Zhilong, 2004). In addition, the city has benefitted from its designation as an ecotourist location within China (Owen, 2005).

Urumqi was established >1300 years ago in a narrow alluvial plain in the arid Xinjiang region. Urumqi also served as an important stop along the Silk Road, but remained a small dynastic outpost until the Chinese government established a permanent military presence in 1755. With the collapse of the Soviet Union in 1991, the central government saw an opportunity to strengthen its status in the region, and gain access to key energy resources and raw materials. The government launched an ambitious policy in the 1990s to open the region to the world, and poured investment into infrastructure and capital construction throughout the province (Becquelin, 2000). Since then, Urumqi has become a leader in coal, oil and petroleum production, and a key player in the steel industry. The region has also been the focus of the central government's campaign to expand agriculture, with emphasis on irrigation projects and increased mechanization to grow cotton (Fricke, Sterr, Bubenzer, & Eitel, 2009). Concurrent with these economic changes, Urumqi has served as the receiving end of a planned, westward migration (Howell, 2011).

4. Datasets and definitions

4.1. Maps of urban expansion from remote sensing data

The land cover change maps for each study area were obtained through historical analysis of 30 m resolution Landsat TM and ETM+ data for five time periods (1988–1995, 1996–2000, 2001–2003, 2004–2006, 2007–2009). Because we assess urban expansion using satellite data, we define urban land as places dominated by the built environment. The 'built environment' includes all non-vegetative, human-constructed elements, such as roads, buildings, etc., and

'dominated' implies coverage greater than 50% of a given landscape unit (i.e. a pixel). Although vegetation such as parks may be contained within a city, these areas are not considered urban, although they may function as urban space. Expansion of urban areas refers to wholesale conversion of land within a landscape unit.

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 lead to different 'mixtures' within pixels (Small & 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 (Long et al., 2009; Webster, 2002). 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 dense time stacks approach providing all cloud-free Landsat data as input (see Schneider, 2012). Multiple on-site 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 in all study areas except Urumqi. Field visits to Urumqi confirmed that two transitions occurred 1988–2009: cropland converted to urban uses, as well as shrubland converted to urban uses.

The final maps were assessed for accuracy using a stratified-random sample of test sites collected for each study area (here, a test site is one Landsat pixel). The test sites were labeled using a double-blind assessment procedure with multiple image sources (including Google Earth very high resolution data) and information from on-site visits (Schneider, 2012; Schneider & Mertes, 2014). The overall accuracies of the maps averaged 90–94%, confirming their suitability for this analysis.

4.2. Socioeconomic data and administrative boundaries

While municipal-level data (NBS, multiple years) contain the most complete set of variables, municipal boundaries vary widely in defining each city's extent. District-level data, on the other hand, are not available prior to 2000 and the statistical variables vary significantly by city. Instead, we turn to the county-level data that make up each municipality (Chengdu Municipal Government, 2011; Chengdu Planning and Management Bureau, 2011; Kunming Municipal Government, 2011; Kunming Planning Bureau, 2011; Urumqi City Government, 2011; Xi'an City Planning Bureau, 2011; Xi'an Municipal Government, 2011). The county is an important administrative level in China; there is evidence that fiscal and administrative decision making are both conducted at the county level (Cheung, 2008; Deuskar, Schneider, & Dastur, 2014), and while municipal boundaries vary through time, county boundaries are considered more stable. As described below, the counties corresponding to the built-up extent and its surrounding nuclei were selected, and population data were collected to match each time point in the satellite maps.

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 by local officials (Fan, 1999; 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. This 'floating population' has been estimated as high as 10% of the total population (Goodkind & West, 2002; Webster et al., 2002). Chinese statistical agencies changed their survey methods in 2000 to include some of these persons in urban population data (Zhou & Ma, 2005; Chan, 2007). These issues make the urban and rural population data unreliable, so we rely on total population at the county level. Although difficult to estimate exact population or economic figures, the census data do provide "reasonable overall figures" (Hvistendahl, 2013).

To tie the socioeconomic data to the maps of urban expansion, county-level administrative boundary data were acquired in GIS format (CIESIN, 1996) for the baseline year, 1988. In a few areas, boundaries were redrawn between 1988 and 2009 to create new counties (e.g. Urumqi); data for these counties were aggregated to the baseline county. For counties that merged (e.g. Chengdu's core), disaggregated township- or district-level data corresponding to the merged county were collected for later periods to create a final dataset consistent with the baseline county boundaries.

4.3. Defining the core and extended urban region for each study area

To define the space of each city within the study area extent (i.e. the Landsat footprint for that city), we used four separate measures based on urban land and administrative data:

(1) **40 km standardized extent.** We first normalized the study extent using a 40 km radius around the original CBD, since this value has been to adequately define the reach of a city's jurisdiction and economic function, including peri-urban growth (Dietzel, Herold, Hemphill, & Clarke, 2005; Haase, Walz, Neubert, & Rosenberg, 2007; Ji et al., 2006; Schneider & Woodcock, 2008; Seto & Fragkias, 2005; Wang & Meng, 1999). The location of each CBD was determined from multiple map sources, city documents, and expert knowledge.
(2) **40 km focus counties.** To link land trends with socioeconomic data, we selected the counties whose majority land area fell within the 40 km buffer. For Kunming, Chengdu, and Urumqi, the selected counties correspond to the municipal boundary (±1–2 counties), while in Xi'an, the selected counties comprise the municipality and five neighboring counties (Fig. 2).
(3) **Core county.** The urban core continues to play an important administrative and functional role in city management. Thus, we delineated the core urban county by selecting the county that contains the original CBD (Fig. 2).
(4) **Digitized urban core.** Since the area of the core county differs significantly across cities (434–2264 km^2), we digitized the approximate outer edge of the core built-up area at each time point. We then used this to estimate the amount of urban land within the raster map for each time point (Fig. 4).

4.4. Defining satellite cities, zones, and corridors from urban planning maps

In addition to assessing the urban core, we investigate trends in (a) satellite cities, and (b) key development corridors and economic zones (Fig. 3). To define satellite cities (or nuclei), 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 by a major transportation network; and (3) the 2009 built-up area had to rank in the top 1% of all urban patches in the study area extent (i.e. the Landsat scene footprint). With this definition, 24 satellite cities were designated for Chengdu, 18 for Xi'an, 18 for Kunming, and 16 for Urumqi. Once the nuclei locations were established, we traced the outer edge at each time point, and estimated the amount of built-up land within those boundaries.

To locate development corridors and industrial zones, we acquired multiple planning maps and documents for each study area (Fig. 3). The master plans revealed that anywhere from four to eight development corridors were established for each city, each with a designated land use and function. For comparison, we selected corridors corresponding to one high-tech zone,

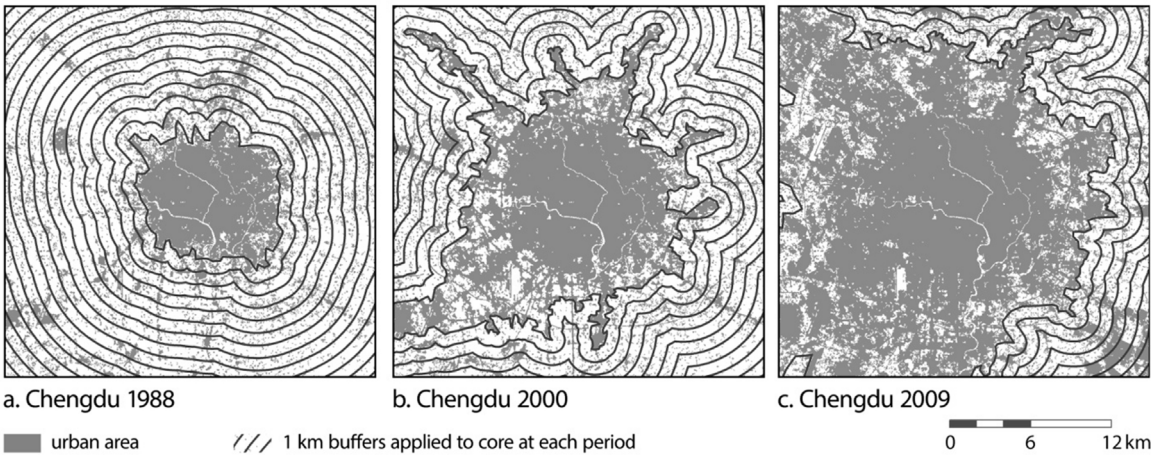

Fig. 4. Illustration of the digitized urban core for Chengdu, as well as the buffer procedure used to assess the location of new urban land relative to the core. The core was digitized for each time point (1988, 1995, 2000, 2003, 2006, 2009), and one kilometer buffers were applied accordingly in each case study city.

one industrial zone, and two residential areas in each city. The corridors were delineated by digitizing the major roadway extending from the CBD, and buffering this by 2 km.

5. Analysis

5.1. Rapid expansion of built-up lands far from the city core

The first hypothesis highlights two separate, yet related, trends: the rate of urban transformation in each study area, as well as the location of new urban land relative to the city core. These trends were explored using four measures (Section 4.3), in conjunction with population data for the core and areas outside the core. Across the 40 km standardized area, the amounts of change are staggering (Fig. 5, Table 2). Chengdu, Xi'an and Kunming have each more than doubled in size: Chengdu now occupies 1237.7 km^2 of land, Xi'an 1016.7 km^2 of land, and Kunming 532.1 km^2 of land. Urumqi has also nearly doubled in size, jumping from 278.1 to 457.0 km^2 over the study period. The average annual rates of change (Table 3) are indicative of such rapid growth: Chengdu averages 3.7%, Xi'an 2.0%, Kunming 4.0%, and Urumqi 2.5% over the 21-year period. Although not as high as rates in the East (coastal cities average >4.0% for the same period, Wang, Li, et al., 2012), they are indeed high when compared to cities across the globe, which average <2.0% change annually (Angel et al., 2005; Schneider & Woodcock, 2008). The population shows a similar increase, 1988–2009 (Table 2): each city added 2–3 million inhabitants across the 40 km counties, increasing population densities in all study regions.

Looking more closely at the rates of change (Fig. 5), urban expansion, in particular, has been more rapid since 2000. All four cities climbed to >3% expansion after 2000. While none of the cities developed prior to reforms, this jump in the 2000s suggests that Western cities have witnessed growth related directly to policy changes and planning. In addition, all cities jumped to average annual rates of 5–7% expansion during the 2006–2009 period. The consistency of this trend across study areas suggests that recent policies aimed to develop China's West have been effective in establishing new buildings and infrastructure during this most recent period. These results may be the lagged effect of earlier policy changes, or may, in fact, suggest a new wave of growth tied to planning initiatives implemented after 2005. In comparison, population growth has been steady across the two time periods (Table 2).

While the 40 km standardized extent provides a useful way to compare cities, these results mask trends within the core. In Chengdu, for example, nearly 500 km^2 of urban land was developed outside of the core county; this constitutes >74% of the total new urban land developed during the 1988–2009 period (Table 3). The results for Xi'an and Urumqi are similar, with 54 and 66% of new urban land developed outside the core county, respectively. In Kunming, the core county is twice the size of the other study areas, and as a result, growth is 39% of the total urban expansion in this study area. Unfortunately, the administrative core county trend lines level off, likely because the core county has consumed all available land, although the contiguous urban land in the core is still expanding. Therefore, the digitized core results help determine how the contiguous urban fabric has developed through time. The amount of urban land added outside the digitized core ranges from 51.8 km^2 in Urumqi, to 184.2 km^2 in Chengdu. These amounts are, in fact, larger than each city's urban core at the start of the study period (53.2–146.0 km^2). In other words, if the growth of small cities outside the core is summed, the total is equivalent to adding another medium-sized city to the landscape in each region.

The growth outside the core parallels an important population shift in each study region (Fig. 6). The population density increased 500–800 persons/km^2 in each core county, 1988–2000, and in Chengdu and Xi'an, the population density increased in counties proximate to the core as well. During the 2000–2009 period, increases in population density are again apparent in each core, at even greater amounts (800–1900 persons/km^2). In this period, each study area also experienced an increase in population density outside the core, adding 50–200 persons/km^2 in core-adjacent counties. These changes represent two distinct, ongoing trends in the West: (1) the emergence of each urban core as a dominant economic and political player in the Western region, as well as (2) dispersion of the city outward, led in part by land development for planned residential and commercial areas and policies that favored rural–urban migration to small cities. Xi'an provides a striking example of these concurrent trends. Population densities in rural areas have been relatively high to support agricultural activities over the past century. As migration restrictions have been lifted, the counties in the Xi'an study area that contain small or mid-sized cities have each increased in population density, while rural counties without an established city/town have witnessed population declines. The effect of this trend is visible in the 1988–2000 period, when nearly all counties exhibit an increase in population density. For 2000–2009, the pull of Xi'an and nearby Xianyang results in rising population density primarily in the core and two counties adjacent to the core, while the remaining counties level off.

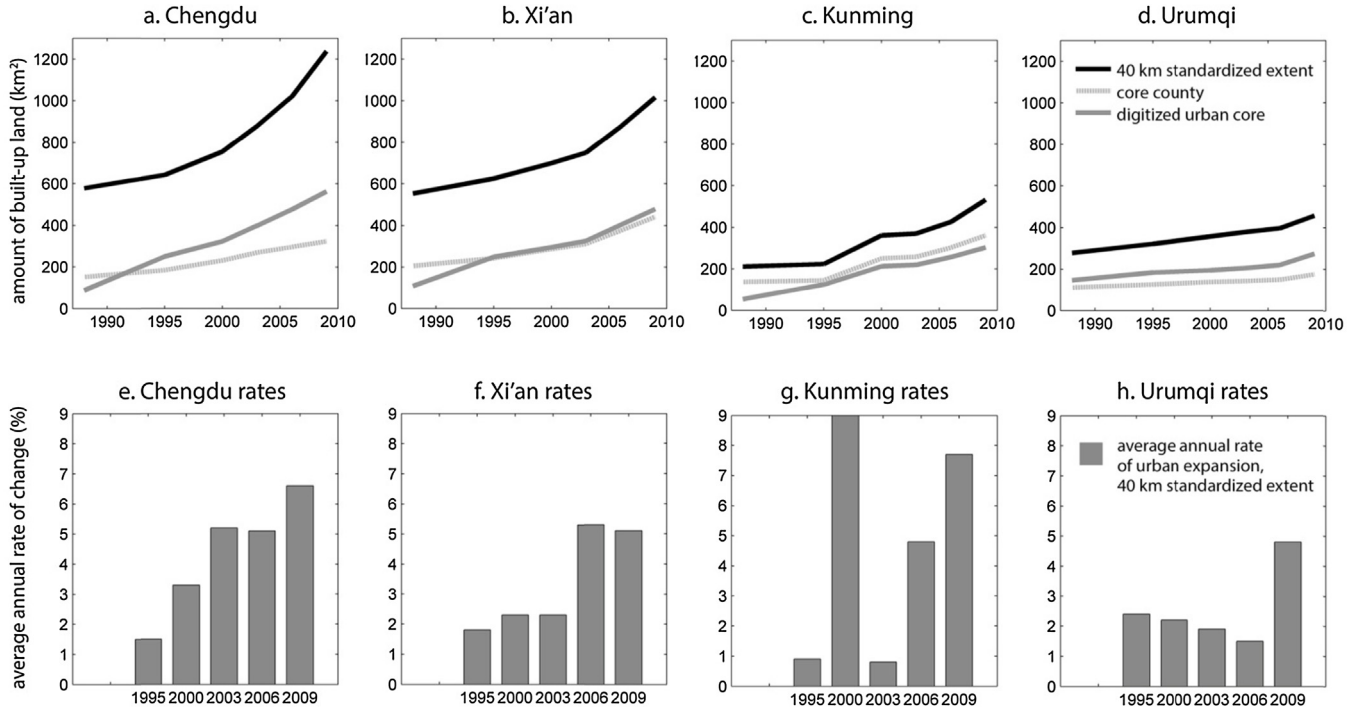

Fig. 5. Amounts of urban land (top row) for each of the study area within the 40 km standardized extent, the core county, and the digitized urban core. The average annual rates of change (bottom row) are shown for urban expansion within the 40 km standardized extent. Note that the years along the bottom row refer to the end date of each period (1988–1995, 1995–2000, 2000–2003, 2003–2006, 2006–2009). A lack of cloud-free Landsat data for Urumqi in 1995 required estimation of land cover rates and amounts for this time point using linear interpolation of the 1990 and 2000 maps.

To compare changes in population to land use trends directly, we also estimated the ratio of the increase in urban land (m^2) to the change in population, 1988–2009 (Fig. 6). As a point of reference, this ratio averages 261 m^2 of urban land developed per person added (261:1) across all study areas. While each core county has a ratio below this average (32–147 m^2 per person added), Fig. 6 shows that nearly all counties outside the core have incredibly high land-to-population ratios (on average, 500:1 in Chengdu and Kunming, and 300:1 in Xi'an and Urumqi). The counties with the highest ratios are again those adjacent to the core.

Table 2
Growth in built-up land and population, 1988–2009, for all four study areas.

	Chengdu				Xi'an				Kunming				Urumqi			
	1988	2000	2009	Admin	1988	2000	2009	Admin	1988	2000	2009	Admin	1988	2000	2009	Admin
1. Amounts of built-up land (km^2)[a]																
40 km focus counties – total[b]	570.5	751.0	1.242.0	7.693	745.3	911.1	1.258.0	10,533	288.2	461.1	653.4	10.362	282.3	369.7	471.6	21.479
Core county	151.5	232.5	323.9	434	205.8	286.5	441.4	858	137.6	251.2	360.7	2.264	111.8	138.9	175.3	945
Counties outside core	419.1	518.5	918.1	7.258	539.5	624.6	816.6	9.676	150.7	209.8	292.7	8.098	170.5	230.8	296.3	20.534
40 km standardized extent – total[c]	577.7	755.2	1237.7	5027	553.2	699.2	1016.7	5027	211.3	361.3	532.1	5027	278.1	357.7	457.0	5027
Digitized urban core	87.2	324.0	563.0		108.7	295.0	478.0		53.2	220.0	303.0		146.9	195.0	274.0	
Outside digitized core	490.5	431.2	674.7		444.5	404.2	538.7		158.2	141.3	229.1		131.1	162.7	183.0	
2. Population (millions)[d]																
40 km focus counties – total[b]	7.14	8.02	9.35		7.44	10.82	10.47		2.99	3.49	4.95		1.63	2.14	3.23	
Core county	2.00	2.34	3.17		2.45	3.02	4.49		1.48	1.81	3.08		1.07	1.55	2.32	
Counties outside core	5.14	5.67	6.17		4.98	7.80	5.98		1.51	1.68	1.87		0.56	0.59	0.91	
3. Population density ($persons/km^2$)[d]																
40 km focus counties[b]																
Core county	4606	5398	7302		2858	3524	5234		655	800	1360		1129	1641	2454	
Counties outside core	709	782	851		515	806	633		186	208	230		27	29	33	

	1988–2000	2000–2009	1988–2000	2000–2009	1988–2000	2000–2009	1988–2000	2000–2009
4. Ratio of increase in urban land (m^2) to change in population								
40 km focus counties[b]								
Core county	236:1	111:1	141:1	106:1	345:1	86:1	56:1	47:1
Counties outside core	187:1	799:1	30:1	−106:1	338:1	450:1	1910:1	208:1

Abbreviations: Admin refers to the area within either the administrative boundary or the 40 km standardized extent.

[a] Amounts of built-up land are estimated from Landsat-based maps of land cover change (Schneider, 2012). Pixels containing >50% constructed surfaces are considered urban.

[b] The 40 km focus counties are those whose majority land area falls within the 40 km radius of the CBD. For Chengdu, Kunming and Urumqi, these counties correspond roughly to the municipality. For Xi'an, these counties comprise the municipality plus five nearby counties.

[c] The 40 km standardized extent is the area within a 40 km buffer of the central business district of each city.

[d] All population data were collected at the county level for the core, and areas outside the core (Sichuan, Shaanxi, Yunnan, and Xinjiang Bureau of Statistics, multiple years).

Table 3
Rates of growth and distribution of built-up land for all four study areas.

	Chengdu				Xi'an			
	Difference 1988–2009 (km^2)	Average annual rate of change 1988–2009 (%)	Distribution of total urban land 2009 (%)	Distribution of new urban land 1988–2009 (%)	Difference 1988–2009 (km^2)	Average annual rate of change 1988–2009 (%)	Distribution of total urban land 2009 (%)	Distribution of new urban land 1988–2009 (%)
Distribution of built-up land[a]								
40 km focus counties – total[b]	671.5	3.8	100.0	100.0	512.7	1.7	100.0	100.0
Core county	172.5	3.7	26.1	25.7	235.6	2.8	35.1	46.0
Counties outside core	499.0	3.8	73.9	74.3	277.1	1.2	64.9	54.0
40 km standardized extent – total[c]	660.1	3.7	100.0	100.0	463.5	2.0	100.0	100.0
Digitized urban core	475.8	9.3	45.5	72.1	369.3	7.3	47.0	79.7
Outside digitized core	184.2	1.5	54.5	27.9	94.2	0.9	53.0	20.3
	Kunming				**Urumqi**			
	Difference 1988–2009 (km^2)	Average annual rate of change 1988–2009 (%)	Distribution of total urban land 2009 (%)	Distribution of new urban land 1988–2009 (%)	Difference 1988–2009 (km^2)	Average annual rate of change 1988–2009 (%)	Distribution of total urban land 2009 (%)	Distribution of new urban land 1988–2009 (%)
Distribution of built-up land[a]								
40 km focus counties – total[b]	365.2	4.2	100.0	100.0	189.3	2.5	100.0	100.0
Core county	223.2	5.6	55.2	61.1	63.5	2.0	37.2	33.6
Counties outside core	142.0	3.1	44.8	38.9	125.8	2.8	62.8	66.4
40 km standardized extent – total[c]	320.8	4.7	100.0	100.0	178.9	2.5	100.0	100.0
Digitized urban core	249.8	9.1	56.9	77.9	127.1	3.2	60.0	71.0
Outside digitized core	71.0	1.9	43.1	22.1	51.8	1.7	40.0	29.0

[a] Amounts of built-up land are estimated from Landsat-based maps of land cover change (Schneider, 2012). Pixels containing at least 50% constructed surfaces are considered urban.

[b] The 40 km focus counties are those whose majority land area falls within the 40 km radius of the CBD. For Chengdu, Kunming and Urumqi, these counties correspond roughly to the municipality. For Xi'an, these counties comprise the municipality plus five nearby counties.

[c] The 40 km standardized extent is the area within a 40 km buffer of the central business district of each city.

Fig. 6. Maps showing the change in population density, 1988–2000 (left); the change in population density, 2000–2009 (middle); and the ratio of new urban land (m^2) to population increase (right). In the latter, the maps of urban land are shown for reference.

Finally, the detailed land cover data allows us to pinpoint development with greater spatial precision than the county-level maps provide. The approach we use is similar to urban–rural transect analysis (Luck & Wu, 2002), but modified so that transects in all directions are considered. We applied a series of 1-km buffers to the digitized core, and estimated the amount of new urban land – normalized by the amount of available developable land in the buffer – within each consecutive buffer. The core urban area was updated for each time period, and the buffers re-estimated accordingly (Fig. 4).

In Fig. 7, a steep slope for a given period indicates that all new urban land was developed close to the original city core, while flattening of the slope with distance indicates that development occurred farther from the city edge (specifically, the core city edge as defined in that period). The results show that in early periods (1988–1995, 1995–2000), nearly all new urban land occurred within 4–5 km of the core in Chengdu and Xi'an, and within 2–3 km of the core in Kunming and Urumqi (Fig. 6). In later periods, the trend lines are flatter, revealing that consecutive buffers all had a large amount of development take place. Development typically occurred up to 20 km from the city core in nearly all cities. Urumqi is the exception, remaining more compact, with land expansion remaining close to the core. Given the lack of planned development zones outside Urumqi and few small towns nearby, growth does not appear to have been pulled outward as it was in the other study areas.

The same buffer analysis was applied to the satellite cities to determine if expansive growth was also apparent in small- and medium-sized cities in each region (Fig. 7). The pooled results reveal 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 these regions. In Xi'an and Urumqi, the lines remain steep over time, suggesting that any growth in small cities occurred consistently within 2 km of the city's edge.

5.2. Transition from monocentric to multi-nucleated urban form

The results from Section 5.1 suggest that, over time, development has occurred farther from existing built-up spaces in China's western cities. Specifically, the digitized urban core of each city comprises just 45–60% of the total urban land in 2009 (Table 3). The question then arises: what is the location and form of the remaining urban land in each study region?

As suggested by the master plans of each city, efforts have focused on small town growth as a means to relieve city congestion and promote regional development. On average, >100 km^2 was developed outside each urban core, 1988–2009, an amount which constitutes 25–30% of all new development in each study area. Visual map assessment suggests that this new urban land is not piecemeal nor scattered, but rather, focused in small cities. The degree to which small cities have grown differs across the study areas, however.

To understand the level of nucleation, we extracted the size, growth rate and distance to the core for each satellite city from the land cover maps. The results reveal three trends (Fig. 8). First, the level of nucleation in 2009 varies across cities: Chengdu is the most nucleated, with 17 nuclei that have expanded to >10 km^2 by 2009. Xi'an is similarly nucleated, with nine of 18 nuclei over 10 km^2 by 2009. In contrast, the rugged terrain in Kunming has constrained small city growth; there is simply not a large amount of developable land, and transportation between nuclei and the core has been limited. Urumqi is unique in that it is far less nucleated than the others. This area has 16 small towns within 40 km of the center, but the majority have remained smaller than 5 km^2. The lack of small town development is, in part, a result of the planning process – all subcenters and development zones were planned within Urumqi's core, rather than outside the city. Moreover, Urumqi's development trajectory differs from the other cities in that economic growth occurred earlier as a result of petroleum and resource extraction. While a desert landscape in U.S. cities often allows for large amounts of land development, in China expansive urban growth is limited by the availability of water and other resources, as well transportation options. In addition, nuclei growth near Chengdu and Xi'an was likely fueled by the large available labor force in nearby agricultural areas; the desert landscape outside Urumqi limited settlement for centuries, so no such labor pool existed.

The second trend apparent in Fig. 8 is that nuclei near the core have expanded more rapidly than those far from the core. This result is not surprising, since agglomeration effects are clearly going to be felt where the friction of distance is low. There are several outliers worth mentioning, however. In several instances, there are large nuclei with high rates of change located 20–30 km from the core. Most are well-established small or medium-sized cities, including Anning near Kunming, Xianyang near Xi'an, and Xindu near Chengdu (all had populations >250,000 in 1988). A few outliers are planned development areas that were built relatively quickly and have become quite large in area. The best examples are two planned nuclei outside Kunming, which include a new international airport zone 25 km to the northeast, and Chenggong, a planned residential and commercial area 25 km southeast of the city.

The final trend is that several towns outside each city have become completely enveloped by the contiguous urban fabric during the 21-year period. Each city's core area (Fig. 8, gray area) has expanded outward by 11–17 km, enveloping more than one quarter of all small cities. Once overtaken by the core, it becomes difficult to distinguish nuclei expansion, since growth becomes part of the infill process of the larger city. These areas remain important functional nodes, however, often serving as subcenters or new CBDs. In Chengdu, these nuclei have become important hubs for both secondary and tertiary activities. More than one-sixth of the 2009 GDP for the Chengdu urban core is attributable to Shuangliu, for example, a new CBD established near the international airport southwest of the city (Sichuan Bureau of Statistics, 2010).

Several studies have established the link between morphological and functional polycentricity (Burger & Meijers, 2012), so the results here may be an indicator of functional polycentricity, especially in Chengdu and Xi'an, where the development of nuclei is most pronounced. It is not possible to draw conclusions on nuclei function, however, without additional analysis of economic performance, employment trends, etc. Unfortunately, disaggregated data are not available or not available for multiple time points, difficult to acquire, or unreliable. The county sizes are also relatively large outside the urban core, such that multiple nuclei fall within one county, making it impossible to connect county-level data to specific nuclei. Despite these issues, we can ascertain the emerging functionality within zones and corridors by assessing land use types depicted in the master plans and documents for each city. This assessment is undertaken in Section 5.3.

5.3. Land use specialization in development zones and corridors

The third hypothesis focuses on two questions: Has land use specialization occurred within each city? If so, how has the spatial structure of different land uses evolved? During the post-reform period, the state has retained a heavy hand in urban structure by designating development zones (ETDZs, HTDZs, etc.) in Western provincial capitals and a few border towns, implementing a number of planning initiatives, and channeling state funds for road-building, infrastructure development, etc. (Lai, 2002; Yeung & Jianfa, 2004). While site-specific development has been at the

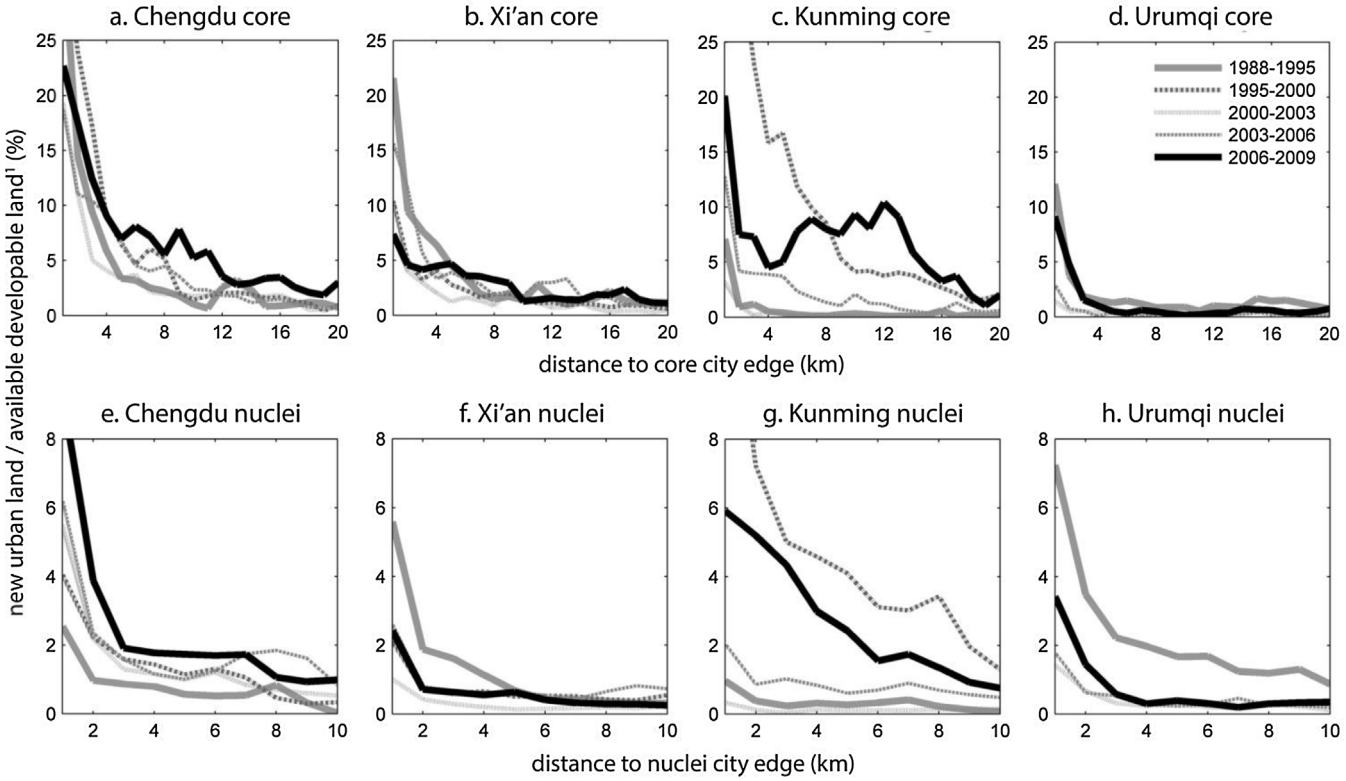

Fig. 7. Ratio of new urban land to the amount of developable land in 1 km rings/buffers extending from the core city (top row) and from the nuclei outside each core city (bottom row) for the four metropolitan areas. In this analysis, the core/nuclei extent varies for each period (see Fig. 5 for an example).

discretion of the city or county, the broader regional and municipal plans to develop zones and nuclei within each study area have left a marked imprint on land use. Thus, our assessment of land use specialization relies primarily on the many urban planning maps and documents available for each study area.

The planning documents (map examples are shown in Fig. 3) reveal four broad categories of land use. First, HTDZs, a large number of state- and provincial-level economic zones, and major economic zones associated with new international airports (e.g. Chengdu, Xi'an, Kunming) are denoted on each map. The majority if not all of the land in these zones (1–50 km^2) are used for industrial purposes. We confirmed the dominant activities and the date that the zones were established using a variety of sources (CADZ, 2013; websites of individual zones). Second, residential areas are usually specified, although their designation is not always clear on the planning maps. Therefore, residential zones – often comprised of new private housing, public housing, and commercial areas – were confirmed using secondary planning documents and information from colleagues in each city. Third, ecological areas are denoted, notably the green belts east and west of Kunming, and the green space south of Xi'an. Finally, commercial areas typically remain in the core; most commercial centers established decades ago have remained shopping and financial centers in the city. The planning maps do not reveal any detailed plans to create new commercial districts outside the core, except for the zones outside Kunming, and one commercial district northwest of Chengdu. Overall, these trends, combined with the corridors depicted in the planning maps, provide a general picture of how land use has become specialized in each city.

Land use specialization often occurs jointly with economic restructuring, so data on the spatial and temporal dynamics of economic activities can corroborate the trends above. Two major transitions have occurred in Chinese cities since reforms began in 1978. First, reforms, globalization, and ongoing migration into cities fostered increased industrialization, which in turn, has led to a decrease in agricultural output as a portion of gross regional product (GRP). Following initial reforms, many metropolitan areas have also undergone a second transition, whereby state and local officials have put emphasis on moving industry out of major coastal cities (either to the periphery, or to central and western provinces) so service sector activities could take hold/increase in the core. This trend has been documented in large cities in Eastern China, including Beijing, Shanghai, Hangzhou, Guangzhou, etc. (Gaubatz, 1999; Qi, Yang, & Jin, 2013; Zhou & Ma, 2000). To determine where Western Chinese cities fall on this trajectory of economic restructuring in the post-reform era, we look at changes in GRP, and changes in GRP by sector for the core county and the area outside the core county (summed across counties) for two time points: the year 2000, shortly after reforms were in place in all study areas, and 2010, the end of our study period (note that disaggregated data prior to 2000 were not available for all study areas).

In Table 4, the growth in GRP is impressive: in less than a decade, all four urban cores have grown to three to four times their 2000 GRP values. Kunming's core has grown nearly tenfold, although part of this growth may be attributable to the large size of its core county. Interestingly, counties outside of Chengdu and Xi'an have GRP values that mirror their cores. By 2009, 40–50% of the total GRP was accumulated outside the core in both regions. Kunming and Urumqi, in comparison, have only 23 and 13% of their total 2009 GRP outside their core counties, respectively. Given the small amounts of land development outside the urban core in Kunming and Urumqi, as well as the small GRP value and lack of GRP growth, the results suggest a link between economic growth and land consumption.

Turning to GRP by sector, it appears that all urban cores except Chengdu may be at an earlier stage in economic restructuring. By the time reforms were initiated in the 1990s, the regional economy of each city was predominantly industrial, with a significant

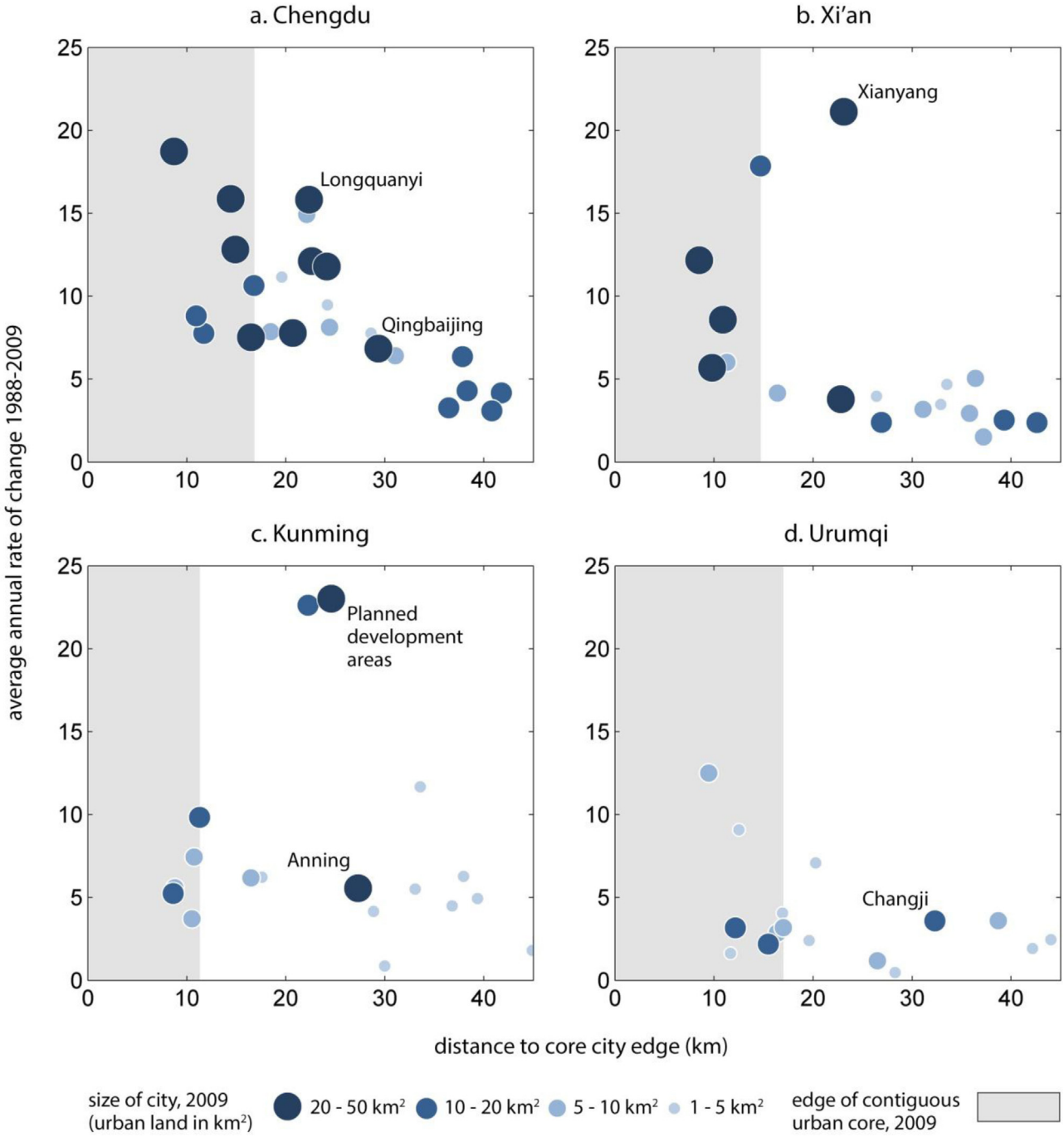

Fig. 8. Scatter plots illustrating the size and location of satellite cities outside major metropolitan areas in Western China: (a) Chengdu, (b) Xi'an, (c) Kunming, and (d) Urumqi. Note the inverse relationship between the average annual rate of change (*y* axis) and distance to the core city (*x* axis). The gray area denotes the extent of the contiguous urban core by the end of the study period (2009), so any cities that fall within this area have been enveloped by the core between 1988 and 2009.

amount of GRP in the secondary sector (35–40%). The agricultural sector (primary industry) remained somewhat high for these provincial capitals, averaging 10–20% of overall GRP throughout the 1990s, although this percentage fell by the year 2000. Over the last decade, the proportion of secondary GRP increased by 6–9 percentage points in all study areas except Chengdu, where tertiary GRP climbed to 72% and secondary GRP dropped. Although the value of tertiary activities is not declining, the proportion of tertiary activities in each core is declining due to the large amounts of secondary sector growth. These trends may reflect an artifact from data collection, however: secondary GRP in early statistical data was mostly comprised of manufacturing, while in later years, a large proportion of secondary GRP came from real estate-related development (often considered part of the service sector). Therefore, the shift from manufacturing to service sector activities may have begun in all regions, but is not reflected in the GRP data.

The GRP data for areas outside the core confirms that secondary industry is rising, shifting up to 23 percentage points in Xi'an and eight percentage points in Chengdu. Both Urumqi and Kunming have the majority of their development zones within their core counties, so a smaller increase in secondary GRP has occurred (1–2%). In addition, the tertiary sector is rising in the counties

Table 4
Real gross regional product (GRP) in 2010 yuan for the core and counties outside the core in each study area.

	Chengdu			Xi'an[c]			Kunming			Urumqi		
	2000	2009	Trend	2000	2009	Trend	2000	2009	Trend	2000	2009	Trend
Core county[a]												
Gross regional product (billion yuan, 2010 values)[b]	62.2	193.8		35.1	104.1		14.8	136.6		32.3	110.8	
GRP by sector[c]:												
Primary (%)	1.1	0.1	–	3.8	1.0	–	0.0	1.2	+	0.6	1.1	+
Secondary (%)	37.6	28.1	–	40.2	49.2	+	35.1	42.2	+	37.2	43.2	+
Tertiary (%)	61.2	71.8	+	55.9	50.8	–	64.9	56.6	–	62.2	55.8	–
Outside core[a]												
Gross regional product (billion yuan, 2010 values)[b]	69.1	191.1		7.9	68.5		14.9	41.1		7.4	16.7	
GRP by sector[c]:												
Primary (%)	15.7	10.6	–	42.2	10.2	–	22.1	17.6	–	20.7	16.0	–
Secondary (%)	47.7	56.2	+	32.2	55.8	+	45.9	46.5	+	39.8	41.0	+
Tertiary (%)	36.6	33.3	–	25.6	34.0	+	32.0	35.9	+	39.5	43.0	+

[a] The core county refers to the county containing the original central business district. The area outside the core refers to the counties whose majority land area falls within a 40 km radius of the CBD. For Chengdu, Kunming and Urumqi, these counties correspond roughly to the municipality. For Xi'an, these counties comprise the municipality plus five nearby counties.

[b] Gross regional product data were collected at the county level for all study areas (Sichuan, Shaanxi, Yunnan, and Xinjiang Bureau of Statistics, multiple years). Real GRP was calculated in 2010 values using the consumer price index information from the World Bank (http://data.worldbank.org) for China.

[c] GRP data for Xi'an were unavailable at the county level for 2000 and 2009, therefore these data refer to 1995 and 2006 estimates (Shaanxi Bureau of Statistics, multiple years).

outside the core in all areas. This indicates the mix of land use that has resulted from the zones outside the core, which likely includes some service-sector activities.

5.4. Differential rates and patterns of growth are linked to different land use types

The fourth hypothesis stems from recent literature that suggests that areas designated for tertiary industry (high tech industry in particular) can be linked directly to high land conversion rates, often with greater fragmentation/sprawl than other parts of the city (Audirac, 2003; Leichenko & Solecki, 2005). To determine if this phenomenon occurred in Western China as land uses became specialized, we selected four zones in each study area (Fig. 3): (a) a high tech industrial zone (orange); (b) a corridor known for heavy industry, both historically and in the present era through designation of an ETDZ in the 1990s (blue); (c) and two areas designated for residential zones (green). Because Urumqi's high tech zone location within the urban fabric makes it is difficult to distinguish its influence, only three zones were assessed for Urumqi. To estimate the location and level of fragmentation of urban land, we applied landscape metrics along the corridor corresponding to each zone using a moving window approach (circular window with radius 2 km, measured at 0.5 km intervals). Although a large number of landscape metrics were assessed, the results showed that all key information could be summarized using mean patch size (MPS, total area of all patches within the moving window, divided by number of patches). Note that the maximum MPS for the moving window is 12.5 km^2; a value this high would suggest a completely filled window (i.e. one large urban patch).

As expected, MPS in nearly all corridors is high near the core city (MPS close to 12 km^2). MPS then declines along the gradient from urban to rural areas, falling to 0–0.1 km^2; values <1 km^2 denote very small patches of urban land, such as villages or piecemeal development. MPS also increases significantly over time in most corridors for the area immediately outside the first ring road (0–10 km along the *x*-axis). In more than half of the corridors, this increase occurred during the first time period (1988–2000). Since the values rise to >10 km^2, this indicates expansion of the contiguous urban core. The growth of satellite cities is also clear in many corridors, appearing as peaks with values >1 km^2. Interestingly, nearly all peaks corresponding to nuclei along the corridors occur in the 2000–2010 period, suggesting that multi-nucleation is a fairly recent phenomenon in Western Chinese cities.

Finally, the increase in MPS in high tech and residential areas is greater than in industrial corridors, as shown by the large distance between the 1988, 2000 and 2009 trend lines in these graphs, and the fact that the jump occurs farther from the urban core (often 10–20 km from the first ring road). This trend is distinct in Chengdu and Xi'an, and to a lesser extent in Kunming. Looking more closely, the results for Chengdu and Xi'an show that the 1988 baseline was higher for industrial zones. This is not surprising, since these corridors were historically industrial areas, containing built-up areas prior to reforms. Growth remains limited in industrial areas in the post-reform era, however. Any factories built in the 1990s and thereafter consumed a finite amount of land, with a limited amount of secondary land development around industrial estates. Commercial areas were typically not established within the zones, and residential land was extremely limited, since factory workers are housed in high-rise dormitories. In contrast, the new high tech and residential corridors (often a mix of commercial and residential space) appear to have consumed more land than their industrial counterparts. This result highlights the fact that new high tech areas and other tertiary industry bring higher incomes as well as foreign nationals, both of which increase the demand for land, especially for residential housing and amenities. Overall, the results suggest that rates and patterns of land consumption are indeed distinct for different land use types, with some convergence in trends across cities (Fig. 9).

6. Discussion

This paper shows that cities in Western China are on a similar development trajectory to that of coastal Chinese cities. Rates of urban expansion are increasing, with average annual rates near 2% for the earliest period (1988–2000), but climbing to 5–7% after 2006 for all four case study cities. The amounts of new urban land are phenomenal; each city has more than doubled in size during the study period. Chengdu's size, especially, is now on par with Shanghai, Guangzhou, and other coastal cities over 3 million persons, which average 1025 km^2 in size in 2010 (Wang, Li, et al., 2012). In addition, nearly one-third of new urban land in each city is outside the contiguous urban core, located in small towns and cities. This result indicates the emergence of a multinucleated urban form consistent with trends in coastal cities. Within each urban region, the master plans reveal the spatial differentiation of urban land into industrial areas, high-tech zones, commercial and residential areas. Empirical analysis using landscape metrics and an urban–rural gradient

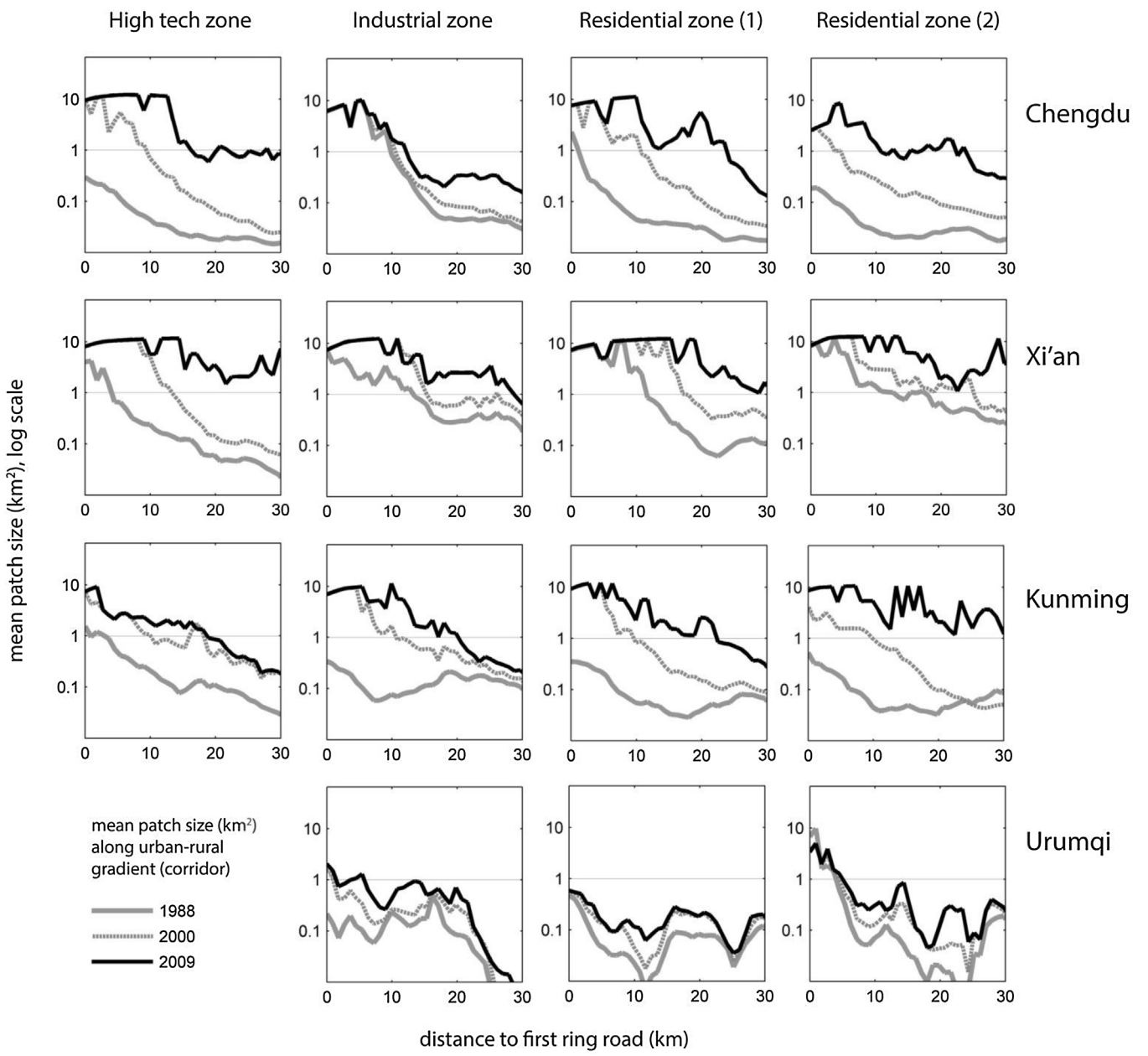

Fig. 9. The average size of urban patches (*y* axis, log scale) estimated for the urban–rural gradient extending along four corridors in each study area.

across corridors suggests that rates and amounts are indeed high in areas designated for tertiary activities and residential growth. These results suggest that, overall, many of the reforms and policies instituted to balance growth in the West to levels in coastal areas have been effective, at least in major metropolitan areas. These cities have become major regional centers, and economic activity in each city constitutes more than 30% of GDP in each province in 2010 (NBS, 2011). These features, taken together, provide increasing evidence that urban expansion processes in Western China may not fit models of urban development based on U.S. or European cities, but align with new models built on the transformation of China's coastal cities that began in the 1980s. As a result, many of the social, economic, and environmental impacts of urban expansion already documented for China's agglomerations in the East may be expected in the Western region as well.

Western Chinese cities are unique from coastal cities for three reasons, however. First, FDI continues to play a minor role in urban growth and expansion, as compared to coastal areas, where FDI has been identified as a major factor spurring rapid land conversion (Wei et al., 2006; Yue et al., 2013). The Chinese government has taken great strides to develop land and infrastructure to draw investment to Western regions, and local leaders have played a key role in soliciting business from across the globe to locate in cities. The flows of capital that helped develop the extended urban regions in many coastal areas have not materialized in Western China, however. Instead, investment from the central government has likely played an important role in the amounts and the location of urban growth across Western China. Given the lag that often occurs between investment and building, it is not surprising that the impacts of domestic investment in the late 1990s and early 2000s are starting to be realized.

The second factor explaining differential rates and patterns of growth in Western cities is also tied to location: none of the study areas has the geographic advantage of a major port to spur growth, nor proximity to investors in Taiwan and Hong Kong. Recent papers by Zhao and Zhang (2007) and Wang, Xu, et al. (2012)

have concluded that the geographic advantage of coastal cities has been an important component in their rapid expansion. Although several Western cities in this study are located on major waterways and significant investments have been made to improve inland 'dry' ports, rail, road and air infrastructure, these regions remain at a disadvantage simply due to distance. Efforts to move Chinese companies out of congested coastal cities and into Central and Western China have not always been successful (Zacharias & Tang, 2010). Without linkages to advanced economies around the world through trade and investment, it may be difficult for Western Chinese cities to emerge as global cities on the international stage. Moreover, many cities located in the sparsely populated, arid, rugged terrain of the west do not have the surplus labor from nearby agricultural areas to help spur ongoing industrialization. This may change, however, as the Chinese government plans to move 250 million into cities in the next decade, as a means to boost the economy through increased domestic demand (Johnson, 2013).

Thirdly, master planning has played a dominant role in the evolution of city structure in the West. The very nature of local plans – focused on economic and high tech development zones, new cities outside the core, and moving industry outside the city – has likely been the leading factor in how cities are developing in the West. At the same time, the role of the central government in locating development zones has had a somewhat unexpected consequence. While coastal areas were opened to investment in the 1980s province-wide, Western city development has remained targeted in major cities due to the perceived advantage of agglomeration economies (Lin, 2002). The effect has been that companies could develop in nearly any city on the coast, evening out the playing field for small and medium-sized cities. In the West, the areas opened for investment in the 1990s have been limited. The earliest reforms to hit the West were those targeted in provincial capitals, which explains why Chengdu, Xi'an, Kunming and Urumqi have all witnessed major land development and structural changes in the last decade. The relative isolation of these cities as well as the focus on large cities has led to a more dominant core, and a multi-nucleated form as opposed to the polycentricity now emerging in coastal areas. The policies governing development zones changed at a critical time in city development (2003–2006), and the final impact of this on growth trajectories remains to be seen. While these changes will likely influence the location and structure of development in Western Chinese cities, the relative isolation of these areas may still continue to hinder their development and economic performance.

The question that emerges from this study is: what lies ahead for Western China? Will cities in the West continue to follow the rapid trajectory of the 2006–2009 period, eventually reaching the expansive urban form of coastal areas? Or, is this a transition period that will slow in subsequent decades? Given the differences in factors driving urban expansion, especially the more limited role of FDI in the West, it is possible that urban expansion may taper off if government investment and intervention slows or ceases. The central government has announced a new focus on bolstering the economy within Central China (Fig. 1), thus putting continued flows of capital to the West at risk. Moreover, the growing literature assessing flows of foreign investment in China suggests that FDI levels in the West may never reach that of coastal areas (Cole, Elliott, & Zhang, 2009; Wei, Luo, & Zhou, 2010).

Although there are clear similarities in the rates and patterns of urbanization emerging in Western China, this research has also revealed critical differences across the study areas. Chengdu and Xi'an are similar in their land development and population trends: both sit in flat areas where expansion in all directions is possible, both are surrounded by productive cropland that has led to surplus income that farmers can use to build homes or invest in businesses, and both have a surplus labor force that can be harnessed for new industrial and service sector growth. Kunming is clearly following a similar trajectory, but growth has occurred more slowly due to geophysical constraints (mountains, lake), as well as the relatively smaller influx of rural population (results show that the ratio of urban land expansion to population growth is high). In the future, Kunming may depart from this trajectory, though, due to new plans to remain compact and grow upward rather than outward: the Chenggong area south of the city is being redesigned based on smart growth concepts of walkable, mixed use neighborhoods (Calthorpe & Associates, 2011). Urumqi is the most divergent of the four study areas, with industrial development that has led to a steady expansion of urban land over time, rather than a boom of growth in the early 2000s. Urumqi has remained more compact for a variety of reasons: low population (despite growth from migration of Han from the coast), master plans oriented at the central city rather than development zones outside the core, and the relative lack of resources (especially water) in its arid environment.

7. Conclusion

The literature on urban expansion, fragmentation, and polycentricity continues to search for common definitions and methods, making cross-country data collection and comparisons more difficult. In response to these definitional issues, this study has sought to provide straightforward, empirical descriptions for many aspects of urban form, including urban land expansion, multi-nucleation, fragmentation, and land use specialization. The patterns of urban form in the Chengdu, Xi'an, Kunming, and Urumqi metropolitan regions in Western China are changing as a result of national development policy and investment, while also following growth trajectories reflecting local conditions. This rapid pace of urbanization and its multi-nucleated form with land use specialization may represent a reasonably unique Western Chinese pattern of modern urban development resulting from robust central government planning and investment. Not only is this pattern distinct from coastal China, but these patterns do not fit traditional models of urban development based on U.S. and European cities. Whether and how these patterns evolve in response to changing investment and economic conditions in Western China will spur continued interest in the area for many years to come.

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