Spatial and Temporal Patterns of Urban Dynamics in Chengdu, 1975–2002

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1. Introduction

Chengdu, the provincial capital of Sichuan, has undergone rapid transformation during China's post-reform period between 1978 and 2003. One of the leading cities in southwest China, Chengdu is second only to Chongqing in population. Chengdu anchors one end of the Chongqing-Chengdu urban corridor, the fourth most populous urban cluster in China. Although the upgrading of Chongqing Municipality to the equivalent of provincial status in 1997 has increased the city's profile and potential as an administrative, land transportation, and manufacturing center, it is expected that Chengdu's regional and strategic importance as a service and high-tech center will increase in the future. With increased economic specialization among Chinese cities, it is expected that Chengdu and Chongqing cities will increasingly complement each other in terms of function, both enhancing their developmental prospects as a result. Further, the development of western China is a major objective of the Tenth Five Year Plan. The "Go West" policy was introduced in 1999.[1]

Between 1978 and 2002, the population within the boundaries of Chengdu city proper increased by 35 percent, from 1.7 to 2.3 million (see Table 1). The population of the entire municipality grew by 25 percent, from 8 to 10 million, with a significant demographic shift

		population					percent increase						
		1980	**1985**	**1990**	**1995**	**2000**	**1980-1985**	**1985-1990**	**1990-1995**	**1995-2000**	**1980-1990**	**1990-2000**	**1980-2000**
Chengdu Municipality		8,225,400	8,626,800	9,195,000	9,716,000	10,033,500	4.88	6.59	5.67	3.27	11.79	9.12	21.98
Chengdu's districts	**Jinniu**			433,600	482,700	565,000			11.32	17.05		30.30	
	Chenghua			438,900	482,300	533,800			9.89	10.68		21.62	
	Qingyang			443,800	466,500	456,800			5.11	-2.08		2.93	
	Jinjiang			395,300	403,200	381,000			2.00	-5.51		-3.62	
	Wuhou			348,600	405,700	407,900			16.38	0.54		17.01	
Chengdu	**total**	1,694,000	1,871,200	2,060,200	2,240,400	2,344,500	10.46	10.10	8.75	4.65	21.62	13.80	38.40
adjacent counties	**Shuangliu**	761,700	795,200	849,400	879,000	861,600	4.40	6.82	3.48	-1.98	11.51	1.44	13.12
	Pixian	386,900	399,200	421,200	441,200	470,900	3.18	5.51	4.75	6.73	8.87	11.80	21.71
	Xindu	478,600	498,800	532,300	571,600	595,900	4.22	6.72	7.38	4.25	11.22	11.95	24.51
	Wenjiang	237,000	249,900	265,000	293,300	305,600	5.44	6.04	10.68	4.19	11.81	15.32	28.95
nearby districts	**Qingbaijiang**	348,800	358,500	374,900	387,700	400,200	2.78	4.57	3.41	3.22	7.48	6.75	14.74
	Longquanyi	340,300	353,500	372,900	450,500	484,800	3.88	5.49	20.81	7.61	9.58	30.01	42.46
outer counties	**Xintang**	748,700	765,200	805,300	822,600	844,600	2.20	5.24	2.15	2.67	7.56	4.88	12.81
	Pengzhou	681,700	702,600	738,100	759,200	774,000	3.07	5.05	2.86	1.95	8.27	4.86	13.54
	Chongzhou	570,500	588,800	622,100	641,300	646,200	3.21	5.66	3.09	0.76	9.04	3.87	13.27
	Xinjin	252,400	261,200	272,800	281,900	289,500	3.49	4.44	3.34	2.70	8.08	6.12	14.70
	Qonglai	578,100	591,400	618,800	636,200	639,800	2.30	4.63	2.81	0.57	7.04	3.39	10.67
	Dayi	439,100	451,500	473,700	486,100	500,200	2.82	4.92	2.62	2.90	7.88	5.59	13.91
	Pujiang	225,900	235,400	245,400	252,200	256,300	4.21	4.25	2.77	1.63	8.63	4.44	13.46
	Dujiangyan	481,700	504,400	542,900	572,800	594,400	4.71	7.63	5.51	3.77	12.71	9.49	23.40

Table 1: Population statistics for Chengdu municipality, 1980–2000.

of population from rural to urban status.[2] The more rapid growth of the city proper relative to the municipality as a whole partially reflects Chengdu's increasing role as a service center. It is the leading center in western China in areas such as finance, higher education, research and development, and aviation. The rapid change in Chengdu's economic function also has important implications for urban form. Extended urban regions with greater specialization in manufacturing experience a larger share of demographic and economic growth on the periphery than do more economically diversified urban regions such as Chengdu. Over the period 1978–2002, the GDP of Chengdu municipality grew seven-fold, with a restructuring of the economy away from the primary sector to the secondary and tertiary sectors. The composition of the three sectors shifted from 27 percent, 50 percent, and 23 percent, respectively, in 1980, to 10 percent, 45 percent, and 45 percent in 2002 (see Table 2).

In Chengdu, as with many other Chinese cities, a complex interplay of government and private, local, national, and increasingly transnational forces have influenced urban growth. Responding to changes in local, national, and international economic drivers, Chengdu is redefining its economic roles and functions, with direct consequences for the city's physical form. In turn, the spatial manifestation of urban development has important implications for Chengdu's economic potential, social and political stability, and environmental and ecological functioning. Extensive, as opposed to compact, urban form requires massive infrastructure investments, increases energy demand, and has broad environmental impacts, including local and regional climate change, loss of wildlife habitat and biodiversity, and increases in pressures on water resources. From the provision of clean drinking water to the construction of transportation and waste water networks, every aspect of the urbanization process has significant environmental implications.

Just as Chengdu's development is a consequence of myriad economic and political drivers, it also reflects the city's current (and past) economic functions and role in regional and international commerce. The current pattern of physical and economic development also sets parameters that affect potential economic and physical futures. Although city size is no longer a predominant indicator of the political or economic importance of a metropolitan region like Chengdu, the spatial configuration of urban change does reflect levels of foreign direct investment (FDI), structural shifts in the economy and employment, rural industrialization patterns, and social behavior and preferences. FDI in particular has significantly influenced the spatial configuration of development in China's coastal cities.

Observed at any one point in time, the dynamic process of urban change often appears piecemeal and chaotic at best. Initial macro patterns of urbanization may be determined by infrastructure investment and development, but ensuing growth of extended metropolitan regions may be unstructured and unregulated—more a mélange of responses to individual opportunities than the result of coordinated action. Only by tracing the evolution of urban form is it possible to understand the influences of policy, economics, and demographics on urban development. Thus, quantifying the spatial and temporal patterns of urban physical growth dynamics is key to understanding the process of urban change. Historically, this has been a difficult task. Urban land use histories have traditionally been derived from statistical yearbooks, field interviews, tax records, paper maps, ground surveys, and census data. While these continue to be important sources of information, their usefulness is constrained by reliability, consistency, and limited geographic coverage.

Satellite remote sensing has revolutionized the process of monitoring and measuring urban land use and urban form dynamics. The routine collection of imagery for most of the Earth's land areas by satellites provides an invaluable historical record covering three decades. This revolutionary development makes it possible to conduct urban land use analyses in most regions of the world for this time period. Satellite remote sensing offers a tremendous advantage in studying urban areas, as it provides recurrent and consistent observations over a large geographic area, reveals explicit patterns of land use, and presents a synoptic view of the landscape.

The primary objective of this discussion paper is to provide a quantitative assessment of the spatial and temporal dynamics of physical urban development in Chengdu city proper and the extended urban region, which approximates Chengdu municipality. The paper seeks to describe and explain the patterns of urban growth in the context of urban planning and economic development. Using satellite data and spatial pattern metrics, the paper evaluates the evolution in urban form according to four spatial frameworks: nine counties of the municipality (outside the city proper), seven districts of Chengdu (five of which are within the city proper), along development corridors, and within ring roads.

2. Chengdu Context

A middle city with origins dating back more than 2,500 years, Chengdu sits virtually in the center of Sichuan and is the province's administrative and cultural center. It is surrounded by the fertile Sichuan plain, whose agricultural productivity has been enhanced over the centuries by elaborate irrigation schemes, as seen in the ancient irrigation works at Dujiangyan, forty-eight kilometers to the northwest of the city. During the rise of the Qin and Han Dynasties, Chengdu developed a strong arts and crafts tradition that continues today. In the late 1950s and early 1960s, many heavy and military industries were moved to Chengdu for strategic and defense reasons. With the modification of the military-industrial complex for civilian production, Chengdu maintains a strong industrial role in the region. Due to changes in economic policies in the early 1990s, Chengdu has rapidly emerged as one of the most important industrial, service, knowledge, and distribution centers of western China. Chengdu is well positioned geographically (both in terms of strategic geographic position and room for expansion on the Sichuan plain) and politically (but to a lesser extent than Chongqing, given the latter's provincial status) to accommodate continued economic growth, particularly as a service, knowledge, and distribution center.

The municipality of Chengdu encompasses the city proper as well as twelve additional county-level cities. The city proper includes five district-level cities (considered the "urban core" of Chengdu) plus two outer district-level cities, Longquanyi and Quingbaijiang (Figures 1, 2, and 3). The extent of the built-up area (areas dedicated to urban uses) of the Chengdu urban core has now surpassed the original city defined by the five districts. Expansion of the city has spilled over or leapfrogged into the adjacent counties of Shuangliu, Wenjiang, Pixian, and Xindu, and nearby districts of Longquanyi and Qingbaijang. The total area of the municipality is approximately 12,390 km^2, with a population of 10.1 million (*Chengdu Statistical Yearbook 2001*). The Chengdu urban core has more than three million inhabitants, with an estimated additional floating population of more than 1.5 million.

Since 1992, with the establishment of a socialist market economic system and the diffusion of economic liberalization policies to the interior, the coastal cities have no longer been the sole foci of development in China. Chengdu has benefited from China's reform policies, which have been a major factor in the urban region's economic success. For

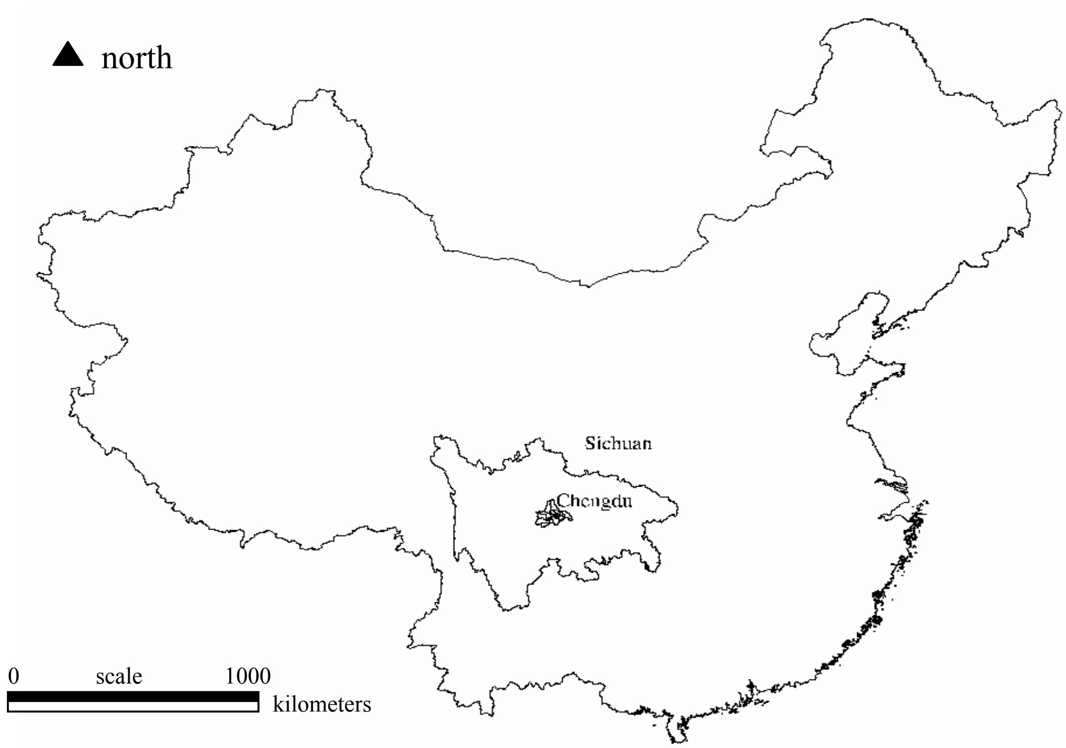


Figure 1: Map of China presenting the study area, Chengdu municipality, within Sichuan province.

Figure 2: Map of counties (white) and districts (grey) of Chengdu municipality.

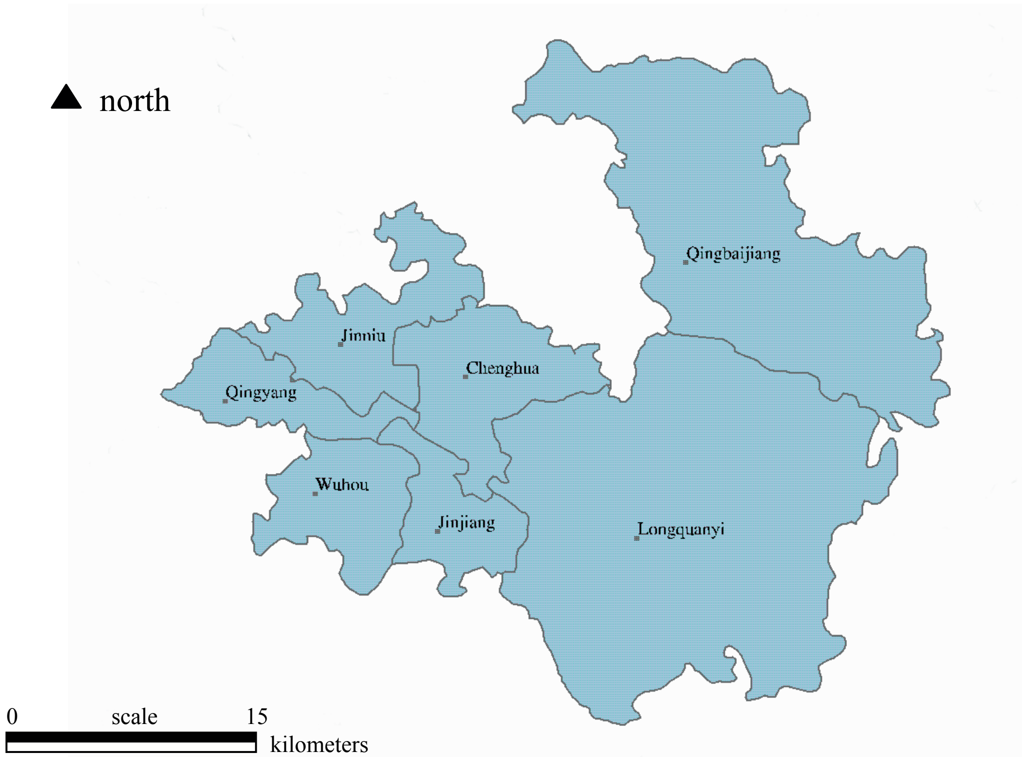


Figure 3: Map of districts of Chengdu municipality. Chengdu urban proper is composed of all seven districts, while the Chengdu urban core comprises five smaller districts to the west.

example, in 1991, the State Council ratified the Chengdu High-Tech Development Zone as the first national-level development zone in Sichuan Province. Chengdu has been targeted by the central government as a center for science and technology, high-level services, commerce, trade, and finance as well as a leading hub of transportation and communications in southwest China. By international standards, Chengdu's economy has also grown at a phenomenal rate since 1980.

Authorities in Chengdu Municipality have adopted aggressive strategies for growth in their Ninth and Tenth Five-Year Plans, outlining specific strategies and locations for industrial development, high-tech parks, tourism, and ecotourism. Improving transportation infrastructure has been a key goal. Hundreds of kilometers of roads have been paved, two additional ring roads have been constructed over the last five years, arterial highways to Nanchong and Chongqing have been completed, and the airport has doubled in capacity to become one of China's four major air hubs and, along with Kunming, the aviation gateway to western China. Another 10,000 km of road development to connect towns and villages to county-level cities has been planned for the next three years.

		primary			secondary			tertiary			total		
		1990	1995	2000	1990	1995	2000	1990	1995	2000	1990	1995	2000
Chengdu Municipality		39,122,700	97,043,400	124,691,200	51,216,200	323,306,300	528,316,100	51,395,200	237,323,700	586,030,700	141,734,100	657,673,400	1,239,038,000
Chengdu's districts	**Jinniu**	640,700	1,185,100	1,440,200	3,458,800	29,400,000	44,005,300	6,061,600	18,982,900	76,062,800	10,161,100	49,568,000	121,508,300
	Chenghua	715,200	1,949,800	1,826,900	7,286,100	43,748,400	58,443,000	3,436,000	13,613,100	46,005,600	11,437,300	59,311,300	106,275,500
	Qingyang	431,200	1,110,100	747,100	3,051,300	12,937,500	27,078,600	8,975,900	33,292,500	72,544,400	12,458,400	47,340,100	100,370,100
	Jinjiang	313,200	636,800	953,300	3,500,100	13,076,100	22,238,100	8,131,300	30,825,600	67,995,600	11,944,600	44,538,500	91,187,000
	Wuhou	197,000	1,325,100	814,000	3,071,000	25,078,600	37,921,500	1,490,400	24,635,300	46,146,400	4,758,400	51,039,000	84,881,900
Chengdu	**total**	2,297,300	6,206,900	5,781,500	20,367,300	124,240,600	189,686,500	28,095,200	121,349,400	308,754,800	50,759,800	251,796,900	504,222,800
adjacent counties	**Shuangliu**	3,441,600	9,471,900	11,458,600	3,398,800	31,273,700	51,580,600	3,008,600	14,571,700	36,295,000	9,849,000	55,317,300	99,334,200
	Pixian	2,366,500	6,461,500	8,360,600	1,719,000	15,622,200	37,205,500	898,000	7,138,800	15,761,300	4,983,500	29,222,500	61,327,400
	Xindu	2,937,200	6,888,300	8,937,200	3,666,900	25,206,300	34,638,400	2,332,100	9,063,200	21,543,800	8,936,200	41,157,800	65,119,400
	Wenjiang	1,425,900	3,675,900	4,797,700	1,535,100	9,319,300	18,923,000	980,400	5,762,300	12,488,900	3,941,400	18,757,500	36,209,600
nearby districts	**Qingbaijiang**	1,764,400	3,724,000	4,369,300	3,409,300	13,975,400	22,581,800	1,700,100	4,675,300	13,733,900	6,873,800	22,374,700	40,685,000
	Longquanyi	1,999,600	7,382,800	10,165,000	1,249,700	9,293,100	17,682,300	2,117,300	7,200,000	23,147,900	5,366,600	23,875,900	50,995,200
outer counties	**Xintang**	3,731,600	8,476,000	11,951,200	2,736,800	10,899,900	22,530,200	2,017,600	8,003,600	21,871,700	8,486,000	27,379,500	56,353,100
	Pengzhou	4,340,100	9,506,900	13,205,500	3,242,200	18,220,900	21,565,800	2,376,900	12,458,100	26,962,700	9,959,200	40,185,900	61,734,000
	Chongzhou	3,698,600	7,299,900	9,954,600	1,996,200	14,276,300	27,883,700	2,002,000	10,539,000	23,583,200	7,696,800	32,115,200	61,421,500
	Xinjin	1,201,900	3,244,800	4,460,300	1,027,000	10,780,600	12,600,700	1,031,200	5,607,500	9,440,800	3,260,100	19,632,900	26,501,800
	Qonglai	3,534,200	7,944,500	9,848,800	2,084,200	13,442,000	23,897,100	1,381,500	8,845,500	22,973,400	6,999,900	30,232,000	56,719,300
	Dayi	2,438,800	5,925,100	7,386,800	1,583,900	7,207,500	18,722,000	952,100	4,005,400	18,803,700	4,974,800	17,138,000	44,912,500
	Pujiang	1,498,200	3,484,000	4,701,500	568,700	3,410,600	8,481,900	491,700	2,273,900	6,439,800	2,558,600	9,168,500	19,623,200
	Dujiangyan	2,446,800	7,350,900	9,312,600	2,631,100	16,137,900	20,336,600	2,010,500	15,830,000	24,229,800	7,088,400	39,318,800	53,879,000

Table 2: Gross domestic product for Chengdu municipality, 1980–2000, divided by primary, secondary, and tertiary industry.

3. Urban Dynamics in the Chengdu Extended Urban Region

To evaluate the evolution of Chengdu urban dynamics, satellite data from 1978, 1988, 1991, 1995, 2000, and 2002 were used to create maps with the following categories:

- agriculture
- natural vegetation
- water
- urban
- new urban areas converted from agriculture
- new urban areas converted from natural vegetation.

These maps were generated using standard remote sensing techniques. Together with digital administrative boundaries provided by the Chengdu Economic Information Center (CDEIC) and county and district level socioeconomic data, these maps were integrated into a geographic information system (GIS) for further analysis using summary spatial and temporal statistics.[3]

3.2. General Trends

The maps derived from the six years (1978, 1988, 1991, 1995, 2000, and 2002) of satellite imagery reveal a number of spatial and temporal trends, which were corroborated by fieldwork and interviews (Figures 4 and 5). During the period from 1978 to 1988 (Figures 4a and 4b), land use change was confined to development contiguous with Chengdu and other established county seat cities. By 1988, urban development had spread east, resulting in significant buildup of the continuous urban fabric. Additionally, scattered urban development occurred in towns and villages that housed clusters of town-village enterprises (TVEs).[4]

From 1988 to 1991 (Figure 4c), growth of Chengdu shifted to the southwest, toward Shuangliu. Airport infrastructure development near Shuangliu began in 1990, and new roads and patchy development are visible between the airport and the edge of the city. A second area of growth appeared in the southeast, where development followed the construction of a new road to Longquanyi. Longquanyi was designated as an Economic and Technical Development Zone during this period, and new roads were constructed on the western edge of the site. New road networks appear in several county-level cities as well, although little new urbanized land is visible near these cities themselves.

From 1991 to 1995 (Figure 4d), contiguous and significant growth occurred along several radial axes. This growth extended the former built-up boundary by two kilometers toward three of the five district cities that make up the city proper: Jinniu in the northwest, Qingyang to the west, and Wuhou to the southwest. As a result, contiguous urban growth is apparent along the edge of the western half of the city. This growth trend to the west continued through the 1990s.

Seven major development axes became prominent during this period: (1) north to Mianyang, (2) northwest to Dujiangyan, (3) west to Chongzhou, (4) southwest to the Shuangliu airport, (5) south to Meishan, (6) east to Chongqing, and (7) northeast to Nanchong (Figure 14). Growth also occurred along smaller axes that extend only a few kilometers from the city, three of which are noticeable in the 1995 map. Development occurred along these axes within a buffer of one-half to one kilometer on either side of the road, most evident in Corridors 1 through 5. Until 2000, minimal urban development occurred along Corridors 6 and 7 (Figure 4e). Outside of Chengdu city proper, road

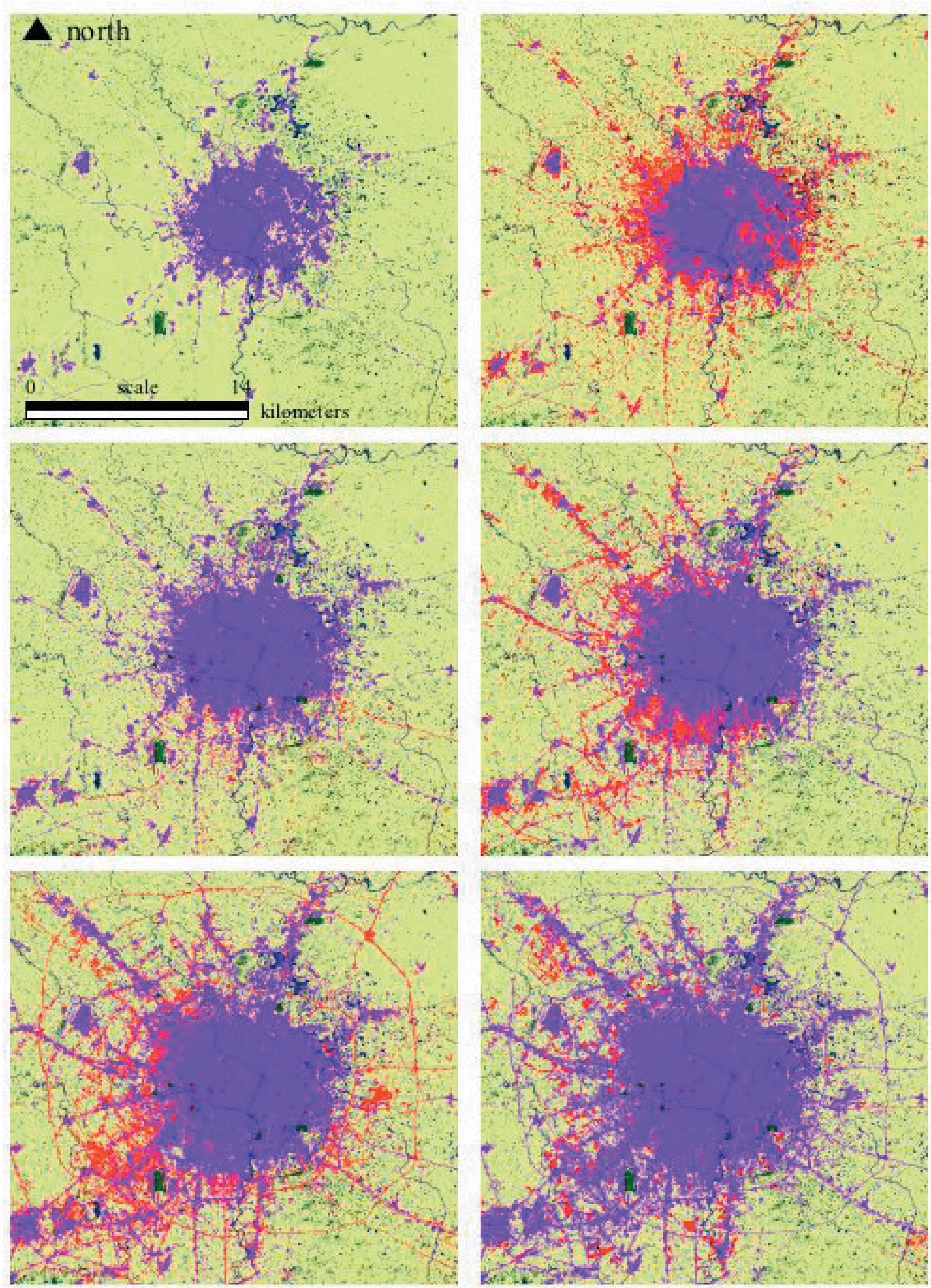


Figure 4: Maps produced from satellite images for six time points, beginning in the upper left and proceeding by row (a) 1978, (b) 1988, (c) 1991, (d) 1995, (e) 2000, and (f) 2002. Urban areas appear purple, new urban growth since the previous time point is indicated in red, agricultural areas are yellow, and natural vegetation (parks, forest) is shown in green.

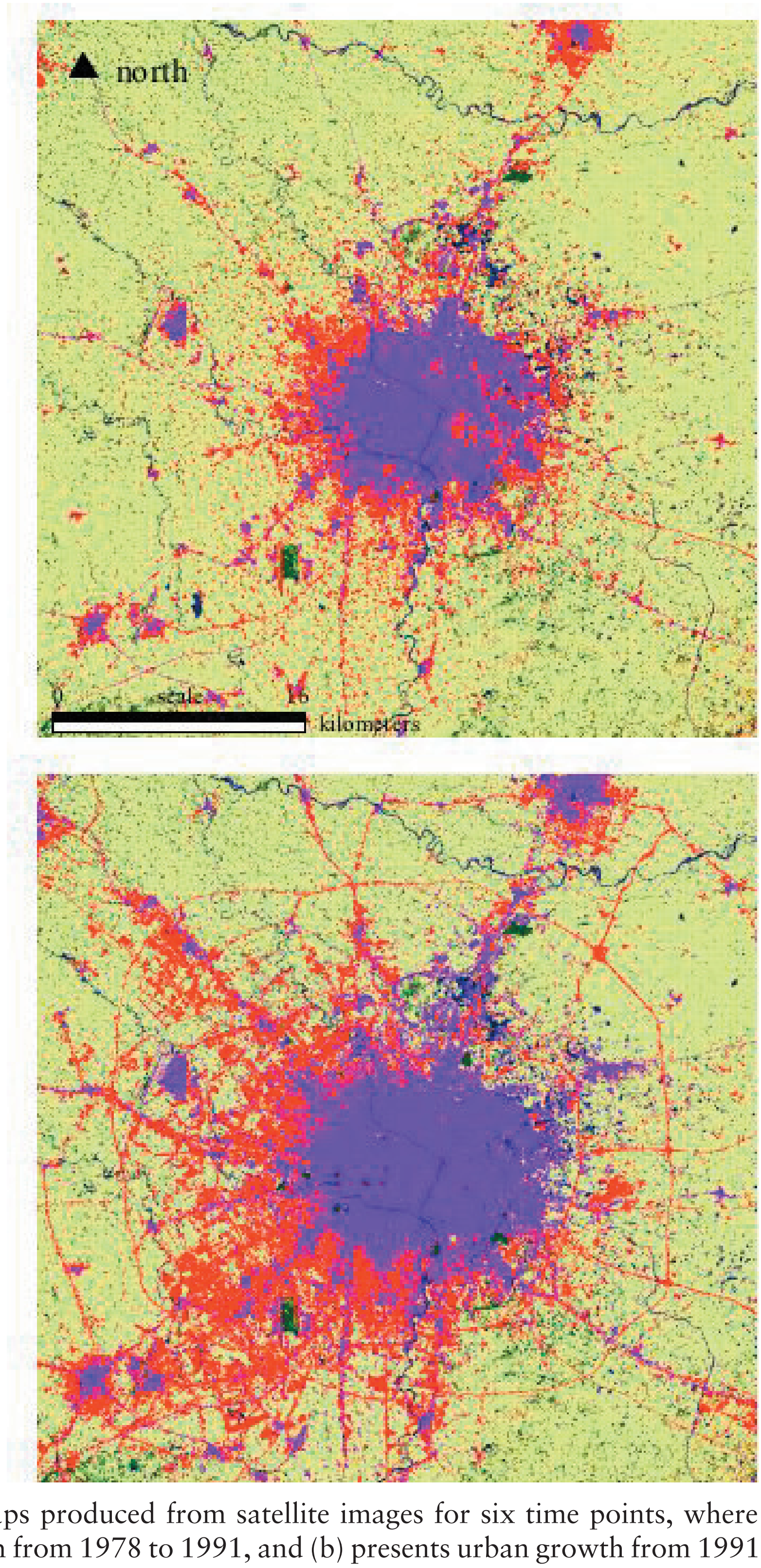


Figure 5: Maps produced from satellite images for six time points, where (a) presents the urban growth from 1978 to 1991, and (b) presents urban growth from 1991 to 2002. Urban areas appear purple, while new urban growth is indicated in red. Note the substantial shift of the city to the west and southwest after 1991.

development occurred in a ring fashion around the county level cities of Pixian, Wenjiang, and Pengzhou. Xindu and Shuangliu also experienced contiguous urban growth.

From 1995 to 2000 (Figure 4e), ring road development is apparent in Chengdu as construction of the third and fourth ring roads was begun. During this period, strong radial dynamics begin to be somewhat counterbalanced by ring road construction. Urban land use intensified within the third ring road and became more dense between the third and fourth ring roads. In addition, urban growth continued along the seven major development corridors, now extending more than one kilometer on either side of the radial roads. Although the areas beyond these 2+ kilometer-wide axes are still dominated by farmland, urban development within two kilometers of the built-up city edge has become more connected, enveloping the urban districts (part of the city proper) of Jinniu, Qingyang, Wuhou, and Jinjiang. By 2000, development in these urban districts was predominantly continuous, rather than corridor in orientation. During this period, five new radial highways were constructed, each within or near (within one to two kilometers) of Corridors 1, 2, 5, 6, and 7. Urban development appears most dense between Wuhou district and Shuangliu, as industry and commerce developed within targeted industrial and high-tech zones. The airport played a very important role in driving this dynamic. Urban land conversion is also noticeable in a new industrial area east of the city in Corridor 7.

From 2000 to 2002 (Figure 4f), urban land conversion is perceptible in several patches near the city's edge. New urban areas within close proximity of the city create a denser urban landscape in the west; in-filling further contributes to this dynamic. Further out (a kilometer or more from the edge of the built-up area), new buildings appear in a more patchy, discontinuous pattern around the entire built-up area, but particularly to the west. The most significant addition in this regard is increased construction of the West Chengdu National High-Tech Zone in Corridor 2.

Finally, Figure 5 presents maps depicting cumulative growth for two periods, 1978–91 (Figure 5a), and 1991–2002 (Figure 5b). Urban development was more balanced in the 1980s, extending outward in all directions. Conversely, new construction during the 1990s was concentrated in the northwest, west, and southwest regions of the city. This pattern of urban development illustrates the limits of urban planning, in that the policy of the Municipal Government during the 1990s was to drive development to the southeast, anchored by the ETDZ at Longquanyi. On the other hand, the Provincial Government's support of the high-tech zone to the northwest (on the Corridor to Pixian and Dujiangyan) is consistent with growth patterns noted. However, it would appear that the prime driver of peripheral development since the early 1990s has been the airport at Shuangliu.

3.3. Urban Dynamics by County and District

The previous section presented general observations related to the entire study area. In this section, urban dynamics are evaluated at the county and district levels for each of the six time periods. Of the thirteen counties comprising the municipality, four are adjacent to Chengdu city proper, namely Shuangliu, Pixian, Xindu, and Wenjiang (Figure 6). Two districts also lie outside the Chengdu urban core, Longquanyi and Qingbaijang. These six local governments, (four counties and two districts) are not at the same administrative level, but they were grouped together for analysis due to their geographic adjacency to Chengdu. Four additional counties are included in the study area as second-order neighbors to Chengdu, including Xintang, Pengzhou, Chongzhou, and Xinjin. Due to a lack of satellite data, the counties of Dujiangyan, Dayi, Qionglai, and Pujiang were not included in the analysis.

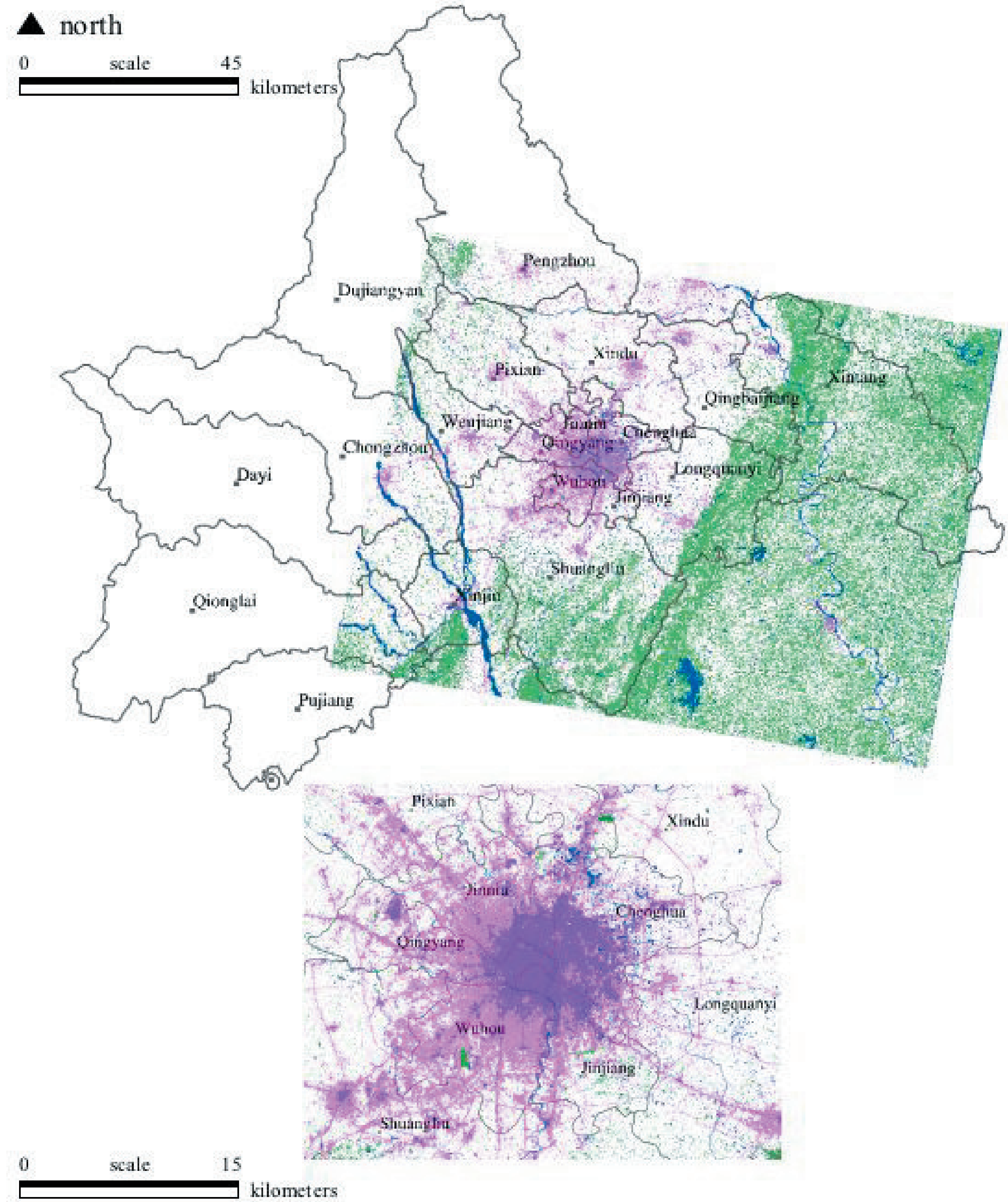
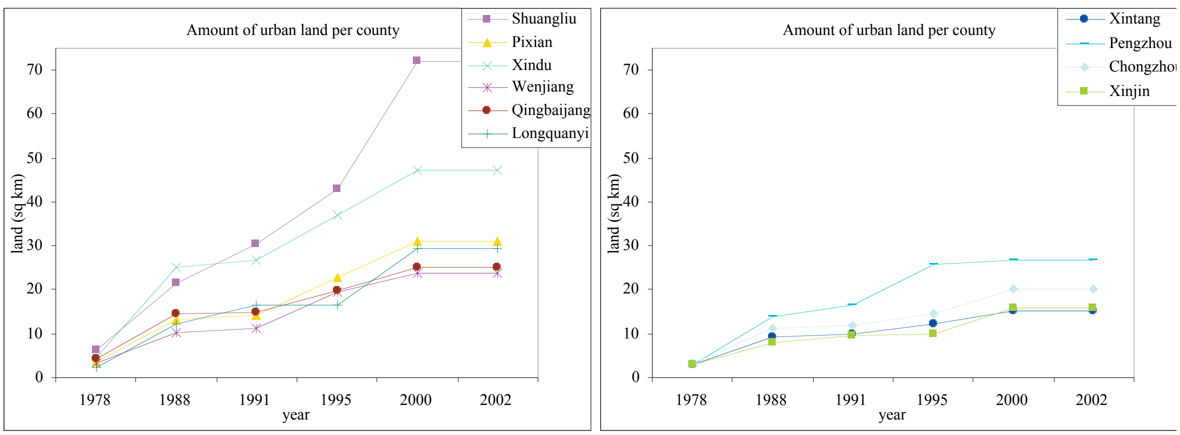


Figure 6: Map of (a) Chengdu municipality showing the extent of the study area provided by satellite images, and (b) Chengdu city encompassing the five districts. Note new urban growth (magenta) surpassing the boundaries of the city. Original city size in 1978 is shown in purple, water bodies blue, natural vegetation green and agriculture white. Areas outside county boundaries were not included in statistical analysis.

3.3.1. County-Level Analysis

Results of analysis of the satellite-derived maps illustrate the emergence of several significant patterns during the period 1978–2002. The amount of urban (built-up) area in Chengdu increased from 81 km^2 to nearly 220 km^2, suggesting both expansion and in-fill of urban areas within the city boundaries (Table 7). While the built-up area grew to nearly three times its 1978 size, Chengdu's adjacent counties and districts developed at even faster rates, increasing from a few square kilometers urbanized in 1978 to between 23 km^2 and 72 km^2 per local government unit in 2002. The urban areas of Shuangliu, Pixian, Xindu and Longquanyi expanded tenfold, while development in Wenjiang and Qingbaijing trailed slightly behind with an increase of nine and six times, respectively, from 1978 to 2002. These rates and spatial patterns are significant because they indicate a trend toward more dispersed urban development, away from the city core. Instead, much of this development is centered in satellite cities (often county level cities). Such development is characterized by increased urban land use per person.



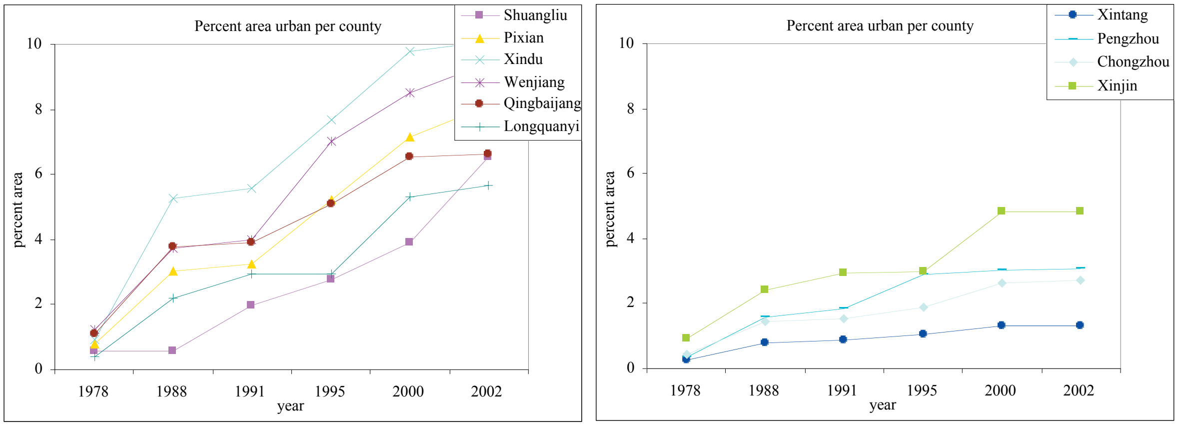
		dist (km)	amount urban (km^2) 1978	1988	1991	1995	2000	2002
	Chengdu	-	81.15	142.1	149.9	182.6	220.0	220.0
adjacent counties	**Shuangliu**	19.5	6.12	21.60	30.29	42.85	71.87	71.87
	Pixian	25.5	3.51	13.17	14.23	22.80	31.11	31.11
	Xindu	18.5	4.49	25.25	26.70	36.96	47.08	47.08
	Wenjiang	24.8	3.44	10.33	11.13	19.51	23.64	23.64
nearby districts	**Qingbaijang**	21	4.30	14.60	15.02	19.68	25.20	25.20
	Longquanyi	28.1	2.31	12.15	16.47	16.47	29.46	29.46
outer counties	**Xintang**	39.2	2.92	9.14	9.92	12.11	15.04	15.04
	Pengzhou	38.2	2.94	13.97	16.44	25.86	26.80	26.80
	Chongzhou	40.3	3.38	11.13	11.74	14.55	20.09	20.09
	Xinjin	38.5	3.02	7.96	9.69	9.86	16.00	16.00

Figure 7, Table 7: Amount of urban land per county (sq km) for each date. The graph on the left presents the six adjacent counties and districts of Chengdu, while the second order neighbors of Chengdu are on the right. Within the table, the first column represents the distance of the county seat from Chengdu's city center.

Relative levels of physical urbanization, outside the Chengdu urban core, are apparent from the data presented in Figure 8 and Table 8. In the surrounding counties, urban land area increased from a fraction of 1 percent in 1978 to more than 5 percent of the total county area in 2002, a ten- to twelve-fold increase. Pixian, Xindu, and Wenjiang had the largest urban areas relative to other land uses (8 to 10 percent), illustrating that the most significant rural-urban land conversion has been toward the north and west. Of the first-order neighbors, Shuangliu had the largest urbanized area in 2002 (Table 7), but Xindu was the most built-up as a percentage of overall county area (Table 8). The high level of urbanization in the Xindu (to Mianyang) corridor is largely explained by the fact that this corridor was urbanized much earlier than the others, as it is the site of many state-owned enterprises (SOEs) during the 1960s and 1970s. The Chengdu urban core is more than 50 percent urban, while the counties further from Chengdu are still predominantly agricultural; urbanization levels range from 1.31 percent in Xintang County in the far east of the municipality (in the outer study area), to 10.08 percent in Xindu, an adjacent county to the north.

Table 9 describes increases in urban land use by local government jurisdiction for each time period. The period 1978–88 had by far the most substantial growth for all counties and districts. However, as mentioned previously, these numbers should be treated with caution as they may overestimate urban change. Further, this time period is much longer (in years) than the other time periods under scrutiny. Annualized rates would show a smaller differential. The different rates of urbanization may, to some extent, reflect policies with respect to establishing targeted development zones. In the period 1988–91, Shuangliu and Longquanyi, two areas targeted for industrial location, exhibited the first signs of substantial land development. While these areas continued to expand during the 1991–95 period, Pixian and Wenjiang developed at even faster rates than their official industrial counterparts. However, Pixian's growth may also reflect explicit spatial policy, in that the Provincial Government has championed the West Chengdu National High-Tech Zone in the Pixian Corridor, between Pixian and Chengdu city. Fieldwork suggests that Pixian and Wenjiang experienced substantial residential development and establishment of high levels of joint venture industry (especially Pixian) during the study period. From 1995 to 2000, Shuangliu and Longquanyi again took the lead in terms of percentage increases in conversion to urban land, although the remaining counties also continued to expand. During the period 2000–02, growth continued in all counties, with Pixian and Wenjiang clearly at the top, significantly driven by high-tech industrial centers located within their boundaries, and associated residential development.

The four outer counties have also experienced substantial increases in urbanization, and their urbanized areas have grown from 3–4 km^2 in 1978 to 15–27 km^2 in 2002 (Table 7). The distance of the four county seats from core Chengdu (each nearly 40 km) is double that of the adjacent counties, which probably explains why growth in urbanized area has not occurred as rapidly. Xintang's terrain—the county straddles the north-south mountain range—sets it at a disadvantage for urban expansion. The construction of the Chengdu–Nanchong expressway after 1990 increased accessibility, however, and urbanization accelerated (although it still remained at low levels) when this key road was completed in the mid-1990s. Similar patterns are evident in Pengzhou and Chongzhou, where urban growth is closely linked to the commencement (which sets off speculation and initial building) and completion of major road projects. Significant construction of roads linking Chengdu's urban core to all county-level cities began in 1990, opening up opportunities for economic



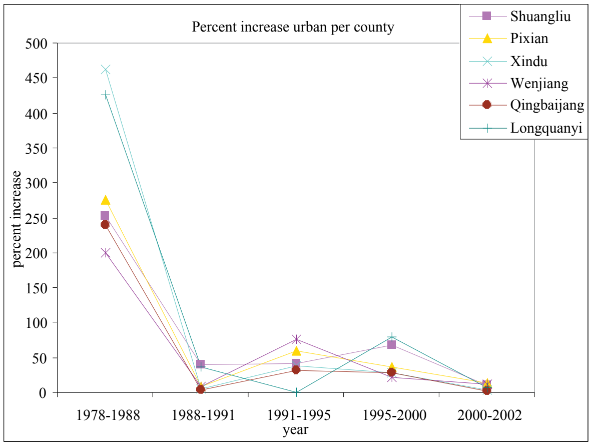
		dist (km)	1978	1988	1991	1995	2000	2002
			percent area urban					
	Chengdu	-	18.69	32.73	34.51	42.03	50.66	50.66
adjacent counties	**Shuangliu**	19.5	0.55	0.57	1.97	2.76	3.90	6.54
	Pixian	25.5	0.80	3.02	3.26	5.23	7.13	8.09
	Xindu	18.5	0.93	5.25	5.55	7.69	9.79	10.08
	Wenjiang	24.8	1.24	3.72	4.01	7.02	8.51	9.43
nearby districts	**Qingbaijang**	21	1.11	3.79	3.89	5.10	6.53	6.63
	Longquanyi	28.1	0.42	2.18	2.96	2.96	5.29	5.64
outer counties	**Xintang**	39.2	0.25	0.79	0.86	1.05	1.30	1.31
	Pengzhou	38.2	0.33	1.57	1.85	2.91	3.01	3.06
	Chongzhou	40.3	0.44	1.45	1.53	1.89	2.61	2.72
	Xinjin	38.5	0.91	2.40	2.93	2.98	4.84	4.84

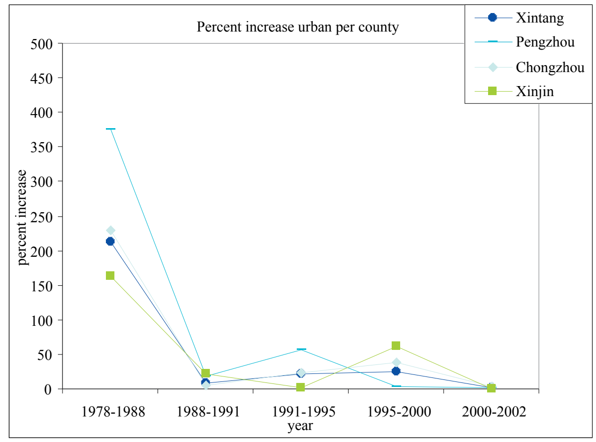
Figure 8, Table 8: Amount of urban land per county, normalized by total area of the county. The graph on the left presents the six adjacent counties and districts of Chengdu, while the second order neighbors of Chengdu are on the right.

activities further from the city than previously. Additional land conversion along new roads is clear in the maps from 1995 (Figure 4d). A substantial portion of Xinjin's growth is likely overflow development related to Shuangliu's airport.

3.3.2. Chengdu Urban District-Level Analysis

Analysis of urban growth patterns within the five city proper districts of Chengdu (Jinniu, Chenghua, Wuhou, Qingyang, and Jinjiang) provides information about the amount and direction of urban physical growth within Chengdu city. The central business district is situated almost directly in the center of the five districts, each of which fans outward in a pie-like manner (Figures 3 and 6). The absolute amount of urbanized land has increased in all five districts, with the greatest increase in Jinniu, Chenghua, and Wuhou (Table 10). District size and shape partly influences this outcome. Some districts have larger areas (e.g., Chenghua) or more of their area falling within the city proper (e.g., Jinniu). Once the level of urbanization is normalized by district size (Figure 11), growth trends are clearly similar



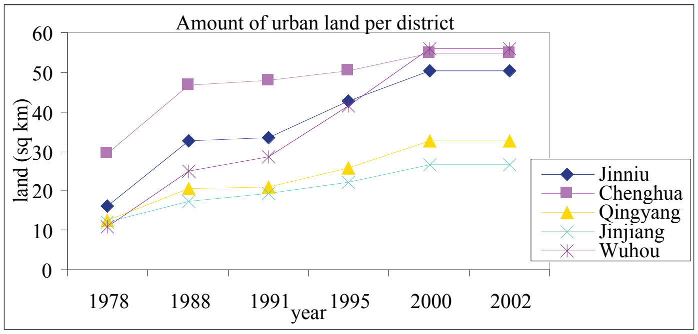


			percent increase per period					
		dist (km)	**1978-1988**	**1988-1991**	**1991-1995**	**1995-2000**	**2000-2002**	**1991-2002**
	Chengdu	-	75.15	5.45	21.8	20.51	0	0
adjacent counties	**Shuangliu**	19.5	253.08	40.24	41.44	67.72	9.12	158.87
	Pixian	25.5	275.43	8.07	60.21	36.48	13.43	148.02
	Xindu	18.5	462.12	5.73	38.44	27.38	2.92	81.49
	Wenjiang	24.8	200.21	7.74	75.27	21.19	10.82	135.39
nearby districts	**Qingbaijang**	21	239.96	2.85	31.02	28.09	1.41	70.20
	Longquanyi	28.1	425.24	35.49	n/a	78.91	6.59	90.71
outer counties	**Xintang**	39.2	212.39	8.61	22.03	24.16	1.26	53.43
	Pengzhou	38.2	375.35	17.65	57.28	3.66	1.73	65.84
	Chongzhou	40.3	229.20	5.55	23.90	38.08	4.13	78.14
	Xinjin	38.5	163.32	21.73	1.79	62.28	0.00	65.20

Figure 9, Table 9: Percent increase of urban land per period for each county. The graph on the left presents the six adjacent counties and districts of Chengdu, while the second order neighbors of Chengdu are on the right. Note that trendlines for percent increase during the 1978–1988 period are far greater than in later periods, due to the possibility of inflated amounts of urban change. Increase during the previous decade (1991–2002) is shown in the last column, although not presented in the figures.

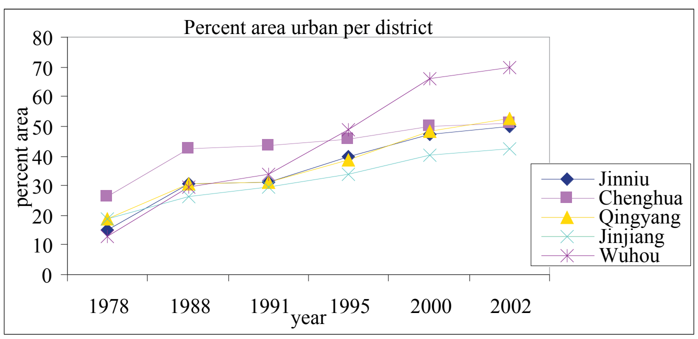
for all districts over the period 1978 to 2002, with the exception of Wuhou district to the southwest, which was nearly 70 percent urbanized by 2002. Most striking is urbanization near Shuangliu airport, the area that contained the smallest amount of urban land in 1978.

In terms of percentage increase in physical urbanization (Figure 12), Wuhou again topped all other districts, exhibiting an astounding 105 percent increase from 1991 to 2002. Jinniu, Qingyang, and Jinjiang exhibited increased urban land conversion during the 1991–95 and 1995–2000 periods, although it is clear that of the three, Qingyang leads in overall percentage increase (Table 12, last column). These results suggest that growth of the city has been predominantly in the northwest, west, and southwest quadrants, as indicated in Figures 5 and 6b. Chenghua and Jinjiang, meanwhile, have the lowest rates of urban land development (the lowest, flattest trend lines in Figures 10, 11, and 12). Ground assessments



		amount urban (km^2)					
		1978	1988	1991	1995	2000	2002
Chengdu's districts	Jinniu	16.27	32.55	33.26	42.65	50.42	50.42
	Chenghua	29.20	46.79	47.77	50.27	54.93	54.93
	Qingyang	12.52	20.59	20.80	25.93	32.42	32.42
	Jinjiang	12.20	17.38	19.29	22.29	26.44	26.44
	Wuhou	10.97	24.82	28.76	41.42	55.80	55.80

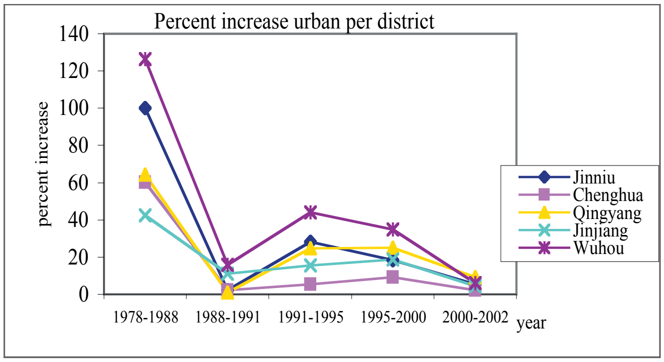
Figure 10, Table 10: Amount of urban land per district (sq km) for each date.



		percent area urban					
		1978	1988	1991	1995	2000	2002
Chengdu's districts	Jinniu	15.21	30.43	31.09	39.86	47.13	49.72
	Chenghua	26.56	42.57	43.46	45.73	49.97	51.08
	Qingyang	18.62	30.62	30.93	38.56	48.20	52.66
	Jinjiang	18.61	26.52	29.42	34.01	40.34	42.17
	Wuhou	12.96	29.33	33.99	48.95	65.94	69.81

Figure 11, Table 11: Amount of urban land per district, normalized by total area of the district.

in the northeast and southeast corroborate that these districts have remained largely farmland and orchards, with little development near new highway and road infrastructure. In comparison, fieldwork in the northwest, west, and southwest confirmed the city's growth trend in that direction. Only small, scattered plots of farmland are visible from the roads along the latter axes, and clearing of older villages and buildings to facilitate new industrial and commercial growth is notable at several locations.



		percent increase for each period					
		1978-1988	**1988-1991**	**1991-1995**	**1995-2000**	**2000-2002**	**1991-2002**
Chengdu's districts	**Jinniu**	100.11	2.18	28.21	18.23	5.50	59.93
	Chenghua	60.26	2.09	5.23	9.26	2.23	17.54
	Qingyang	64.44	1.03	24.65	25.00	9.25	70.23
	Jinjiang	42.52	10.95	15.59	18.62	4.53	43.32
	Wuhou	126.32	15.88	44.00	34.72	5.86	105.37

Figure 12, Table 12: Percent increase of urban land by district for each period. Increase during the previous decade (1991–2002) is shown in the last column.

3.3.3. Urban Land Use Efficiency

The amount of urban land conversion relative to unit increase in population or economic growth (GDP) sheds light on urban land-use efficiencies. Two indices were developed for this purpose: urban land-use change per additional person (a standard measure used in China) and urban land-use change per additional unit of GDP (Table 13). High urban land-use efficiency signifies that a small amount of land is converted per unit increase in population or GDP. Conversely, low land-use efficiency indicates that the urban land requirement per person or unit of economic activity is high. Comparing the district results to the municipal average (Table 13, last row) by population, Wuhou exhibits greater than average ratios from 1991 to 1995 and from 1995 to 2000. In other words, 0.22 square meters (m^2) of land was converted for urban uses for each additional person from 1991 to 1995 in Wuhou, as compared to the municipal mean of 0.18 m^2 per person. This figure jumps to 6.54 during the 1995–2000 period, indicating that far more land was converted to urban uses per person than average. The magnitude of change suggests that growth must be attributed to special development in the area (possibly airport development), rather than to urban sprawl.

On the other hand, districts Jinniu and Chenghua have urban lower than average land conversion to population increment ratios, indicating efficient rural to urban land conversion despite increasing populations. In the case of Chenghua, it is clear from Tables 10, 11, and 12 that land conversion has been minimal. For Jinniu in the northwest, population growth has been substantial, but has not required significant land conversion. Growth has most likely taken a contiguous, compact form, and been focused on residential development.[5] Field assessments in the area reveal a large increase in apartment buildings since 1991, corroborating this trend.

Finally, it is important to note the inefficient land conversion to population change ratios of Qingyang and Jinjiang in the 1995–2000 period. Although land has been converted for urban uses in these districts, the number of urban inhabitants has declined. Expansion in this area is clearly not population driven, but is instead attributable to infrastructure, commercial, and industrial development. Despite increased availability of employment in these districts, the population has shifted to other districts and counties.

In terms of changing levels of GDP (Table 13, last two columns), urban land-use efficiency per GDP is high, suggesting that for every one Yuan increase in GDP, less land is converted than the prevailing mean. The exception again is Wuhou district, where large amounts of land (4.3 m^2) have been converted for each one Yuan increase in GDP. Low rates of land conversion relative to GDP increments reflect rapid economic growth. This growth is based partially on efficiency gains that have increasingly resulted in more effective use of existing urban infrastructure, and enabled construction of more land-conserving urban features, such as high-rise buildings.

Similar examination of economic and demographic data was performed for the counties outside of Chengdu city. During the 1988–91 period, few counties deviate significantly from the mean ratios for land conversion to population increments, except Shuangliu, Xinjin, and Longquanyi. Again, this result indicates increased sprawl and/or the presence of additional factors driving land conversion (such as construction of airport facilities and industrial parks that result in high land conversion without corresponding absorption of population). It is clear that Shuangliu and Xinjin are changing due to the increased commerce/industry from airport expansion, while Longquanyi's designation as

		change land/change pop (m^2/person)				change land/change gdp (m^2/yuan)	
		1978-1988	**1988-1991**	**1991-1995**	**1995-2000**	**1990-1995**	**1995-2000**
Chengdu's districts	**Jinniu**			0.19	0.09	2.38	1.08
	Chenghua			0.06	0.09	0.52	0.99
	Qingyang			0.23	-0.67	1.47	1.22
	Jinjiang			**0.38**	-0.19	0.92	0.89
	Wuhou			0.22	**6.54**	**2.73**	**4.25**
Chengdu	**total**	0.03	0.04	0.18	0.36	1.63	1.48
adjacent counties	**Shuangliu**	0.18	**0.45**	**0.42**	**-1.67**	**2.76**	**6.59**
	Pixian	0.36	0.07	**0.43**	0.28	**3.53**	2.59
	Xindu	0.40	0.19	0.26	0.42	**3.19**	**4.22**
	Wenjiang	0.31	0.08	0.30	0.34	**5.65**	2.37
nearby districts	**Qingbaijang**	0.48	0.05	0.36	0.44	**3.01**	**3.02**
	Longquanyi	0.30	**1.27**	n/a	0.38	n/a	**4.79**
outer counties	**Xintang**	0.14	0.04	0.13	0.13	1.16	1.01
	Pengzhou	0.21	0.22	**0.45**	0.06	**3.12**	0.44
	Chongzhou	0.18	0.04	0.15	**1.13**	1.15	1.89
	Xinjin	0.24	**0.47**	0.02	0.81	0.11	**8.94**
total study area		0.28	0.10	0.20	0.49	2.08	2.45

Table 13: Ratio of change in urban land to change in population (first four columns), and ratio of change in urban land to change in gross domestic product (GDP, last two columns on the right). Figures shown in bold are significantly higher than municipal averages (last row). Note that statistics for Longquanyi are not available for 1995 due to cloud cover in the satellite image.

an Economic and Technical Development Zone may have driven significant land expansion without corresponding increases in population.

From 1991 to 1995, three counties exhibit elevated urban land conversion per population increase: Shuangliu, Pixian (a High-Tech Zone was designated in Pixian during this period), and Pengzhou, located on the northern edge of the study area. Pengzhou is developing land in similar fashion to its neighbors, although with less population growth. The land conversion to GDP increment ratio is elevated for Pengzhou as well, 3.12 m^2 converted per Yuan increase in GDP. Of the four outer counties included in the study area, Pengzhou is the only one to experience elevated levels of land conversion per GDP increase. All counties and districts adjacent to Chengdu have elevated land conversion per GDP increase ratios. These figures provide evidence of movement of industry away from the Chengdu urban core to fringe areas.

Finally, the 1995–2000 period highlights Shuangliu's continued urban land expansion. Despite negative population growth, both industrial and commercial activities and land-use increased substantially, resulting in a high land conversion to population growth ratio. In addition, the amount of land converted per GDP increase is high for Shuangliu (6.59 m^2 per Yuan). It is possible that these ratios will decrease in the future, as construction levels decline and GDP rises from infrastructure and building development during the 1995–2000 period. Significant land conversion per GDP increase is also apparent in Xindu, Qingbaijang, Longquanyi, and Xinjin. Urban development in these areas has been triggered by domestic and foreign investment in the north and east. These areas are less economically vital, meaning that GDP increases are unlikely to be as rapid as in the Shuangliu area. Lower land conversion to GDP increase ratios in the outer counties suggest that increases in GDP have occurred without substantial urban land conversion (only 0.4 to 1.9 m^2 per Yuan, compared to the municipal average of 2.45). In the outer counties, GDP increases have been driven by intensification of agriculture and growth in tourism, activities which demand less urban land than manufacturing and bedroom community development.

3.3.4. Urban Dynamics by Corridor

One major goal of this research is to understand the relationship between drivers and spatial patterns of urban development. An urban-rural gradient provides a method in which study plots can be arranged in a transect along the gradient of urbanization (McDonnell and Pickett 1990). Using this method, seven corridors were identified in the study area. These corridors were defined initially along major transportation networks apparent in the 1988 satellite imagery (the 1978 data is not suitable for detecting roads due to coarse resolution). The roads were then buffered on either side by 2 km to create a corridor width of 4 km (Figure 14). Of the seven corridors, four were greater than 38 km in length (Corridors 1–4), while three corridors were limited in length (20 to 30 km) by elevation changes restricting urban and road network expansion (Corridors 5–7). In this section, urban dynamics are explored within each corridor as well as compared across corridors. In addition to analysis of the amounts of urban land and percent increase in urban land (Tables 15, 16, and 17), the corridors were examined using spatial pattern metrics to assess the level of contiguity or patchiness of urban land development over the twenty-five-year study time period.

Results of the analysis show that the amount of urban land has increased in all seven corridors, with a sizeable increase after 1995 (Table 15). Overall, the trends indicate that the majority of growth occurred along the three corridors to the northwest, south, and southwest (Corridors 2, 4, 5), followed closely by growth to the west (Corridor 3). The characteristics

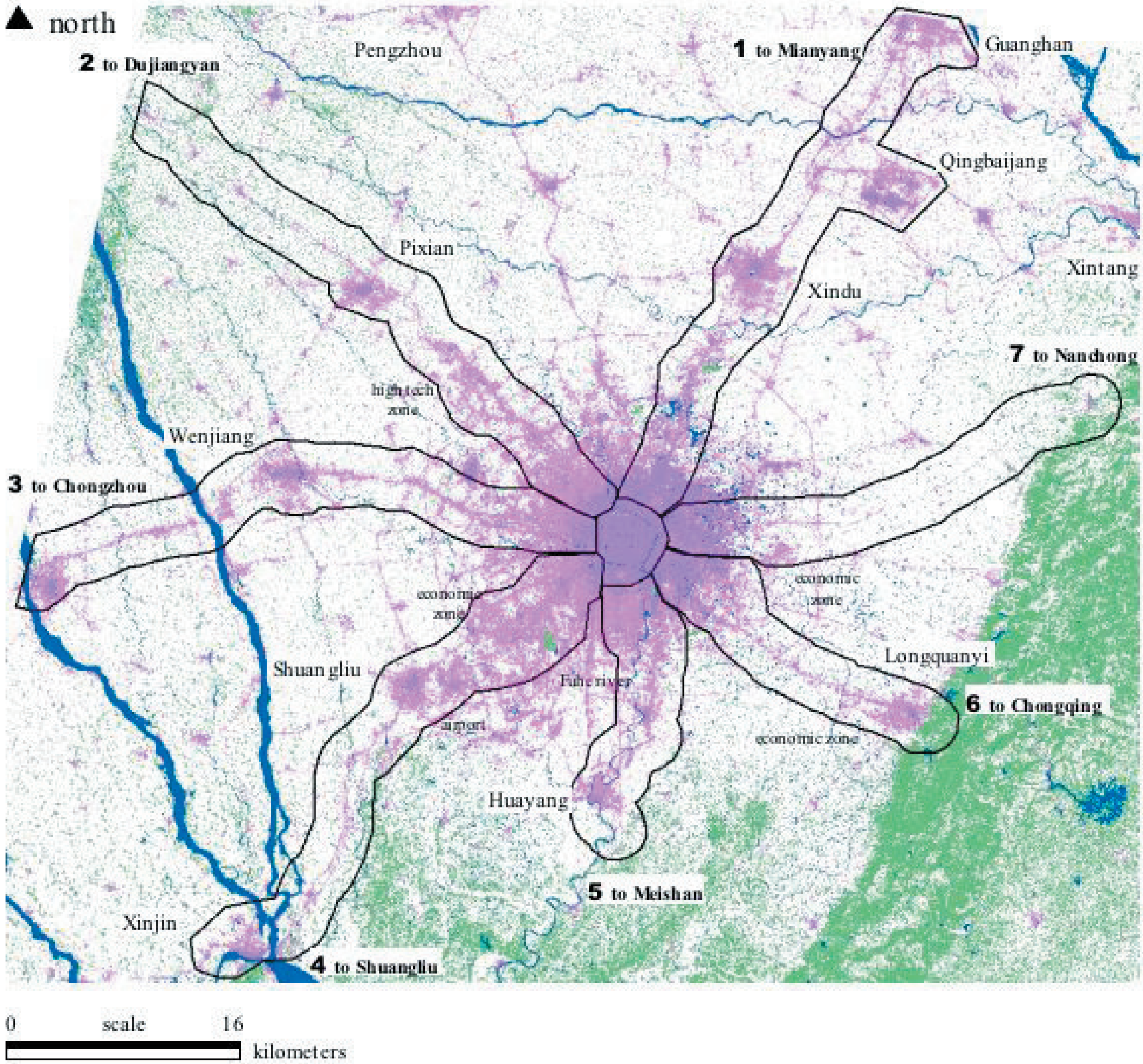
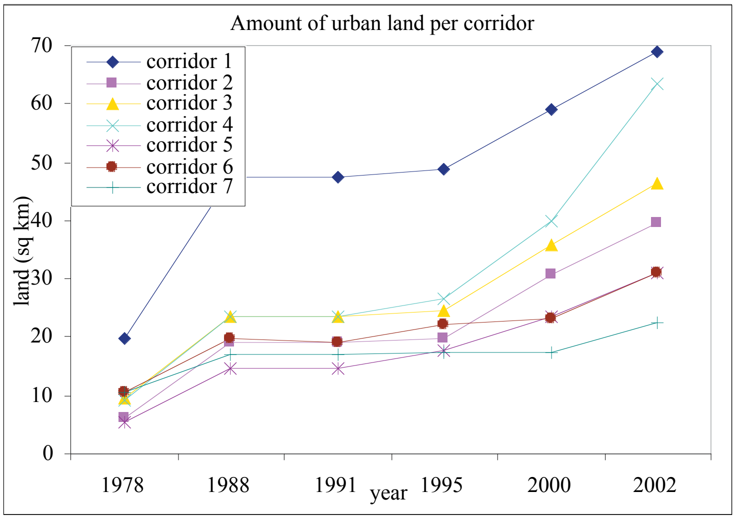


Figure 14: Map of seven corridors extending from Chengdu city to county-level cities.

and growth patterns of each corridor are discussed in the following sections.

Corridor 1 NE to Mianyang

The first corridor extends 38 km toward Mianyang municipality, northeast of the Chengdu urban core. This corridor is set apart by an early rise in amount of urban land (Figure 15), attributed to the fact that the corridor between Chengdu and Mianyang was the site of heavy state-owned industry, much of it related to the defense industry, during the 1960s and 1970s. Miangyang (outside the study area) is still a major manufacturing center, including the site of the world's largest television manufacturing facility. However, this former advantage (heavy investment in SOEs) has become a disadvantage, as the driver of the region's (and China's) economy has switched to the private sector. Corridor 1 contains the largest amount of urban



				amount urban (km^2)					
corr	**direction**	**length (km)**	**area (km^2)**	**1978**	**1988**	**1991**	**1995**	**2000**	**2002**
1	**NE to Mianyang**	38.0	189.5	19.72	47.46	47.52	48.78	59.06	69.15
2	**NW to Dujiangyan**	42.0	169.7	6.22	18.96	19.00	19.83	30.79	39.72
3	**W to Chongzhou**	40.2	163.3	9.56	23.62	23.64	24.49	35.89	46.59
4	**SW to Shuangliu**	39.6	177.9	9.37	23.54	23.53	26.63	40.01	63.38
5	**S to Meishan**	19.3	85.7	5.56	14.63	14.63	17.80	23.57	31.24
6	**SE to Chongqing**	23.2	94.9	10.65	19.68	19.24	22.15	23.17	31.11
7	**E to Nanchong**	32.4	127.1	10.58	17.21	17.22	17.35	17.36	22.48

Figure 15, Table 15: Amount of urban land per corridor (sq km) for each date. Length of each buffer is provided in the first column.

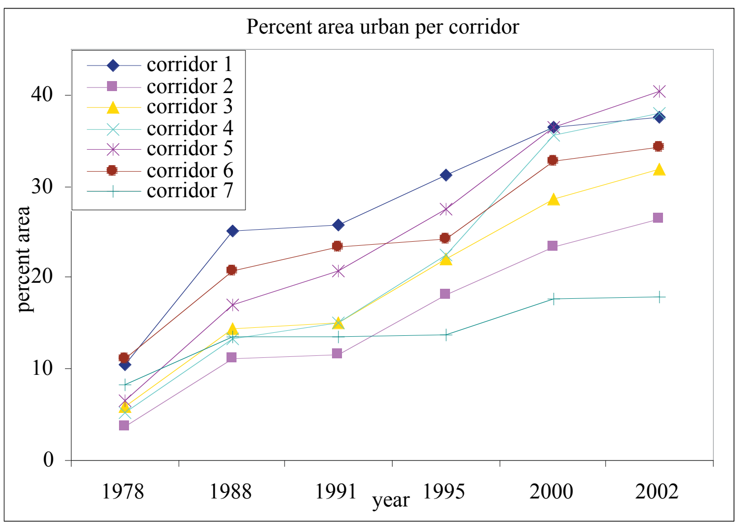
land of any of the corridors, primarily due to the presence of three satellite cities: Xindu, Qingbaijang, and Guanghan. All three of these cities are associated with heavy industry SOEs established several decades ago. Satellite city development to house heavy industry was the norm during the 1970s, and these three centers typify this type of development. Each of these cities has increased in area, and several roads connecting the cities to one another and to Chengdu were completed in the early 1990s. Urban land conversion has not occurred contiguous to Chengdu, but rather within 0.5 km of the road and in ring fashion around the three satellite cities. Land northeast of Chengdu is swampy, and decreased land conversion may be the result of added cost to fill land before construction begins. Analysis of the satellite imagery and fieldwork revealed that very few sites have been filled in this manner, and these relatively expensive conversions have occurred only during the last two years. Completion of the highway to Xindu after 1995 facilitated movement and growth beyond the waterlogged area, spurring land conversion farther from the city rather than in a more contiguous manner.

Corridor 2 NW to Dujiangyan

In contrast, Corridor 2 has undergone urban land conversion more proximate to the Chengdu urban core, within five km of the city's edge in Jinniu District and near the County Seat of Pixian. Although the corridor extends 42 km to Qing Cheng Mountain, the birthplace of Taoism, and the location of the Wolong giant panda nature reserve, urban expansion along the corridor is minimal past Pixian city (10 km from Chengdu city). Construction of an expressway during the late 1990s facilitated travel directly from Pixian to Dujiangyan and the cultural sites, and may have limited further peri-urban development along the corridor while at the same time enabling Dujiangyan (a district with approximately 600,000 people) to grow faster. Corridor 2 also contains a high-tech zone, the West Chengdu National High-Tech Development Zone (approximately halfway between Pixian and the city center), which has driven large increases in urban land conversion in its vicinity from 1991 onward and sustained high levels of conversion until 2002. As growth continues, it is clear that the site of this national high-tech zone will be enveloped by Chengdu to become part of the contiguous built-up city. New industry and commerce are located within a rectilinear street pattern in this high-tech zone, cleared in the early 1990s of older buildings, houses, and villages. Field analysis revealed a number of new apartment buildings in the area, although many of the buildings constructed in the last two years remain empty, suggesting an investment bubble.

Corridor 3 W to Chongzhou

Corridor 3 encompasses changes in Qingyang District (within Chengdu city) and Wenjiang



corr	direction	length (km)	area (km^2)	percent area urban 1978	1988	1991	1995	2000	2002
1	**NE to Mianyang**	38.0	189.5	10.40	25.04	25.76	31.16	36.49	37.50
2	**NW to Dujiangyan**	42.0	169.7	3.67	11.17	11.68	18.14	23.40	26.33
3	**W to Chongzhou**	40.2	163.3	5.86	14.47	15.01	21.99	28.54	31.90
4	**SW to Shuangliu**	39.6	177.9	5.26	13.23	15.00	22.49	35.62	37.91
5	**S to Meishan**	19.3	85.7	6.49	17.08	20.78	27.51	36.46	40.31
6	**SE to Chongqing**	23.2	94.9	11.22	20.74	23.34	24.34	32.78	34.30
7	**E to Nanchong**	32.4	127.1	8.32	13.53	13.65	13.66	17.68	17.92

Figure 16, Table 16: Amount of urban land per corridor, normalized by total area of the corridor (second column).

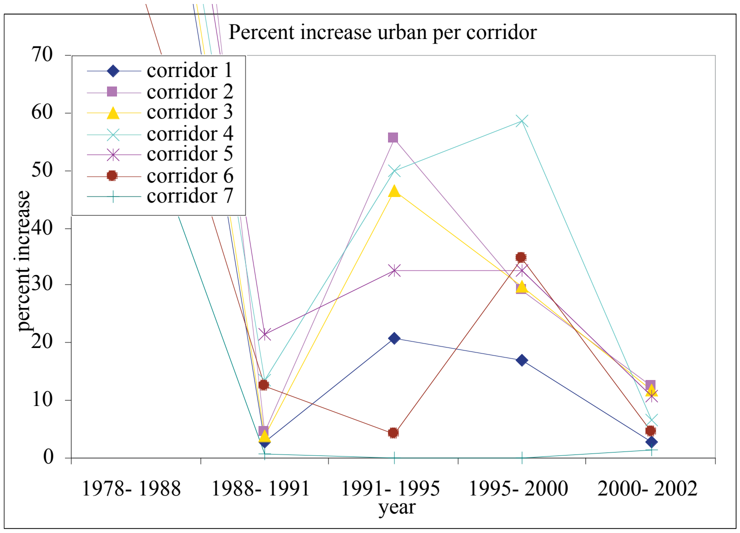
and Chongzhou counties. Distinguished by urban land conversion throughout the buffer, the third corridor has the highest level of conversion of roadside land along its 40 km length of the seven corridors studied. Trends in increase in urban land, both in terms of absolute and percentage increases (Tables 15, 17) follow a similar pattern to those seen in Corridor 2, with a sharp rise in land conversion in 1995 after key roads were paved and widened. New developments include a mix of residential buildings typical of peri-urban areas in China, such as new villas for farmers, a number of new suburban-style housing complexes, and small industry such as garment and shoe factories, and printing firms. Investment in urban infrastructure is evident in both Corridors 2 and 3, particularly in county seats where new streets are clean and wide, landscaping is extensive, and older buildings and heavy industry are noticeably absent. Moreover, land along the main road through Corridor 3 is accessible at many crossroads, unlike most other corridors. This difference is perceptible when compared to new roads in the east and northeast, where exits are few and tolls are charged, decreasing accessibility to the land except near expressway exits/entrances. Increased access likely accounts for the high level of development adjacent to the highway along the length of Corridor 3. If access to the highway defining Corridor 3 is severely limited in the future, land development dynamics may change by becoming more concentrated (aggregated).

Corridor 4 SW to Shuangliu

The fourth corridor (to the southwest) is by far the leader in urban land development, including accelerated growth in Wuhou District (in Chengdu city) and expansion of Shuangliu and Xinjin. There has been a 150 percent increase in urban land in Corridor 4 since 1991 (Table 17). Economic development associated with airport, industrial and commercial expansion, and highway construction have combined to drive land conversion, both within and near the Chengdu urban core and near Shuangliu City. The few remaining agricultural plots are patchy and small scale, and several sites have been leased for specialized food production (e.g., mushrooms) as opposed to rice/wheat or local subsistence production. In other cases, proximity to industry and employment has affected cropping cycles as well, since farmland is now planted with one crop of rice per year rather than multiple crops of rice, wheat, and vegetables.

Corridor 5 S to Meishan

The southern corridor to Meishan represents a continuation of urban development in Wuhou District, as well as development in Jinjiang District (both within Chengdu city) and Huayang in southern Shuangliu County. Land conversion was high following completion of a major highway extending south to Meishan in 1995. Meishan is an area of considerable economic activity for example, it is the headquarters of Motorola's western China operations. Dominated by the Fuhe River, agriculture remains a significant land use due to rich soils and accessible irrigation water. Intermixed with agricultural plots are a number of small industries, including a new cluster of small-scale timber companies and several furniture manufacturers. Land along the major roads is still occupied by older buildings built in the 1980s or earlier, and streets are narrower and less manicured than to the west. Growth in Corridor 5 near Chengdu has been more leapfrog in character than in other corridors (particularly Corridor 3), as the city expands its edge and envelops nearby towns in the Jinjiang District. Development of parks along the riverfront and efforts to make the river clean and navigable have led to new building since 2000, notably new apartments opposite the River Viewing Park and roadside commercial buildings past the third ring road.



corr	direction	length (km)	area (km^2)	percent increase for each period 1978-1988	1988-1991	1991-1995	1995-2000	2000-2002	1991-2002
1	NE to Mianyang	38.0	189.5	140.68	2.89	20.96	17.07	2.78	45.55
2	NW to Dujiangyan	42.0	169.7	204.70	4.57	55.29	28.99	12.50	125.35
3	W to Chongzhou	40.2	163.3	147.01	3.78	46.44	29.80	11.77	112.46
4	SW to Shuangliu	39.6	177.9	151.27	13.41	49.90	58.39	6.44	152.73
5	S to Meishan	19.3	85.7	163.18	21.65	32.40	32.52	10.57	94.01
6	SE to Chongqing	23.2	94.9	84.76	12.57	4.25	34.68	4.63	46.91
7	E to Nanchong	32.4	127.1	62.69	0.83	0.07	0.00	1.33	31.32

Figure 17, Table 17: Percent increase of urban land by corridor for each period. Increase during the previous decade (1991–2002) is shown in the last column.

Also included within this corridor is Huayang city, the nearest of the six satellite cities to Chengdu city. Huayang has quadrupled its area since 1988, becoming not only a scenic area with restaurants, pedestrian walkways, and parks along its northern edge on the Fuhe River, but also an industrial center, supported by the opening of a new highway linking Huayang to the Longquanyi industrial area east of Chengdu.

Corridor 6 SE to Chongqing

The sixth corridor stretches 23 km to Longquanyi, a small district city designated a special economic zone in 1995. Despite substantial growth of Longquanyi and construction of a rectilinear road complex west of the city (the site of the industrial park), land conversion along the corridor is confined to within 0.5 km of the road and has tapered off following the 1995–2000 push (35 percent increase during 1995–2000, 4 percent increase during 2000–2002, from Table 17). Agricultural land use dominates Corridor 6 throughout the twenty-five-year study period, distinct from other areas. Much of the agriculture is high value, particularly peach orchards. There is a growing eco-tourism industry based on scenic tours and hotel stays among the orchards. Although this may limit urban land conversion in the orchard areas itself, spillover effects from the associated amenity image are likely to support urbanization in Longquanyi itself, and the adjacent economic, technological development zone (ETDZ). Following completion of a new expressway from Longquanyi to Chongqing in the early 1990s, the corridor currently extends to Xintang County, 20 km past Longquanyi. Urban development past Longquanyi is limited, however, by a north-south mountain range.

Corridor 7 E to Nanchong

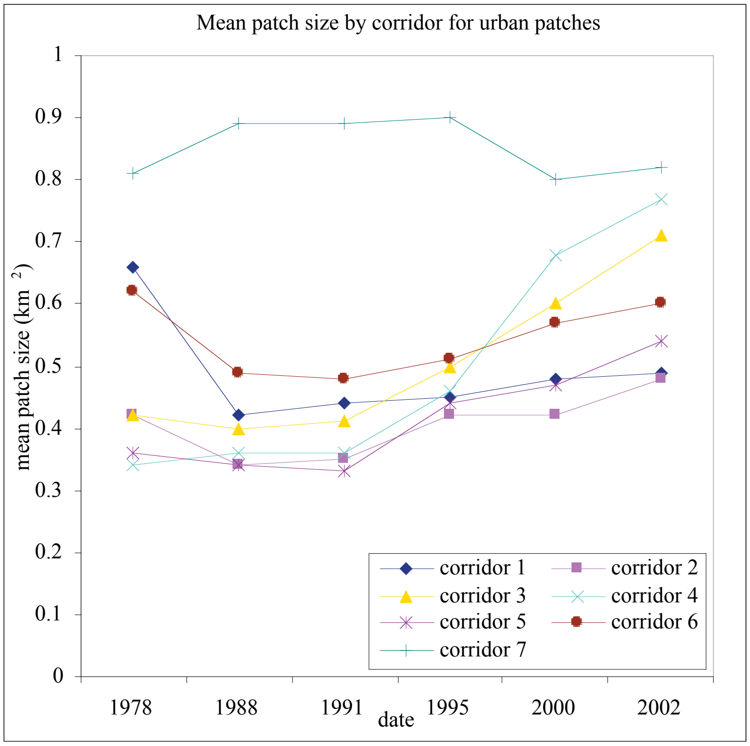
With an increase in urban land of only 31 percent from 1991 to 2002 (Table 17), the seventh corridor exhibits the least amount of urban development. Extending east, Corridor 7 includes several small towns and villages, and a new industrial zone two km from the edge of the Chengdu urban core built-up area. The expressway to Nanchong, completed in 2000, facilitates trade and commerce with neighboring municipalities, but has brought little growth to this corridor. Urban growth is lower due to the absence of a satellite city within the corridor, as in each of the other six corridors. Road construction and municipal investment are high, although the corridor does not have urban infrastructure in place west of the city (such as widened streets) to draw investment, especially FDI. Field assessments revealed that manufacturing in the area is primarily heavy industry, and no new residential housing or smaller industries are present. There are compelling underlying reasons for the lack of development in this corridor. These include the fact that agricultural land capability in the corridor is very poor, therefore locals over the last several decades have been unable to accumulate household surpluses to establish small businesses or build better housing (such as villas). This contrasts with the situation west of the city, where quality of agricultural land is much higher. Second, the northeast quadrant of Chengdu has long been known for heavy, polluting industry, and this negative image (exacerbated by the fact that the area is downwind of formerly industrial northeast Chengdu) has been transferred to the corridor.

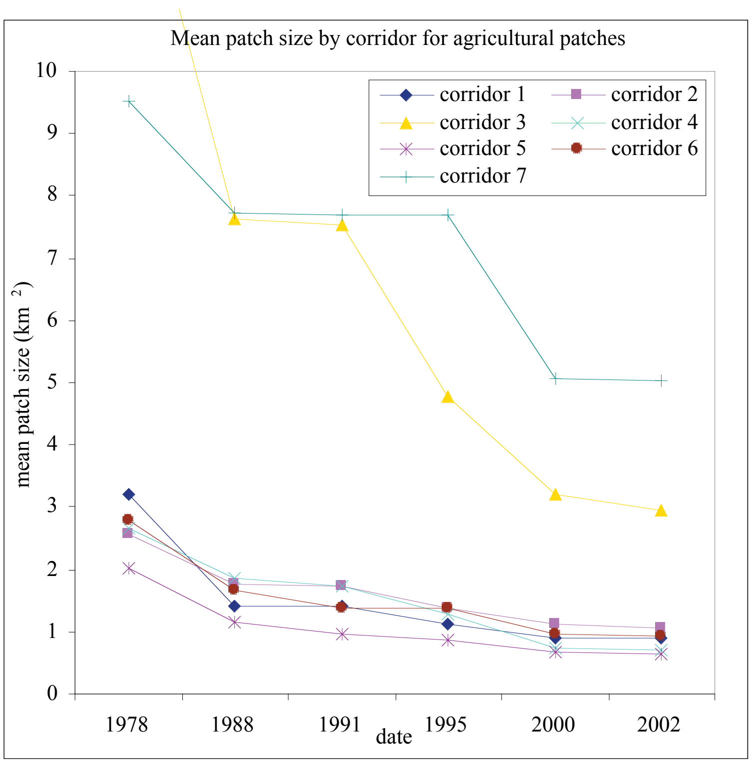
Spatial pattern metrics

In addition to quantifying amounts of land urbanized in each corridor over time, it is possible to quantify the evolution in urban form using spatial pattern metrics or indices. These metrics provide a quick characterization of the spatial patterns of (a) whole landscapes, (b) land cover types within landscapes, or (c) specific *patches*, or contiguous areas of a given land cover type within the landscape. For this analysis, the *landscape* is defined by the area within the corridors outlined in Figure 14. The basic assumption of this approach is that corridors with differing economic and demographic structures will result in different distributions of built-up land and agricultural land. Accordingly, the spatial metrics provide additional information to those described in the previous tables and figures.

Two simple spatial pattern metrics were selected based on their information content and suitability for analysis of changing urban areas: mean patch size and landscape shape index. Results of the two metrics are presented in Figures 18 and 19.

Mean patch size (MPS) is a fundamental aspect of the landscape pattern, since it conveys the size of contiguous area of a given land cover type within each corridor. If the patches of contiguous urban land are small, for instance, MPS will be low, indicating that the corridor contains fewer uninterrupted urban areas. In contrast, if the plots of continuous urban land are large in area, such as in central business districts or areas of continuous urban growth, MPS will be high. Throughout the twenty-five-year time period, MPS for all





Figures 18a and 18b: Mean patch size (MPS) for urban areas in each corridor (a) and for agricultural areas of each corridor (b).

corridors remains quite low (Figures 18a and 18b), below one km^2, indicating that overall urban areas are small and patchy in nature.

Corridor 7 to the east (Figure 18a, top trend line) has experienced a very different pattern of urban development than the other corridors. Very little land has been converted to urban uses within the corridor, so only the urban land contiguous to the Chengdu urban core has been analyzed for its patch size, resulting in a greater than average mean patch size. Mean patch size drops slightly after 1995, however, as growth begins in a new industrial area outside the city. The remaining six corridors experience drops in MPS in 1988, indicative of discontinuous, patchy urban form after 1988 and 1991. MPS increases in 1995, and all six corridors climb until 2002, a positive sign. (To some extent this is statistically expected. After many patches have been formed, it is more likely that new growth attaches to existing patches, rather than starting new patches that result in a higher MPS reading.) Corridors 3 and 4 (west and southwest) reach high values after 1995, as the areas between urban patches fill in and the city again becomes more continuous in form.

As a corollary, MPS for agricultural areas is examined in Figure 18b. The results are as expected: as urban areas increase and become more continuous, agricultural plots decrease in size and become less continuous. All seven corridors witness declining agricultural patch sizes, although the magnitude of the agricultural plots is different than for urban plots. The mean agricultural land size is well above 1 km^2, averaging 2 km^2 for Corridors 1, and 2–6, and above 3 km^2 for Corridors 3 and 7. Corridor 3, for example, drops from a mean agricultural plot of 16 km^2 in 1978 to less than 3 km^2 in 2002. This result clearly corroborates the rapid growth of urban land throughout the length of Corridor 3.

The *Landscape shape index (LSI)* provides a standardized measure of the perimeter length of all patches of one land cover type in the landscape (i.e., the sum of the "edge" of all patches). LSI indices provide a measure of (1) how much land has been developed (since the metric is not standardized by total area), and (2) how irregular the urban form is, or in other words, if the corridor is becoming more irregular and discontinuous over time (increasing LSI), or more continuous (decreasing LSI). LSI increases without limit as landscape shape becomes more irregular and/or as the perimeter length of the patches increases.

Differences in shape index over time (Figure 19) are quite subtle for all seven corridors. All increase slightly during the study period, although drastic changes are not evident in any of the corridors. This slight increase indicates a greater number of urban patches, as well as increasing scattering of development. Corridors 1, 2, 4, and 5 (the top four trend lines) have the highest LSI; these areas contain the longest urban perimeter and hence more complex shapes. Corridors 1, 2, 3, and 4 rise more sharply than Corridors 5, 6, and 7, suggesting these areas have increasing complexity in urban form. This result validates the map results, confirming Corridors 5, 6, and 7 (south and east) have undergone less land conversion and, associated with this dynamic, exhibit less patchy development.

3.3.5. Urban Land Dynamics within Ring Roads

Classic theories of urban morphology describe urban form as a series of concentric zones or rings with differentiated functions within each zone (Park et al.1925). These ideas were later modified to include sectoral and nuclei development related to transportation infrastructure (Hoyt 1939, Harris and Ullman 1945). Accordingly, we have assessed Chengdu's urban development utilizing a concentric ring framework to determine the rate of urban expansion outward from the core, as well as the nature/structure of land conversion within each ring.

In the case of Chengdu city, concentric rings for analysis are best delineated by the

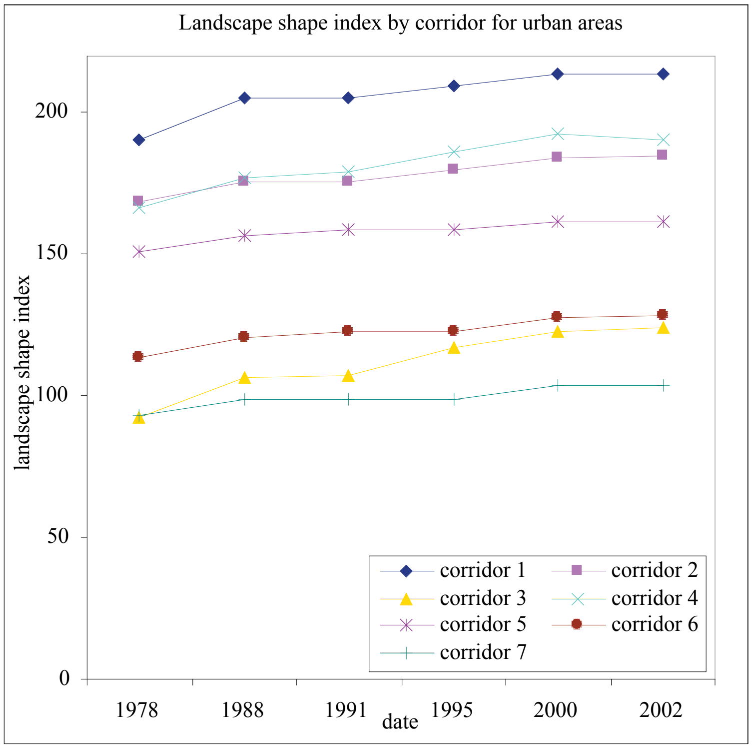


Figure 19: Landscape shape index (LSI) for urban areas in each corridor.

ring roads built during the period 1978–2002 (Figure 20). The first ring road around the city was completed prior to 1978, and satellite imagery from 1978 indicates that the area within the road was completely converted to urban uses by this time (Figure 4a). A second ring road was completed by 1988, and is visible as new urban land (red) in the map from this period (Figure 4b). Of interest is the addition of third and fourth ring roads after 1995, built partly in response to the accelerated growth of the city. In addition to the area within the second, third, and fourth ring roads, a final ring can be drawn along highways connecting the ring of satellite cities circling Chengdu city.

The area within the second ring road (Figure 20, ring A) is the most developed of all rings, encompassing the core downtown area. This area has been contiguously urban since 1988, as evident in Figure 20 and Tables 21, 22, and 23. As such, the amount of urban land has increased only slightly, from 90 percent in 1978 to currently more than 97 percent in this area (Table 21). The remaining 3 percent is comprised of parks and water bodies, land- uses which most likely will not be converted to urban in the future.

Outside the second ring road (ring B), land conversion has increased rapidly since 1978. This ring contains the largest amount of urban land of the outer three rings until 2002, when it was eclipsed by the area outside the third ring road (ring C). When the amounts of urban land (Table 22) are normalized by the ring area, it is clear that ring B is more urbanized (78 percent) than ring C (30 percent). This is as expected. Development is essentially occurring outward from the center of the city. The rise in urban land use within ring B occurred early (82 percent increase 1978–88), with strong pushes during the 1991–95 and 1995–2000 periods (Table 23).

Ring C remains dominated by farmland, although patchy urban areas have increased during the study period, from 2.7 to 30.6 percent (Table 22), an increase of over 1,000

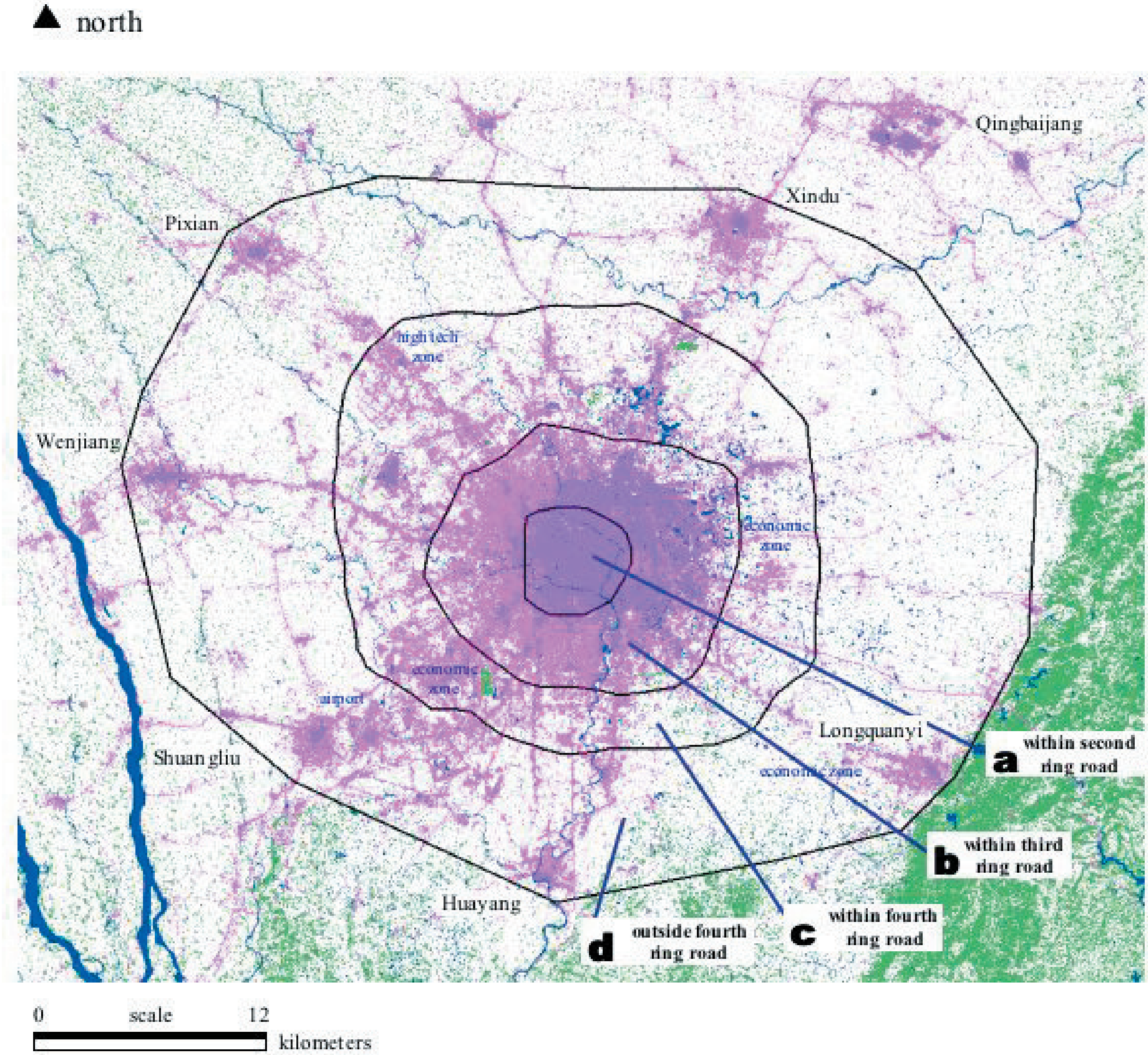
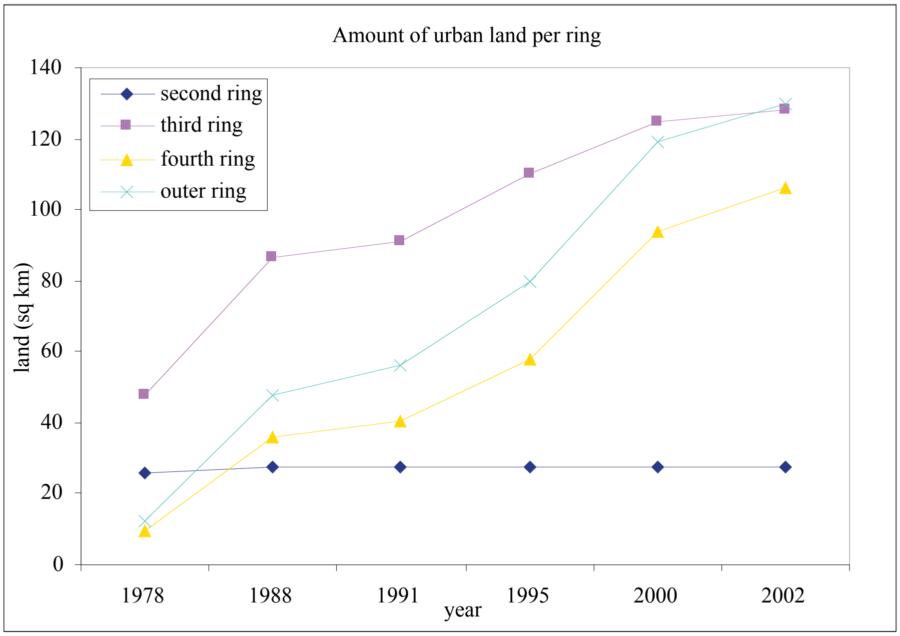


Figure 20: Map of four rings (a through d) encompassing Chengdu city and its nearby satellite cities.

percent. The majority of growth within ring C has occurred along transportation lines, within the seven corridors previously discussed as well as along five additional radial spokes. The third ring road was completed in 2001 and the fourth ring in 2002, with an additional 4 percent of land within these roads converted in the last two years alone. Given the increase in accessibility, a large percentage of the apartment buildings built in Chengdu since 1995 have been located in ring C, primarily in the northwest and southwest quadrants of the ring. These quadrants also continue to attract new industrial and commercial activities that locate not only in designated zones but also overflow into nondesignated areas (such as agricultural areas).

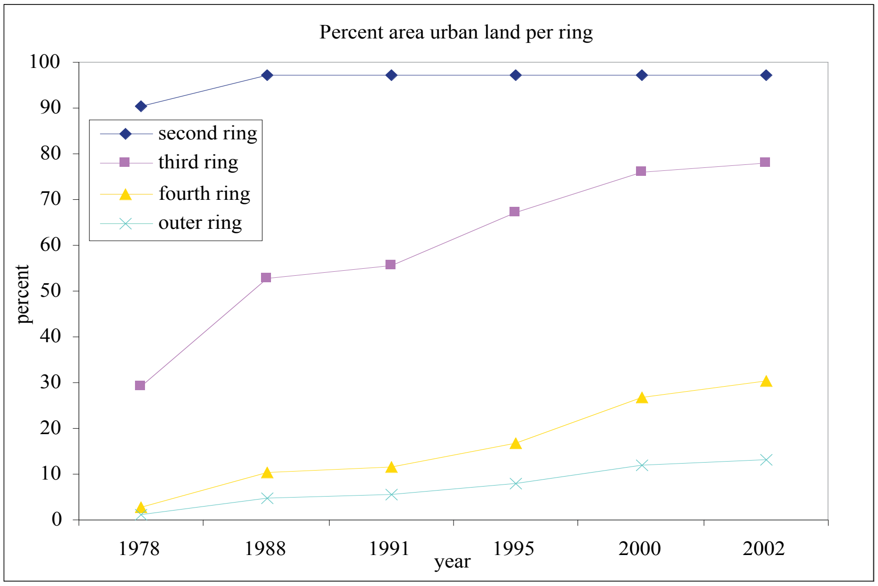
Although predominantly farmland, land conversion along transportation corridors and near satellite cities has begun to transform land within the outer ring (ring D) to



			amount urban (km^2)					
ring	**location**	**area (km^2)**	**1978**	**1988**	**1991**	**1995**	**2000**	**2002**
A	**within second ring**	28.31	25.60	27.49	27.50	27.51	27.52	27.52
B	**within third ring**	163.81	47.68	86.62	90.85	110.21	124.58	128.07
C	**within fourth ring**	348.31	9.44	36.05	40.21	58.15	93.68	106.52
D	**outside fourth ring**	992.66	12.45	47.97	56.26	79.97	119.20	129.73

Figure 21, Table 21: Amount of urban land per ring (sq km) for each date. Area of each ring is provided in the first column.

urban uses. Percentage increases in urban land (Table 23) appear far greater for rings C and D because both rings contained little urban land (less than 2 percent of the land area) at the beginning of the study period. These areas still contain only small amounts of urban land relative to their overall areas, but urban land has increased by 165 and 131 percent, respectively, in the last decade alone (1992–2002). The most significant urban land conversion push is evident in the 1995–2000 period, facilitated by the completion of many new roads during those years. It is unlikely that the vast area within ring D will ever be converted to urban use completely (given that urbanization demographic pressures will decrease dramatically during the second half of the twenty-first century), although more than 13 percent of its area has already been built up. As the satellite cities grow, and the Shuangliu corridor expands further, the percentage of land in urban uses will continue to rise.



			percent area urban					
ring	location	area (km^2)	1978	1988	1991	1995	2000	2002
A	second ring	28.31	90.42	97.11	97.14	97.17	97.22	97.22
B	third ring	163.81	29.10	52.88	55.46	67.28	76.05	78.18
C	fourth ring	348.31	2.71	10.35	11.54	16.70	26.89	30.58
D	outside fourth ring	992.66	1.25	4.83	5.67	8.06	12.01	13.07

Figure 22, Table 22: Amount of urban land per ring, normalized by total area of the ring (first column).

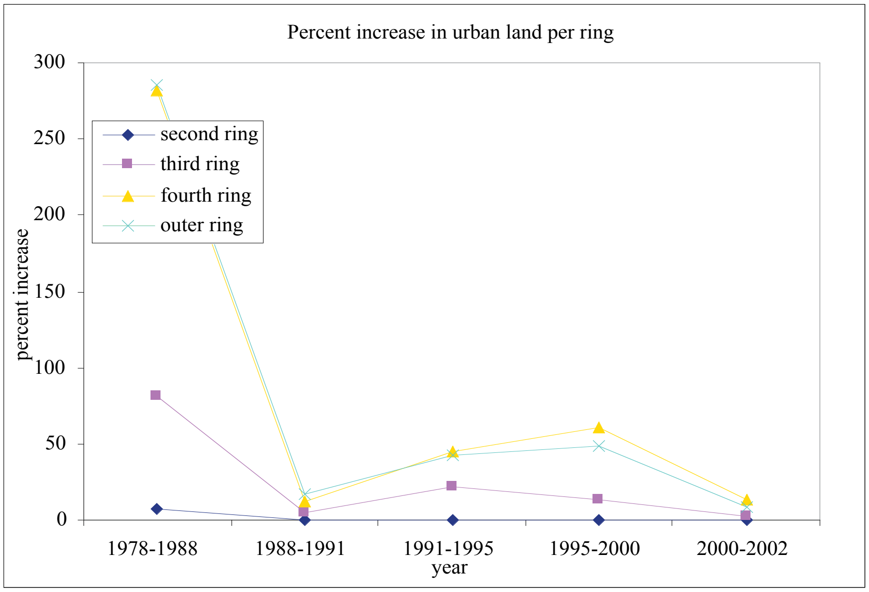
4. Summary of Findings

Our main findings can be summarized as follows:

(i) Urbanization in the Chengdu extended urban region is primarily occurring to the northwest, west, and southwest, and has been doing so since the early 1990s. Before 1990, development was more balanced and multidirectional in orientation. Notably, the current pattern of growth directly contradicts official physical plans for the municipality, which advocate physical development to the east, and especially the southeast.

(ii) Urbanization has been and continues to be radial in orientation, extending outward from the Chengdu urban core along key highways and expressways. To date, ring roads appear to be playing a lesser role in shaping development than in some other Chinese cities, particularly Beijing. The future role of the ring roads in shaping the urban form of the extended Chengdu region remains to be seen.

(iii) Related to the foregoing, corridors extending radially from Chengdu have been the sites of the most land conversion to urban uses, although different urban patterns are perceptible within each of these axes. Corridors 2 and 3 (northwest and west), for instance, present patchy urban expansion throughout the extent of the corridor due to increased accessibility to land along major roads. Corridor 4, however, exhibits densification near Chengdu as



			percent increase for each period					
ring	location	area (km^2)	1978-1988	1988-1991	1991-1995	1995-2000	2000-2002	1991-2002
A	**second ring**	28.31	7.40	0.03	0.04	0.05	0.00	0.09
B	**third ring**	163.81	81.68	4.89	21.31	13.03	2.81	40.96
C	**fourth ring**	348.31	282.02	11.55	44.62	61.09	13.72	164.93
D	**outside fourth ring**	992.66	285.35	17.28	42.14	49.05	8.83	130.57

Figure 23, Table 23: Percent increase of urban land by ring for each period. Increase during the previous decade (1991–2002) is shown in the last column.

a result of airport development and new industrial expansion. Spatial pattern metrics corroborate these results, providing a means to quantitatively measure dispersion of the city along corridors.

(iv) Although we have data on conversion of agricultural land to urban uses, we lack detailed spatial data on farming systems and the value of farm output. However, based on satellite imagery and field observations, the impacts of peri-urban development appear to induce different effects in different areas. For example, as illustrated in the case of Corridor 4 (to Shuangliu) we see clear intensification of agricultural production (through market, access, and other effects), such as the growing of high-value mushrooms. In the same corridor, however, peri-urbanization seems to have also resulted in agricultural land near built-up areas not being cultivated, even though it has not yet been urbanized. This effect is probably the result of speculative impacts.

(v) Based on our indices of patchiness, development became increasingly scattered in most of the peri-urban area until 1995, but this trend may be reversing. In areas near the Chengdu urban core, particularly to the southwest (Corridor 6) near Shuangliu, scatter (patchiness) is reducing through significant in-filling and development contiguous to built-up areas. Patchiness is particularly the case where access to highways is not controlled and in newly opening up areas, such as the area beyond the fourth ring road.

Less stringent planning and building controls associated with the rise of land markets, and the decentralization of planning and building permit controls to the county/district level are also contributing to patchiness. The fact that the peri-urban economy and landscape are shaped to a significant extent by the private sector (both firms and purchasers of private residences) creates a further disconnect between the physical form objectives of the municipality and actual spatial behavior. In the past (1960s and 1970s), when Corridor 1 was the main agent of peri-urbanization, the regional economy was driven by SOEs.

(vi) Many of the satellite towns that were established in the 1970s are still important anchors of growth in the peri-urban area. However, other key drivers of development have joined satellite towns to shape peri-urban structure. In particular, highways connecting these satellite towns to Chengdu city (and recently to each other) drive physical growth, and create corridors as wide as 2 km alongside them. The Shuangliu airport indirectly encourages physical development more than the satellite towns. Moreover, high-tech facilities on the edge of Chengdu, particularly the West Chengdu National High-Tech Zone, have played a considerable role in driving development to the northwest.

(vii) Although our information base limited analysis of differentiation to within the urban fabric, there is clearly increasing specialization, in terms of land- uses and growing socioeconomic differentiation within the residential land market. For example, luxury condominiums and gated communities are concentrated in the west and southwest, in nearby counties of Shuangliu, Wenjiang, and Pixian.

This differentiation results from increased overall specialization in the extended urban region's economy, which in turn is being fostered by large-scale economic clusters and the creation of specific industrial zones. In addition, the privatization of housing (with the concordant demise of the workplace community) has brought about much greater separation of place of work and residence. However, much of this dynamic builds on past realities and trends. For example, northeast Chengdu (Chenghua District) and the eastern edge of the city have been a less desirable residential location for many years, based on their reputation as locations of heavy industry.

(viii) A key development is the rise of significant peri-urban residential communities, frequently within, adjoining, or near satellite towns. In particular, Wenjiang and Huayang cities contain large planned residential communities. Many of those who live in these communities work in Chengdu city (with its strong and rapidly growing service and high-tech economy), creating significant commuter flows.

(ix) Poor agricultural conditions may inhibit peri-urban development. However, this is a hypothesis, rather than a finding. For example, in the Nanchong Corridor (7), peri-urbanization is limited. It may be that subsistence agricultural conditions do not generate household income surpluses to drive bottom-up peri-urban development, such as the establishment of small and medium enterprises (SMEs), or the construction of villas. On the other hand, Corridor 2 (to Pixian and Dujiangyan) is known for the high quality of it agricultural land; considerable bottom-up peri-urbanization is therefore evident in this corridor by farming communities with large numbers of villas. If this hypothesis proves true, agricultural land around large Chinese cities will continue to come under strong urbanization pressure, not only because it is flatter and easier to develop, but also because local residents have more capital available to drive bottom-up peri-urban change.

5. Land Use Planning and Policy Implications

The land use planning and policy implications of this, and related, research on peri-urbanization in Chengdu are more fully examined in a companion discussion paper entitled *Peri-Urbanization Development Dynamics in the Chengdu Extended Urban Region: Impacts, Adaptation, and Policy Implications* (Webster 2003). Planning issues examined in that paper related to the foregoing analysis include:

(i) How can physical planning in Chengdu and elsewhere in China better incorporate economic drivers into physical planning processes? For example, trying to push development to the east in Chengdu is rational in the sense that such urban expansion would be onto lower capability farmland, and where water supply constraints and cultural heritage areas are not a concern as in the west. At the same time, the location of the airport, the major high-tech park, and the existence of significant rural household surpluses that drive bottom-up peri-urbanization, all of which are driving development to the west, have made the official plan largely unobtainable. There is obviously a need to better integrate key economic investments, local economic development processes, knowledge of economic drivers, and physical/land use planning.

(ii) Satellite cities were originally built to intercept heavy industries being moved from remote areas to the coast, thereby retaining them in western China. In this role, they have been quite successful. However, now that the economy of the extended urban region is changing significantly, the role of the satellite towns is evolving rapidly. Should the satellite cities continue to play an important role in shaping the extended urban region, acting as bedroom communities, centers of light industry, etc.? Or should development be increasingly encouraged contiguous to the Chengdu urban core, which is likely to be more energy, environmentally, and human time efficient?

(iii) Regardless of the extent of satellite city growth, it is clear that considerable numbers of people do, and will, live in satellite cities, many of them commuting to the Chengdu urban core on a daily basis. How can this be done in a manner that is economical of human time and energy resources? In the Shuangliu Corridor case, a light rail system may be feasible. In the other corridors, this is probably not feasible, at least in the short run. Options such as high occupancy vehicle (HOV) lanes should be implemented to give preference to buses and other efficient people carriers.

(iv) Zones C and D (Figure 20) are of major concern in terms of urban planning, since this is where the bulk of new development will occur. The municipality's recent announcement that they will build two very large "new towns in town" in this area (one to the south, and one to the southeast) indicates that even more urbanization will occur in these zones over the next twenty years than would otherwise be the case. Since the extended urban region's population growth is limited, this development is likely to be at the expense of the satellite cities and the corridors connecting them to the city proper.

In Zones C and D, every effort should be made to encourage compact, relatively high-density development around definable community/town centers (as is being proposed by the municipality). To the extent possible, highly productive farmland should be retained. River frontage, and ecologically and aesthetically noteworthy landscapes should be retained as parkland (as is municipal policy).

(v) It is obvious that the old building blocks, e.g., ETDZs based on manufacturing (especially SOEs), are losing relative power in shaping the extended urban region to new drivers, such as airports, high-tech areas, and vibrant bottom-up clusters (such as the shoe cluster). This situation should be accepted and built into public processes to shape the extended urban region.

(vi) Overbuilding peri-urban infrastructure should be avoided because:

(a) The nature of the extended urban region's economy is changing, becoming more oriented to services, high-tech industry, aviation, and tourism. Unlike dominantly manufacturing cities (such as Chongqing), such an urban economy results in fewer peri-urban pressures.

(b) Plans by the municipality, if implemented, to develop "new towns" contiguous to the built-up area to house over two million people, will result in less pressure on the peri-urban area.

(c) In the long run (second half of the twenty-first century), demographic pressures on Chengdu (and on most Chinese cities) will be substantially reduced as a result of reduced rural-urban migration and natural population effects (an aging population).

(vii) Since 1992, many land use planning and building permit functions have been decentralized to the district/county level. Although there are many advantages to such decentralization (e.g., bringing urban planning processes closer to the people), there are also disadvantages, such as the ability to see and plan for the extended urban region as a whole. Currently, the municipality is reviewing the level of urban planning decentralization. What appears to be needed is a layered system. Such a system would keep aspects of the planning process that affect people (e.g., community design) close to the people, while also retaining and strengthening the municipal-scale regional planning function that corresponds to the geographic scale of the region's economy.

Decentralization has been a factor in the overbuilding of infrastructure in parts of the peri-urban area. Each district/county expects faster than average demographic and economic growth and attempts to build infrastructure for this eventuality.

(viii) Tourism is more important in Chengdu than in other peri-urban areas of China. This is particularly the case along Corridor 2 to Dujiangyan (site of the famous ancient irrigation system, birthplace of Taoism, and home of the giant panda habitat). Since tourism generates heavy peak flows of tourists (summer, weekends) and requires high quality environments to be sustained, this characteristic of Chengdu's peri-urban area warrants particular attention.

(ix) Last, but not least, in-filling of land, within the contiguous city, on its edge, and in satellite towns, is key to sustainable development in the Chengdu extended urban region. This is already occurring along Corridors 2 and 4. Public processes should encourage in-filling rather than development of new patches.

6. Conclusions

The Chengdu extended urban region is changing rapidly. Its economy is evolving quickly to services, high-tech industry, education, and tourism, all complementing its traditional manufacturing base. At the same time, rural-urban migration is becoming easier through liberalization of the *hukou* system (i.e., household registration). Motorization is accelerating (Chengdu has one of the highest automobile ownership rates in China), while the urban region's role in southwest China continues to evolve, particularly in terms of competition and cooperation with Chongqing.

All these dynamics are affecting the Chengdu extended urban region's urban form. In this paper we have attempted to describe and interpret these changes, and introduce urban planning and development issues flowing from them. The latter are addressed in a companion discussion paper (Webster 2003), which brings more detailed socioeconomic data to bear on the physical form analysis put forward in this paper.

The stakes are high in terms of shaping physical form in the Chengdu urban region. It is clear that there are trade-offs involved, such as the question of whether to encourage contiguous development or satellite city formation. No matter which route is taken, much can be done to protect valuable farmland and water resources, minimize wastage of human time and energy, and increase levels of amenity within the urban region.

Globalization forces are still very weak in Chengdu (as measured by MNC presence, FDI, foreign tourists) compared with most other large cities in China. Forces at play are currently more domestic in nature. However, international forces are expected to play a greater role in shaping the extended urban region in the future, adding yet another important driver to the evolution of the urban region's economy and physical form.

Appendix A: Technical Methodology

A1. Background

Remote sensing data has been incorporated in studies of urbanization and its environmental effects for nearly two decades. The bulk of urban mapping research is primarily based on the recognition of consistent thematic patterns observable in relatively fine resolution remote sensing imagery (Jensen and Toll 1982, Longley and Mesev 2000). Often, these studies investigate the magnitude of growth in one city at a time, for purposes of environmental assessment and growth management.

Researchers have proposed a number of different methods to detect urban change (Singh 1989, Mas 1999). Supervised techniques—those that rely on training data or examples of landscape types used during map processing—include traditional maximum likelihood classifiers (Dimyati et al. 1996, Weng 2001, Seto et al. 2002), as well as new machine learning algorithms such as decision tree classifiers (Chan et al. 2001) and neural networks (Paola and Schowengerdt 1995, Liu and Lathrop 2002). Supervised methods suffer from one significant limitation: all require training data, and are only as effective as the quality of the training sites used.

Unsupervised techniques, on the other hand, which do not require training data, include image differencing and ratioing (Green et al. 1994, Sunar 1998), image regression (Ridd and Liu 1998), multidate clustering (Ehlers et al. 1990, Tadesse et al. 2001), multidate principal component transformation or other linear transformation (Li and Yeh 1998, Radberger 2000), and change vector analysis (Sohl 1999). Unsupervised methods, although computationally faster, require substantial time and expertise to label the final output.

A third option often used in change detection studies is post-classification change comparison, in which the images of each date are classified independently (using either unsupervised or supervised methods) and then the two maps compared (Xu et al. 2000, Yang and Lo 2002). This method can produce change maps with poor accuracy, however, since errors in the classified maps of each date are compounded in the new map.

A2. Methods

For this work, the identification of changes in urban areas was accomplished in three phases: (1) image preprocessing, (2) change detection using supervised methods, and (3) accuracy assessment. The study area is Chengdu municipality in Sichuan province, China (Figures 1, 4) and is covered by one Landsat TM scene. Eight images were acquired between 1978 and 2002 for WRS path 129, row 39 (Table A1).

The land cover classes of interest were determined by end user requirements. Since this research focuses on change of land to urban uses, the primary classes of interest were *stable*, unchanged areas of (1) urban, (2) natural vegetation, (3) agriculture, and (4) water, as well as areas newly converted to urban uses, or *change* land cover types (5–9, Table A2). Although several *change* classes were probable, image interpretation and on-site visits confirmed that only agricultural land has been converted to urban areas, and thus only five *change* classes were necessary. Conversion of other land cover types to urban uses was minimal and assumed to be negligible in this study.

A total of 1,052 training sites were selected based on field work in Chengdu in October 2002, ranging in size from one to ten pixels (900 to 8,000 sq m). Following the

Acquisition date	Landsat satellite
21 August 1978	3
1 May 1988	4
24 April 1991	4
16 August 1992	5
5 May 1995	5
2 November 2000	7
23 December 2001	7
7 October 2002	7

Table A1: Characteristics of Landsat images used in the study.

no.	*stable* classes	# sites	examples of land use	no.	*change* classes	# sites
1	urban and built up	185	industrial, commercial, residential areas,	**5**	agriculture to urban, 1988	40
			roads and transportation corridors	**6**	agriculture to urban, 1991	26
2	natural vegetation	51	parks, forests, greenspace	**7**	agriculture to urban, 1995	102
3	agriculture	222	rice, wheat, vegetable cropland, orchards	**8**	agriculture to urban, 2000	145
4	water bodies	24	rivers, lakes, reservoirs, fish ponds	**9**	agriculture to urban, 2002	46

Table A2: Stable and change land cover classes, and number of training sites for each class.

convention to train the classifier with 80 percent of the sample and test classifier accuracy with the remaining 20 percent unseen by the algorithm, 152 sites (~15 percent) were set aside for validation purposes (Section A2.3). The remaining 900 sites yielded 16,990 training pixels. Distribution of the 900 training sites among the *stable* and *change* classes is shown in Table A2.

A2.1 Preprocessing

Geometric correction was used during the first phase to ensure that the pixels of each image line up with one another in a common map coordinate system (Schowengerdt 1997). All images were registered to a master image using a second order transformation with 0.5 RMS error and nearest neighbor resampling. Accurate coregistration is imperative if images of different years are compared. Additional radiometric calibration was not necessary. The classification method used does not require reflectance values, but rather, can infer land cover change from relative changes in the DN values.

Preprocessing also included exploratory unsupervised clustering of land cover types in the six images. These initial results revealed significant confusion among different land cover types in different quadrants of the image. For example, dry riverbeds in the southwest quadrant were consistently confused with new urban areas in the northeast. To alleviate this confusion during classification (phase two), all six images were partitioned into four quadrants. These quadrants were delineated based on areas of common agricultural and vegetation types (Figure A1).

A2.1 Classification

The second phase of work included estimating the quantity and type of land use/land cover changes apparent in the images. One common problem when mapping urban change is the confusion between bare agricultural plots (which occur following harvest, during early stages of vegetation growth, and while fallow) and new urban areas. Both of these land cover types appear very bright in the infrared. In this research, the problem is further compounded

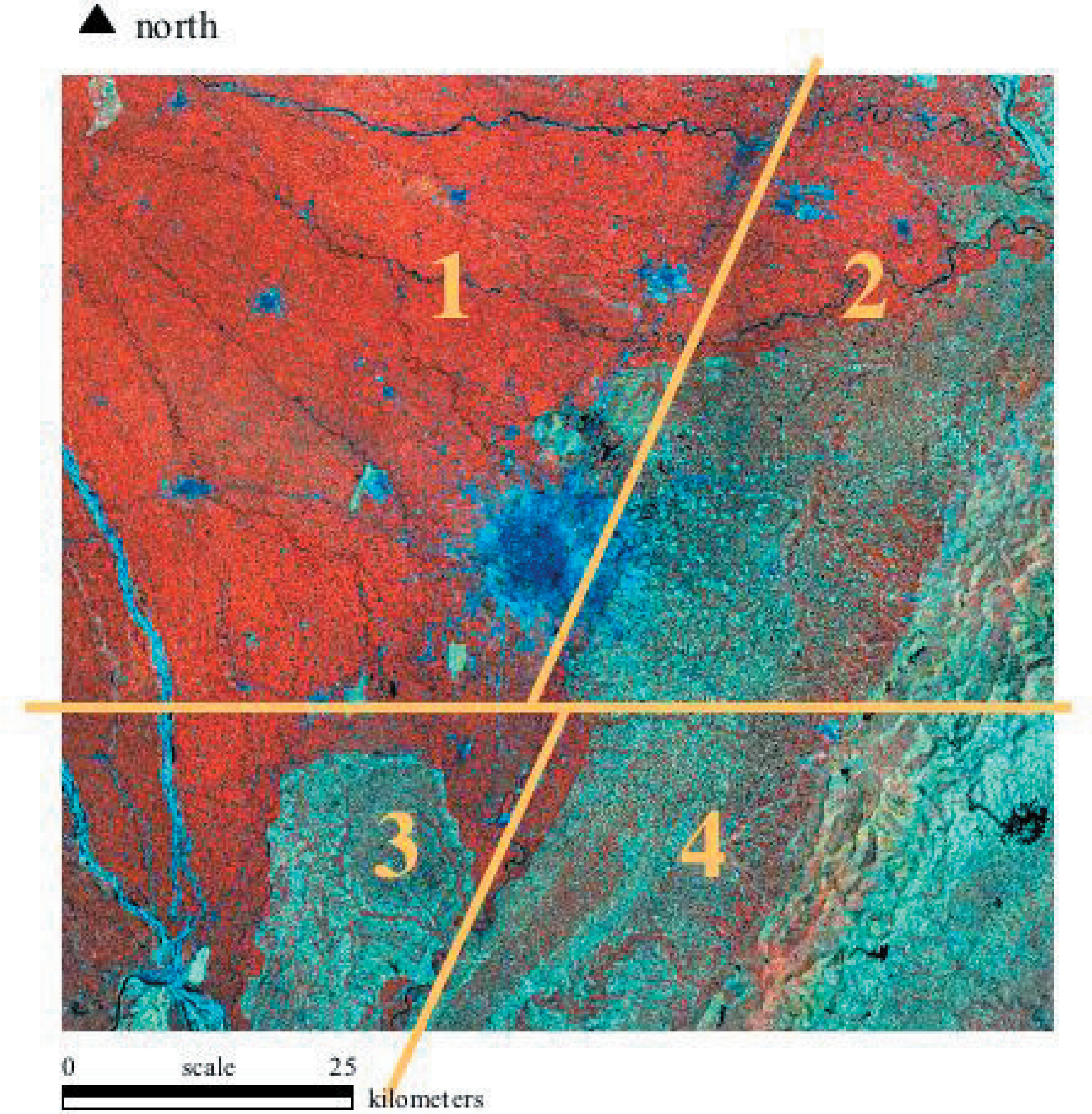


Figure A1: The four quadrants of the Chengdu study area used during image processing. The image shown is May 1988, bands 4, 3, and 2 set to red, green, and blue, where vegetation appears red and cities appear dark blue.

by the agrarian practices of the Chengdu region: availability of irrigation water and mild climate permit two to three crops per year with high inter-year and intra-year variability. Following the lead of several researchers (Brisco et al. 1995, Pax-Lenney et al. 1996, Oetter et al. 2000), a reliable means to distinguish agricultural plots from new urban plots is use of multiple images distributed over several seasons: spring green up (April, May), peak greenness of primary rice crop (August), and green up/peak greenness of secondary crop (December) (note the dates of acquired imagery in Table A1). By using information from multiple seasons, vegetation will probably be captured at least once. As a result, the temporal information allows the classifier to distinguish if a plot of land is agriculture (with varying amounts of vegetation over time), or if it has been converted to urban uses (consistently low amounts of vegetation).

After consideration of the methods/issues discussed above, a supervised multidate change detection approach was chosen. The method employed to map *stable* and *change* land cover classes relies on a supervised decision tree classification algorithm (C4.5), which has been widely used in the machine learning community (Quinlan 1993). Decision trees have recently received increased attention for remote sensing problems, and have been especially effective for multidate change detection problems because they are able to handle noisy or missing data, they require no *a priori* assumptions regarding the distribution of the input data, and they can handle complex, nonlinear relations between features and classes (Fayyad et al. 1992, Friedl and Brodley 1997).

Decision tree algorithms employ a hierarchical classification procedure that recursively partitions a data set into smaller subdivisions. The "tree" is composed of a root node, a set of internal nodes, and a set of terminal or leaf nodes. The splits defined at each internal node are estimated from training data using a statistical "learning" procedure that creates more homogeneous subsets of the data. In C4.5, each split is determined by a metric called the information gain ratio, which measures the reduction in entropy in the data produced by a split. Using this metric, decisions are made at the split that maximize the reduction in entropy of the training data in the descendent nodes (for detailed information, please refer to Quinlan 1993). The splitting process continues until each leaf node contains only observations from a single class or no gain in information results from further splitting. The class label is then assigned based on the terminal leaf node into which the observation falls.

A crucial step in the use of a decision tree is to correct the tree for overfitting by pruning the leaf nodes. Training data often contain noise, which decision trees split into leaf nodes (Quinlan 1987). This results in overfitting to noise in the data. The C4.5 algorithm uses error-based pruning to minimize this effect (Quinlan 1993).

A relatively new technique, known as "boosting", has been widely shown to increase classification accuracies using supervised algorithms, since it reduces misclassification errors and is resistant to overfitting (Friedl and Brodley 1999, McIver and Friedl 2001). Boosting improves classification accuracy by estimating multiple classifiers while systematically varying the training sample. At each iteration of the classifier, the training sample is modified to focus the classification algorithm on examples that were difficult to classify in the previous iteration. Once the iterations of the classifier are complete, the boosting algorithm computes a weighted vote for each pixel, assigning probabilities of class membership for each class at every pixel (Quinlan 1996). C4.5 with boosting thus produces two outputs:

(1) probabilities of each class at every pixel (values ranging from zero to 100 percent for every class), and
(2) a predicted class label based on the class with the highest probability from (1).

Initial results from the predicted class map for Chengdu (output 2) revealed substantial confusion among land cover classes, and overall accuracy of the map was below 50 percent. The *change* areas were often not represented, but were instead labeled *stable urban* or *stable agriculture*. Inspection of the class probabilities (output 1) revealed that the incorrectly labeled pixels consistently had a second most probable class that was the **correct** class. For example, a pixel converted to urban in 2002 was labeled *class 3*, agriculture, because the classifier reported 50 percent probability that the pixel belonged to this class. The second most likely label, though, was *class 9*, urban change, with a reported 45 percent probability.

With this in mind, the probability maps were extracted from the decision tree output for the five *change* classes. Using a density slicing technique, each probability map was compared directly with color combinations of the Landsat images to visually assess which probability values corresponded to areas of *change*. Once this value was determined, a binary mask of *change* areas was created and overlaid on the original classified map containing predicted values for the *stable* land cover classes (output 2) to create a final map of *change* and *stable* land cover types for each date. Results of this procedure are shown in Figures 5 and 6.

Because per-pixel classifications tend to be noisy due to minor misregistration effects, spatial information was extracted from the images and combined with the final output to produce a per-region map of land cover classes. A segmentation algorithm was used that exploits the correlation between neighboring pixels to aggregate neighboring pixels into polygons (Woodcock and Harward 1992). The resulting polygons are combined with the class map and labeled on the basis of the classes inside each polygon using a majority rule. In addition to removing isolated pixels, or speckle, from the final map, this method takes advantage of important spatial information in the remote sensing images.

As is necessary with virtually all maps made with remotely sensed data, a postclassification editing step was conducted. Each map was reviewed and relabeled as needed, using color composites of the images and information from on site visits. Some *stable* or *change* urban areas near Chengdu and Longquanyi were classified as agriculture. These areas were limited to the immediate region surrounding the city, and nearly all were misclassified due to cloud cover in one or more of the images. Therefore, map editing was necessary to ensure map accuracy.

A2.3 Accuracy Assessment

To validate the maps of land use change, the third phase involved ground-based accuracy assessment. Validating the maps of land use change is critical in order to improve methodology, improve area estimates, and understand biases in analysis (Congalton 1991, Gopal and Woodcock 1994). Accuracy assessment was performed using 152 training sites held out from the classification process. The results of the accuracy assessment are presented in Table A3.

map class	ground truth									user's accuracy (%)
	ag	*ag to urban 88*	*ag to urban 91*	*ag to urban 95*	*ag to urban 00*	*ag to urban 02*	*urban*	*nat veg*	*water*	
agriculture	**304**	14	4	12	21	18	5	31		74.3
ag to urban 88		**203**	24	3	4		42			73.6
ag to urban 91	1		**40**	2	5		1			81.6
ag to urban 95	7		21	**133**	4					80.6
ag to urban 00	3		7	14	**78**					76.5
ag to urban 02	4				12	**26**				61.9
urban		2	5				**459**			98.5
nat veg							1	**621**		99.8
water		1	4					12	**210**	92.5
producer's accuracy (%)	95.3	92.3	38.1	81.1	62.9	59.1	90.4	93.5	100.0	**88.0**

Table A3: Confusion matrix comparing ground truth field data (horizontal axis) to map categories (vertical axis) for 150 sites (2358) pixels. The number correct for each class is shown in bold, and overall accuracy of the map is shown in the lower right corner. The user's accuracy refers to the probability of a map class on the map being the true class on the ground. The producer's accuracy refers to the probability of a particular class on the ground being correctly classified in the map.

map class	ground truth									user's accuracy (%)
	ag	*ag to urban 88*	*ag to urban 91*	*ag to urban 95*	*ag to urban 00*	*ag to urban 02*	*urban*	*nat veg*	*water*	
agriculture	**24**		1	1	1	2	1	2		75.0
ag to urban 88		**23**	1	1			6			74.2
ag to urban 91			**7**	1	1					77.8
ag to urban 95			1	**18**	1					90.0
ag to urban 00			2		**10**					83.3
ag to urban 02					1	**3**				75.0
urban			1				**24**			96.0
nat veg								**10**		100.0
water			1					1	**5**	71.4
producer's accuracy (%)	100.0	100.0	50.0	85.7	71.4	60.0	77.4	76.9	100.0	**82.7**

Table A4: Confusion matrix comparing ground truth data to map categories for one pixel from each of 150 sites. The number correct for each class is shown and bold, and overall accuracy is presented in the lower right corner.

Notes

[1] For more detail on China's Western Development Program, see Lai 2002.

[2] *Chengdu Statistical Yearbook*, 2001.

[3]Details of the methodology are provided in Appendix A.

[4] While growth appears substantial in some areas, estimates of urban conversion of agricultural land could be inflated due to differences in satellite data in 1978 and 1988. Remote sensing estimates may overestimate the amount of agricultural land in 1978, because the resolution of the 1970s imagery is too coarse to differentiate urban features (e.g., roads, buildings) from agricultural land. Consequently, urban land could be underestimated in 1978, thus overstating urban growth between the 1978 and 1988.

[5] High levels of residential development lead, per se, to lower ratios, because the higher the population growth for a given amount of land conversion, the lower the ratio.

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