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Research Paper

The rapid and massive urban and industrial land expansions in China between 1990 and 2010: A CLUD-based analysis of their trajectories, patterns, and drivers

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HIGHLIGHTS

- China's urban and industrial lands increased by 4.23×10^4 km^2 between 1990 and 2010.
- The urban lands' expansion rate in the 2000s was 2.15 times that in the 1990s.
- The industrial lands' expansion rate in the 2000s was 5.79 times that in the 1990s.
- National policies played a more important role than economic factors.
- The use of China Land Use/Cover Dataset (CLUD) in national level analysis is effective.

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ABSTRACT

The past two decades saw rapid and massive urbanization and industrialization in China. Despite much research has been reportedly done at local and regional scales, little has been reported on the trajectories, patterns, and drivers of these two intertwining processes at the national level. This is mainly due to the fact that until recently, high resolution spatial data of land use and land cover change were not available at national level. The research reported in this paper aimed to fill this knowledge gap. Employing the China Land Use/Cover Dataset (CLUD), a national land use/cover change database our research team developed over the past decade, we analyzed the two intertwining processes at a 5 year interval from 1990 to 2010 to identify their trajectories, spatiotemporal patterns, and driving forces. Among out key findings are that (1) the nation's urban and industrial land areas increased from 4.85×10^4 km^2 in 1990 to 9.08×10^4 km^2 in 2010; (2) compared to those in the 1990s, the expansion rates of urban land and industrial land in the 2000s were respectively 2.15 and 5.79 times higher; (3) the expansion rates varied significantly across regions, revealing a distinctive spatial pattern with coastal regions being the fastest and the northeastern the slowest; (4) national development strategies and regional land-use policies had prominent impacts on land expansions; while (5) socioeconomic factors along with local and regional land-use policies explained the regional variations.

1. Introduction

More than half of the global population now lives in cities and the global urban population is predicted to reach 6.29 billion by 2050 (United Nations, 2012). Population growth and emerging trends of immigration to urban areas created serious environmental problems, especially in developing countries in Asia, such as China and India (Montgomery, 2008; Xiang, Stuber, & Meng, 2011). Industrialization is another process emerging in developing countries along with rapid urbanization (Deng, Huang, Rozelle, & Uchida, 2008). Urbanization and industrialization have become major factors affecting ecosystem services and environmental quality (Grimm et al., 2008; Kaza, 2013; Pickett et al., 2011; Seto, Guneralp, & Hutyra, 2012; Wu, 2014). Conversions from natural lands to urban and industrial lands have substantially affected the carbon cycle (Normile, 2008; Zhang et al., 2008), hydrological

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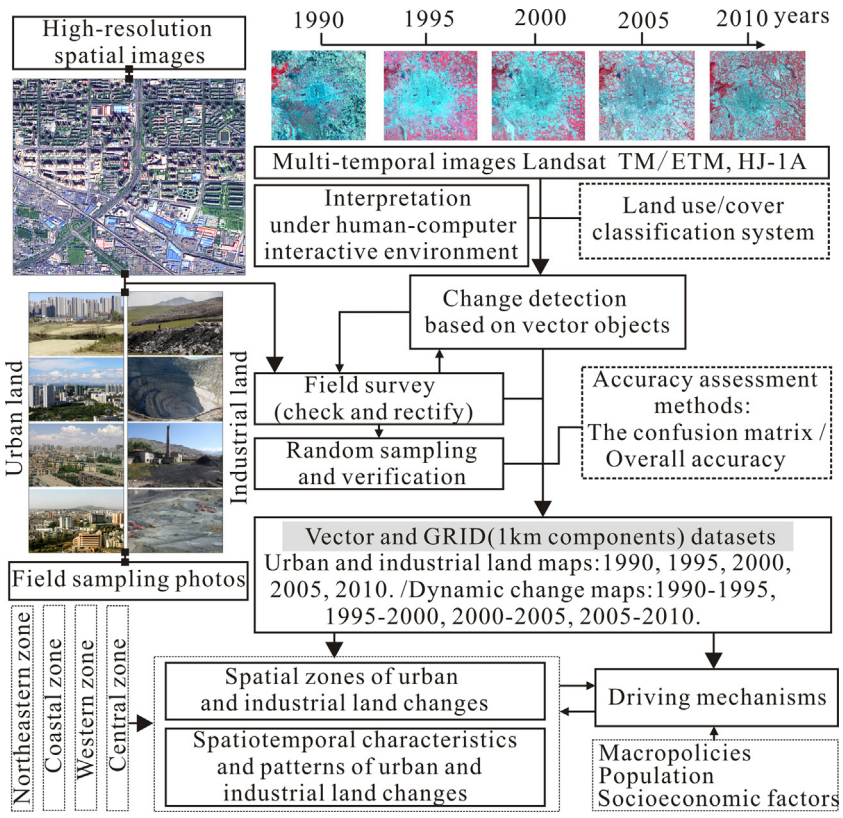

Fig. 1. Framework of data processing and analysis.

processes (McDonald et al., 2011; Mitchell, Mein, & McMahon, 2001), and surface energy balances (Bierwagen et al., 2010; Kuang, 2012; Kuang, Dou et al., 2015) of land ecosystems. Meanwhile, the accompanied environmental problems such as urban heat island effects and air pollution, severe smog and haze in particular, constitute a significant threat to human health (Kuang, Liu et al., 2015; Lu, 2007; Matus et al., 2012; Normile, 2008; Parrish & Zhu, 2009; Weng, Lu, & Schubring, 2004; Xiang et al., 2011; Zhang et al., 2013; Zhou et al., 2004).

The implementation of China's economic reform and open policy in 1978 stimulated rapid urbanization and industrialization in the country. In the early 1990s, the transition from a centrally planned economy to a socialist market economy greatly accelerated urbanization and industrialization in China (Gu & Shen, 2003). From 1990 to 2010, China's gross domestic product (GDP) underwent an unprecedented increase at an average rate of 10% per year; in the same time period, the number of prefecture-level cities increased from 188 to 287. The percentage of the population living in urban areas increased from 26.4% in 1990 to 49.9% in 2010 (National Bureau of Statistics of China, 2011) and exceeded 50% by the end of 2012. For the first time in its history, China became a predominantly urbanized country.

In this context, understanding the spatiotemporal patterns and driving forces of urban and industrial land expansions at the national scale is important to informed land use planning and sustainable development. Many studies have indeed investigated the spatiotemporal patterns of urban expansion in megacities, such as Beijing, Shanghai, and Guangzhou (Kuang, Chi, Lu, & Dou, 2014; Li, Zhou, & Ouyang, 2013; Schneider & Mertes, 2014; Wu & Zhang, 2012; Zhang, Ban, Liu, & Hu, 2011). Moreover, the spatiotemporal trajectories, patterns and socioeconomic driving forces of urban land expansion have been investigated at the urban agglomeration scale, including the Pearl River Delta, the Yangtze River Delta (Li & Yeh, 2004; Seto & Fragkias, 2005; Tian, Jiang, Yang, & Zhang, 2011; Weng, 2002), and the Beijing–Tianjin–Hebei agglomeration region (Kuang, 2011; Tan, Li, Xie, & Lu, 2005). However, because of the lack of high resolution national data, national scale analysis has been limited in both quality and quantity, inevitably creating knowledge gaps and leaving many important issues unaddressed or even unattended. While a limited number of studies focused on the urbanization processes, driving forces, and the reductions in the area of cultivated land during the 20th century (Deng et al., 2008; Liu, Liu et al., 2005; Liu, Xu, Zhuang, & Gao, 2005; Liu, Zhan, & Deng, 2005; Tian et al., 2005), little if any attention was paid to the industrialization process (Kuang et al., 2014; Wang et al., 2012). The claim that the country's urban expansion has been undergoing a transformation from a mode of clustering expansion to a mode of dispersed sprawling (for example,

Table 1
Urban and industrial land classification system.

1st level classes	Subclasses	Description
Urban and industrial land	–	Land used for urban and industrial land
	Urban land	Land used for residential, commercial, industrial, recreational, and transportation in cities and towns
	Industrial land	Land used for factories, quarries, mining, and oil-field wastes outside cities as well as land for special uses, such as roads and airports

Deng et al., 2015; Xu & Min, 2013) remains to be vindicated. Furthermore, there is still a knowledge gap on the effects of national policies on urban and industrial land changes. Since the beginning of the 21st century, for instance, China has implemented a series of national policies for regional development – including the Western Development, the Revitalization of the Northeast, and the Rise of Central China campaigns – to accelerate regional development, respectively, in the western, northeastern, and central China. The exact effects of these policies on national urban and industrial land expansions, however, are not well understood.

The China Land Use/Cover Dataset (CLUD) is a national high resolution database developed recently by our research team at the Chinese Academy of Sciences through a decadal effort aiming to build foundations for scholars to fill those gaps above mentioned (Liu, Liu, Zhuang, Zhang, & Deng, 2003; Liu, Zhan et al., 2005; Liu et al., 2010). It contains the longest time-series dataset available for continuously monitoring urban expansion dynamics at a national

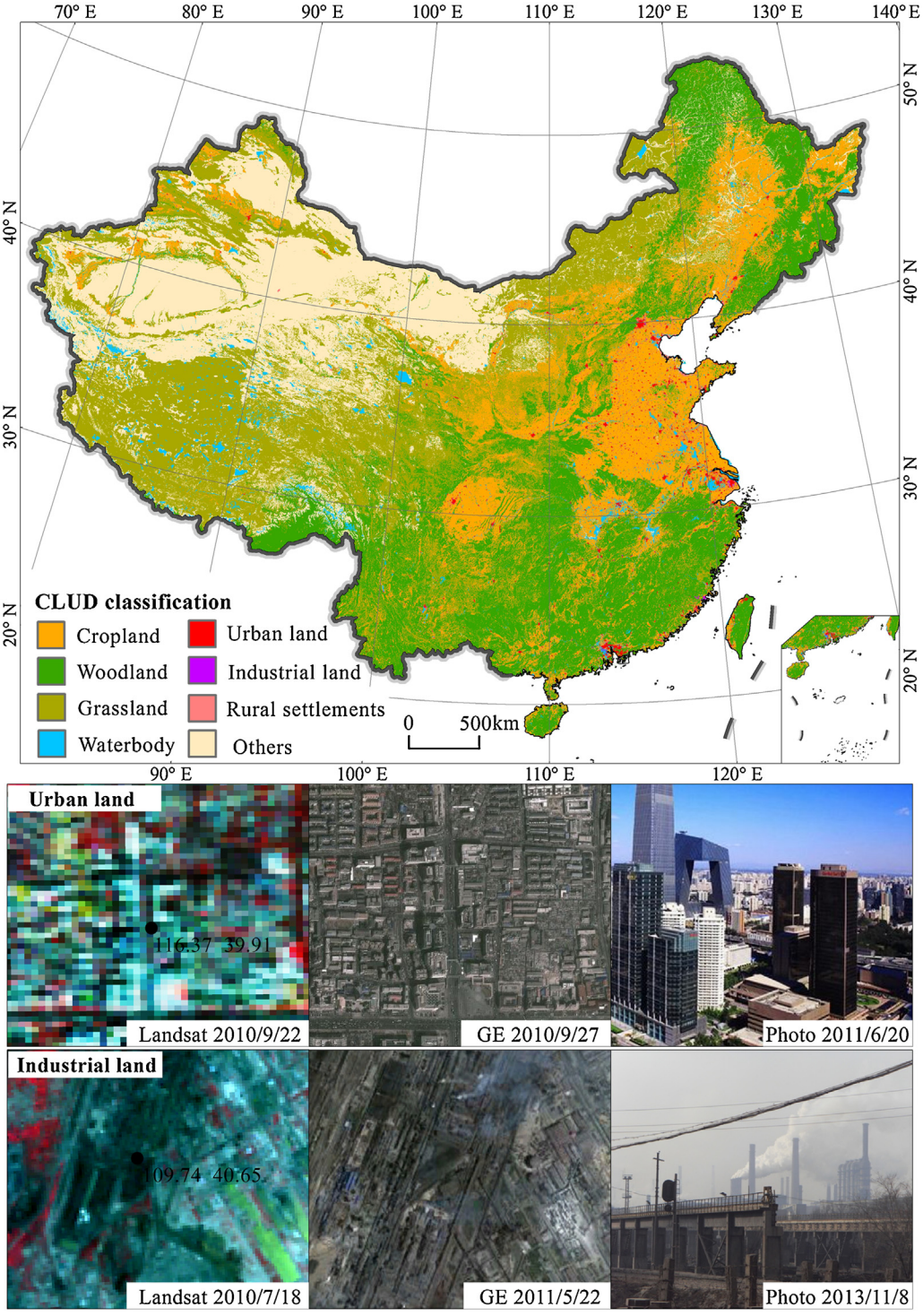

Fig. 2. CLUD 2010 with six general categories and built-up land subclasses.

scale in China (Deng et al., 2015; Tian et al., 2005; Xu & Min, 2013), and has been used to analyze the national urban land expansion at a 5-year interval from 1990 to 2000 (Jiang, Deng, & Seto, 2012; Kuang, Liu, Zhang, Lu, & Xiang, 2013; Liu et al., 2014; Wang et al., 2012). As part of our ongoing CLUD-based research to fill existent knowledge gaps at national level, the study reported in this paper aims to address the following two questions: what are the spatiotemporal trajectories and patterns of the national urban and industrial land expansions from 1990 to 2010? What are the major driving forces?

2. Methodology and implementation procedures

Fig. 1 shows the methodology for data processing and analyses. Urban and industrial land expansion datasets for the periods 1990–1995, 1995–2000, 2000–2005, and 2005–2010 were extracted from the CLUD database. Based on these data, gridded maps were developed to show the spatial intensity of urban and industrial land expansions at 1 km resolution across China in each of the time periods (Liu, Liu et al., 2005). Spatiotemporal patterns of urban and industrial expansions during 1990–2010 were then analyzed. We further compared the expansion rates of urban and industrial lands in different economic zones and investigated the effects of national policies and socioeconomic factors on the land expansions. The consequences of the urban and industrial expansions were also discussed.

2.1. Data

The CLUD dataset was generated from two sources: the Landsat TM/ETM+, and HJ-1A/1B images by CCRSDA, 2015. Its classification system includes six classes (cropland; forest; grassland; water bodies; built-up land and unused land) and 25 subclasses (Table 1 after Liu, Liu et al., 2005; also Zhang et al., 2014). Fig. 2 shows the result of CLUD 2010 with the six general categories and built-up land subclasses. Based on the CLUD urban and industrial maps in 1990, 1995, 2000, 2005, and 2010, the expansions of urban and industrial lands in the time periods 1990–1995, 1995–2000, 2000–2005, and 2005–2010 were investigated.

The accuracy assessments for CLUD have been addressed in previous studies (Kuang et al., 2013; Liu et al., 2003; Liu, Liu et al., 2005; Liu, Xu et al., 2005; Liu et al., 2010; Liu et al., 2014). In order to sustain the specific classification accuracy of the urban and industrial lands used in this study, we conducted additional validations in more than 10% of the counties in China. The ground truth datasets included GPS locations, photographs, landscape records, and high-resolution Google Earth images of more than 7875 sampling points for each period. The producer's accuracies of urban land and industrial land were 94.3% and 91.8%, respectively, and the users' accuracies were 93.7% and 91.8%, respectively. The detailed accuracy assessment results are given in Table 2.

2.2. Analysis of the rates and patterns of expansion of urban and industrial lands

The average rate of the annual expansion of urban or industrial land (ER, $km^2\ yr^{-1}$) is calculated by Eq. (1):

$$ER = \frac{S_{t2} - S_{t1}}{\Delta t} \quad (1)$$

where S_{t2} and S_{t1} are the urban or industrial land area (km^2) in year t_2 and t_1, respectively, and Δt is the number of years between t_2 and t_1.

For spatial analysis, we adopted China economic–geographical zoning scheme as it matches the spatial extents delineated in the national policies for regional development (Huang, Wei, He, & Li, 2015; Liu, Liu et al., 2005; Xu & Min, 2013). According to levels of socioeconomic development and national policies for regional development, the entire country of China was divided into four economic–geographical zones (Fig. 3a): (1) the coastal zone, an area of $90 \times 10^4\ km^2$ covering Shanghai, Beijing, Tianjin, Macau, and Hong Kong municipalities and Shandong, Guangdong, Jiangsu, Hebei, Zhejiang, Hainan, Fujian, and Taiwan provinces; (2) the western zone, an area of $682 \times 10^4\ km^2$ covering Chongqing municipality and Yunnan, Sichuan, Guizhou, Shanxi, Gansu, Qinghai, Inner Mongolia, Ningxia, Guangxi, Xinjiang, and Tibet provinces; (3) the central zone, an area of $97 \times 10^4\ km^2$ covering Anhui, Shaanxi, Jiangxi, Henan, Hubei, and Hunan provinces; and (4) the northeastern zone, an area of $91 \times 10^4\ km^2$, covering Jilin, Heilongjiang, and Liaoning provinces.

2.3. Evaluation of driving forces

Socioeconomic factors and national policies are the dominant drivers of urban and industrial land expansions. Based on statistics data (National Bureau of Statistics of China, 1991, 1996, 2001, 2006, 2011), we collected socioeconomic indicators, including the non-agriculture population, GDP, increased industrial production value, and fixed-asset investments in industrial production at provincial level. To investigate the effects of the national policies, we compared the time and place of policy implementation with the dynamics of urban and industrial land expansions.

Statistical analyses were used to explore the relationships between other socioeconomic factors and the expansions of urban and industrial lands. Specifically, the Pearson correlation coefficients between the expansions of urban land and changes in the non-agriculture population and GDP were calculated. In

Table 2
Confusion matrix of the CLUD 2010 validation.

Class	Ground truth (GT) samples (pixels)								Total classified pixels	User's accuracy (%)
	Cropland	Woodland	Grassland	Water body	Urban land	Industrial land	Rural settlement	Other		
Classification										
Cropland	1410	21	67	1	2	1	2	26	1530	92.16
Woodland	33	1697	83	4	4	2	3	34	1860	91.24
Grassland	49	132	1880	5	6	7	4	67	2150	87.44
Water body	1	0	8	158	0	0	0	3	170	92.94
Urban land	3	0	5	0	281	2	1	8	300	93.67
Industrial land	5	2	5	1	1	176	1	4	195	90.26
Rural settlements	1	0	2	1	0	1	156	9	170	91.76
Other	31	18	101	2	4	3	3	1338	1500	89.20
Total GT pixels	1533	1870	2151	172	298	192	170	1489	7875	
Producer's accuracy (%)	91.98	91.98	90.75	87.40	91.86	94.30	91.67	91.76	89.86	

addition, the correlation was calculated between the expansion of industrial land and increments of industrial production and fixed-asset investments.

To determine the dominant drivers for each economic–geographical zone, the effects of national policies and other socioeconomic factors on the changes in urban and industrial land use were analyzed with a mixed qualitative and quantitative method. The interviewees include managers and experts from more than ten provinces and from several national agencies, including the National Development and Reform Commission, the Ministry of Land Resource, the Ministry of Urban Planning, and the Environment Protection Agency. The interview results were then used as input to the Mind Map analysis (http://thinkbuzan.com/) to quantitatively assess the effects of national

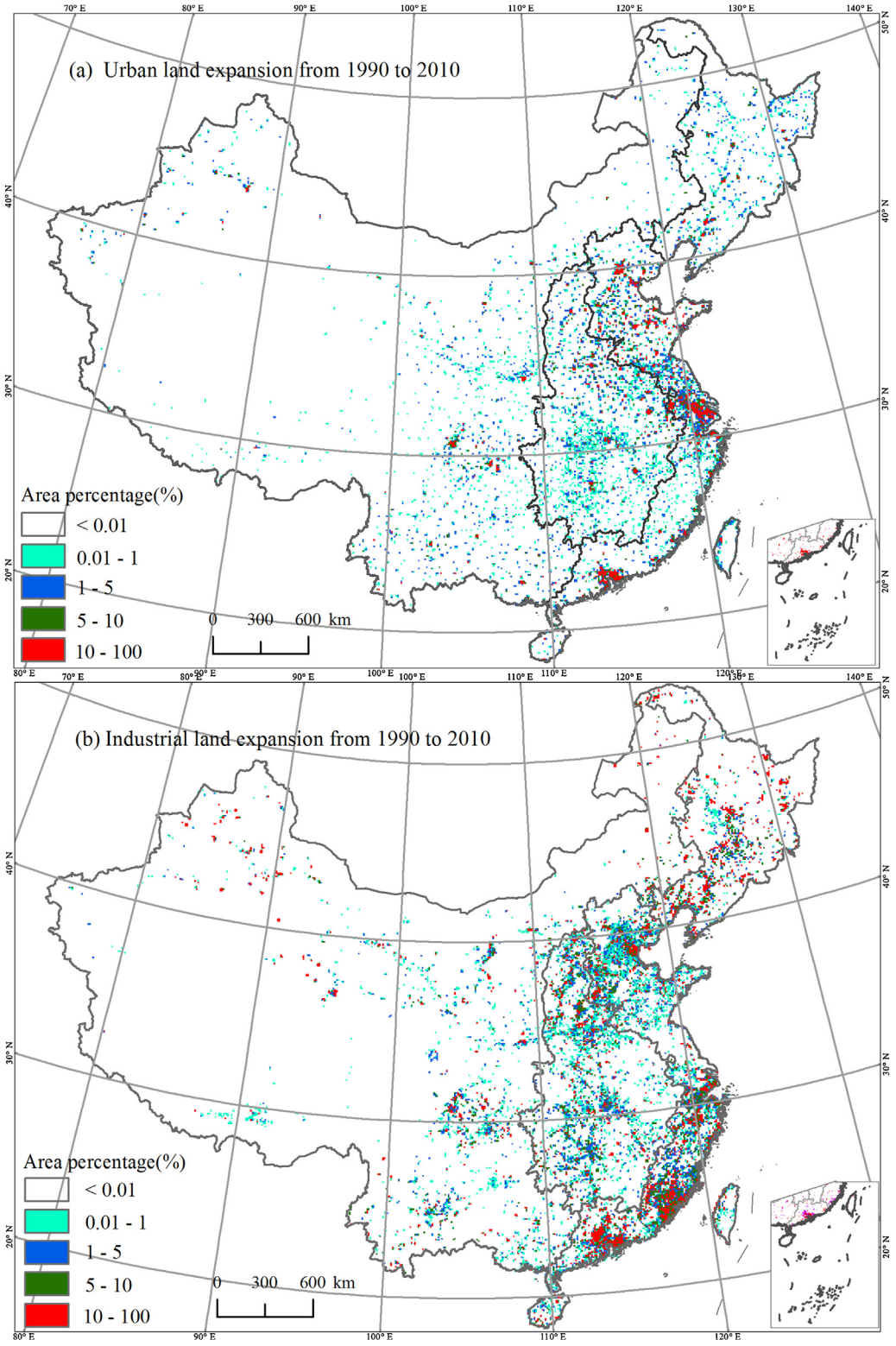

Fig. 3. Proportion of expansion of urban and industrial lands from 1990 to 2010 with a cell size of 10 km × 10 km.

Table 3
Area of expansion of urban and industrial lands from 1990 to 2010.

Year/period	Coastal zone		Western zone		Central zone		Northeastern zone		Total	
	Urban land	Industrial land	Urban land	Industrial land	Urban land	Industrial land	Urban land	Industrial land	Urban land	Industrial land
	Land area (km^2)									
1990	17, 257.43	8296.07	5106.27	2741.09	6960.57	1761.17	5021.53	1344.28	34,345.80	14,142.62
1995	21, 512.61	8883.57	5822.68	2867.97	8344.33	2155.98	5330.37	1442.33	41,010.00	15,349.86
2000	22, 095.40	9776.87	6513.13	3003.59	8562.08	2337.85	5410.23	1443.78	42,580.85	16,562.10
2005	28, 561.09	13, 031.35	7685.62	3838.22	10,154.22	2892.33	5605.73	1612.40	52,006.67	21,374.31
2010	32, 730.69	16, 933.32	9605.88	6094.30	11,915.72	5511.10	6031.19	2026.48	60,283.48	30,565.20
	Area of expansion (km^2)									
1990–1995	4255.18	587.5	716.41	126.88	1383.76	394.81	308.84	98.05	6664.19	1207.24
1995–2000	582.79	893.3	690.45	135.62	217.75	181.87	79.86	1.45	1570.85	1212.24
2000–2005	6465.69	3254.48	1172.49	834.63	1592.14	554.48	195.50	168.62	9425.82	4812.21
2005–2010	4169.60	3901.97	1920.26	2256.08	1761.50	2618.77	425.46	414.08	8276.82	9190.89
1990–2010	15, 473.26	8637.25	4499.61	3353.21	4955.15	3749.93	1009.66	682.2	25,937.68	16,422.58
	Rate of expansion ($km^2\ yr^{-1}$)									
1990–1995	851.04	117.50	143.28	25.38	276.75	78.96	61.77	19.61	1332.84	241.45
1995–2000	116.56	178.66	138.09	27.12	43.55	36.37	15.97	0.29	314.17	242.45
2000–2005	1293.14	650.90	234.50	166.93	318.43	110.90	39.10	33.72	1885.16	962.44
2005–2010	833.92	780.39	384.05	451.22	352.30	523.75	85.09	82.82	1655.36	1838.18
1990–2010	773.66	431.86	224.98	167.66	247.76	187.50	50.48	34.11	1296.88	821.13
	Expansion ratio (%)									
1990–1995	24.66	7.08	14.03	4.63	19.88	22.42	6.15	7.29	19.40	8.54
1995–2000	2.71	10.06	11.86	4.73	2.61	8.44	1.50	0.10	3.83	7.90
2000–2005	29.26	33.29	18.00	27.79	18.60	23.72	3.61	11.68	22.14	29.06
2005–2010	14.60	29.94	24.99	58.78	17.35	90.54	7.59	25.68	15.91	43.00
1990–2010	89.66	104.11	88.12	122.33	71.19	212.92	20.11	50.75	75.52	116.12

policies and socioeconomic factors to urban and industrial land expansions (Budd, 2004; Seto, 2011). These effects were then classified into three levels: significant (++), fair (+), and limited (−) (Table 5).

3. Results

3.1. General characteristics of urban and industrial land expansions at the national level

The total urban and industrial land area of China was $9.08 \times 10^4\ km^2$ in 2010, accounting for 0.95% of the total land surface area. The area of urban land ($6.0 \times 10^4\ km^2$) was about twice the area of industrial land ($3.1 \times 10^4\ km^2$) (Table 3). The urban land was mainly distributed in the coastal zone (54.29%) as a result of the higher levels of economic development in areas such as the Beijing, Shanghai, and Guangzhou urban agglomerations. China's urban and industrial land expanded 87% from 1990 to 2010 (Table 3). It is noteworthy that the expansion of industrial land (+116%) was much faster than that of urban land (+76%).

On the decadal scale, the rate of urban expansion accelerated from $1647\ km^2\ yr^{-1}$ in the 1990s to $3540\ km^2\ yr^{-1}$ in the 2000s. The expansion rate of industrial land increased even more dramatically, from $242\ km^2\ yr^{-1}$ in the 1990s to $1400\ km^2\ yr^{-1}$ in the 2000s (Table 3). On a finer scale of 5 years, the temporal trajectories were complex (Table 3). The urban expansion rates decreased in 1995–2000 and peaked in 2000–2005. The expansion rates of industrial land remained slow ($241\ km^2\ yr^{-1}$) in the 1990s, but increased sharply in 2000–2005 ($962\ km^2\ yr^{-1}$) and 2005–2010 ($1838\ km^2\ yr^{-1}$).

3.2. Spatiotemporal patterns of urban and industrial land expansions

Regional differences in the expansion of urban and industrial lands were notable among the four zones (Fig. 3). The coastal zone, which accounts for 9.36% of the national land area, accounted for 59.32% of the national expansion of urban and industrial lands from 1990 to 2010, including an increase in urban land of $1.51 \times 10^4\ km^2$ and an increase in industrial land of $1.01 \times 10^4\ km^2$. The coastal zone played a leading role in China's economic development during this period; economic development in the other three zones was on track with the development trajectory of the coastal zone, but with different time lags. In the coastal zone, the expansion of urban and industrial lands was faster in the 2000s ($1874\ km^2\ yr^{-1}$) than in the 1990s ($635\ km^2\ yr^{-1}$). The rapid expansion of the megacities (e.g. Beijing, Shanghai, and Guangzhou) in 2000–2010 is shown in Fig. 4. The central zone experienced an urban expansion of $0.48 \times 10^4\ km^2$ and an expansion in industrial land of $0.44 \times 10^4\ km^2$ from 1990 to 2010. The combined expansion rate of urban and industrial lands in the 2000s ($699\ km^2\ yr^{-1}$) was higher than in the 1990s ($218\ km^2\ yr^{-1}$). The western and northeastern zones experienced expansions of urban and industrial lands of 0.83×10^4 and $0.18 \times 10^4\ km^2$, respectively, from 1990 to 2010. The western zone also had a higher rate of urban expansion in the 2000s ($660\ km^2\ yr^{-1}$) than in the 1990s ($168\ km^2\ yr^{-1}$). The same phenomenon was found in the city of Chengdu in the western zone (Fig. 4). The expansion of urban and industrial lands in the northeastern zone was not notable (Table 3). Fig. 4 indicates that the northeastern cities, e.g. Harbin, Changchun, and Shenyang, had less urban expansion than the cities in the other zones between 1990 and 2010. The magnitudes and spatial patterns of expansion of urban and industrial lands among the different zones varied considerably between 1990–2000 and 2000–2010.

The expansion rates of urban and industrial lands varied during the 5-year interval between 1990 and 2010 (Figs. 5 and 6). Sharp decreases in the expansion of urban and industrial lands occurred during the period 1995–2000 (Table 3) and urban land expansion in the four zones showed different variations during the period 2000–2010. In the coastal zone, the urbanization expansion reached its peak in 2000–2005, followed by a deceleration from 2005 to 2010. However, the other three zones showed continuous

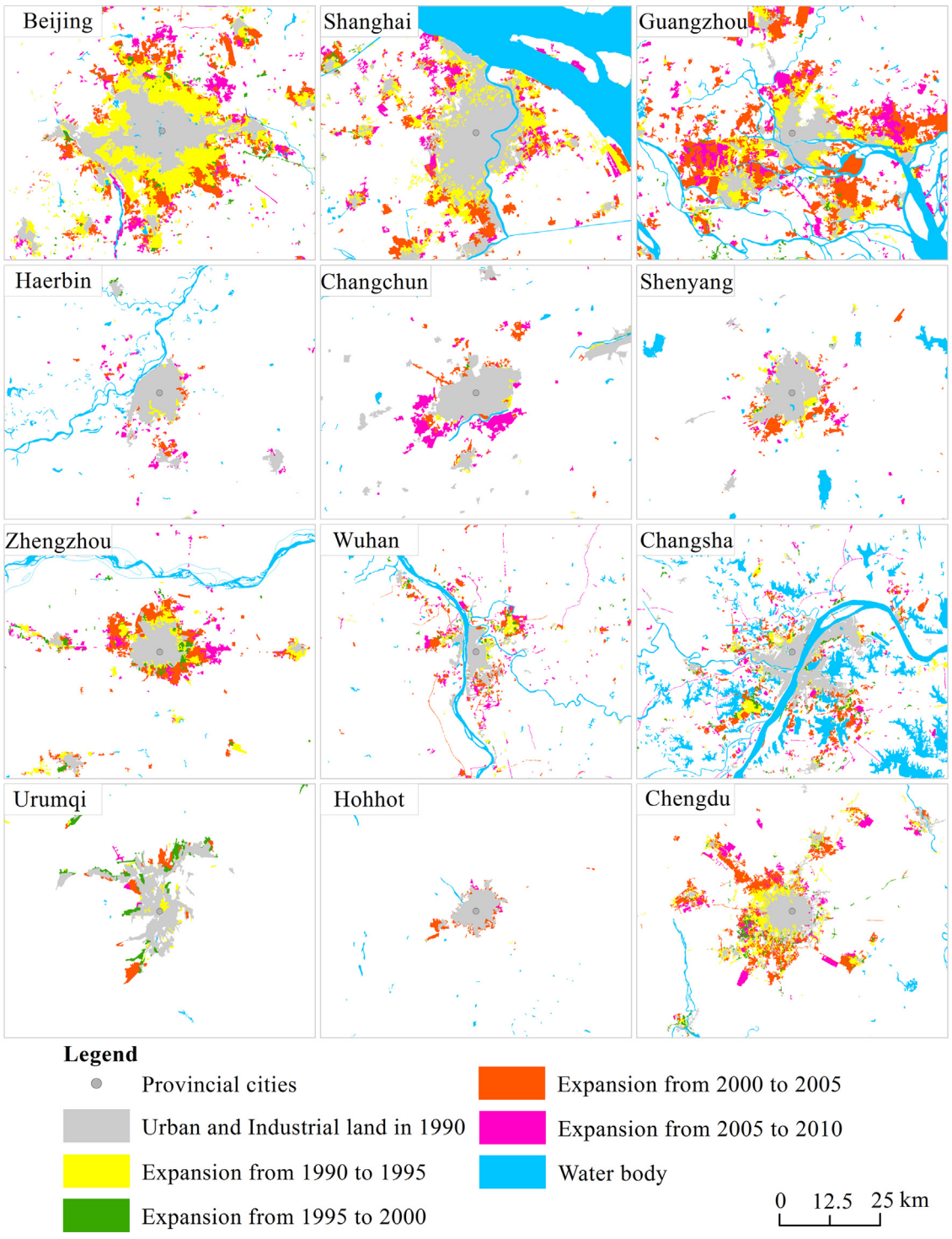

Fig. 4. Hotspots of urban and industrial land expansions in four zones of China: Beijing, Shanghai, and Guangzhou in the coastal zone; Harbin, Changchun, and Shenyang in the northeastern zone; Zhengzhou, Wuhan, and Changsha in the central zone; and Urumqi, Hohhot and Chengdu in the western zone.

increases. All four zones saw increased industrial land expansion (Table 3).

3.3. *Driving forces of urban and industrial land expansions*

3.3.1. *Effects of national policies*

Changes in urban and industrial land use between 1990 and 2010 were related to the nation's policy dynamics across different development stages (Fig. 7). With the implementation of economic reforms and the open policy in 1978, China entered a new era of urbanization and industrialization. With the establishment of the socialist market economy system in 1992, the economy showed an upward trajectory and urban and industrial lands began to expand rapidly. In particular, the development of real estate industry and the institutionalization of new investment and development zones were the main drivers of urban and industrial land expansions from 1990 to 1995. To prevent dramatic and extensive urban sprawl and the related loss of cropland, the central government issued a series of laws and regulations for cropland protection from the early 1990s (Liu, Zhan et al., 2005). For example, regulations on

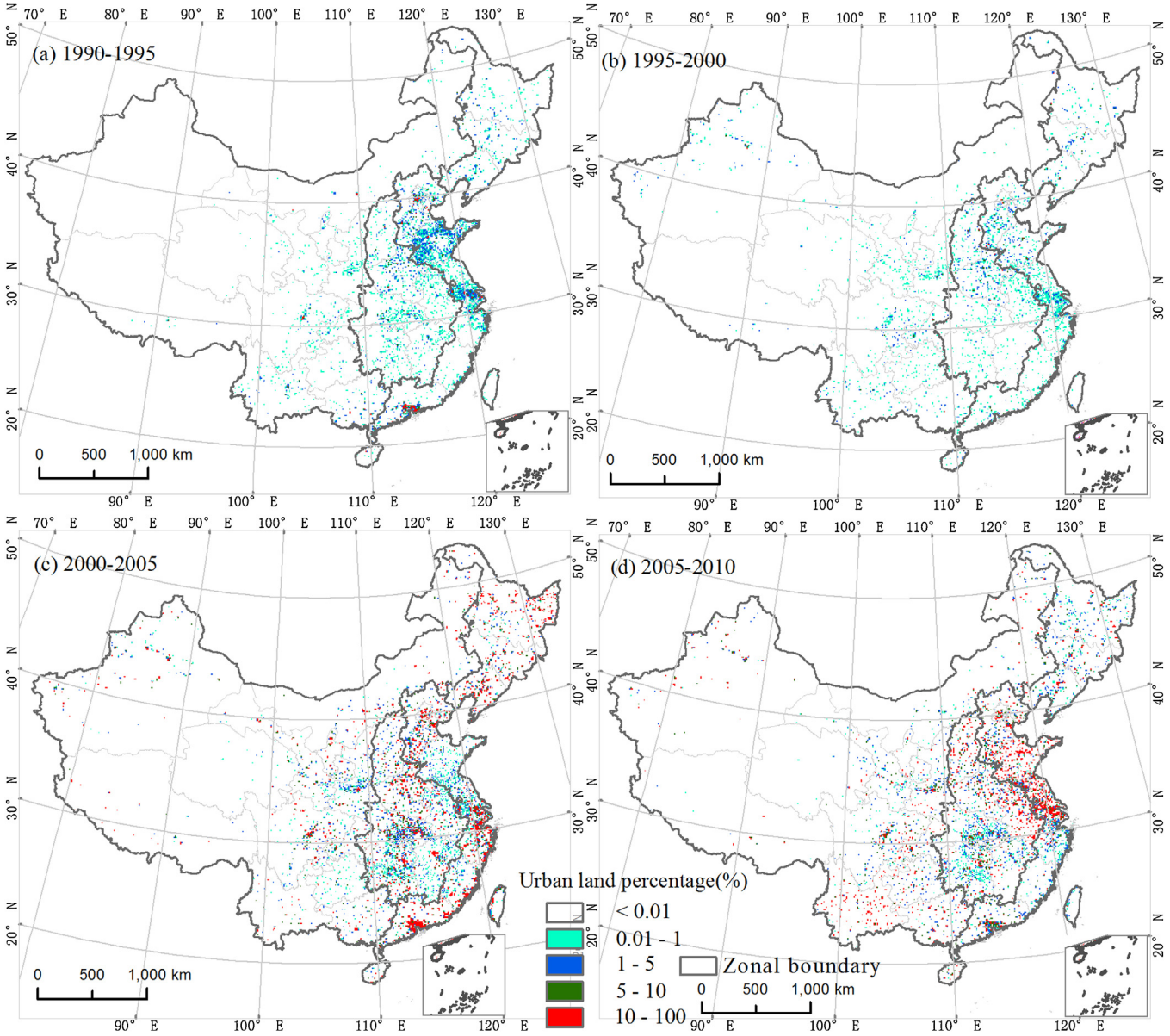

Fig. 5. Urban expansion from 1990 to 2010 in four phases: (a) 1990–1995; (b) 1995–2000; (c) 2000–2005; and (d) 2005–2010. Cell size of 10 km × 10 km.

the National Protection of Prime Farmland were issued in 1994 to protect prime farmland and promote the sustainable development of agricultural production. With the implementation of the revised Land Management Law of P.R. China in 1998, cropland protection became a primary national policy. As a result, the combined expansion of urban and industrial lands decreased from 787 $km^2\ yr^{-1}$ during 1990–1995 to 278 $km^2\ yr^{-1}$ during 1995–2000 (Table 3).

After China joined the World Trade Organization (WTO) in 2001, urbanization and industrialization again accelerated and the central government implemented a series of regional development plans to equalize regional development, including the China Western Development Plan in 2000, the Northeast Area Revitalization Plan in 2004, and the Rise of Central China Plan in 2006. As a result, a large amount of the central government's investments was targeted to infrastructure in these regions. These development campaigns promoted regional urban and industrial land expansions in the inland regions, a trend that was particularly notable in the western and central zones, where urban and industrial lands increased more rapidly in the 2000s than in the 1990s (Fig. 5).

3.3.2. *Influence of socioeconomic factors*

In addition to the qualitative analysis of the policy effects, the relationships between socioeconomic variables and urban and industrial land expansions were also examined, As shown in Table 4, increases in the non-agricultural population significantly correlate with the expansion of urban land in all four intervals between 1990 and 2010 (Fig. 8); GDP growth closely correlates with the expansion of urban land, especially during 2000–2005 with the highest correlation coefficient (0.82). The correlations between the expansion of industrial and urban land and industrial growth, as manifested by the increase in industrial production and fixed-asset investments, are significant. Industrial land expansion is widely distributed in the primary mining regions of China, including provinces of Shanxi and Hebei, and the Inner Mongolia Autonomous Region (Fig. 3). In general, population growth and economic development are the prime driving forces of the expansion of urban and industrial lands; however, significant divergence in these driving forces is observed for the periods of 1995–2000 and 2000–2005. This finding indicates that national policies have

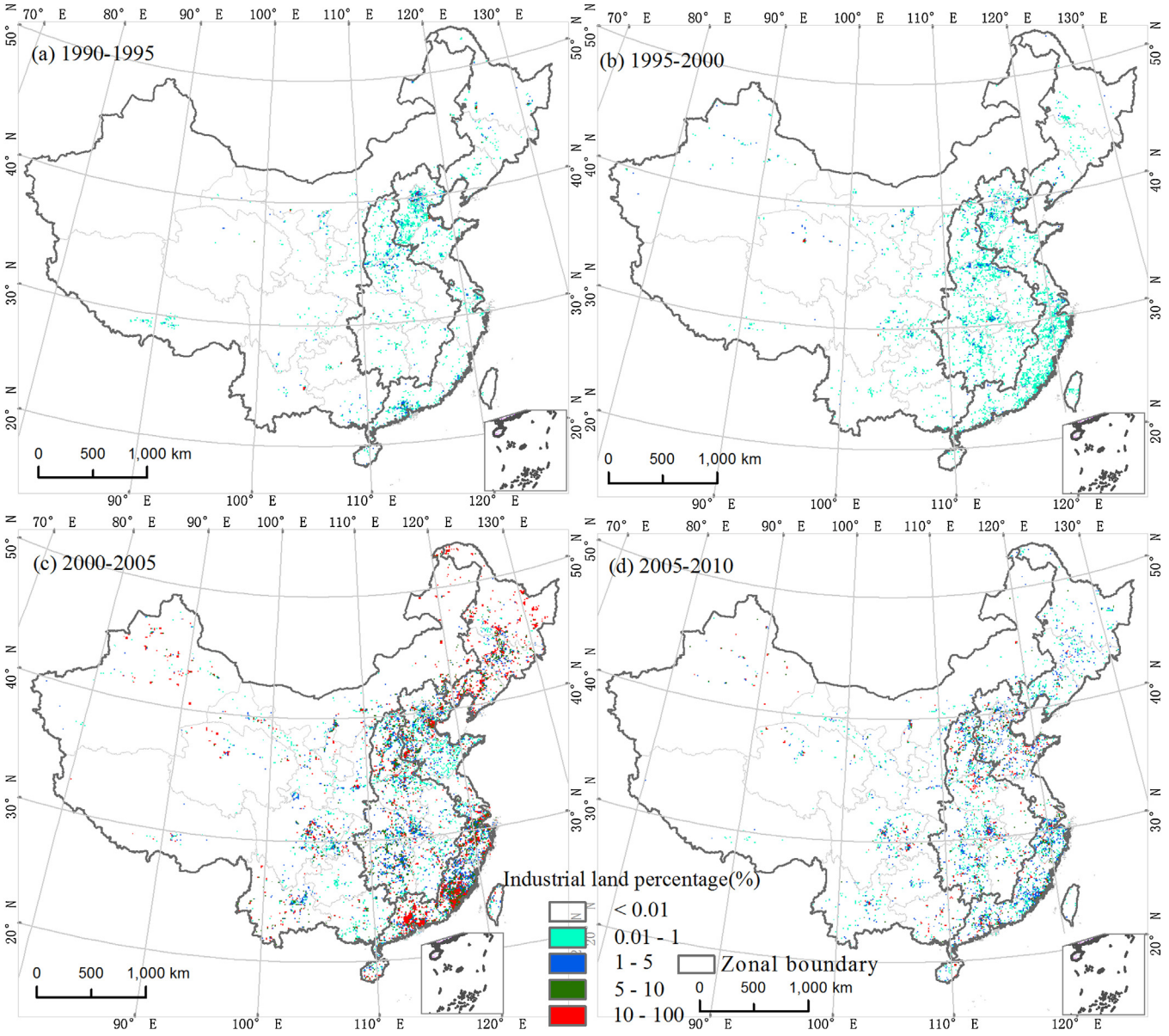

Fig. 6. Industrial expansion from 1990 to 2010 in four phases: (a) 1990–1995; (b) 1995–2000; (c) 2000–2005; and (d) 2005–2010. Cell size of 10 km × 10 km.

stronger influences on the expansion of urban and industrial lands than population and economic factors (Fig. 7).

3.4. Contribution levels of the major drivers

The contribution levels of different policy and socioeconomic drivers on the expansion of urban and industrial lands are summarized in Table 5. The socialist market economy system promoted the expansion of urban and industrial lands, whereas the Regulations on the Protection of Prime Farmland in 1994 and the Land Management Law revision in 1998 played important roles in restraining these expansions from 1995 to 2000. Non-agriculture population growth, economic development (e.g. increases in GDP), and the economic stimulus in the wake of China's landmark WTO membership accelerated the expansion of urban and industrial lands in the 2000s. These economic stimuli promoted major infrastructure projects, including railways, freeways, energy structures, harbors, and airports, which contributed to the expansion of industrial land. In summary, rapid urbanization and industrialization during the first 5 years of the 1990s can be attributed to fast economic development and the large-scale construction of developing industrial zones across China. The implementation of policies related to the protection of farmland in the following 5 years (1995–2000) restrained the expansion of urban and industrial lands. Since 2000, a series of regional development campaigns have promoted the rapid expansions of urban and industrial lands in these target regions.

4. Discussions

4.1. The effectiveness of CLUD-based research

Our study presented the spatiotemporal trajectories and patterns of national urban and industrial land expansions, and revealed notable differences between the two decadal periods (1990–2000 and 2000–2010). As previous studies did not consider the expansion of the industrial lands (Deng et al., 2015; Liu, He, Zhang, Huang, & Yang, 2012; Tian et al., 2005; Wang et al., 2012; Xu & Min, 2013), our study is the first of its kind that investigated the spatiotemporal characteristics of national urban and industrial land dynamics

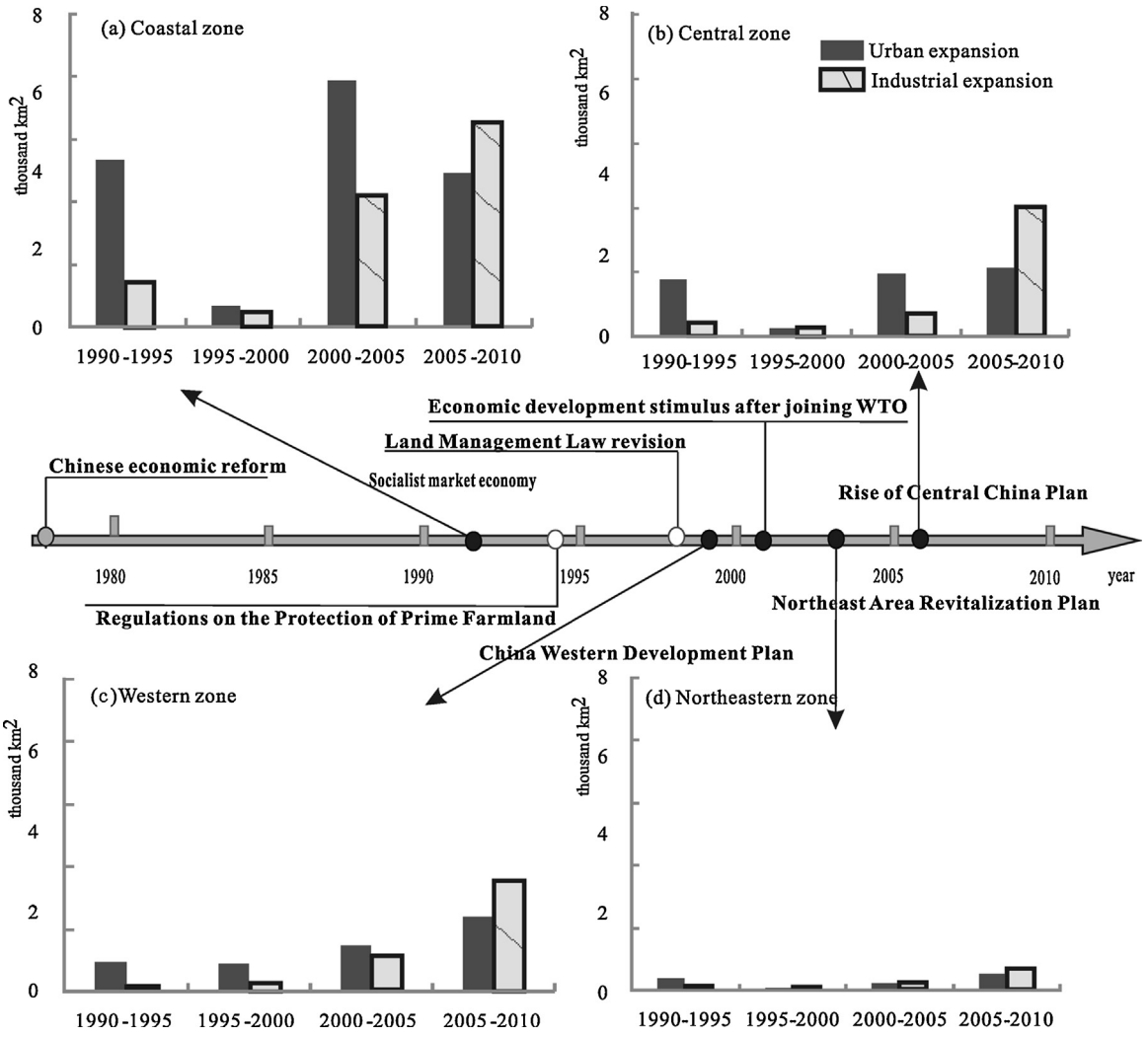

Fig. 7. Impact of policies on various urban and industrial land expansions between 1990 and 2010 in four zones: (a) coastal; (b) central; (c) western; and (d) northeastern. The land-use policies implemented in China since Chinese economic reform are marked on the time axis. Black dots represent the policies or campaigns promoting the expansion of urban and industrial lands; white dots represent the policies constraining the expansion of urban and industrial lands; and gray dots represent the policies and regulations before 1990.

Table 4
Correlation between expansion of urban and industrial lands and socioeconomic variables.

Variable	1990–1995	1995–2000	2000–2005	2005–2010
Expansion of urban land				
Non-agriculture population change	0.83***	0.67***	0.81***	0.80***
GDP change	0.77***	−0.181*	0.82***	0.60***
Expansion of industrial land				
Increased value of industrial production	0.56**	0.42**	0.60**	0.48**
Fixed-asset investments in industrial production	0.49**	0.49**	0.54**	0.50**

Note: Statistical sample number is 34.
*** $P \leq 0.001$.
** $0.001 < P < 0.01$.
* $P \geq 0.01$.

separately. The success in differentiating these two types of built-up lands and using them in a national level analysis would have not been possible without the readily availability of high resolution land use/cover data from CLUD. Indeed, the study is but a latest showcase of the effectiveness of CLUD-based research.

4.2. Spatiotemporal trajectories and patterns

This research indicates that urban areas in China doubled from 1990 to 2010 and the expansion rate in the 2000s was higher than that in the 1990s, consistent with other studies (Kuang et al., 2013; Wang et al., 2012). Furthermore, different growth rates and modes were observed between urban and industrial lands across China from 1990 to 2010. The in-filling and poly-nuclei urbanization in the 1990s has evolved into an extensive sprawling of mega built-up areas in the 2000s (Kuang et al., 2014; Taubenböck et al., 2014; Xu & Min, 2013). In comparison, the industrial lands experienced an accelerated expansion in the 2000s than in the 1990s due to increasing infrastructure construction (e.g., high-speed railways and freeways) and mining (e.g., coal and petroleum).

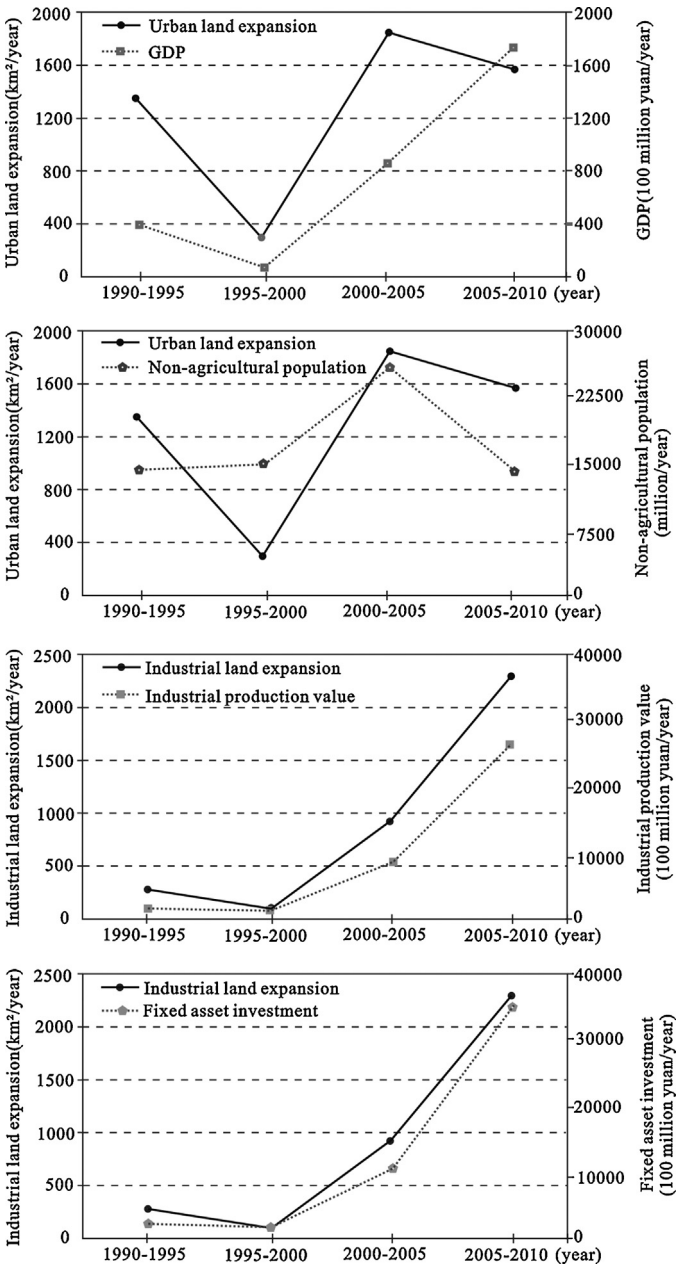

Fig. 8. Relationships among changes in the non-agriculture population, gross domestic product (GDP), and expansion of urban and industrial lands.

4.3. The main driver of the expansions

Our results also show that the differences in the urban and industrial land expansion are mainly a result of national policy dynamics (Fig. 7 and Table 5). A literature review revealed that the dominant driving factors of China's rapid urban expansion were population and economic growth, and national policies (Deng et al., 2015; Huang et al., 2015; Liu, Zhan et al., 2005). Globalization has been identified as another driver that has resulted in urban expansion since the beginning of the 21st century, especially in the coastal zone of China (Huang et al., 2015; Jiang et al., 2012; Seto & Kaufmann, 2003). Based on quantitative and qualitative analyses, we identified the contribution diversity from these driving forces in the expansion pattern of urban and industrial lands. The immigration from rural to urban areas, fixed-asset investments, and GDP growth could directly cause the expansion of urban and industrial lands (Fig. 8). However, their effects have been overridden by national development strategies and regional land-use policies, which are higher level drivers to the expansion of urban and industrial lands (Fig. 7). For example, China Western Development strategy resulted in the more prominent expansion of urban and industrial lands in the 2000s than in the 1990s (Table 5 and Fig. 7).

4.4. Implications for national development strategies and regional land-use policies

Since 2014, the Chinese government has been promoting a new urbanization strategy to develop human-oriented, efficient, and sustainable cities (Fang & Ma, 2013; Zeng, Zhang, Cui, & He, 2015). The CLUD-based research can be an effective instrument in support of its implementation. For example, with the CLUD data, we found that there has been an increase in low density land use and even vacant lands in newly expanded areas since the beginning of the 21st century. This underscores the eminent need for a national policy that adapts "smart growth" strategies to improve land use efficiency. According to our investigation, for another example, the majority of urban and industrial land expansion (63%) between 1990 and 2010 took place on cropland, resulting in a conversion of 1.90% of the nation's cropland area (2.80×10^4 km^2) into urban or industrial land. As most of these converted cropland used to be of high productivity, their loss has inevitably imposed significant vulnerability to the national food supply system (Song & Pijanowski, 2014). This CLUD-based research finding therefore vindicates the importance of strictly enforcing the existent national policy on prime farmland protection.

Potentially, a CLUD-based time-series analysis of the expansion of urban and industrial lands could also be used to generate information useful for planners and policy makers. For example, it can be employed to inform environmental planners by identifying hotspots for the effects of urbanization and industrialization on ecological and environmental processes, such as the carbon cycle and air pollution.

Table 5
Contribution levels of policies and socioeconomic factors to the expansion of urban and industrial lands.

Variable	1990–1995	1995–2000	2000–2005	2005–2010
Socialist market economy	++	–	++	++
Regulations on the Protection of Prime Farmland, Land Management Law revision	+	++	+	+
Economic development stimulus after joining WTO	++	–	++	++
China Western Development Plan	N/A	N/A	++(W)	++(W)
Rise of Central China Plan	N/A	N/A	N/A	+(C)
Northeast Area Revitalization Plan	N/A	N/A	N/A	–(N)
Non-agriculture population growth and GDP	++(U)	–(U)	++(U)	++(U)
Increased value of industrial production and fixed-asset investments	+(E)	–(E)	+(E)	+(E)

Note: ++, significant effects; +, moderate effects; –, almost no impact; N/A, not applicable; W, C, and N represent western, central, and northeastern China, respectively; U and E represent urban and industrial land expansions, respectively.

5. Conclusions

With the high resolution CLUD data, this study investigated the expansion patterns of urban and industrial lands in China from 1990 to 2010. Especially, we reported the industrial land expansion characteristics at the national scale for first time. We found that the expansion rates of urban and industrial lands accelerated in the latter half of the study period (2000–2010) and that industrial land expanded more rapidly than urban land. Our study also suggested that national policies played a critically important role in the land developments and that the promulgation and implementation of national policies and regional land-use regulations should consider tradeoffs among the expansion of urban and industrial lands, cropland protection, ecological restoration, and environmental pollution control. Our study also demonstrated the potential for the CLUD-based time-series research to contribute both to scholarly literature on urbanization and industrialization and to national policy making.

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